ATTACHMENT 9.1

Index to Attachment 9

Submission to Dendrobium Coal Mine Extension Project (SSI-33143123).

Relevant Climate Change Documents for Consideration

#	Documents	Date
1.	IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.	2022
2.	IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.	2022
3.	IPCC, 2022: Chapter 11: Australasia [Lawrence, J., B. Mackey, F. Chiew, M.J. Costello, K. Hennessy, N. Lansbury, U.B. Nidumolu, G. Pecl, L. Rickards, N. Tapper, A. Woodward, A. Wreford et al.)]. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.	2022
4.	IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.	2021
5.	Friedlingstein, P et al. (2021) *Global Carbon Budget 2021*, Earth Syst. Sci. Data, pp.1-191.	2021
6.	State of NSW and the Environment Protection Authority: *NSW State of the Environment 2021*, December 2021	2021
7.	WMO (2021) *State of Global Climate 2021*, WMO Provisional Report	2021
8.	SEI, IISD, ODI, E3G, and UNEP (2021) *The Production Gap Report: 2021 Report. Governments' planned fossil fuel production remains dangerously out of sync with Paris Agreement limits*	2021
9.	Climate Action Tracker *Warming Projections Global Update - November 2021*	2021
10.	International Energy Agency (2021) *Net Zero by 2050: A Roadmap for the Global Energy Sector*	2021
11.	Steffen, W. and Bradshaw, S. (2021) *Hitting Home: The Compounding Costs of Climate Inaction*	2021
12.	CSIRO and Australian Government Bureau of Meteorology (2020) *State of the Climate 2020*	2020

13.	Welsby, D, Price, J, Pye, S, and Elkins, P (2021) *Unextractable fossil fuels in a 1.5C world*, Nature, 597	2020
14.	IPCC (2019) *Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]	2019
15.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Impacts on biodiversity*	2019
16.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Impacts on crop suitability*	2019
17.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Impacts on fire weather*	2019
18.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Projected climate*	2019
19.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Projected changes in snowmaking conditions*	2019
20.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Impacts of extreme rainfall on soil erosivity and hillslope erosion*	2019
21.	State of NSW and Department of Planning, Industry and Environment (2019) *Climate change impacts in the NSW and ACT Alpine region: Impacts on water availability*	2019
22.	IPCC (2018) Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]	2018
23.	Steffen W et al. (2018) *Trajectories of the Earth System in the Anthropocene. Proceedings of the National Academy of Sciences*, *115*(33), pp.8252-8259.	2018
24.	Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.	2013

DOCUMENT 1

INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

Summary for Policymakers

WGIII

Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Climate Change 2022
Mitigation of Climate Change

Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

Summary for Policymakers

Edited by

Priyadarshi R. Shukla
Co-Chair, Working Group III

Jim Skea
Co-Chair, Working Group III

Raphael Slade
Head of TSU (Science)

Alaa Al Khourdajie
Senior Scientist

Renée van Diemen
Senior Scientist

David McCollum
Senior Scientist

Minal Pathak
Senior Scientist

Shreya Some
Scientist

Purvi Vyas
Science Officer

Sigourney Luz
Communications Manager

Roger Fradera
Head of TSU (Operations)

Malek Belkacemi
IT/Web Manager

Apoorva Hasija
Publication Manager

Juliette Malley
Senior Administrator

Géninha Lisboa
TSU Administrator

Front cover photograph: Matt Bridgestock, Director and Architect at John Gilbert Architects

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Summary for Policymakers

SPM

Summary for Policymakers

Drafting Authors:
Jim Skea (United Kingdom), Priyadarshi R. Shukla (India), Andy Reisinger (New Zealand), Raphael Slade (United Kingdom), Minal Pathak (India), Alaa Al Khourdajie (United Kingdom/Syria), Renée van Diemen (the Netherlands/United Kingdom), Amjad Abdulla (Maldives), Keigo Akimoto (Japan), Mustafa Babiker (Sudan/Saudi Arabia), Quan Bai (China), Igor A. Bashmakov (the Russian Federation), Christopher Bataille (Canada), Göran Berndes (Sweden), Gabriel Blanco (Argentina), Kornelis Blok (the Netherlands), Mercedes Bustamante (Brazil), Edward Byers (Austria/Ireland), Luisa F. Cabeza (Spain), Katherine Calvin (the United States of America), Carlo Carraro (Italy), Leon Clarke (the United States of America), Annette Cowie (Australia), Felix Creutzig (Germany), Diriba Korecha Dadi (Ethiopia), Dipak Dasgupta (India), Heleen de Coninck (the Netherlands), Fatima Denton (Ghana/the Gambia), Shobhakar Dhakal (Nepal/Thailand), Navroz K. Dubash (India), Oliver Geden (Germany), Michael Grubb (United Kingdom), Céline Guivarch (France), Shreekant Gupta (India), Andrea N. Hahmann (Chile/Denmark), Kirsten Halsnaes (Denmark), Paulina Jaramillo (the United States of America), Kejun Jiang (China), Frank Jotzo (Australia), Tae Yong Jung (Republic of Korea), Suzana Kahn Ribeiro (Brazil), Smail Khennas (Algeria), Şiir Kılkış (Turkey), Silvia Kreibiehl (Germany), Volker Krey (Austria), Elmar Kriegler (Germany), William F. Lamb (Germany/United Kingdom), Franck Lecocq (France), Shuaib Lwasa (Uganda), Nagmeldin Mahmoud (Sudan), Cheikh Mbow (the United States of America/ Senegal), David McCollum (the United States of America), Jan Christoph Minx (Germany), Catherine Mitchell (United Kingdom), Rachid Mrabet (Morocco), Yacob Mulugetta (Ethiopia/ United Kingdom), Gert-Jan Nabuurs (the Netherlands), Gregory F. Nemet (the United States of America/Canada), Peter Newman (Australia), Leila Niamir (Iran/Germany), Lars J. Nilsson (Sweden), Sudarmanto Budi Nugroho (Indonesia), Chukwumerije Okereke (Nigeria/ United Kingdom), Shonali Pachauri (India), Anthony Patt (Switzerland), Ramón Pichs-Madruga (Cuba), Joana Portugal-Pereira (Brazil), Lavanya Rajamani (India), Keywan Riahi (Austria), Joyashree Roy (India/Thailand), Yamina Saheb (France/Algeria), Roberto Schaeffer (Brazil), Karen C. Seto (the United States of America), Shreya Some (India), Linda Steg (the Netherlands), Ferenc L. Toth (Hungary), Diana Ürge-Vorsatz (Hungary), Detlef P. van Vuuren (the Netherlands), Elena Verdolini (Italy), Purvi Vyas (India), Yi-Ming Wei (China), Mariama Williams (Jamaica/Switzerland), Harald Winkler (Republic of South Africa).

Contributing Authors:
Parth Bhatia (India), Sarah Burch (Canada), Jeremy Emmet-Booth (New Zealand), Jan S. Fuglestvedt (Norway), Meredith Kelller (The United States of America), Jarmo Kikstra (Austria/ The Netherlands), Michael König (Germany), Malte Meinshausen (Australia/Germany), Zebedee Nicholls (Australia), Kaj-Ivar van der Wijst (The Netherlands).

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A. Introduction and Framing

The Working Group III (WGIII) contribution to the IPCC's Sixth Assessment Report (AR6) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change.[1] Levels of confidence[2] are given in () brackets. Numerical ranges are presented in square [] brackets. References to Chapters, Sections, Figures and Boxes in the underlying report and Technical Summary (TS) are given in {} brackets.

The report reflects new findings in the relevant literature and builds on previous IPCC reports, including the WGIII contribution to the IPCC's Fifth Assessment Report (AR5), the WGI and WGII contributions to AR6 and the three Special Reports in the Sixth Assessment cycle,[3] as well as other UN assessments. Some of the main developments relevant for this report include {TS.1, TS.2}:

- **An evolving international landscape.** The literature reflects, among other factors: developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement {13, 14, 15, 16}; the UN 2030 Agenda for Sustainable Development including the Sustainable Development Goals (SDGs) {1, 3, 4, 17}; and the evolving roles of international cooperation {14}, finance {15} and innovation {16}.

- **Increasing diversity of actors and approaches to mitigation.** Recent literature highlights the growing role of non-state and sub-national actors including cities, businesses, Indigenous Peoples, citizens including local communities and youth, transnational initiatives, and public-private entities in the global effort to address climate change {5, 13, 14, 15, 16, 17}. Literature documents the global spread of climate policies and cost declines of existing and emerging low emission technologies, along with varied types and levels of mitigation efforts, and sustained reductions in greenhouse gas (GHG) emissions in some countries {2, 5, 6, 8, 12, 13, 16}, and the impacts of, and some lessons from, the COVID-19 pandemic. {1, 2, 3, 5, 13, 15, Box TS.1, Cross-Chapter Box 1 in Chapter 1}

- **Close linkages between climate change mitigation, adaptation and development pathways.** The development pathways taken by countries at all stages of economic development impact GHG emissions and hence shape mitigation challenges and opportunities, which vary across countries and regions. Literature explores how development choices and the establishment of enabling conditions for action and support influence the feasibility and the cost of limiting emissions {1, 3, 4, 5, 13, 15, 16}. Literature highlights that climate change mitigation action designed and conducted in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the societies within which they take place, will be more acceptable, durable and effective {1, 3, 4, 5}. This report covers mitigation from both targeted measures, and from policies and governance with other primary objectives.

- **New approaches in the assessment.** In addition to the sectoral and systems chapters {3, 6, 7, 8, 9, 10, 11, 12}, the report includes, for the first time in a WGIII report, chapters dedicated to demand for services, and social aspects of mitigation {5, Box TS.11}, and to innovation, technology development and transfer {16}. The assessment of future pathways in this report covers near term (to 2030), medium term (up to 2050), and long term (to 2100) time scales, combining assessment of existing pledges and actions {4, 5}, with an assessment of emissions reductions, and their implications, associated with long-term temperature outcomes up to the year 2100 {3}.[4] The assessment of modelled global pathways addresses ways of shifting development pathways towards sustainability. Strengthened collaboration between IPCC Working Groups is reflected in Cross-Working Group Boxes that integrate

[1] The Report covers literature accepted for publication by 11 October 2021.

[2] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers, typeset in italics: *very low*, *low*, *medium*, *high* and *very high*. The assessed likelihood of an outcome or a result is described as: *virtually certain* 99–100% probability; *very likely* 90–100%; *likely* 66–100%; *more likely than not* 50–100%; *about as likely as not* 33–66%; *unlikely* 0–33%; *very unlikely* 0–10%; *exceptionally unlikely* 0–1%. Additional terms may also be used when appropriate, consistent with the IPCC uncertainty guidance: https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

[3] The three Special Reports are: Global Warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018); Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019).

[4] The term 'temperature' is used in reference to 'global surface temperatures' throughout this SPM as defined in footnote 8 of the AR6 WGI SPM (see note 14 of Table SPM.2). Emission pathways and associated temperature changes are calculated using various forms of models, as summarised in Box SPM.1 and Chapter 3, and discussed in Annex III.

physical science, climate risks and adaptation, and the mitigation of climate change.[5]

- **Increasing diversity of analytic frameworks from multiple disciplines including social sciences.** This report identifies multiple analytic frameworks to assess the drivers of, barriers to and options for, mitigation action. These include: economic efficiency, including the benefits of avoided impacts; ethics and equity; interlinked technological and social transition processes; and socio-political frameworks, including institutions and governance {1, 3, 13, Cross-Chapter Box 12 in Chapter 16}. These help to identify risks and opportunities for action, including co-benefits and just and equitable transitions at local, national and global scales. {1, 3, 4, 5, 13, 14, 16, 17}

Section B of this Summary for Policymakers (SPM) assesses *Recent developments and current trends*, including data uncertainties and gaps. Section C, *System transformations to limit global warming*, identifies emission pathways and alternative mitigation portfolios consistent with limiting global warming to different levels, and assesses specific mitigation options at the sectoral and system level. Section D addresses *Linkages between mitigation, adaptation, and sustainable development*. Section E, *Strengthening the response*, assesses knowledge of how enabling conditions of institutional design, policy, finance, innovation and governance arrangements can contribute to climate change mitigation in the context of sustainable development.

[5] Namely: Economic Benefits from Avoided Climate Impacts along Long-Term Mitigation Pathways {Cross-Working Group Box 1 in Chapter 3}; Urban: Cities and Climate Change {Cross-Working Group Box 2 in Chapter 8}; and Mitigation and Adaptation via the Bioeconomy {Cross-Working Group Box 3 in Chapter 12}.

SPM

B. Recent Developments and Current Trends

B.1 Total net anthropogenic GHG emissions[6] have continued to rise during the period 2010–2019, as have cumulative net CO_2 emissions since 1850. Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

B.1.1 Global net anthropogenic GHG emissions were 59 ± 6.6 $GtCO_2$-eq[7,8] in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990. The annual average during the decade 2010–2019 was 56 ± 6.0 $GtCO_2$-eq, 9.1 $GtCO_2$-eq yr^{-1} higher than in 2000–2009. This is the highest increase in average decadal emissions on record. The average annual rate of growth slowed from 2.1% yr^{-1} between 2000 and 2009 to 1.3% yr^{-1} between 2010 and 2019. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

B.1.2 Growth in anthropogenic emissions has persisted across all major groups of GHGs since 1990, albeit at different rates. By 2019, the largest growth in absolute emissions occurred in CO_2 from fossil fuels and industry followed by CH_4, whereas the highest relative growth occurred in fluorinated gases, starting from low levels in 1990 (*high confidence*). Net anthropogenic CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF) are subject to large uncertainties and high annual variability, with *low confidence* even in the direction of the long-term trend.[9] (Figure SPM.1) {Figure 2.2, Figure 2.5, 2.2, Figure TS.2}

B.1.3 Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400 ± 240 $GtCO_2$ (*high confidence*). Of these, more than half (58%) occurred between 1850 and 1989 [1400 ± 195 $GtCO_2$], and about 42% between 1990 and 2019 [1000 ± 90 $GtCO_2$]. About 17% of historical cumulative net CO_2 emissions since 1850 occurred between 2010 and 2019 [410 ± 30 $GtCO_2$].[10] By comparison, the current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C with a probability of 50% has been assessed as 500 $GtCO_2$, and as 1150 $GtCO_2$ for a probability of 67% for limiting warming to 2°C. Remaining carbon budgets depend on the amount of non-CO_2 mitigation (±220 $GtCO_2$) and are further subject to geophysical uncertainties. Based on central estimates only, cumulative net CO_2 emissions between 2010 and 2019 compare to about four-fifths of the size of the remaining carbon budget from 2020 onwards for a 50% probability of limiting global warming to 1.5°C, and about one-third of the remaining carbon budget for a 67% probability to limit global warming to 2°C. Even when taking uncertainties into account, historical emissions between 1850 and 2019 constitute a large share of total carbon budgets for these global

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6 Net GHG emissions in this report refer to releases of greenhouse gases from anthropogenic sources minus removals by anthropogenic sinks, for those species of gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change (UNFCCC): CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF); methane (CH_4); nitrous oxide (N_2O); and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), as well as nitrogen trifluoride (NF_3). Different datasets for GHG emissions exist, with varying time horizons and coverage of sectors and gases, including some that go back to 1850. In this report, GHG emissions are assessed from 1990, and CO_2 sometimes also from 1850. Reasons for this include data availability and robustness, scope of the assessed literature, and the differing warming impacts of non-CO_2 gases over time.

7 GHG emission metrics are used to express emissions of different greenhouse gases in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalent (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The choice of metric depends on the purpose of the analysis, and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {Cross-Chapter Box 2 in Chapter 2, Supplementary Material 2.SM.3, Box TS.2; AR6 WGI Chapter 7 Supplementary Material}

8 In this SPM, uncertainty in historic GHG emissions is reported using 90% uncertainty intervals unless stated otherwise. GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur.

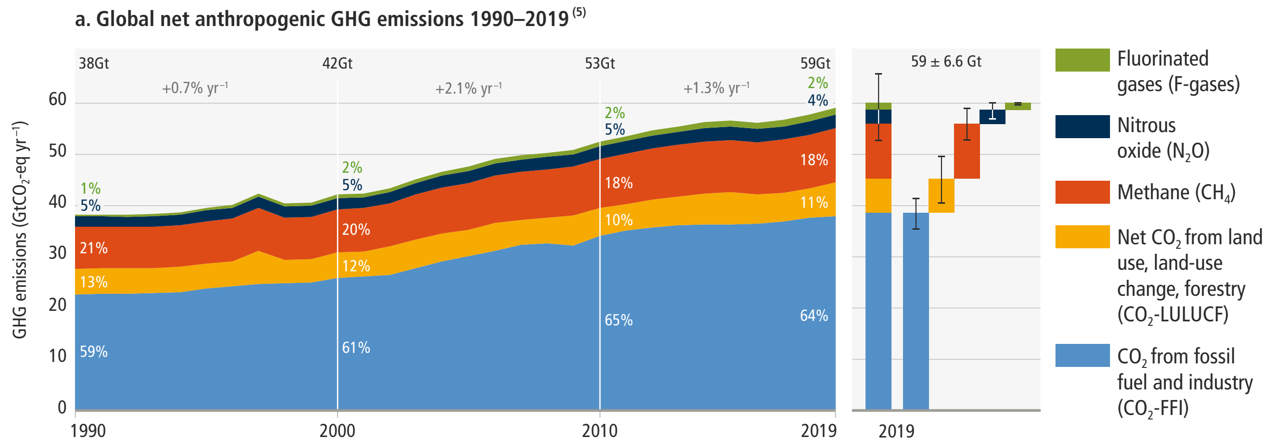
9 Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO_2 fluxes from land reported by global bookkeeping models used here are estimated to be about 5.5 $GtCO_2$ yr^{-1} higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO_2-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

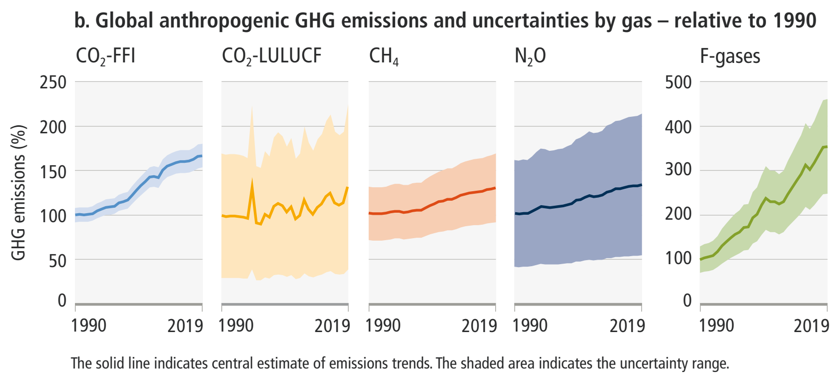
10 For consistency with WGI, historical cumulative CO_2 emissions from 1850 to 2019 are reported using 68% confidence intervals.

warming levels.[11,12] Based on central estimates only, historical cumulative net CO_2 emissions between 1850 and 2019 amount to about four-fifths[12] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$), and to about two thirds[12] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {Figure 2.7, 2.2, Figure TS.3, WGI Table SPM.2}

B.1.4 Emissions of CO_2-FFI dropped temporarily in the first half of 2020 due to responses to the COVID-19 pandemic (*high confidence*), but rebounded by the end of the year (*medium confidence*). The annual average CO_2-FFI emissions reduction in 2020 relative to 2019 was about 5.8% [5.1–6.3%], or 2.2 [1.9–2.4] $GtCO_2$ (*high confidence*). The full GHG emissions impact of the COVID-19 pandemic could not be assessed due to a lack of data regarding non-CO_2 GHG emissions in 2020. {Cross-Chapter Box 1 in Chapter 1, Figure 2.6, 2.2, Box TS.1, Box TS.1 Figure 1}

Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.





	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2-FFI	38 ± 3	15	167
CO_2-LULUCF	6.6 ± 4.6	1.6	133
CH_4	11 ± 3.2	2.4	129
N_2O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	59 ± 6.6	21	154

Figure SPM.1 | Global net anthropogenic GHG emissions ($GtCO_2$-eq yr^{-1}) 1990–2019. Global net anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 from land use, land-use change and forestry (CO_2-LULUCF)[9]; methane (CH_4); nitrous oxide (N_2O); and fluorinated gases (HFCs, PFCs, SF_6, NF_3).[6] **Panel a** shows aggregate annual global net anthropogenic GHG emissions by groups of gases from 1990 to 2019 reported in $GtCO_2$-eq converted based on global warming potentials with a 100-year time horizon (GWP100-AR6) from the IPCC Sixth Assessment Report Working Group I (Chapter 7). The fraction of global emissions for each gas is shown for 1990, 2000, 2010 and 2019; as well as the aggregate average annual growth rate between these decades. At the right side of Panel a, GHG emissions in 2019 are broken down into individual components with the associated uncertainties (90% confidence interval) indicated by the error bars: CO_2-FFI ±8%; CO_2-LULUCF ±70%; CH_4 ±30%; N_2O ±60%; F-gases ±30%; GHG ±11%. Uncertainties in GHG emissions are assessed in Supplementary Material 2.2. The single-year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. **Panel b** shows global anthropogenic CO_2-FFI, net CO_2-LULUCF, CH_4, N_2O and F-gas emissions individually for the period 1990–2019, normalised relative to 100 in 1990. Note the different scale for the included F-gas emissions compared to other gases, highlighting its rapid growth from a low base. Shaded areas indicate the uncertainty range. Uncertainty ranges as shown here are specific for individual groups of greenhouse gases and cannot be compared. The table shows the central estimate for: absolute emissions in 2019; the absolute change in emissions between 1990 and 2019; and emissions in 2019 expressed as a percentage of 1990 emissions. {2.2, Figure 2.5, Supplementary Material 2.2, Figure TS.2}

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[11] The carbon budget is the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given likelihood, taking into account the effect of other anthropogenic climate forcers. This is referred to as the 'total carbon budget' when expressed starting from the pre-industrial period, and as the 'remaining carbon budget' when expressed from a recent specified date. The total carbon budgets reported here are the sum of historical emissions from 1850 to 2019 and the remaining carbon budgets from 2020 onwards, which extend until global net zero CO_2 emissions are reached. {Annex I: Glossary; WGI SPM}

[12] Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

B.2 Net anthropogenic GHG emissions have increased since 2010 across all major sectors globally. An increasing share of emissions can be attributed to urban areas. Emissions reductions in CO_2 from fossil fuels and industrial processes (CO_2-FFI), due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. (*high confidence*) {2.2, 2.4, 6.3, 7.2, 8.3, 9.3, 10.1, 11.2}

B.2.1 In 2019, approximately 34% (20 GtCO_2-eq) of total net anthropogenic GHG emissions came from the energy supply sector, 24% (14 GtCO_2-eq) from industry, 22% (13 GtCO_2-eq) from agriculture, forestry and other land use (AFOLU), 15% (8.7 GtCO_2-eq) from transport and 6% (3.3 GtCO_2-eq) from buildings.[13] If emissions from electricity and heat production are attributed to the sectors that use the final energy, 90% of these indirect emissions are allocated to the industry and buildings sectors, increasing their relative GHG emissions shares from 24% to 34%, and from 6% to 16%, respectively. After reallocating emissions from electricity and heat production, the energy supply sector accounts for 12% of global net anthropogenic GHG emissions. (*high confidence*) {Figure 2.12, 2.2, 6.3, 7.2, 9.3, 10.1, 11.2, Figure TS.6}

B.2.2 Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%), but remained roughly constant at about 2% yr^{-1} in the transport sector (*high confidence*). Emissions growth in AFOLU, comprising emissions from agriculture (mainly CH_4 and N_2O) and forestry and other land use (mainly CO_2) is more uncertain than in other sectors due to the high share and uncertainty of CO_2-LULUCF emissions (*medium confidence*). About half of total net AFOLU emissions are from CO_2-LULUCF, predominantly from deforestation[14] (*medium confidence*). {Figure 2.13, 2.2, 6.3, 7.2, Figure 7.3, 9.3, 10.1, 11.2, TS.3}

B.2.3 The global share of emissions that can be attributed to urban areas is increasing. In 2015, urban emissions were estimated to be 25 GtCO_2-eq (about 62% of the global share) and in 2020, 29 GtCO_2-eq (67–72% of the global share).[15] The drivers of urban GHG emission are complex and include population size, income, state of urbanisation and urban form. (*high confidence*) {8.1, 8.3}

B.2.4 Global energy intensity (total primary energy per unit GDP) decreased by 2% yr^{-1} between 2010 and 2019. Carbon intensity (CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) per unit primary energy) decreased by 0.3% yr^{-1}, with large regional variations, over the same period mainly due to fuel switching from coal to gas, reduced expansion of coal capacity, and increased use of renewables. This reversed the trend observed for 2000–2009. For comparison, the carbon intensity of primary energy is projected to decrease globally by about 3.5% yr^{-1} between 2020 and 2050 in modelled scenarios that limit warming to 2°C (>67%), and by about 7.7% yr^{-1} globally in scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot.[16] (*high confidence*) {Figure 2.16, 2.2, 2.4, Table 3.4, 3.4, 6.3}

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13 Sector definitions can be found in Annex II.9.1.

14 Land overall constituted a net sink of –6.6 (±4.6) GtCO_2 yr^{-1} for the period 2010–2019, comprising a gross sink of –12.5 (±3.2) GtCO_2 yr^{-1} resulting from responses of all land to both anthropogenic environmental change and natural climate variability, and net anthropogenic CO_2-LULUCF emissions +5.7 (±4.0) GtCO_2 yr^{-1} based on bookkeeping models. {Table 2.1, 7.2, Table 7.1}

15 This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {8.1, Annex I: Glossary}

16 See Box SPM.1 for the categorisation of modelled long-term emission scenarios based on projected temperature outcomes and associated probabilities adopted in this report.

B.3 Regional contributions[17] to global GHG emissions continue to differ widely. Variations in regional, and national per capita emissions partly reflect different development stages, but they also vary widely at similar income levels. The 10% of households with the highest per capita emissions contribute a disproportionately large share of global household GHG emissions. At least 18 countries have sustained GHG emission reductions for longer than 10 years. (*high confidence*) (Figure SPM.2) {Figure 1.1, Figure 2.9, Figure 2.10, Figure 2.25, 2.2, 2.3, 2.4, 2.5, 2.6, Figure TS.4, Figure TS.5}

B.3.1 GHG emissions trends over 1990–2019 vary widely across regions and over time, and across different stages of development, as shown in Figure SPM.2. Average global per capita net anthropogenic GHG emissions increased from 7.7 to 7.8 tCO_2-eq, ranging from 2.6 tCO_2-eq to 19 tCO_2-eq across regions. Least developed countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq and 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF.[18] (*high confidence*) (Figure SPM.2) {Figure1.2, Figure 2.9, Figure 2.10, 2.2, Figure TS.4}

B.3.2 Historical contributions to cumulative net anthropogenic CO_2 emissions between 1850 and 2019 vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI (1650 ± 73 $GtCO_2$-eq) and net CO_2-LULUCF (760 ± 220 $GtCO_2$-eq) emissions.[10] Globally, the major share of cumulative CO_2-FFI emissions is concentrated in a few regions, while cumulative CO_2-LULUCF[9] emissions are concentrated in other regions. LDCs contributed less than 0.4% of historical cumulative CO_2-FFI emissions between 1850 and 2019, while SIDS contributed 0.5%. (*high confidence*) (Figure SPM.2) {Figure 2.10, 2.2, TS.3, Figure 2.7}

B.3.3 In 2019, around 48% of the global population lives in countries emitting on average more than 6 tCO_2-eq per capita, excluding CO_2-LULUCF. 35% live in countries emitting more than 9 tCO_2-eq per capita. Another 41% live in countries emitting less than 3 tCO_2-eq per capita. A substantial share of the population in these low-emitting countries lack access to modern energy services.[19] Eradicating extreme poverty, energy poverty, and providing decent living standards[20] to all in these regions in the context of achieving sustainable development objectives, in the near-term, can be achieved without significant global emissions growth. (*high confidence*) (Figure SPM.2) {Figure 1.2, 2.2, 2.4, 2.6, 3.7, 4.2, 6.7, Figure TS.4, Figure TS.5}

B.3.4 Globally, the 10% of households with the highest per capita emissions contribute 34–45% of global consumption-based household GHG emissions,[21] while the middle 40% contribute 40–53%, and the bottom 50% contribute 13–15%. (*high confidence*) {2.6, Figure 2.25}

B.3.5 At least 18 countries have sustained production-based GHG and consumption-based CO_2 emission reductions for longer than 10 years. Reductions were linked to energy supply decarbonisation, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure. Some countries have reduced production-based GHG emissions by a third or more since peaking, and some have achieved several years of consecutive reduction rates of around 4% yr^{-1}, comparable to global reductions in scenarios limiting warming to 2°C (>67%) or lower. These reductions have only partly offset global emissions growth. (*high confidence*) (Figure SPM.2) {Figure TS.4, 2.2, 1.3.2}

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17 See Annex II, Part 1 for regional groupings adopted in this report.

18 In 2019, LDCs are estimated to have emitted 3.3% of global GHG emissions, and SIDS are estimated to have emitted 0.6% of global GHG emissions, excluding CO_2-LULUCF. These country groupings cut across geographic regions and are not depicted separately in Figure SPM.2. {Figure 2.10}

19 In this report, access to modern energy services is defined as access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive uses. {Annex I: Glossary}

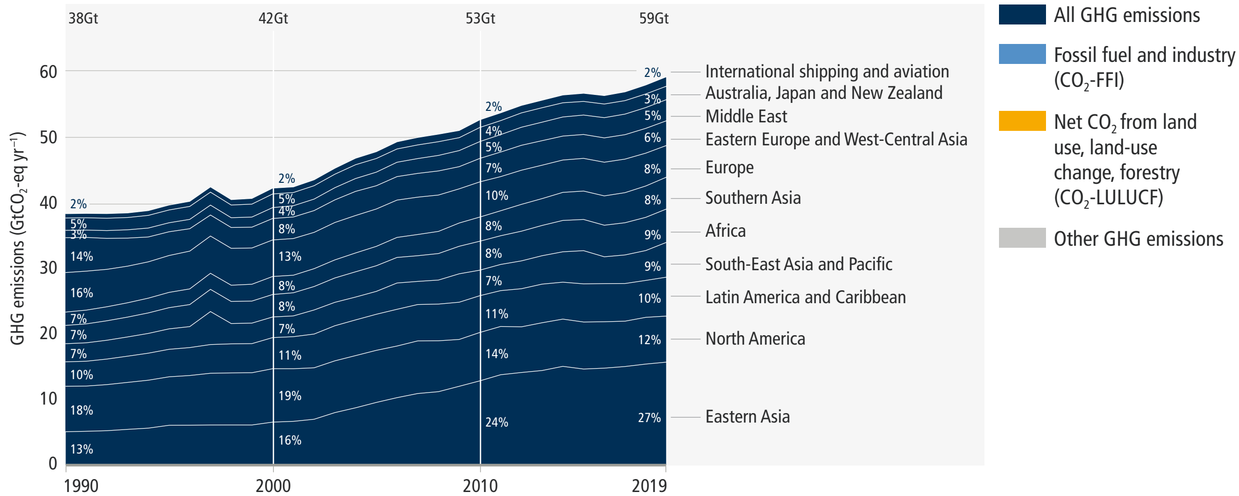
20 In this report, decent living standards are defined as a set of minimum material requirements essential for achieving basic human well-being, including nutrition, shelter, basic living conditions, clothing, health care, education, and mobility. {5.1}

21 Consumption-based emissions refer to emissions released to the atmosphere to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region). The bottom 50% of emitters spend less than USD3 PPP (purchasing power parity) per capita per day. The top 10% of emitters (an open-ended category) spend more than USD23 PPP per capita per day. The wide range of estimates for the contribution of the top 10% results from the wide range of spending in this category and differing methods in the assessed literature. {2.6, Annex I: Glossary}

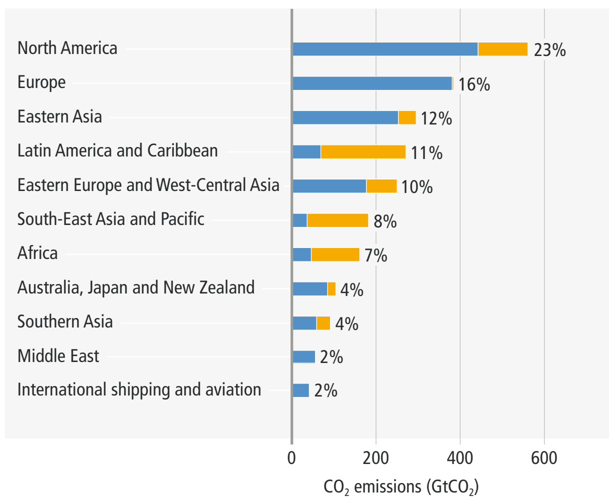
SPM

Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850.

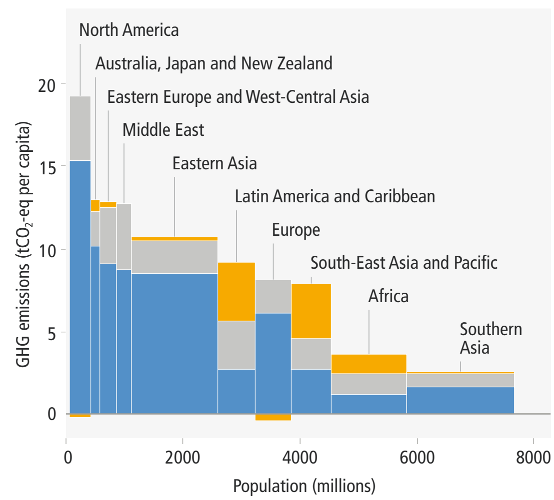
a. Global net anthropogenic GHG emissions by region (1990–2019)



b. Historical cumulative net anthropogenic CO_2 emissions per region (1850–2019)



c. Net anthropogenic GHG emissions per capita and for total population, per region (2019)



d. Regional indicators (2019) and regional production vs consumption accounting (2018)

	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita ($USD1000_{ppp}2017$ per person)[1]	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019[2] (production basis)										
% GHG contributions	9%	3%	27%	6%	8%	10%	5%	12%	9%	8%
GHG emissions intensity (tCO_2-eq / $USD1000_{ppp}$ 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO_2-eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO_2-FFI, 2018, per person										
Production-based emissions (tCO_2-FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO_2-FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

[1] GDP per capita in 2019 in USD2017 currency purchasing power basis.
[2] Includes CO_2-FFI, CO_2-LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in Annex II, Part I.

Figure SPM.2 | Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850 to 2019.

Figure SPM.2 (continued): Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850 to 2019. Panel a shows global net anthropogenic GHG emissions by region (in $GtCO_2$-eq yr^{-1} (GWP100-AR6)) for the time period 1990–2019.[6] Percentage values refer to the contribution of each region to total GHG emissions in each respective time period. The single-year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. Regions are as grouped in Annex II. **Panel b** shows the share of historical cumulative net anthropogenic CO_2 emissions per region from 1850 to 2019 in $GtCO_2$. This includes CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) and net CO_2 emissions from land use, land-use change, forestry (CO_2-LULUCF). Other GHG emissions are not included.[6] CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ±70% (90% confidence interval). **Panel c** shows the distribution of regional GHG emissions in tonnes CO_2-eq per capita by region in 2019. GHG emissions are categorised into: CO_2-FFI; net CO_2-LULUCF; and other GHG emissions (methane, nitrous oxide, fluorinated gases, expressed in CO_2-eq using GWP100-AR6). The height of each rectangle shows per capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each region. Emissions from international aviation and shipping are not included. In the case of two regions, the area for CO_2-LULUCF is below the axis, indicating net CO_2 removals rather than emissions. CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ±70% (90% confidence interval). **Panel d** shows population, GDP per person, emission indicators by region in 2019 for percentage GHG contributions, total GHG per person, and total GHG emissions intensity, together with production-based and consumption-based CO_2-FFI data, which is assessed in this report up to 2018. Consumption-based emissions are emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., region). Emissions from international aviation and shipping are not included. {1.3, Figure 1.2, 2.2, Figure 2.9, Figure 2.10, Figure 2.11, Annex II}

B.4 The unit costs of several low-emission technologies have fallen continuously since 2010. Innovation policy packages have enabled these cost reductions and supported global adoption. Both tailored policies and comprehensive policies addressing innovation systems have helped overcome the distributional, environmental and social impacts potentially associated with global diffusion of low-emission technologies. Innovation has lagged in developing countries due to weaker enabling conditions. Digitalisation can enable emission reductions, but can have adverse side effects unless appropriately governed. (*high confidence*) (Figure SPM.3) {2.2, 6.3, 6.4, 7.2, 12.2, 16.2, 16.4, 16.5, Cross-Chapter Box 11 in Chapter 16}

B.4.1 From 2010 to 2019, there have been sustained decreases in the unit costs of solar energy (85%), wind energy (55%), and lithium-ion batteries (85%), and large increases in their deployment, e.g., >10× for solar and >100× for electric vehicles (EVs), varying widely across regions (Figure SPM.3). The mix of policy instruments which reduced costs and stimulated adoption includes public R&D, funding for demonstration and pilot projects, and demand pull instruments such as deployment subsidies to attain scale. In comparison to modular small-unit size technologies, the empirical record shows that multiple large-scale mitigation technologies, with fewer opportunities for learning, have seen minimal cost reductions and their adoption has grown slowly. (*high confidence*) {1.3, 1.5, Figure 2.5, 2.5, 6.3, 6.4, 7.2, 11.3, 12.2, 12.3, 12.6, 13.6, 16.3, 16.4, 16.6}

B.4.2 Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Appropriately designed policies and governance have helped address distributional impacts and rebound effects. Innovation has provided opportunities to lower emissions and reduce emission growth and created social and environmental co-benefits (*high confidence*). Adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity. In many countries, especially those with limited institutional capacities, several adverse side effects have been observed as a result of diffusion of low-emission technology, for example, low-value employment, and dependency on foreign knowledge and suppliers. Low-emission innovation along with strengthened enabling conditions can reinforce development benefits, which can, in turn, create feedbacks towards greater public support for policy. (*medium confidence*) {9.9, 13.6, 13.7, 16.3, 16.4, 16.5, 16.6, Cross-Chapter Box 12 in Chapter 16, TS.3}

B.4.3 Digital technologies can contribute to mitigation of climate change and the achievement of several SDGs (*high confidence*). For example, sensors, internet of things, robotics, and artificial intelligence can improve energy management in all sectors, increase energy efficiency, and promote the adoption of many low-emission technologies, including decentralised renewable energy, while creating economic opportunities (*high confidence*). However, some of these climate change mitigation gains can be reduced or counterbalanced by growth in demand for goods and services due to the use of digital devices (*high confidence*). Digitalisation can involve trade-offs across several SDGs, for example, increasing electronic waste, negative impacts on labour markets, and exacerbating the existing digital divide. Digital technology supports decarbonisation only if appropriately governed (*high confidence*). {5.3, 10, 12.6, 16.2, Cross-Chapter Box 11 in Chapter 16, TS.5, Box TS.14}

SPM

The unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen, and their use continues to rise.

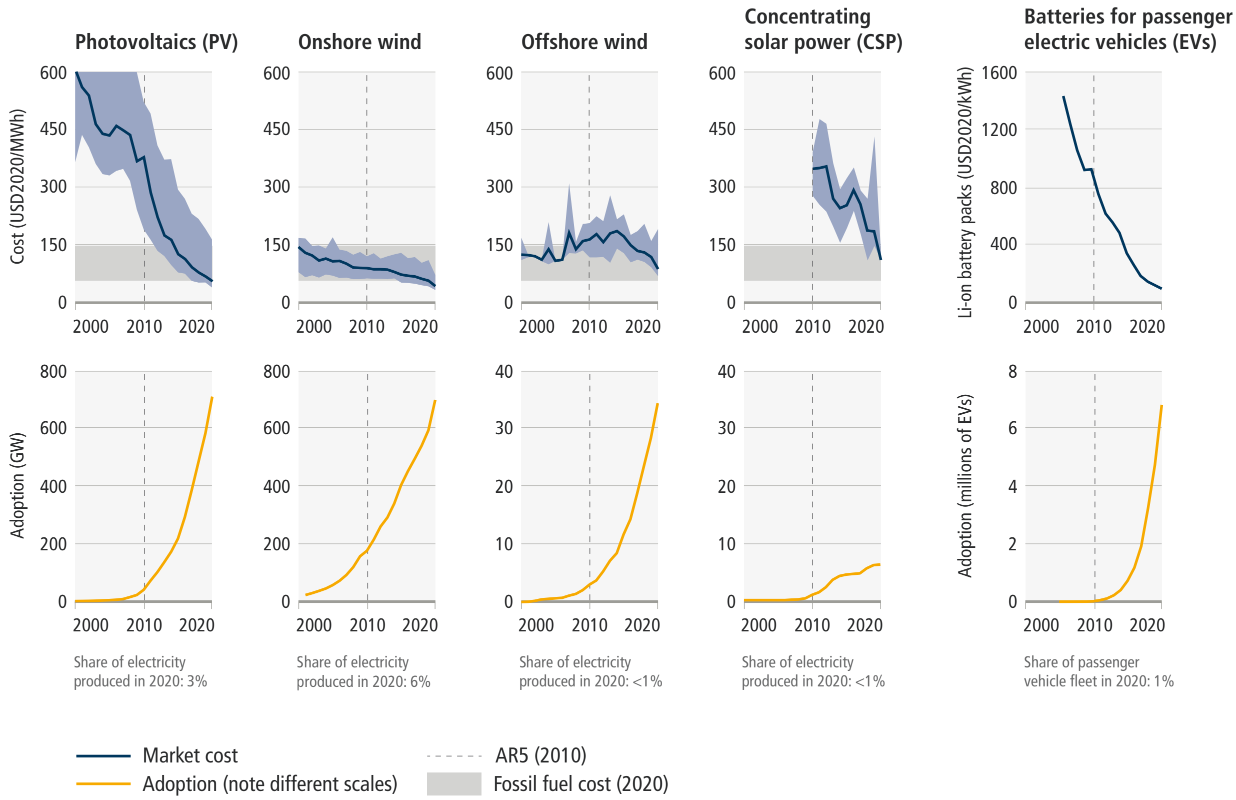


Figure SPM.3 | Unit cost reductions and use in some rapidly changing mitigation technologies. The **top panel** shows global costs per unit of energy (USD per MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Grey shading indicates the range of unit costs for new fossil fuel (coal and gas) power in 2020 (corresponding to USD55–148 per MWh). In 2020, the levelised costs of energy (LCOE) of the four renewable energy technologies could compete with fossil fuels in many places. For batteries, costs shown are for 1 kWh of battery storage capacity; for the others, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced. The literature uses LCOE because it allows consistent comparisons of cost trends across a diverse set of energy technologies to be made. However, it does not include the costs of grid integration or climate impacts. Further, LCOE does not take into account other environmental and social externalities that may modify the overall (monetary and non-monetary) costs of technologies and alter their deployment. The **bottom panel** shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. A vertical dashed line is placed in 2010 to indicate the change since AR5. Shares of electricity produced and share of passenger vehicle fleet are indicated in text for 2020 based on provisional data, i.e., percentage of total electricity production (for PV, onshore wind, offshore wind, CSP) and of total stock of passenger vehicles (for EVs). The electricity production share reflects different capacity factors; for example, for the same amount of installed capacity, wind produces about twice as much electricity as solar PV. {2.5, 6.4} Renewable energy and battery technologies were selected as illustrative examples because they have recently shown rapid changes in costs and adoption, and because consistent data are available. Other mitigation options assessed in the report are not included as they do not meet these criteria.

B.5 There has been a consistent expansion of policies and laws addressing mitigation since AR5. This has led to the avoidance of emissions that would otherwise have occurred and increased investment in low-GHG technologies and infrastructure. Policy coverage of emissions is uneven across sectors. Progress on the alignment of financial flows towards the goals of the Paris Agreement remains slow and tracked climate finance flows are distributed unevenly across regions and sectors. (*high confidence*) {5.6, 13.2, 13.4, 13.5, 13.6, 13.9, 14.3, 14.4, 14.5, Cross-Chapter Box 10 in Chapter 14, 15.3, 15.5}

B.5.1 The Kyoto Protocol led to reduced emissions in some countries and was instrumental in building national and international capacity for GHG reporting, accounting and emissions markets (*high confidence*). At least 18 countries that had Kyoto targets for the first commitment period have had sustained absolute emission reductions for at least a decade from 2005, of which two were countries with economies in transition (*very high confidence*). The Paris Agreement, with near universal participation, has led to policy development and target-setting at national and sub-national levels, in particular in relation to mitigation, as well as enhanced transparency of climate action and support (*medium confidence*). {14.3, 14.6}

B.5.2 The application of diverse policy instruments for mitigation at the national and sub-national levels has grown consistently across a range of sectors (*high confidence*). By 2020, over 20% of global GHG emissions were covered by carbon taxes or emissions trading systems, although coverage and prices have been insufficient to achieve deep reductions (*medium confidence*). By 2020, there were 'direct' climate laws focused primarily on GHG reductions in 56 countries covering 53% of global emissions (*medium confidence*). Policy coverage remains limited for emissions from agriculture and the production of industrial materials and feedstocks (*high confidence*). {5.6, 7.6, 11.5, 11.6, 13.2, 13.6}

B.5.3 In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to avoided global emissions of several $GtCO_2$-eq yr^{-1} (*medium confidence*). At least 1.8 $GtCO_2$-eq yr^{-1} can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments. Growing numbers of laws and executive orders have impacted global emissions and were estimated to result in 5.9 $GtCO_2$-eq yr^{-1} less emissions in 2016 than they otherwise would have been. (*medium confidence*) (Figure SPM.3) {2.2, 2.8, 6.7, 7.6, 9.9, 10.8, 13.6, Cross-chapter Box 10 in Chapter 14}

B.5.4 Annual tracked total financial flows for climate mitigation and adaptation increased by up to 60% between 2013/14 and 2019/20 (in USD2015), but average growth has slowed since 2018[22] (*medium confidence*). These financial flows remained heavily focused on mitigation, are uneven, and have developed heterogeneously across regions and sectors (*high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilise USD100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). Markets for green bonds, ESG (environmental, social and governance) and sustainable finance products have expanded significantly since AR5. Challenges remain, in particular around integrity and additionality, as well as the limited applicability of these markets to many developing countries. (*high confidence*) {Box 15.4, 15.3, 15.5, 15.6, Box 15.7}

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[22] Estimates of financial flows (comprising both private and public, domestic and international flows) are based on a single report which assembles data from multiple sources and which has applied various changes to their methodology over the past years. Such data can suggest broad trends but is subject to uncertainties.

B.6 Global GHG emissions in 2030 associated with the implementation of Nationally Determined Contributions (NDCs) announced prior to COP26[23] would make it *likely* that warming will exceed 1.5°C during the 21st century.[24] *Likely* limiting warming to below 2°C would then rely on a rapid acceleration of mitigation efforts after 2030. Policies implemented by the end of 2020[25] are projected to result in higher global GHG emissions than those implied by NDCs. (*high confidence*) (Figure SPM.4) {3.3, 3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

B.6.1 Policies implemented by the end of 2020 are projected to result in higher global GHG emissions than those implied by NDCs, indicating an implementation gap. A gap remains between global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 and those associated with modelled mitigation pathways assuming immediate action (for quantification see Table SPM.1).[26] The magnitude of the emissions gap depends on the global warming level considered and whether only unconditional or also conditional elements of NDCs[27] are considered.[28] (*high confidence*) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

B.6.2 Global emissions in 2030 associated with the implementation of NDCs announced prior to COP26 are lower than the emissions implied by the original NDCs[29] (*high confidence*). The original emissions gap has fallen by about 20% to one-third relative to pathways that limit warming to 2°C (>67%) with immediate action (category C3a in Table SPM.2), and by about 15–20% relative to pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (category C1 in Table SPM.2) (*medium confidence*). (Figure SPM.4) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

Table SPM.1 | Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emissions gaps. *Emissions projections for 2030 and absolute differences in emissions are based on emissions of 52–56 $GtCO_2$-eq yr^{-1} in 2019 as assumed in underlying model studies. (*medium confidence*) {4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4}

	Implied by policies implemented by the end of 2020 ($GtCO_2$-eq yr^{-1})	Implied by NDCs announced prior to COP26	
		Unconditional elements ($GtCO_2$-eq yr^{-1})	Including conditional elements ($GtCO_2$-eq yr^{-1})
Median projected global emissions (min–max)*	57 [52–60]	53 [50–57]	50 [47–55]
Implementation gap between implemented policies and NDCs (median)		4	7
Emissions gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action		10–16	6–14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action		19–26	16–23

23 NDCs announced prior to COP26 refer to the most recent Nationally Determined Contributions submitted to the UNFCCC up to the literature cut-off date of this report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter. 25 NDC updates were submitted between 12 October 2021 and the start of COP26.

24 This implies that mitigation after 2030 can no longer establish a pathway with less than 67% probability to exceed 1.5°C during the 21st century, a defining feature of the class of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assessed in this report (category C1 in Table SPM.2). These pathways limit warming to 1.6°C or lower throughout the 21st century with a 50% likelihood.

25 The policy cut-off date in studies used to project GHG emissions of 'policies implemented by the end of 2020' varies between July 2019 and November 2020. {Table 4.2}

26 Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled pathways that limit warming to 2°C (>67%) based on immediate action are summarised in category C3a in Table SPM.2. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table SPM.2).

27 In this report, 'unconditional' elements of NDCs refer to mitigation efforts put forward without any conditions. 'Conditional' elements refer to mitigation efforts that are contingent on international cooperation, for example bilateral and multilateral agreements, financing or monetary and/or technological transfers. This terminology is used in the literature and the UNFCCC's NDC Synthesis Reports, not by the Paris Agreement. {4.2.1, 14.3.2}

28 Two types of gaps are assessed: the implementation gap is calculated as the difference between the median of global emissions in 2030 implied by policies implemented by the end of 2020 and those implied by NDCs announced prior to COP26. The emissions gap is calculated as the difference between GHG emissions implied by the NDCs (minimum/maximum emissions in 2030) and the median of global GHG emissions in modelled pathways limiting warming to specific levels based on immediate action and with stated likelihoods as indicated (Table SPM.2).

29 Original NDCs refer to those submitted to the UNFCCC in 2015 and 2016. Unconditional elements of NDCs announced prior to COP26 imply global GHG emissions in 2030 that are 3.8 [3.0–5.3] $GtCO_2$-eq yr^{-1} lower than those from the original NDCs, and 4.5 [2.7–6.3] $GtCO_2$-eq yr^{-1} lower when conditional elements of NDCs are included. NDC updates at or after COP26 could further change the implied emissions.

B.6.3 Modelled global emission pathways consistent with NDCs announced prior to COP26 that limit warming to 2°C (>67%) (category C3b in Table SPM.2) imply annual average global GHG emissions reduction rates of 0–0.7 $GtCO_2$-eq yr^{-1} during the decade 2020–2030, with an unprecedented acceleration to 1.4–2.0 $GtCO_2$-eq yr^{-1} during 2030–2050 (*medium confidence*). Continued investments in unabated high-emitting infrastructure and limited development and deployment of low-emitting alternatives prior to 2030 would act as barriers to this acceleration and increase feasibility risks (*high confidence*). {3.3, 3.5, 3.8, Cross-Chapter Box 5 in Chapter 4}

B.6.4 Modelled global emission pathways consistent with NDCs announced prior to COP26 will *likely* exceed 1.5°C during the 21st century. Those pathways that then return warming to 1.5°C by 2100 with a likelihood of 50% or greater imply a temperature overshoot of 0.15°C–0.3°C (42 pathways in category C2 in Table SPM.2). In such pathways, global cumulative net-negative CO_2 emissions are –380 [–860 to –200] $GtCO_2$[30] in the second half of the century, and there is a rapid acceleration of other mitigation efforts across all sectors after 2030. Such overshoot pathways imply increased climate-related risk, and are subject to increased feasibility concerns,[31] and greater social and environmental risks, compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (*high confidence*) (Figure SPM.4, Table SPM.2) {3.3, 3.5, 3.8, 12.3; AR6 WGII SPM B.6}

Projected global GHG emissions from NDCs announced prior to COP26 would make it *likely* that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C.

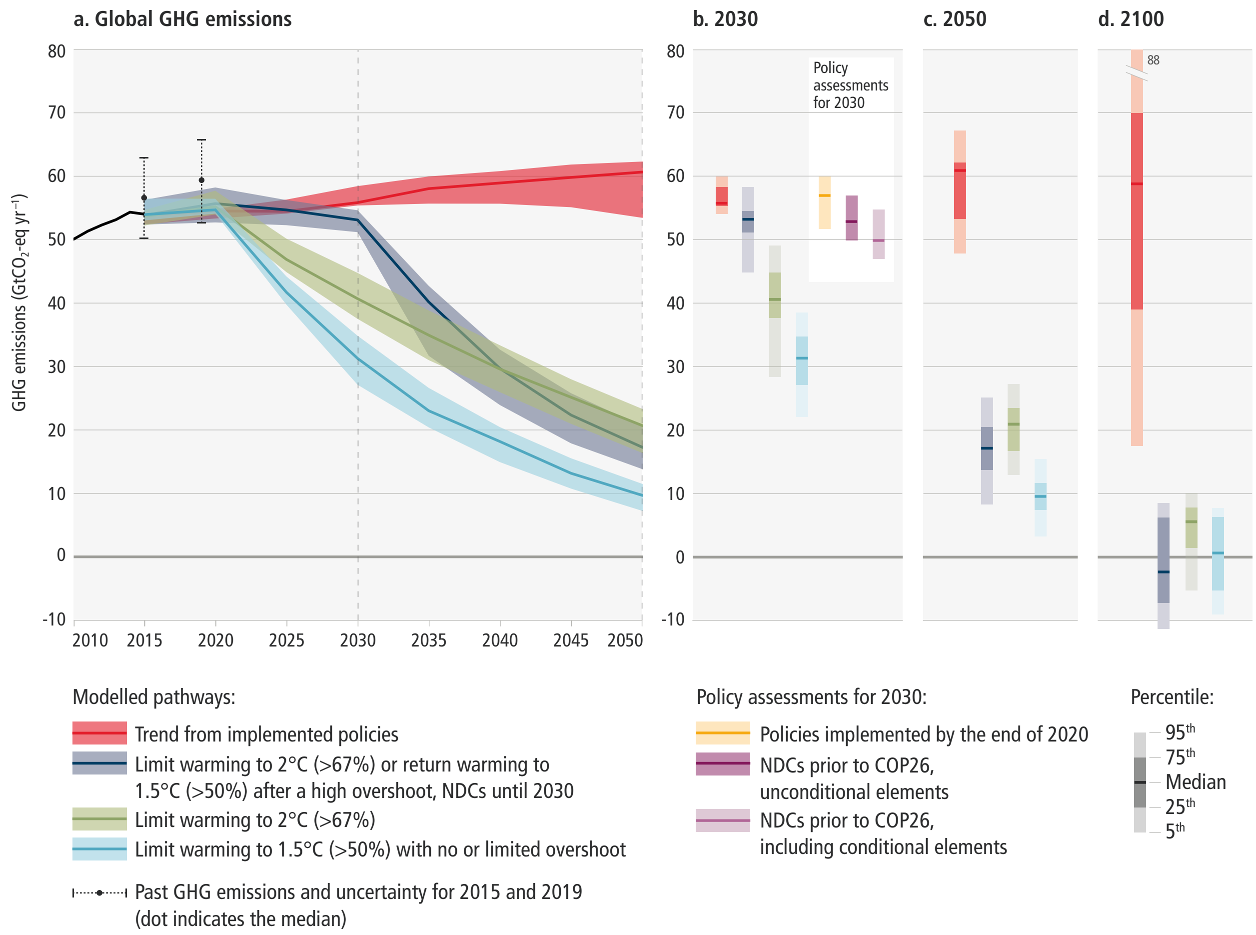

Figure SPM.4 | Global GHG emissions of modelled pathways (funnels in Panel a, and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b).

30 Median and *very likely* range [5th to 95th percentile].

31 Returning to below 1.5°C in 2100 from GHG emissions levels in 2030 associated with the implementation of NDCs is infeasible for some models due to model-specific constraints on the deployment of mitigation technologies and the availability of net negative CO_2 emissions.

Figure SPM.4 (continued): Global GHG emissions of modelled pathways (funnels in Panel a, and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b). Panel a shows global GHG emissions over 2015–2050 for four types of assessed modelled global pathways:

- Trend from implemented policies: Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030 (29 scenarios across categories C5–C7, Table SPM.2).
- Limit to 2°C (>67%) or return warming to 1.5°C (>50%) after a high overshoot, NDCs until 2030: Pathways with GHG emissions until 2030 associated with the implementation of NDCs announced prior to COP26, followed by accelerated emissions reductions *likely* to limit warming to 2°C (C3b, Table SPM.2) or to return warming to 1.5°C with a probability of 50% or greater after high overshoot (subset of 42 scenarios from C2, Table SPM.2).
- Limit to 2°C (>67%) with immediate action: Pathways that limit warming to 2°C (>67%) with immediate action after 2020[26] (C3a, Table SPM.2).
- Limit to 1.5°C (>50%) with no or limited overshoot: Pathways limiting warming to 1.5°C with no or limited overshoot (C1, Table SPM.2 C1). All these pathways assume immediate action after 2020.

Past GHG emissions for 2010–2015 used to project global warming outcomes of the modelled pathways are shown by a black line[32] and past global GHG emissions in 2015 and 2019 as assessed in Chapter 2 are shown by whiskers. **Panels b, c and d** show snapshots of the GHG emission ranges of the modelled pathways in 2030, 2050, and 2100, respectively. Panel b also shows projected emissions outcomes from near-term policy assessments in 2030 from Chapter 4.2 (Tables 4.2 and 4.3; median and full range). GHG emissions are in CO_2-equivalent using GWP100 from AR6 WGI. {3.5, 4.2, Table 4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4}

B.7 Projected cumulative future CO_2 emissions over the lifetime of existing and currently planned fossil fuel infrastructure without additional abatement exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. They are approximately equal to total cumulative net CO_2 emissions in pathways that limit warming to 2°C (>67%). (*high confidence*) {2.7, 3.3}

B.7.1 If historical operating patterns are maintained,[33] and without additional abatement,[34] estimated cumulative future CO_2 emissions from existing fossil fuel infrastructure, the majority of which is in the power sector, would, from 2018 until the end of its lifetime, amount to 660 [460–890] $GtCO_2$. They would amount to 850 [600–1100] $GtCO_2$ when unabated emissions from currently planned infrastructure in the power sector is included. These estimates compare with cumulative global net CO_2 emissions from all sectors of 510 [330–710] $GtCO_2$ until the time of reaching net zero CO_2 emissions[35] in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and 890 [640–1160] $GtCO_2$ in pathways that limit warming to 2°C (>67%). (*high confidence*) (Table SPM.2) {2.7, Figure 2.26, Figure TS.8}

B.7.2 In modelled global pathways that limit warming to 2°C (>67%) or lower, most remaining fossil fuel CO_2 emissions until the time of global net zero CO_2 emissions are projected to occur outside the power sector, mainly in industry and transport. Decommissioning and reduced utilisation of existing fossil fuel-based power sector infrastructure, retrofitting existing installations with CCS,[36] switches to low-carbon fuels, and cancellation of new coal installations without CCS are major options that can contribute to aligning future CO_2 emissions from the power sector with emissions in the assessed global modelled least-cost pathways. The most appropriate strategies will depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) (Box SPM.1) {Table 2.7, 2.7, 3.4, 6.3, 6.5, 6.7}

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32 See Box SPM.1 for a description of the approach to project global warming outcomes of modelled pathways and its consistency with the climate assessment in AR6 WGI.

33 Historical operating patterns are described by load factors and lifetimes of fossil fuel installations as observed in the past (average and range).

34 Abatement here refers to human interventions that reduce the amount of greenhouse gases that are released from fossil fuel infrastructure to the atmosphere.

35 Total cumulative CO_2 emissions up to the time of global net zero CO_2 emissions are similar but not identical to the remaining carbon budget for a given temperature limit assessed by Working Group I. This is because the modelled emission scenarios assessed by Working Group III cover a range of temperature levels up to a specific limit, and exhibit a variety of reductions in non-CO_2 emissions that also contribute to overall warming. {Box 3.4}

36 In this context, capture rates of new installations with CCS are assumed to be 90–95%+ {11.3.5}. Capture rates for retrofit installations can be comparable, if plants are specifically designed for CCS retrofits {11.3.6}.

C. System Transformations to Limit Global Warming

C.1 Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action.[i,37] In both types of modelled pathways, rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (*high confidence*). Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100[38,39] (*medium confidence*). (Table SPM.2, Figure SPM.4, Figure SPM.5) {3.3, 3.4}

C.1.1 Net global GHG emissions are projected to fall from 2019 levels by 27% [13–45%] by 2030 and 63% [52–76%][40] by 2050 in global modelled pathways that limit warming to 2°C (>67%) and assuming immediate action (category C3a, Table SPM.2). This compares with reductions of 43% [34–60%] by 2030 and 84% [73–98%] by 2050 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1, Table SPM.2) (*high confidence*).[41] In modelled pathways that return warming to 1.5°C (>50%) after a high overshoot,[42] GHG emissions are reduced by 23% [0–44%] in 2030 and by 75% [62–91%] in 2050 (C2, Table SPM.2) (*high confidence*). Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8 [2.1–3.4] °C by 2100 (*medium confidence*).[23] (Figure SPM.4) {3.3}

C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36–70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61–109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31–63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [–5 to +55%]; and F-gases are reduced by 85% [20–90%].[43] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}

C.1.3 In modelled pathways consistent with the continuation of policies implemented by the end of 2020, GHG emissions continue to rise, leading to global warming of 3.2 [2.2–3.5] °C by 2100 (within C5–C7, Table SPM.2) (*medium confidence*). Pathways that exceed warming of >4°C (≥50%) (C8, SSP5-8.5, Table SPM.2) would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). Such warming could occur in emission pathways consistent with policies implemented by the end of 2020 if climate sensitivity is higher than central estimates (*high confidence*). (Table SPM.2, Figure SPM.4) {3.3, Box 3.3}

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37 All reported warming levels are relative to the period 1850–1900. If not otherwise specified, 'pathways' always refer to pathways computed with a model. Immediate action in the pathways refers to the adoption of climate policies between 2020 and at latest 2025 intended to limit global warming at a given level.

38 Long-term warming is calculated from all modelled pathways assuming mitigation efforts consistent with national policies that were implemented by the end of 2020 (scenarios that fall into policy category P1b of Chapter 3) and that pass through the 2030 GHG emissions ranges of such pathways assessed in Chapter 4 (see footnote 25). {3.2, Table 4.2}

39 Warming estimates refer to the 50th and [5th–95th] percentile across the modelled pathways and the median temperature change estimate of the probabilistic WGI climate model emulators.[a]

40 In this report, emissions reductions are reported relative to 2019 modelled emission levels, while in SR1.5 emissions reductions were calculated relative to 2010. Between 2010 and 2019 global GHG and global CO_2 emissions have grown by 12% (6.5 $GtCO_2$-eq) and 13% (5.0 $GtCO_2$) respectively. In global modelled pathways assessed in this report that limit warming to 1.5°C (>50%) with no or limited overshoot, GHG emissions are projected to be reduced by 37% [28–57%] in 2030 relative to 2010. In the same type of pathways assessed in SR1.5, GHG emissions are reduced by 45% (40–60% interquartile range) relative to 2010. In absolute terms, the 2030 GHG emissions levels of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are higher in AR6 (31 [21–36] $GtCO_2$-eq) than in SR1.5 (28 (26–31 interquartile range) $GtCO_2$-eq). (Figure SPM.1, Table SPM.2) {3.3, SR1.5}

41 Scenarios in this category limit peak warming to 2°C throughout the 21st century with close to, or more than, 90% likelihood.

42 This category contains 91 scenarios with immediate action and 42 scenarios that are consistent with the NDCs until 2030.

43 These numbers for CH_4, N_2O, and F-gases are rounded to the nearest 5% except numbers below 5%.

Table SPM.2 | Key characteristics of the modelled global emissions pathways. Summary of projected CO_2 and GHG emissions, projected net zero timings and the resulting global warming outcomes. Pathways are categorised (rows), according to their likelihood of limiting warming to different peak warming levels (if peak temperature occurs before 2100) and 2100 warming levels. Values shown are for the median [p50] and 5th–95th percentiles [p5–p95], noting that not all pathways achieve net zero CO_2 or GHGs.

p50 [p5–p95] [a]			GHG emissions ($GtCO_2$-eq yr^{-1}) [g]			GHG emissions reductions from 2019 (%) [h]			Emissions milestones [i, j]				Cumulative CO_2 emissions ($GtCO_2$) [m]		Cumulative net-negative CO_2 emissions ($GtCO_2$)	Global mean temperature changes 50% probability (°C) [n]		Likelihood of peak global warming staying below (%) [o]		
Category [b, c, d] [# pathways]	Category/subset label	WGI SSP & WGIII IPs/IMPs alignment [e, f]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net zero CO_2 (% net zero pathways)	Net zero GHGs (% net zero pathways) [k, l]	2020 to net zero CO_2	2020–2100	Year of net zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			Projected median annual GHG emissions in the year across the scenarios, with the 5th–95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53–58] $GtCO_2$-eq.			Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th–95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.			Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th–95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.		Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net zero, with the 5th–95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.		Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net zero or until 2100, with the 5th–95th percentile interval in square brackets.		Median cumulative net-negative CO_2 emissions between the year of net zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850–1900, at peak warming and in 2100, for the median value across the scenarios and the 5th–95th percentile interval in square brackets.		Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th–95th percentile interval in square brackets.		
C1 [97]	limit warming to 1.5°C (>50%) with no or limited overshoot		31 [21–36]	17 [6–23]	9 [1–15]	43 [34–60]	69 [58–90]	84 [73–98]				2095–2100 (52%) [2050–…]	510 [330–710]	320 [–210 to 570]	–220 [–660 to –20]	1.6 [1.4–1.6]	1.3 [1.1–1.5]	38 [33–58]	90 [86–97]	100 [99–100]
C1a [50]	… with net zero GHGs	SSP1–1.9, SP LD	33 [22–37]	18 [6–24]	8 [0–15]	41 [31–59]	66 [58–89]	85 [72–100]	2020–2025 (100%) [2020–2025]		2050–2055 (100%) [2035–2070]	2070–2075 (100%) [2050–2090]	550 [340–760]	160 [–220 to 620]	–360 [–680 to –140]	1.6 [1.4–1.6]	1.2 [1.1–1.4]	38 [34–60]	90 [85–98]	100 [99–100]
C1b [47]	… without net zero GHGs	Ren	29 [21–36]	16 [7–21]	9 [4–13]	48 [35–61]	70 [62–87]	84 [76–93]				…–… [0%] […–…]	460 [320–590]	360 [10–540]	–60 [–440 to 0]	1.6 [1.5–1.6]	1.4 [1.3–1.5]	37 [33–56]	89 [87–96]	100 [99–100]
C2 [133]	return warming to 1.5°C (>50%) after a high overshoot	Neg	42 [31–55]	25 [17–34]	14 [5–21]	23 [0–44]	55 [40–71]	75 [62–91]	2020–2025 (100%) [2020–2030]	[2020–2025]	2055–2060 (100%) [2045–2070]	2070–2075 (87%) [2055–…]	720 [530–930]	400 [–90 to 620]	–360 [–680 to –60]	1.7 [1.5–1.8]	1.4 [1.2–1.5]	24 [15–42]	82 [71–93]	100 [99–100]
C3 [311]	limit warming to 2°C (>67%)		44 [32–55]	29 [20–36]	20 [13–26]	21 [1–42]	46 [34–63]	64 [53–77]	2020–2025 (100%) [2020–2030]	[2020–2025]	2070–2075 (93%) [2055–…]	…–… (30%) [2075–…]	890 [640–1160]	800 [510–1140]	–40 [–290 to 0]	1.7 [1.6–1.8]	1.6 [1.5–1.8]	20 [13–41]	76 [68–91]	99 [98–100]
C3a [204]	… with action starting in 2020	SSP1–2.6	40 [30–49]	29 [21–36]	20 [14–27]	27 [13–45]	47 [35–63]	63 [52–76]	2020–2025 (100%) [2020–2025]		2070–2075 (91%) [2055–…]	…–… (24%) [2080–…]	860 [640–1180]	790 [480–1150]	–30 [–280 to 0]	1.7 [1.6–1.8]	1.6 [1.5–1.8]	21 [14–42]	78 [69–91]	100 [98–100]

Table SPM.2 (continued):

p50 [p5–p95] [a]			GHG emissions ($GtCO_2$-eq yr^{-1}) [g]			GHG emissions reductions from 2019 (%) [h]			Emissions milestones [i, j]				Cumulative CO_2 emissions ($GtCO_2$) [m]		Cumulative net-negative CO_2 emissions ($GtCO_2$)	Global mean temperature changes 50% probability (°C) [n]		Likelihood of peak global warming staying below (%) [o]		
Category [b, c, d] [# pathways]	Category/subset label	WGI SSP & WGIII IPs/IMPs alignment [e, f]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net zero CO_2 (% net zero pathways)	Net zero GHGs (% net zero pathways) [k, l]	2020 to net zero CO_2	2020–2100	Year of net zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			Projected median annual GHG emissions in the year across the scenarios, with the 5th–95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53–58] $GtCO_2$-eq.			Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th–95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.			Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th–95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.		Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net zero, with the 5th–95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.		Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net zero or until 2100, with the 5th–95th percentile interval in square brackets.		Median cumulative net-negative CO_2 emissions between the year of net zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850–1900, at peak warming and in 2100, for the median value across the scenarios and the 5th–95th percentile interval in square brackets.		Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th–95th percentile interval in square brackets.		
C3b [97]	**… NDCs until 2030**	GS	52 [47–56]	29 [20–36]	18 [10–25]	5 [0–14]	46 [34–63]	68 [56–82]			2065–2070 (97%) [2055–2090]	…–… (41%) [2075–…]	910 [720–1150]	800 [560–1050]	–60 [–300 to 0]	1.8 [1.6–1.8]	1.6 [1.5–1.7]	17 [12–35]	73 [67–87]	99 [98–99]
C4 [159]	**limit warming to 2°C (>50%)**		50 [41–56]	38 [28–44]	28 [19–35]	10 [0–27]	31 [20–50]	49 [35–65]	2020–2025 (100%) [2020–2030]		2080–2085 (86%) [2065–…]	…–… (31%) [2075–…]	1210 [970–1490]	1160 [700–1490]	–30 [–390 to 0]	1.9 [1.7–2.0]	1.8 [1.5–2.0]	11 [7–22]	59 [50–77]	98 [95–99]
C5 [212]	**limit warming to 2.5°C (>50%)**		52 [46–56]	45 [37–53]	39 [30–49]	6 [–1 to 18]	18 [4–33]	29 [11–48]			…–… (41%) [2080–…]	…–… (12%) [2090–…]	1780 [1400–2360]	1780 [1260–2360]	0 [–160 to 0]	2.2 [1.9–2.5]	2.1 [1.9–2.5]	4 [0–10]	37 [18–59]	91 [83–98]
C6 [97]	**limit warming to 3°C (>50%)**	SSP2–4.5 ModAct	54 [50–62]	53 [48–61]	52 [45–57]	2 [–10 to 11]	3 [–14 to 14]	5 [–2 to 18]	2030–2035 (96%) [2020–2090]	2020–2025 (97%)				2790 [2440–3520]			2.7 [2.4–2.9]	0 [0–0]	8 [2–18]	71 [53–88]
C7 [164]	**limit warming to 4°C (>50%)**	SSP3–7.0 CurPol	62 [53–69]	67 [56–76]	70 [58–83]	–11 [–18 to 3]	–19 [–31 to 1]	–24 [–41 to –2]	2085–2090 (57%) [2040–…]	2090–2095 (56%)	no net zero		no net zero	4220 [3160–5000]	no net zero	temperature does not peak by 2100	3.5 [2.8–3.9]	0 [0–0]	0 [0–2]	22 [7–60]
C8 [29]	**exceed warming of 4°C (≥50%)**	SSP5–8.5	71 [69–81]	80 [78–96]	88 [82–112]	–20 [–34 to –17]	–35 [–65 to –29]	–46 [–92 to –36]	2080–2085 (90%) [2070–…]					5600 [4910–7450]			4.2 [3.7–5.0]	0 [0–0]	0 [0–0]	4 [0–11]

Table SPM.2 (continued):

[a] Values in the table refer to the 50th and [5th–95th] percentile values across the pathways falling within a given category as defined in Box SPM.1. For emissions-related columns these values relate to the distribution of all the pathways in that category. Harmonised emissions values are given for consistency with projected global warming outcomes using climate emulators. Based on the assessment of climate emulators in AR6 WGI (WG1 Chapter 7, Box 7.1), two climate emulators are used for the probabilistic assessment of the resulting warming of the pathways. For the 'Temperature change' and 'Likelihood' columns, the single upper-row values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). Subsequently, the 5th and 95th percentile values across all pathways for each emulator are calculated. The coolest and warmest outcomes (i.e., the lowest p5 of two emulators, and the highest p95, respectively) are shown in square brackets. These ranges therefore cover both the uncertainty of the emissions pathways as well as the climate emulators' uncertainty.

[b] For a description of pathways categories see Box SPM.1.

[c] All global warming levels are relative to 1850–1900. (See footnote n below and Box SPM.1[45] for more details.)

[d] C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in Figure SPM.4. Two pathways derived from a cost-benefit analysis have been added to C3a, whilst 10 pathways with specifically designed near-term action until 2030, whose emissions fall below those implied by NDCs announced prior to COP26, are not included in either of the two subsets.

[e] Alignment with the categories of the illustrative SSP scenarios considered in AR6 WGI, and the Illustrative (Mitigation) Pathways (IPs/IMPs) of WGIII. The IMPs have common features such as deep and rapid emissions reductions, but also different combinations of sectoral mitigation strategies. See Box SPM.1 for an introduction of the IPs and IMPs, and Chapter 3 for full descriptions. {3.2, 3.3, Annex III.II.4}

[f] The Illustrative Mitigation Pathway 'Neg' has extensive use of carbon dioxide removal (CDR) in the AFOLU, energy and the industry sectors to achieve net negative emissions. Warming peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as C3, it strongly exhibits the characteristics of C2 high-overshoot pathways, hence it has been placed in the C2 category. See Box SPM.1 for an introduction of the IPs and IMPs.

[g] The 2019 range of harmonised GHG emissions across the pathways [53–58 $GtCO_2$-eq] is within the uncertainty ranges of 2019 emissions assessed in Chapter 2 [53–66 $GtCO_2$-eq].[49] (Figure SPM.1, Figure SPM.2, Box SPM.1)

[h] Rates of global emission reduction in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonised modelled global emissions in 2019 rather than the global emissions reported in SPM Section B and Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WGI.[49] {Annex III.II.2.5}. Negative values (e.g., in C7, C8) represent an increase in emissions.

[i] Emissions milestones are provided for five-year intervals in order to be consistent with the underlying five-year time-step data of the modelled pathways. Peak emissions (CO_2 and GHGs) are assessed for five-year reporting intervals starting in 2020. The interval 2020–2025 signifies that projected emissions peak as soon as possible between 2020 and at latest before 2025. The upper five-year interval refers to the median interval within which the emissions peak or reach net zero. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile five-year interval and the upper bound of the 95th percentile five-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones.

[j] Percentiles reported across all pathways in that category include those that do not reach net zero before 2100 (fraction of pathways reaching net zero is given in round brackets). If the fraction of pathways that reach net zero before 2100 is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with '…'. The fraction of pathways reaching net zero includes all with reported non-harmonised, and/or harmonised emissions profiles that reach net zero. Pathways were counted when at least one of the two profiles fell below 100 $MtCO_2$ yr^{-1} until 2100.

[k] The timing of net zero is further discussed in SPM C2.4 and Cross-Chapter Box 3 in Chapter 3 on net zero CO_2 and net zero GHG emissions.

[l] For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO_2-eq defined by the 100-year global warming potential. For each pathway, reporting of CO_2, CH_4, and N_2O emissions was the minimum required for the assessment of the climate response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. {See Annex III.II.5}

[m] Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonised net CO_2 emissions, ensuring consistency with the WGI assessment of the remaining carbon budget.[50] {Box 3.4}

[n] Global mean temperature change for category (at peak, if peak temperature occurs before 2100, and in 2100) relative to 1850–1900, based on the median global warming for each pathway assessed using the probabilistic climate model emulators calibrated to the AR6 WGI assessment.[12] (See also Box SPM.1) {Annex III.II.2.5; WGI Cross-Chapter Box 7.1}

[o] Probability of staying below the temperature thresholds for the pathways in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the AR6 WGI assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (e.g., category C2 and some pathways in C1), the probabilities of staying below at the end of the century are higher than the probabilities at peak temperature.

C.1.4 Global modelled pathways falling into the lowest temperature category of the assessed literature (C1, Table SPM.2) are on average associated with a higher median peak warming in AR6 compared to pathways in the same category in SR1.5. In the modelled pathways in AR6, the likelihood of limiting warming to 1.5°C has on average declined compared to SR1.5. This is because GHG emissions have risen since 2017, and many recent pathways have higher projected emissions by 2030, higher cumulative net CO_2 emissions and slightly later dates for reaching net zero CO_2 or net zero GHG emissions. High mitigation challenges, for example, due to assumptions of slow technological change, high levels of global population growth, and high fragmentation as in the Shared Socio-economic Pathway SSP3, may render modelled pathways that limit warming to 2°C (>67%) or lower infeasible. (*medium confidence*) (Table SPM.2, Box SPM.1) {3.3, 3.8, Annex III Figure II.1, Annex III Figure II.3}

Box SPM.1 | Assessment of Modelled Global Emission Scenarios

A wide range of modelled global emission pathways and scenarios from the literature is assessed in this report, including pathways and scenarios with and without mitigation.[44] Emissions pathways and scenarios project the evolution of GHG emissions based on a set of internally consistent assumptions about future socio-economic conditions and related mitigation measures.[45] These are quantitative projections and are neither predictions nor forecasts. Around half of all modelled global emission scenarios assume cost-effective approaches that rely on least-cost emission abatement options globally. The other half look at existing policies and regionally and sectorally differentiated actions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. Global emission pathways, including those based on cost-effective approaches, contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. This assessment focuses on their global characteristics. The majority of the assessed scenarios (about 80%) have become available since the SR1.5, but some were assessed in that report. Scenarios with and without mitigation were categorised based on their projected global warming over the 21st century, following the same scheme as in the SR1.5 for warming up to and including 2°C. {1.5, 3.2, 3.3, Annex III.II.2, Annex III.II.3}

Scenario categories are defined by their likelihood of exceeding global warming levels (at peak and in 2100) and referred to in this report as follows:[46,47]

- Category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades.[48]
- Category C2 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and exceed warming of 1.5°C during the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1°C–0.3°C for up to several decades.
- Category C3 comprises modelled scenarios that limit peak warming to 2°C throughout the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that limit warming to 2°C (>67%).
- Categories C4, C5, C6 and C7 comprise modelled scenarios that limit warming to 2°C, 2.5°C, 3°C, 4°C, respectively, throughout the 21st century with a likelihood of greater than 50%. In some scenarios in C4 and many scenarios in C5–C7, warming continues beyond the 21st century.

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44 In the literature, the terms 'pathways' and 'scenarios' are used interchangeably, with the former more frequently used in relation to climate goals. For this reason, this SPM uses mostly the term (emissions and mitigation) pathways. {Annex III.II.1.1}

45 Key assumptions relate to technology development in agriculture and energy systems and socio-economic development, including demographic and economic projections. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures. Additional scenarios may be developed. The underlying population assumptions range from 8.5 to 9.7 billion in 2050 and 7.4 to 10.9 billion in 2100 (5–95th percentile) starting from 7.6 billion in 2019. The underlying assumptions on global GDP growth (ppp) range from 2.5 to 3.5% per year in the 2019–2050 period and 1.3 to 2.1% per year in the 2050–2100 (5–95th percentile). Many underlying assumptions are regionally differentiated. {1.5; 3.2; 3.3; Figure 3.9; Annex III.II.1.4; Annex III.II.3}

46 The future scenario projections presented here are consistent with the total observed increase in global surface temperature between 1850–1900 and 1995–2014 as well as to 2011–2020 (with best estimates of 0.85°C and 1.09°C, respectively) assessed in WGI. The largest contributor to historical human-induced warming is CO_2, with historical cumulative CO_2 emissions from 1850 to 2019 being 2400 ± 240 $GtCO_2$. {WGI SPM A.1.2, WGI Table SPM.2, WGI Table 5.1, WGIII SPM Section B}.

47 In case no explicit likelihood is provided, the reported warming levels are associated with a likelihood of >50%.

48 Scenarios in this category are found to have simultaneous likelihood to limit peak global warming to 2°C throughout the 21st century of close to and more than 90%.

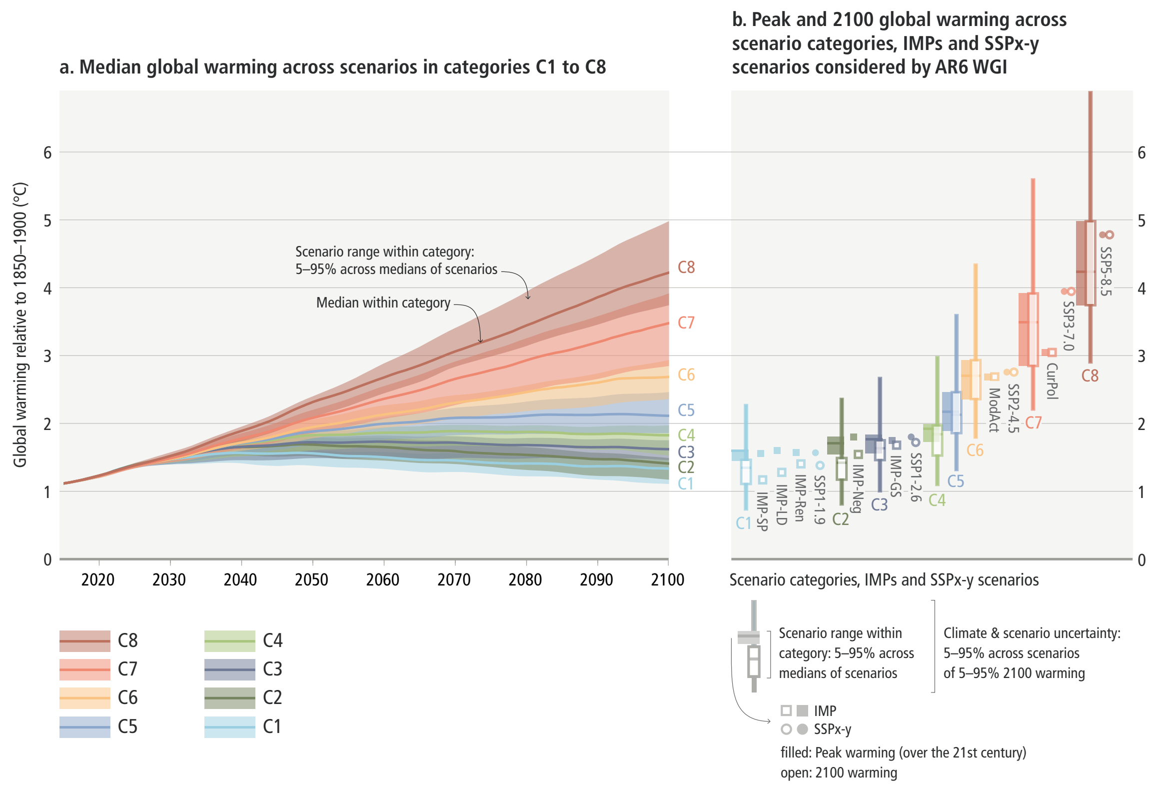
Box SPM.1 (continued)

- Category C8 comprises modelled scenarios that exceed warming of 4°C during the 21st century with a likelihood of 50% or greater. In these scenarios warming continues to rise beyond the 21st century.

Categories of modelled scenarios are distinct and do not overlap; they do not contain categories consistent with lower levels of global warming, for example, the category of C3 scenarios that limit warming to 2°C (>67%) does not include the C1 and C2 scenarios that limit or return warming to 1.5°C (>50%). Where relevant, scenarios belonging to the group of categories C1–C3 are referred to in this report as scenarios that limit warming to 2°C (>67%) or lower.

Methods to project global warming associated with the scenarios were updated to ensure consistency with the AR6 WGI assessment of physical climate science.[49] {3.2, Annex III.II.2.5; AR6 WGI Cross-Chapter Box 7.1}

The range of assessed scenarios results in a range of 21st century projected global warming.



Box SPM.1, Figure 1 | Projected global mean warming of the ensemble of modelled scenarios included in the climate categories C1–C8 and IMPs (based on emulators calibrated to the WGI assessment), as well as five illustrative scenarios (SSPx-y) as considered by AR6 WGI. Panel a shows the p5–p95 range of projected median warming across global modelled pathways within a category, with the category medians (line). **Panel b** shows the peak and 2100 emulated temperature outcomes for the categories C1 to C8 and for IMPs, and the five illustrative scenarios (SSPx-y) as considered by AR6 WGI. The boxes show the p5–p95 range within each scenario category, as in panel a. The combined p5–p95 range across scenarios and the climate uncertainty for each category C1–C8 is also shown for 2100 warming (thin vertical lines). (Table SPM.2) {Figure 3.11; AR6 WGI Figure SPM.8}

[49] This involved improved methodologies to use climate emulators (MAGICC7 and FAIR v1.6), which were evaluated and calibrated to closely match the global warming response to emissions as assessed in AR6 WGI. It included harmonisation of global GHG emissions in 2015 in modelled scenarios (51–56 $GtCO_2$-eq; 5th to 95th percentiles) with the corresponding emission value underlying the CMIP6 projected climate response assessed by WGI (54 $GtCO_2$-eq), based on similar data sources of historical emissions that are updated over time. The assessment of past GHG emissions in Chapter 2 of the report is based on a more recent dataset providing emissions of 57 [±6.3] $GtCO_2$-eq in 2015 (B.1). Differences are well within the assessed uncertainty range, and arise mainly from differences in estimated CO_2-LULUCF emissions, which are subject to large uncertainties, high annual variability and revisions over time. Projected rates of global emission reduction in mitigation scenarios are reported relative to modelled global emissions in 2019 rather than the global emissions reported in Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WG I. {Annex III.II.2.5}

Box SPM.1 (continued)

These updated methods affect the categorisation of some scenarios. On average across scenarios, peak global warming is projected to be lower by up to about 0.05 [±0.1] °C than if the same scenarios were evaluated using the SR1.5 methodology, and global warming in 2100 is projected to be lower by about 0.1 [±0.1] °C. {Annex III.II.2.5.1, Annex III Figure II.3}

Resulting changes to the emission characteristics of scenario categories described in Table SPM.2 interact with changes in the characteristics of the wider range of emission scenarios published since the SR1.5. Proportionally more scenarios assessed in AR6 are designed to limit temperature overshoot and more scenarios limit large-scale net negative CO_2 emissions than in SR1.5. As a result, AR6 scenarios in the lowest temperature category (C1) generally reach net zero GHG emissions later in the 21st century than scenarios in the same category assessed in SR1.5, and about half do not reach net zero GHG by 2100. The rate of decline of GHG emissions in the near term by 2030 in category C1 scenarios is very similar to the assessed rate in SR1.5, but absolute GHG emissions of category C1 scenarios in AR6 are slightly higher in 2030 than in SR1.5, since the reductions start from a higher emissions level in 2020. (Table SPM.2) {Annex III, 2.5, 3.2, 3.3}

The large number of global emissions scenarios assessed, including 1202 scenarios with projected global warming outcomes using climate emulators, come from a wide range of modelling approaches. They include the five illustrative scenarios (Shared Socio-economic Pathways; SSPs) assessed by WGI for their climate outcomes but cover a wider and more varied set in terms of assumptions and modelled outcomes. For this assessment, Illustrative Mitigation Pathways (IMPs) were selected from this larger set to illustrate a range of different mitigation strategies that would be consistent with different warming levels. The IMPs illustrate pathways that achieve deep and rapid emissions reductions through different combinations of mitigation strategies. The IMPs are not intended to be comprehensive and do not address all possible themes in the underlying report. They differ in terms of their focus, for example, placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that results in net negative global GHG emissions (IMP-Neg), and efficient resource use as well as shifts in consumption patterns globally, leading to low demand for resources, while ensuring a high level of services and satisfying basic needs (IMP-LD) (Figure SPM.5). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation (IMP-SP). The IMPs reach different climate goals as indicated in Table SPM.2 and Box SPM.1, Figure 1. {1.5, 3.1, 3.2, 3.3, 3.6, Figure 3.7, Figure 3.8, Box 3.4, Annex III.II.2.4}

C.2 Global net zero CO_2 emissions are reached in the early 2050s in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and around the early 2070s in modelled pathways that limit warming to 2°C (>67%). Many of these pathways continue to net negative CO_2 emissions after the point of net zero. These pathways also include deep reductions in other GHG emissions. The level of peak warming depends on cumulative CO_2 emissions until the time of net zero CO_2 and the change in non-CO_2 climate forcers by the time of peaking. Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*) (Table SPM.2) {3.3, 3.5, Box 3.4, Cross-Chapter Box 3 in Chapter 3, AR6 WGI SPM D1.8}

C.2.1 Modelled global pathways limiting warming to 1.5°C (>50%) with no or limited overshoot are associated with projected cumulative net CO_2 emissions[50] until the time of net zero CO_2 of 510 [330–710] $GtCO_2$. Pathways limiting warming to 2°C (>67%) are associated with 890 [640–1160] $GtCO_2$ (Table SPM.2). (*high confidence*) {3.3, Box 3.4}

C.2.2 Modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot involve more rapid and deeper near-term GHG emissions reductions through to 2030, and are projected to have less net negative CO_2 emissions and less carbon dioxide removal (CDR) in the longer term, than pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category). Modelled pathways that limit warming to 2°C (>67%) have on average lower net negative CO_2 emissions compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and pathways that return warming

[50] Cumulative net CO_2 emissions from the beginning of the year 2020 until the time of net zero CO_2 in assessed pathways are consistent with the remaining carbon budgets assessed by WGI, taking account of the ranges in the WGIII temperature categories and warming from non-CO_2 gases. {Box 3.4}

to 1.5°C (>50%) after a high overshoot (C1 and C2 categories respectively). Modelled pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category) show near-term GHG emissions reductions similar to pathways that limit warming to 2°C (>67%) (C3 category). For a given peak global warming level, greater and more rapid near-term GHG emissions reductions are associated with later net zero CO_2 dates. (*high confidence*) (Table SPM.2) {3.3, Table 3.5, Cross-Chapter Box 3 in Chapter 3, Annex I: Glossary}

C.2.3 Future non-CO_2 warming depends on reductions in non-CO_2 GHGs, aerosols and their precursors, and ozone precursor emissions. In modelled global low-emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq yr^{-1}, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]).[51] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*) {3.3; AR6 WGI SPM D1.7}

C.2.4 At the time of global net zero GHG emissions, net negative CO_2 emissions counterbalance metric-weighted non-CO_2 GHG emissions. Typical emissions pathways that reach and sustain global net zero GHG emissions based on the 100-year global warming potential (GWP-100)[7] are projected to result in a gradual decline of global warming. About half of the assessed pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1 category) reach net zero GHG emissions during the second half of the 21st century. These pathways show greater reduction in global warming after the peak to 1.2 [1.1–1.4] °C by 2100 than modelled pathways in the same category that do not reach net zero GHG emissions before 2100 and that result in warming of 1.4 [1.3–1.5] °C by 2100. In modelled pathways that limit warming to 2°C (>67%) (C3 category), there is no significant difference in warming by 2100 between those pathways that reach net zero GHGs (around 30%) and those that do not (*high confidence*). In pathways that limit warming to 2°C (>67%) or lower and that do reach net zero GHG, net zero GHG occurs around 10–40 years later than net zero CO_2 emissions (*medium confidence*). {Cross-Chapter Box 2 in Chapter 2, 3.3, Cross-Chapter Box 3 in Chapter 3; AR6 WGI SPM D1.8}

C.3 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%), involve rapid and deep and in most cases immediate GHG emission reductions in all sectors. Modelled mitigation strategies to achieve these reductions include transitioning from fossil fuels without CCS to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand side measures and improving efficiency, reducing non-CO_2 emissions, and deploying carbon dioxide removal (CDR) methods to counterbalance residual GHG emissions. Illustrative Mitigation Pathways (IMPs) show different combinations of sectoral mitigation strategies consistent with a given warming level. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4, 6.4, 6.6}

C.3.1 There is a variation in the contributions of different sectors in modelled mitigation pathways, as illustrated by the Illustrative Mitigation Pathways (IMPs). However, modelled pathways that limit warming to 2°C (>67%) or lower share common characteristics, including rapid and deep GHG emission reductions. Doing less in one sector needs to be compensated by further reductions in other sectors if warming is to be limited. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4}

C.3.2 In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, the global use of coal, oil and gas in 2050 is projected to decline with median values of about 95%, 60% and 45% respectively, compared to 2019. The interquartile ranges are (80 to 100%), (40 to 75%) and (20 to 60%) and the p5–p95 ranges are [60 to 100%], [25 to 90%] and [–30 to +85%], respectively. In modelled pathways that limit warming to 2°C (>67%), these projected declines have a median value and interquartile range of 85% (65 to 95%), 30% (15 to 50%) and 15% (–10 to +40%) respectively by 2050. The use of coal, oil and gas without CCS in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot is projected to be reduced to a greater degree, with median values of about 100%, 60% and 70% in 2050 compared to 2019. The interquartile ranges are (95 to 100%), (45 to 75%) and (60 to 80%) and the p5–p95 ranges about [85 to 100%], [25 to 90%] and [35 to 90%] for coal, oil and gas respectively. In these global modelled pathways, in 2050 almost all electricity is supplied from zero- or low-carbon sources, such as renewables or fossil fuels with CCS, combined with increased

[51] All numbers here rounded to the closest 5%, except values below 5% (for F-gases).

electrification of energy demand. As indicated by the ranges, choices in one sector can be compensated for by choices in another while being consistent with assessed warming levels.[52] (*high confidence*) {3.4, 3.5, Table 3.6, Figure 3.22, Figure 6.35}

C.3.3 In modelled pathways that reach global net zero CO_2 emissions: at the point they reach net zero, 5–16 $GtCO_2$ of emissions from some sectors are compensated for by net negative CO_2 emissions in other sectors. In most global modelled pathways that limit warming to 2°C (>67%) or lower, the AFOLU sector, via reforestation and reduced deforestation, and the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors. (*high confidence*) (Figure SPM.5e,f) {3.4}

C.3.4 In modelled pathways that reach global net zero GHG emissions, at the point they reach net zero GHG, around 74% [54 to 90%] of global emissions reductions are achieved by CO_2 reductions in energy supply and demand, 13% [4 to 20%] by CO_2 mitigation options in the AFOLU sector, and 13% [10 to 18%] through the reduction of non-CO_2 emissions from land-use, energy and industry (*medium confidence*). (Figure SPM.5f) {3.3, 3.4}

C.3.5 Methods and levels of CDR deployment in global modelled mitigation pathways vary depending on assumptions about costs, availability and constraints.[53] In modelled pathways that report CDR and that limit warming to 1.5°C (>50%) with no or limited overshoot, global cumulative CDR during 2020–2100 from bioenergy with carbon dioxide capture and storage (BECCS) and direct air carbon dioxide capture and storage (DACCS) is 30–780 $GtCO_2$ and 0–310 $GtCO_2$, respectively. In these modelled pathways, the AFOLU sector contributes 20–400 $GtCO_2$ net negative emissions. Total cumulative net negative CO_2 emissions including CDR deployment across all options represented in these modelled pathways are 20–660 $GtCO_2$. In modelled pathways that limit warming to 2°C (>67%), global cumulative CDR during 2020–2100 from BECCS and DACCS is 170–650 $GtCO_2$ and 0–250 $GtCO_2$ respectively, the AFOLU sector contributes 10–250 $GtCO_2$ net negative emissions, and total cumulative net negative CO_2 emissions are around 40 [0–290] $GtCO_2$. (Table SPM.2) (*high confidence*) {Table 3.2, 3.3, 3.4}

C.3.6 All mitigation strategies face implementation challenges, including technology risks, scaling, and costs. Many challenges, such as dependence on CDR, pressure on land and biodiversity (e.g., bioenergy) and reliance on technologies with high upfront investments (e.g., nuclear), are significantly reduced in modelled pathways that assume using resources more efficiently (e.g., IMP-LD) or that shift global development towards sustainability (e.g., IMP-SP). (*high confidence*) (Figure SPM.5) {3.2, 3.4, 3.7, 3.8, 4.3, 5.1}

52 Most but not all models include the use of fossil fuels for feedstock with varying underlying standards.

53 Aggregate levels of CDR deployment are higher than total net negative CO_2 emissions given that some of the deployed CDR is used to counterbalance remaining gross emissions. Total net negative CO_2 emissions in modelled pathways might not match the aggregated net negative CO_2 emissions attributed to individual CDR methods. Ranges refer to the 5–95th percentile across modelled pathways that include the specific CDR method. Cumulative levels of CDR from AFOLU cannot be quantified precisely given that: (i) some pathways assess CDR deployment relative to a baseline; and (ii) different models use different reporting methodologies that in some cases combine gross emissions and removals in AFOLU. Total CDR from AFOLU equals or exceeds the net negative emissions mentioned.

Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.

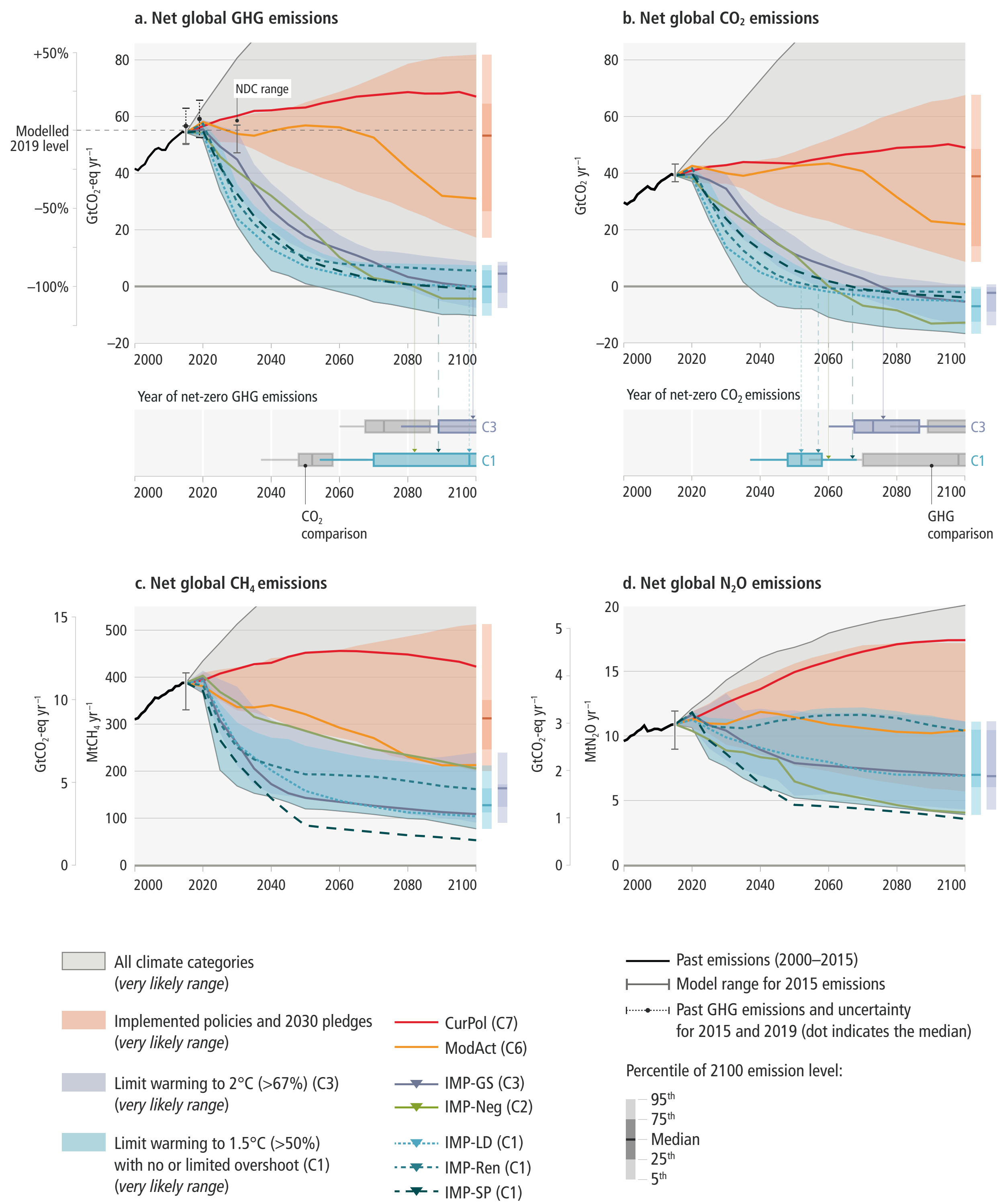


Figure SPM.5 | Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies.

Net zero CO_2 and net zero GHG emissionsare possible through different modelled mitigation pathways.

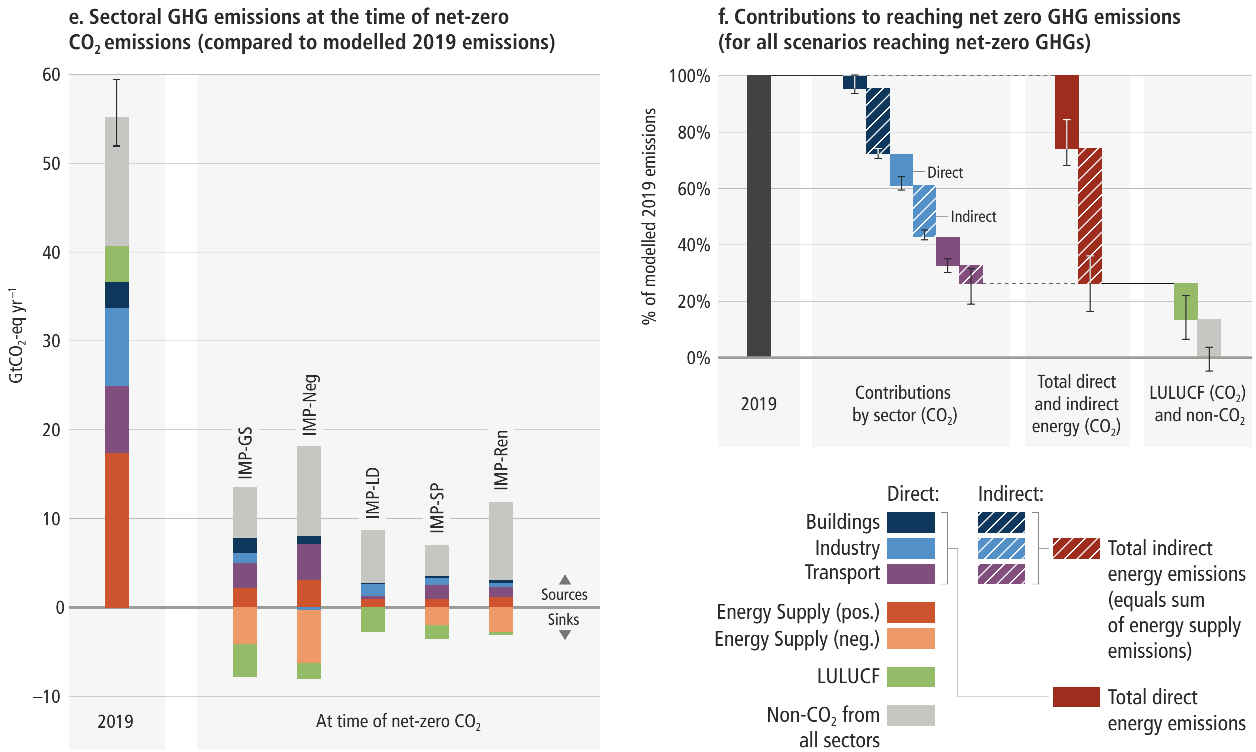


Figure SPM.5 (continued): Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies. Panels a and b show the development of global GHG and CO_2 emissions in modelled global pathways (upper sub-panels) and the associated timing of when GHG and CO_2 emissions reach net zero (lower sub-panels). **Panels c and d** show the development of global CH_4 and N_2O emissions, respectively. Coloured ranges denote the 5th to 95th percentile across pathways. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020 and pathways assuming implementation of NDCs (announced prior to COP26). Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that limit warming to 2°C (>67%) are shown in light purple (category C3). The grey range comprises all assessed pathways (C1–C8) from the 5th percentile of the lowest warming category (C1) to the 95th percentile of the highest warming category (C8). The modelled pathway ranges are compared to the emissions from two pathways illustrative of high emissions (CurPol and ModAct) and five IMPs: IMP-LD, IMP-Ren, IMP-SP, IMP-Neg and IMP-GS. Emissions are harmonised to the same 2015 base year. The vertical error bars in 2015 show the 5–95th percentile uncertainty range of the non-harmonised emissions across the pathways, and the uncertainty range, and median value, in emission estimates for 2015 and 2019. The vertical error bars in 2030 (panel a) depict the assessed range of the NDCs, as announced prior to COP26 (Figure SPM.4).[23] **Panel e** shows the sectoral contributions of CO_2 and non-CO_2 emissions sources and sinks at the time when net zero CO_2 emissions are reached in the IMPs. Positive and negative emissions for different IMPs are compared to the GHG emissions from the year 2019. Energy supply (neg.) includes BECCS and DACCS. DACCS features in only two of the five IMPs (IMP-REN and IMP-GS) and contributes <1% and 64%, respectively, to the net negative emissions in Energy Supply (neg.). **Panel f** shows the contribution of different sectors and sources to the emissions reductions from a 2019 baseline for reaching net zero GHG emissions. Bars denote the median emissions reductions for all pathways that reach net zero GHG emissions. The whiskers indicate the p5–p95 range. The contributions of the service sectors (transport, buildings, industry) are split into direct (demand-side) as well as indirect (supply-side) CO_2 emissions reductions. Direct emissions represent demand-side emissions due to the fuel use in the respective demand sector. Indirect emissions represent upstream emissions due to industrial processes and energy conversion, transmission and distribution. In addition, the contributions from the LULUCF sector and reductions from non-CO_2 emissions sources (green and grey bars) are displayed. {3.3, 3.4}

C.4 Reducing GHG emissions across the full energy sector requires major transitions, including a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation. The continued installation of unabated fossil fuel[54] infrastructure will 'lock-in' GHG emissions. (*high confidence*) {2.7, 6.6, 6.7, 16.4}

C.4.1 Net-zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels, and use of CCS in the remaining fossil fuel system;[54] electricity systems that emit no net CO_2; widespread electrification of the energy system including end uses; energy carriers such as sustainable biofuels, low-emissions hydrogen, and derivatives in applications less amenable to electrification; energy conservation and efficiency; and greater physical, institutional, and operational integration across the energy system. CDR will be needed to counterbalance residual emissions in the energy sector. The most appropriate strategies depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) {3.4, 6.6, 11.3, 16.4}

C.4.2 Unit cost reductions in key technologies, notably wind power, solar power, and storage, have increased the economic attractiveness of low-emission energy sector transitions through 2030. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. Low-emission energy sector transitions will have multiple co-benefits, including improvements in air quality and health. The long-term economic attractiveness of deploying energy system mitigation options depends, *inter alia*, on policy design and implementation, technology availability and performance, institutional capacity, equity, access to finance, and public and political support. (*high confidence*) (Figure SPM.3) {3.4, 6.4, 6.6, 6.7, 13.7}

C.4.3 Electricity systems powered predominantly by renewables are becoming increasingly viable. Electricity systems in some countries and regions are already predominantly powered by renewables. It will be more challenging to supply the entire energy system with renewable energy. Even though operational, technological, economic, regulatory, and social challenges remain, a variety of systemic solutions to accommodate large shares of renewables in the energy system have emerged. A broad portfolio of options, such as integrating systems, coupling sectors, energy storage, smart grids, demand-side management, sustainable biofuels, electrolytic hydrogen and derivatives, and others will ultimately be needed to accommodate large shares of renewables in energy systems. (*high confidence*) {Box 6.8, 6.4, 6.6}

C.4.4 Limiting global warming to 2°C or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure (*high confidence*). Depending on its availability, CCS could allow fossil fuels to be used longer, reducing stranded assets (*high confidence*). The combined global discounted value of the unburned fossil fuels and stranded fossil fuel infrastructure has been projected to be around USD1–4 trillion from 2015 to 2050 to limit global warming to approximately 2°C, and it will be higher if global warming is limited to approximately 1.5°C (*medium confidence*). In this context, coal assets are projected to be at risk of being stranded before 2030, while oil and gas assets are projected to be more at risk of being stranded towards mid-century. A low-emission energy sector transition is projected to reduce international trade in fossil fuels. (*high confidence*) {6.7, Figure 6.35}

C.4.5 Global methane emissions from energy supply, primarily fugitive emissions from production and transport of fossil fuels, accounted for about 18% [13–23%] of global GHG emissions from energy supply, 32% [22–42%] of global CH_4 emissions, and 6% [4–8%] of global GHG emissions in 2019 (*high confidence*). About 50–80% of CH_4 emissions from these fossil fuels could be avoided with currently available technologies at less than USD50 tCO_2-eq^{-1} (*medium confidence*). {6.3, 6.4.2, Box 6.5, 11.3, 2.2.2, Table 2.1, Figure 2.5, Annex1: Glossary}

C.4.6 CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological CO_2 storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C. Enabling

[54] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more from power plants, or 50–80% of fugitive methane emissions from energy supply. {Box 6.5, 11.3}

conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*) {2.5, 6.3, 6.4, 6.7, 11.3, 11.4, Cross-Chapter Box 8 in Chapter 12, Figure TS.31; SRCCL Chapter 5}

C.5 Net zero CO_2 emissions from the industrial sector are challenging but possible. Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes. Progressing towards net zero GHG emissions from industry will be enabled by the adoption of new production processes using low- and zero-GHG electricity, hydrogen, fuels, and carbon management. (*high confidence*) {11.2, 11.3, 11.4, Box TS.4}

C.5.1 The use of steel, cement, plastics, and other materials is increasing globally, and in most regions. There are many sustainable options for demand management, materials efficiency, and circular material flows that can contribute to reduced emissions, but how these can be applied will vary across regions and different materials. These options have a potential for being more used in industrial practice and would need more attention from industrial policy. These options, as well as new production technologies, are generally not considered in recent global scenarios nor in national economy-wide scenarios due to relative newness. As a consequence, the mitigation potential in some scenarios is underestimated compared to bottom-up industry-specific models. (*high confidence*) {3.4, 5.3, Figure 5.7, 11.2, Box 11.2, 11.3, 11.4, 11.5.2, 11.6}

C.5.2 For almost all basic materials – primary metals,[55] building materials and chemicals – many low- to zero-GHG intensity production processes are at the *pilot* to *near-commercial* and in some cases *commercial* stage but they are not yet established industrial practice. Introducing new sustainable production processes for basic materials could increase production costs but, given that only a small fraction of consumer costs are based on materials, such new processes are expected to translate into minimal cost increases for final consumers. Hydrogen direct reduction for primary steelmaking is *near-commercial* in some regions. Until new chemistries are mastered, deep reduction of cement process emissions will rely on already commercialised cementitious material substitution and the availability of CCS. Reducing emissions from the production and use of chemicals would need to rely on a life cycle approach, including increased plastics recycling, fuel and feedstock switching, and carbon sourced through biogenic sources, and, depending on availability, carbon capture and use (CCU), direct air CO_2 capture, as well as CCS. Light industry, mining and manufacturing have the potential to be decarbonised through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps) and low- or zero-GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based and other synthetic fuels). (*high confidence*) {Table 11.4, Box 11.2, 11.3, 11.4}

C.5.3 Action to reduce industry sector emissions may change the location of GHG-intensive industries and the organisation of value chains. Regions with abundant low-GHG energy and feedstocks have the potential to become exporters of hydrogen-based chemicals and materials processed using low-carbon electricity and hydrogen. Such reallocation will have global distributional effects on employment and economic structure. (*medium confidence*) {Box 11.1}

C.5.4 Emissions-intensive and highly traded basic materials industries are exposed to international competition, and international cooperation and coordination may be particularly important in enabling change. For sustainable industrial transitions, broad and sequential national and sub-national policy strategies reflecting regional contexts will be required. These may combine policy packages including: transparent GHG accounting and standards; demand management; materials and energy efficiency policies; R&D and niche markets for commercialisation of low-emission materials and products; economic and regulatory instruments to drive market uptake; high quality recycling, low-emissions energy and other abatement infrastructure (e.g., for CCS); and socially inclusive phase-out plans of emissions-intensive facilities within the context of just transitions. The coverage of mitigation policies could be expanded nationally and sub-nationally to include all industrial emission sources, and both available and emerging mitigation options. (*high confidence*) {11.6}

[55] Primary metals refers to virgin metals produced from ore.

C.6 Urban areas can create opportunities to increase resource efficiency and significantly reduce GHG emissions through the systemic transition of infrastructure and urban form through low-emission development pathways towards net-zero emissions. Ambitious mitigation efforts for established, rapidly growing and emerging cities will encompass (i) reducing or changing energy and material consumption, (ii) electrification, and (iii) enhancing carbon uptake and storage in the urban environment. Cities can achieve net-zero emissions, but only if emissions are reduced within and outside of their administrative boundaries through supply chains, which will have beneficial cascading effects across other sectors. (*very high confidence*) {8.2, 8.3, 8.4, 8.5, 8.6, Figure 8.21, 13.2}

C.6.1 In modelled scenarios, global consumption-based urban CO_2 and CH_4 emissions[15] are projected to rise from 29 $GtCO_2$-eq in 2020 to 34 $GtCO_2$-eq in 2050 with moderate mitigation efforts (intermediate GHG emissions, SSP2-4.5), and up to 40 $GtCO_2$-eq in 2050 with low mitigation efforts (high GHG emissions, SSP3-7.0). With ambitious and immediate mitigation efforts, including high levels of electrification and improved energy and material efficiency, global consumption-based urban CO_2 and CH_4 emissions could be reduced to 3 $GtCO_2$-eq in 2050 in the modelled scenario with very low GHG emissions (SSP1-1.9).[56] (*medium confidence*) {8.3}

C.6.2 The potential and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use, spatial form, development level, and state of urbanisation (*high confidence*). Strategies for established cities to achieve large GHG emissions savings include efficiently improving, repurposing or retrofitting the building stock, targeted infilling, and supporting non-motorised (e.g., walking, bicycling) and public transport. Rapidly growing cities can avoid future emissions by co-locating jobs and housing to achieve compact urban form, and by leapfrogging or transitioning to low-emissions technologies. New and emerging cities will have significant infrastructure development needs to achieve high quality of life, which can be met through energy efficient infrastructures and services, and people-centred urban design (*high confidence*). For cities, three broad mitigation strategies have been found to be effective when implemented concurrently: (i) reducing or changing energy and material use towards more sustainable production and consumption; (ii) electrification in combination with switching to low-emission energy sources; and (iii) enhancing carbon uptake and storage in the urban environment, for example through bio-based building materials, permeable surfaces, green roofs, trees, green spaces, rivers, ponds and lakes.[57] (*very high confidence*) {5.3, Figure 5.7, Supplementary Material Table 5.SM.2, 8.2, 8.4, 8.6, Figure 8.21, 9.4, 9.6, 10.2}

C.6.3 The implementation of packages of multiple city-scale mitigation strategies can have cascading effects across sectors and reduce GHG emissions both within and outside a city's administrative boundaries. The capacity of cities to develop and implement mitigation strategies varies with the broader regulatory and institutional settings, as well as enabling conditions, including access to financial and technological resources, local governance capacity, engagement of civil society, and municipal budgetary powers. (*very high confidence*) {Figure 5.7, Supplementary Material Table 5.SM.2, 8.4, 8.5, 8.6, 13.2, 13.3, 13.5, 13.7, Cross-Chapter Box 9 in Chapter 13}

C.6.4 A growing number of cities are setting climate targets, including net-zero GHG targets. Given the regional and global reach of urban consumption patterns and supply chains, the full potential for reducing consumption-based urban emissions to net zero GHG can be met only when emissions beyond cities' administrative boundaries are also addressed. The effectiveness of these strategies depends on cooperation and coordination with national and sub-national governments, industry, and civil society, and whether cities have adequate capacity to plan and implement mitigation strategies. Cities can play a positive role in reducing emissions across supply chains that extend beyond cities' administrative boundaries, for example through building codes and the choice of construction materials. (*very high confidence*) {8.4, Box 8.4, 8.5, 9.6, 9.9, 13.5, 13.9}

[56] These scenarios have been assessed by WGI to correspond to intermediate, high and very low GHG emissions.

[57] These examples are considered to be a subset of nature-based solutions or ecosystem-based approaches.

C.7. In modelled global scenarios, existing buildings, if retrofitted, and buildings yet to be built, are projected to approach net zero GHG emissions in 2050 if policy packages, which combine ambitious sufficiency, efficiency, and renewable energy measures, are effectively implemented and barriers to decarbonisation are removed. Low ambition policies increase the risk of locking-in buildings' carbon for decades, while well-designed and effectively implemented mitigation interventions (in both new buildings and existing ones if retrofitted), have significant potential to contribute to achieving SDGs in all regions while adapting buildings to future climate. (*high confidence*) {9.1, 9.3, 9.4, 9.5, 9.6, 9.9}

C.7.1 In 2019, global direct and indirect GHG emissions from buildings and emissions from cement and steel use for building construction and renovation were 12 $GtCO_2$-eq. These emissions include indirect emissions from offsite generation of electricity and heat, direct emissions produced onsite and emissions from cement and steel used for building construction and renovation. In 2019, global direct and indirect emissions from non-residential buildings increased by about 55% and those from residential buildings increased by about 50% compared to 1990. The latter increase, according to the decomposition analysis, was mainly driven by the increase of the floor area per capita, population growth and the increased use of emission-intensive electricity and heat while efficiency improvements have partly decreased emissions. There are great differences in the contribution of each of these drivers to regional emissions. (*high confidence*) {9.3}

C.7.2 Integrated design approaches to the construction and retrofit of buildings have led to increasing examples of zero energy or zero carbon buildings in several regions. However, the low renovation rates and low ambition of retrofitted buildings have hindered the decrease of emissions. Mitigation interventions at the design stage include buildings typology, form, and multi-functionality to allow for adjusting the size of buildings to the evolving needs of their users and repurposing unused existing buildings to avoid using GHG-intensive materials and additional land. Mitigation interventions include: at the construction phase, low-emission construction materials, highly efficient building envelope and the integration of renewable energy solutions;[58] at the use phase, highly efficient appliances/equipment, the optimisation of the use of buildings and their supply with low-emission energy sources; and at the disposal phase, recycling and re-using construction materials. (*high confidence*) {9.4, 9.5, 9.6, 9.7}

C.7.3 By 2050, bottom-up studies show that up to 61% (8.2 $GtCO_2$) of global building emissions could be mitigated. Sufficiency policies[59] that avoid the demand for energy and materials contribute 10% to this potential, energy efficiency policies contribute 42%, and renewable energy policies 9%. The largest share of the mitigation potential of new buildings is available in developing countries while in developed countries the highest mitigation potential is within the retrofit of existing buildings. The 2020–2030 decade is critical for accelerating the learning of know-how, building the technical and institutional capacity, setting the appropriate governance structures, ensuring the flow of finance, and in developing the skills needed to fully capture the mitigation potential of buildings. (*high confidence*) {9.3, 9.4, 9.5, 9.6, 9.7, 9.9}

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58 Integration of renewable energy solutions refers to the integration of solutions such as solar photovoltaics, small wind turbines, solar thermal collectors, and biomass boilers.

59 Sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries.

C.8 Demand-side options and low-GHG emissions technologies can reduce transport sector emissions in developed countries and limit emissions growth in developing countries (*high confidence*). Demand-focused interventions can reduce demand for all transport services and support the shift to more energy efficient transport modes (*medium confidence*). Electric vehicles powered by low-emissions electricity offer the largest decarbonisation potential for land-based transport, on a life cycle basis (*high confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Sustainable biofuels, low-emissions hydrogen, and derivatives (including synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Many mitigation strategies in the transport sector would have various co-benefits, including air quality improvements, health benefits, equitable access to transportation services, reduced congestion, and reduced material demand (*high confidence*). {10.2, 10.4, 10.5, 10.6, 10.7}

C.8.1 In scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot, global transport-related CO_2 emissions fall by 59% (42–68% interquartile range) by 2050 relative to modelled 2020 emissions, but with regionally differentiated trends (*high confidence*). In global modelled scenarios that limit warming to 2°C (>67%), transport-related CO_2 emissions are projected to decrease by 29% [14–44% interquartile range] by 2050 compared to modelled 2020 emissions. In both categories of scenarios, the transport sector likely does not reach zero CO_2 emissions by 2100 so negative emissions are likely needed to counterbalance residual CO_2 emissions from the sector (*high confidence*). {3.4, 10.7}

C.8.2 Changes in urban form (e.g., density, land-use mix, connectivity, and accessibility) in combination with programmes that encourage changes in consumer behaviour (e.g., transport pricing) could reduce transport-related greenhouse gas emissions in developed countries and slow growth in emissions in developing countries (*high confidence*). Investments in public inter- and intra-city transport and active transport infrastructure (e.g., bicycle and pedestrian pathways) can further support the shift to less GHG-intensive transport modes (*high confidence*). Combinations of systemic changes, including teleworking, digitalisation, dematerialisation, supply chain management, and smart and shared mobility may reduce demand for passenger and freight services across land, air, and sea (*high confidence*). Some of these changes could lead to induced demand for transport and energy services, which may decrease their GHG emissions reduction potential (*medium confidence*). {5.3, 10.2, 10.8}

C.8.3 Electric vehicles powered by low-GHG emissions electricity have large potential to reduce land-based transport GHG emissions, on a life cycle basis (*high confidence*). Costs of electrified vehicles, including automobiles, two- and three-wheelers, and buses, are decreasing and their adoption is accelerating, but they require continued investments in supporting infrastructure to increase scale of deployment (*high confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and complement conventional electric rail systems (*medium confidence*). There are growing concerns about critical minerals needed for batteries. Material and supply diversification strategies, energy and material efficiency improvements, and circular material flows can reduce the environmental footprint and material supply risks for battery production (*medium confidence*). Sourced sustainably and with low-GHG emissions feedstocks, bio-based fuels, blended or unblended with fossil fuels, can provide mitigation benefits, particularly in the short and medium term (*medium confidence*). Low-GHG emissions hydrogen and hydrogen derivatives, including synthetic fuels, can offer mitigation potential in some contexts and land-based transport segments (*medium confidence*). {3.4, 6.3, 10.3, 10.4, 10.7, 10.8, Box 10.6}

C.8.4 While efficiency improvements (e.g., optimised aircraft and vessel designs, mass reduction, and propulsion system improvements) can provide some mitigation potential, additional CO_2 emissions mitigation technologies for aviation and shipping will be required (*high confidence*). For aviation, such technologies include high energy density biofuels (*high confidence*), and low-emission hydrogen and synthetic fuels (*medium confidence*). Alternative fuels for shipping include low-emission hydrogen, ammonia, biofuels, and other synthetic fuels (*medium confidence*). Electrification could play a niche role for aviation and shipping for short trips (*medium confidence*) and can reduce emissions from port and airport operations (*high confidence*). Improvements to national and international governance structures would further enable the decarbonisation of shipping and aviation (*medium confidence*). Such improvements could include, for example, the implementation of stricter efficiency and carbon intensity standards for the sectors (*medium confidence*). {10.3. 10.5, 10.6, 10.7, 10.8, Box 10.5}

C.8.5 The substantial potential for GHG emissions reductions, both direct and indirect, in the transport sector largely depends on power sector decarbonisation, and low-emissions feedstocks and production chains (*high confidence*). Integrated transport and energy infrastructure planning and operations can enable sectoral synergies and reduce the environmental, social, and economic impacts of decarbonising the transport and energy sectors (*high confidence*). Technology transfer and financing can support developing countries leapfrogging or transitioning to low-emissions transport systems thereby providing multiple co-benefits (*high confidence*). {10.2, 10.3, 10.4, 10.5, 10.6, 10.7, 10.8}

C.9 AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced removals, but cannot fully compensate for delayed action in other sectors. In addition, sustainably sourced agricultural and forest products can be used instead of more GHG-intensive products in other sectors. Barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects. There are many country-specific opportunities to provide co-benefits (such as biodiversity conservation, ecosystem services, and livelihoods) and avoid risks (for example, through adaptation to climate change). (*high confidence*) {7.4, 7.6, 7.7, 12.5, 12.6}

C.9.1 The projected economic mitigation potential of AFOLU options between 2020 and 2050, at costs below USD100 tCO_2-eq^{-1}, is 8–14 $GtCO_2$-eq yr^{-1} [60] (*high confidence*). 30–50% of this potential is available at less than USD20 tCO_2-eq and could be upscaled in the near term across most regions (*high confidence*). The largest share of this economic potential [4.2–7.4 $GtCO_2$-eq yr^{-1}] comes from the conservation, improved management, and restoration of forests and other ecosystems (coastal wetlands, peatlands, savannas and grasslands), with reduced deforestation in tropical regions having the highest total mitigation. Improved and sustainable crop and livestock management, and carbon sequestration in agriculture (the latter including soil carbon management in croplands and grasslands, agroforestry and biochar), can contribute 1.8–4.1 $GtCO_2$-eq yr^{-1} reduction. Demand-side and material substitution measures, such as shifting to balanced, sustainable healthy diets,[61] reducing food loss and waste, and using bio-materials, can contribute 2.1 [1.1–3.6] $GtCO_2$-eq yr^{-1} reduction. In addition, demand-side measures together with the sustainable intensification of agriculture can reduce ecosystem conversion and CH_4 and N_2O emissions, and free up land for reforestation and restoration, and the production of renewable energy. The improved and expanded use of wood products sourced from sustainably managed forests also has potential through the allocation of harvested wood to longer-lived products, increasing recycling or material substitution. AFOLU mitigation measures cannot compensate for delayed emission reductions in other sectors. Persistent and region-specific barriers continue to hamper the economic and political feasibility of deploying AFOLU mitigation options. Assisting countries to overcome barriers will help to achieve significant mitigation (*medium confidence*). (Figure SPM.6) {7.1, 7.4, 7.5, 7.6}

C.9.2 AFOLU carbon sequestration and GHG emission reduction options have both co-benefits and risks in terms of biodiversity and ecosystem conservation, food and water security, wood supply, livelihoods and land tenure and land-use rights of Indigenous Peoples, local communities and small land owners. Many options have co-benefits but those that compete for land and land-based resources can pose risks. The scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g., scale, method), and context (e.g., soil, biome, climate, food system, land ownership) that vary geographically and over time. Risks can be avoided when AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize co-benefits while limiting trade-offs. (*high confidence*) {7.4, 7.6, 12.3}

C.9.3 Realising the AFOLU mitigation potential entails overcoming institutional, economic and policy constraints and managing potential trade-offs (*high confidence*). Land-use decisions are often spread across a wide range of land owners; demand-side measures depend on billions of consumers in diverse contexts. Barriers to the implementation of AFOLU mitigation include insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, low incomes and the lack of access to alternative sources of income, and the risk of reversal. Limited access to technology, data, and know-how is a barrier to implementation. Research and development are key for all measures. For example, measures for the mitigation of agricultural CH_4 and N_2O emissions with emerging technologies show promising results. However, the mitigation of agricultural CH_4 and N_2O emissions is still constrained by cost, the diversity and complexity of agricultural systems, and by increasing demands to raise agricultural yields, and increasing demand for livestock products. (*high confidence*) {7.4, 7.6}

C.9.4 Net costs of delivering 5–6 $GtCO_2$ yr^{-1} of forest-related carbon sequestration and emission reduction as assessed with sectoral models are estimated to reach to about USD400 billion yr^{-1} by 2050. The costs of other AFOLU mitigation measures are highly context specific. Financing needs in AFOLU, and in particular in forestry, include both the direct effects of any changes in

60 The global top-down estimates and sectoral bottom-up estimates described here do not include the substitution of emissions from fossil fuels and GHG-intensive materials. 8–14 $GtCO_2$-eq yr^{-1} represents the mean of the AFOLU economic mitigation potential estimates from top-down estimates (lower bound of range) and global sectoral bottom-up estimates (upper bound of range). The full range from top-down estimates is 4.1–17.3 $GtCO_2$-eq yr^{-1} using a 'no policy' baseline. The full range from global sectoral studies is 6.7–23.4 $GtCO_2$-eq yr^{-1} using a variety of baselines. (*high confidence*)

61 'Sustainable healthy diets' promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described in FAO and WHO. The related concept of 'balanced diets' refers to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

activities as well as the opportunity costs associated with land-use change. Enhanced monitoring, reporting and verification capacity, and the rule of law, are crucial for land-based mitigation in combination with policies also recognising interactions with wider ecosystem services, could enable engagement by a wider array of actors, including private businesses, NGOs, and Indigenous Peoples and local communities. (*medium confidence*) {7.6, 7.7}

C.9.5 Context specific policies and measures have been effective in demonstrating the delivery of AFOLU carbon sequestration and GHG emission reduction options but the above-mentioned constraints hinder large scale implementation (*medium confidence*). Deploying land-based mitigation can draw on lessons from experience with regulations, policies, economic incentives, payments (e.g., for biofuels, control of nutrient pollution, water regulations, conservation and forest carbon, ecosystem services, and rural livelihoods), and from diverse forms of knowledge such as Indigenous knowledge, local knowledge and scientific knowledge. Indigenous Peoples, private forest owners, local farmers and communities manage a significant share of global forests and agricultural land and play a central role in land-based mitigation options. Scaling successful policies and measures relies on governance that emphasises integrated land-use planning and management framed by SDGs, with support for implementation. (*high confidence*) {7.4, Box 7.2, 7.6}

C.10 Demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand-side mitigation response options are consistent with improving basic well-being for all. (*high confidence*) (Figure SPM.6) {5.3, 5.4, Figure 5.6, Figure 5.14, 8.2, 9.4, 10.2, 11.3, 11.4, 12.4, Figure TS.22}

C.10.1 Infrastructure design and access, and technology access and adoption, including information and communication technologies, influence patterns of demand and ways of providing services, such as mobility, shelter, water, sanitation, and nutrition. Illustrative global low-demand scenarios, accounting for regional differences, indicate that more efficient end-use energy conversion can improve services while reducing the need for upstream energy by 45% by 2050 compared to 2020. Demand-side mitigation potential differs between and within regions, and some regions and populations require additional energy, capacity, and resources for human well-being. The lowest population quartile by income worldwide faces shortfalls in shelter, mobility, and nutrition. (*high confidence*) {5.2, 5.3, 5.4, 5.5, Figure 5.6, Figure 5.10, Table 5.2, Figure TS.20, Figure TS.22}

C.10.2 By 2050, comprehensive demand-side strategies across all sectors could reduce CO_2 and non-CO_2 GHG emissions globally by 40–70% compared to the 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020. With policy support, socio-cultural options and behavioural change can reduce global GHG emissions of end-use sectors by at least 5% rapidly, with most of the potential in developed countries, and more until 2050, if combined with improved infrastructure design and access. Individuals with high socio-economic status contribute disproportionately to emissions and have the highest potential for emissions reductions, e.g., as citizens, investors, consumers, role models, and professionals. (*high confidence*) (Figure SPM.6) {5.2, 5.3, 5.4, 5.5, 5.6, Supplementary Material Table 5.SM.2, 8.4, 9.9, 13.2, 13.5, 13.8, Figure TS.20}

C.10.3 A range of 5–30% of global annual GHG emissions from end-use sectors are avoidable by 2050, compared to 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020, through changes in the built environment, new and repurposed infrastructures and service provision through compact cities, co-location of jobs and housing, more efficient use of floor space and energy in buildings, and reallocation of street space for active mobility (*high confidence*). (Figure SPM.6) {5.3.1, 5.3.3, 5.4, Figure 5.7, Figure 5.13, Table 5.1, Table 5.5, Supplementary Material Table 5.SM.2, 8.4, 9.5, 10.2, 11.3, 11.4, Table 11.6, Box TS.12}

C.10.4 Choice architecture[62] can help end-users adopt, as relevant to consumers, culture and country contexts, low-GHG-intensive options such as balanced, sustainable healthy diets[61] acknowledging nutritional needs; food waste reduction; adaptive heating and cooling choices for thermal comfort; building-integrated renewable energy; and electric light-duty vehicles, and shifts to walking, cycling, shared pooled and public transit; and sustainable consumption by intensive use of longer-lived repairable products (*high confidence*). Addressing inequality and many forms of status consumption[63] and focusing on wellbeing supports climate change mitigation efforts (*high confidence*). (Figure SPM.6) {2.4.3, 2.6.2, 4.2.5, 5.1, 5.2, 5.3, 5.4, Figure 5.4, Figure 5.10, Table 5.2, Supplementary Material Table 5.SM.2, 7.4.5, 8.2, 8.4, 9.4, 10.2, 12.4, Figure TS.20}

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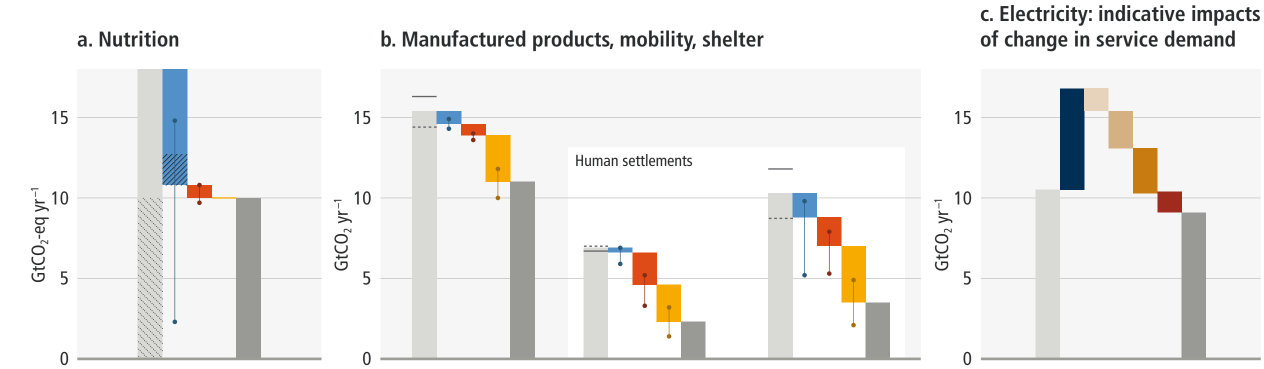
[62] 'Choice architecture' describes the presentation of choices to consumers, and the impact that presentation has on consumer decision-making.

[63] 'Status consumption' refers to the consumption of goods and services which publicly demonstrates social prestige.

Demand-side mitigation can be achieved through changes in socio-cultural factors, infrastructure design and use, and end-use technology adoption by 2050.



	a.	b.			c.
End-use sectors	**Food**	**Industry**	**Land transport**	**Buildings**	**Electricity**
Services for well-being	Nutrition	Manufactured products	Mobility	Shelter	
	Socio-cultural factors	Socio-cultural factors			Additional electrification (+60%)
	Dietary shift (shifting to balanced, sustainable healthy diets), avoidance of food waste and over-consumption	Shift in demand towards sustainable consumption, such as intensive use of longer-lived repairable products	Teleworking or telecommuting; active mobility through walking and cycling	Social practices resulting in energy saving; lifestyle and behavioural changes	Additional emissions from increased electricity generation to enable the end-use sectors' substitution of electricity for fossil fuels, e.g. via heat pumps and electric cars {Table SM5.3; 6.6}
	Infrastructure use	Infrastructure use			Industry; Land transport; Buildings; Load management[2] — **Demand-side measures –73%**
	Choice architecture[1] and information to guide dietary choices; financial incentives; waste management; recycling infrastructure	Networks established for recycling, repurposing, remanufacturing and reuse of metals, plastics and glass; labelling low-emissions materials and products	Public transport; shared mobility; compact cities; spatial planning	Compact cities; rationalisation of living floor space; architectural design; urban planning (e.g., green roof, cool roof, urban green spaces etc.)	Reduced emissions through demand-side mitigation options (in end-use sectors: buildings, industry and land transport) which has potential to reduce electricity demand[3]
	End-use technology adoption	End-use technology adoption			
	Currently estimates are not available (for lab-based meat and similar options – no quantitative literature available, overall potential considered in socio-cultural factors)	Green procurement to access material-efficient products and services; access to energy-efficient and CO_2 neutral materials	Electric vehicles; shift to more efficient vehicles	Energy efficient building envelopes and appliances; shift to renewables	

Total emissions 2050: Mean ---- IEA-STEPS —— IP_ModAct

AFOLU
Direct reduction of food related emissions, excluding reforestation of freed up land

Total emissions 2050
Socio-cultural factors
Infrastructure use
End-use technology adoption

Emissions that cannot be avoided or reduced through demand-side options are assumed to be addressed by supply-side options

Add. electrification
Industry
Land transport
Buildings
Load management

[1] The presentation of choices to consumers, and the impact of that presentation on consumer decision-making.

[2] Load management refers to demand-side flexibility that cuts across all sectors and can be achieved through incentive design like time of use pricing/monitoring by artificial intelligence, diversification of storage facilities, etc.

[3] The impact of demand-side mitigation on electricity sector emissions depends on the baseline carbon intensity of electricity supply, which is scenario dependent.

Figure SPM.6 | Indicative potential of demand-side mitigation options by 2050. Figure SPM.6 covers the indicative potential of demand-side options for the year 2050. Figure SPM.7 covers cost and potentials for the year 2030. Demand-side mitigation response options are categorised into three broad domains: 'socio-cultural factors', associated with individual choices, behaviour, lifestyle changes, social norms, and culture; 'infrastructure use', related to the design and use of supporting hard and soft infrastructure that enables changes in individual choices and behaviour; and 'end-use technology adoption', referring to the uptake of technologies by end-users. Demand-side mitigation is a central element of the IMP-LD and IMP-SP scenarios (Figure SPM.5). **Panel a** (Nutrition) demand-side potentials in 2050 assessment is based on bottom-up studies and is estimated following the 2050 baseline for the food sector presented in peer-reviewed literature (more information in Supplementary Material 5.II, and Section 7.4.5). **Panel b** (Manufactured products, mobility, shelter) the assessment of potentials for total emissions in 2050 are estimated based on approximately 500 bottom-up studies representing all global regions (detailed list is in Supplementary Material Table 5.SM.2). Baseline is provided by the sectoral mean GHG emissions in 2050 of the two scenarios consistent with policies announced by national governments until 2020. The heights of the coloured columns represent the potentials represented by the median value. These are based on a range of values available in the case studies from literature shown in Supplementary Material 5.SM.II. The range is shown by the dots connected by dotted lines representing the highest and the lowest potentials reported in the literature. **Panel a** shows the demand-side potential of socio-cultural factors and infrastructure use. The median value of direct emissions (mostly non-CO_2) reduction through socio-cultural factors is 1.9 $GtCO_2$-eq without considering land-use change through reforestation of freed up land. If changes in land-use pattern enabled by this change in food demand are considered, the indicative potential could reach 7 $GtCO_2$-eq. Panel b illustrates mitigation potential in industry, land transport and buildings end-use sectors through demand-side options. Key options are presented in the summary table below the figure and the details are in Supplementary Material Table 5.SM.2. **Panel c** visualises how sectoral demand-side mitigation options (presented in panel b) change demand on the electricity distribution system. Electricity accounts for an increasing proportion of final energy demand in 2050 (additional electricity bar) in line with multiple bottom-up studies (detailed list is in Supplementary Material Table 5.SM.3), and Chapter 6 (Section 6.6). These studies are used to compute the impact of end-use electrification which increases overall electricity demand. Some of the projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of socio-cultural factors and infrastructure use in end-use electricity use in buildings, industry, and land transport found in literature based on bottom-up assessments. Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options. {5.3, Figure 5.7, Supplementary Material 5.SM.II}

SPM

C.11 The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors. Upscaling the deployment of CDR depends on developing effective approaches to address feasibility and sustainability constraints especially at large scales. (*high confidence*) {3.4, 7.4, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.1 CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. CDR methods vary in terms of their maturity, removal process, time scale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (*high confidence*). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 $GtCO_2$ yr^{-1}, e.g., blue carbon management) to higher potential (>3 $GtCO_2$ yr^{-1}, e.g., agroforestry); costs range from lower cost (e.g., USD-45–100 per tCO_2 for soil carbon sequestration) to higher cost (e.g., USD100–300 per tCO_2 for DACCS) (*medium confidence*). Estimated storage time scales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to 10,000 years or more for methods that store carbon in geological formations (*high confidence*). The processes by which CO_2 is removed from the atmosphere are categorised as biological, geochemical or chemical. Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods (*high confidence*). {7.4, 7.6, 12.3, Table 12.6, Cross-Chapter Box 8 in Chapter 12, Table TS.7; AR6 WGI 5.6}

C.11.2 The impacts, risks and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*). Reforestation, improved forest management, soil carbon sequestration, peatland restoration and blue carbon management are examples of methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context (*high confidence*). In contrast, afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure (*high confidence*). Ocean fertilisation, if implemented, could lead to nutrient redistribution, restructuring of ecosystems, enhanced oxygen consumption and acidification in deeper waters (*medium confidence*). {7.4, 7.6, 12.3, 12.5}

C.11.3 The removal and storage of CO_2 through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, CO_2 stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalinisation) and as carbon in biochar is less prone to reversal. (*high confidence*) {6.4, 7.4, 12.3}

C.11.4 In addition to deep, rapid, and sustained emission reductions CDR can fulfil three different complementary roles globally or at country level: lowering net CO_2 or net GHG emissions in the near term; counterbalancing 'hard-to-abate' residual emissions (e.g., emissions from agriculture, aviation, shipping, industrial processes) in order to help reach net zero CO_2 or net zero GHG emissions in the mid-term; and achieving net negative CO_2 or GHG emissions in the long term if deployed at levels exceeding annual residual emissions. (*high confidence*) {3.3, 7.4, 11.3, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.5 Rapid emission reductions in all sectors interact with future scale of deployment of CDR methods, and their associated risks, impacts and co-benefits. Upscaling the deployment of CDR methods depends on developing effective approaches to address sustainability and feasibility constraints, potential impacts, co-benefits and risks. Enablers of CDR include accelerated research, development and demonstration, improved tools for risk assessment and management, targeted incentives and development of agreed methods for measurement, reporting and verification of carbon flows. (*high confidence*) {3.4, 7.6, 12.3}

C.12 Mitigation options costing USD100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half the 2019 level by 2030 (*high confidence*). Global GDP continues to grow in modelled pathways[64] but, without accounting for the economic benefits of mitigation action from avoided damages from climate change nor from reduced adaptation costs, it is a few percent lower in 2050 compared to pathways without mitigation beyond current policies. The global economic benefit of limiting warming to 2°C is reported to exceed the cost of mitigation in most of the assessed literature (*medium confidence*). (Figure SPM.7) {3.6, 3.8, Cross-Working Group Box 1 in Chapter 3, 12.2, Box TS.7}

C.12.1 Based on a detailed sectoral assessment of mitigation options, it is estimated that mitigation options costing USD100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half of the 2019 level by 2030 (options costing less than USD20 tCO_2-eq^{-1} are estimated to make up more than half of this potential).[65] For a smaller part of the potential, deployment leads to net cost savings. Large contributions with costs less than USD20 tCO_2-eq^{-1} come from solar and wind energy, energy efficiency improvements, reduced conversion of natural ecosystems, and CH_4 emissions reductions (coal mining, oil and gas, waste). The mitigation potentials and mitigation costs of individual technologies in a specific context or region may differ greatly from the provided estimates. The assessment of the underlying literature suggests that the relative contribution of the various options could change beyond 2030. (*medium confidence*) (Figure SPM.7) {12.2}

C.12.2 The aggregate effects of climate change mitigation on global GDP are small compared to global projected GDP growth in assessed modelled global scenarios that quantify the macroeconomic implications of climate change mitigation, but that do not account for damages from climate change nor adaptation costs (*high confidence*). For example, compared to pathways that assume the continuation of policies implemented by the end of 2020, assessed global GDP reached in 2050 is reduced by 1.3–2.7% in modelled pathways assuming coordinated global action starting between now and 2025 at the latest to limit warming to 2°C (>67%). The corresponding average reduction in annual global GDP growth over 2020–2050 is 0.04–0.09 percentage points. In assessed modelled pathways, regardless of the level of mitigation action, global GDP is projected to at least double (increase by at least 100%) over 2020–2050. For modelled global pathways in other temperature categories, the reductions in global GDP in 2050 compared to pathways that assume the continuation of policies implemented by the end of 2020 are as follows: 2.6–4.2% (C1), 1.6–2.8% (C2), 0.8–2.1% (C4), 0.5–1.2% (C5). The corresponding reductions in average annual global GDP growth over 2020–2050, in percentage points, are as follows: 0.09–0.14 (C1), 0.05–0.09 (C2), 0.03–0.07 (C4), 0.02–0.04 (C5).[66] There are large variations in the modelled effects of mitigation on GDP across regions, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation[67] (*high confidence*). Country-level studies also show large variations in the effect of mitigation on GDP depending notably on the level of mitigation and on the way it is achieved (*high confidence*). Macroeconomic implications of mitigation co-benefits and trade-offs are not quantified comprehensively across the above scenarios and depend strongly on mitigation strategies (*high confidence*). {3.6, 4.2, Box TS.7, Annex III.I.2, Annex III.I.9, Annex III.I.10 and Annex III.II.3}

C.12.3 Estimates of aggregate economic benefits from avoiding damages from climate change, and from reduced adaptation costs, increase with the stringency of mitigation (*high confidence*). Models that incorporate the economic damages from climate change find that the global cost of limiting warming to 2°C over the 21st century is lower than the global economic benefits of reducing warming, unless: (i) climate damages are towards the low end of the range; or, (ii) future damages are discounted at high rates (*medium confidence*).[68] Modelled pathways with a peak in global emissions between now and 2025 at the latest, compared to modelled pathways with a later peak in global emissions, entail more rapid near-term transitions and higher up-front investments, but bring long-term gains for the economy, as well as earlier benefits of avoided climate change impacts (*high confidence*). The precise magnitude of these gains and benefits is difficult to quantify. {1.7, 3.6, Cross-Working Group Box 1 in Chapter 3, Box TS.7; AR6 WGII SPM B.4}

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64 In modelled pathways that limit warming to 2°C (>67%) or lower.

65 The methodology underlying the assessment is described in the caption to Figure SPM.7.

66 These estimates are based on 311 pathways that report effects of mitigation on GDP and that could be classified in temperature categories, but that do not account for damages from climate change nor adaptation costs and that mostly do not reflect the economic impacts of mitigation co-benefits and trade-offs. The ranges given are interquartile ranges. The macroeconomic implications quantified vary largely depending on technology assumptions, climate/emissions target formulation, model structure and assumptions, and the extent to which pre-existing inefficiencies are considered. Models that produced the pathways classified in temperature categories do not represent the full diversity of existing modelling paradigms, and there are in the literature models that find higher mitigation costs, or conversely lower mitigation costs and even gains. {1.7, 3.2, 3.6, Annex III.I.2, Annex III.I.9, Annex III.I.10 and Annex III.II.3}

67 In modelled cost-effective pathways with a globally uniform carbon price, without international financial transfers or complementary policies, carbon intensive and energy exporting countries are projected to bear relatively higher mitigation costs because of a deeper transformation of their economies and changes in international energy markets. {3.6}

68 The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C.

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Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

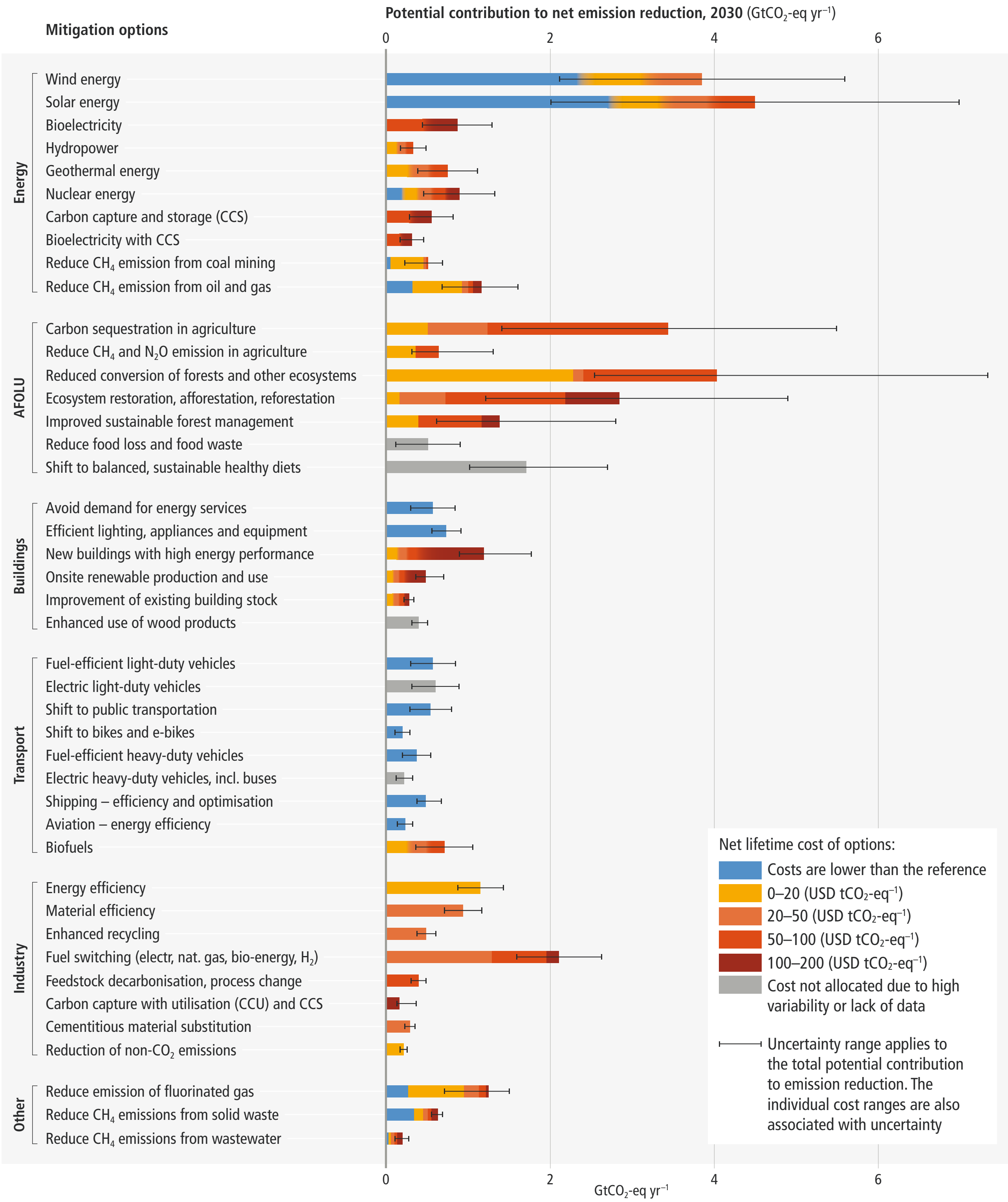

Figure SPM.7 | Overview of mitigation options and their estimated ranges of costs and potentials in 2030.

Figure SPM.7 (continued): Overview of mitigation options and their estimated ranges of costs and potentials in 2030. Costs shown are net lifetime costs of avoided greenhouse gas emissions. Costs are calculated relative to a reference technology. The assessments per sector were carried out using a common methodology, including definition of potentials, target year, reference scenarios, and cost definitions. The mitigation potential (shown in the horizontal axis) is the quantity of net GHG emission reductions that can be achieved by a given mitigation option relative to a specified emission baseline. Net GHG emission reductions are the sum of reduced emissions and/or enhanced sinks. The baseline used consists of current policy (around 2019) reference scenarios from the AR6 scenarios database (25/75 percentile values). The assessment relies on approximately 175 underlying sources, that together give a fair representation of emission reduction potentials across all regions. The mitigation potentials are assessed independently for each option and are not necessarily additive. {12.2.1, 12.2.2} The length of the solid bars represents the mitigation potential of an option. The error bars display the full ranges of the estimates for the total mitigation potentials. Sources of uncertainty for the cost estimates include assumptions on the rate of technological advancement, regional differences, and economies of scale, among others. Those uncertainties are not displayed in the figure. Potentials are broken down into cost categories, indicated by different colours (see legend). Only discounted lifetime monetary costs are considered. Where a gradual colour transition is shown, the breakdown of the potential into cost categories is not well known or depends heavily on factors such as geographical location, resource availability, and regional circumstances, and the colours indicate the range of estimates. Costs were taken directly from the underlying studies (mostly in the period 2015–2020) or recent datasets. No correction for inflation was applied, given the wide cost ranges used. The cost of the reference technologies were also taken from the underlying studies and recent datasets. Cost reductions through technological learning are taken into account.[69]

– When interpreting this figure, the following should be taken into account:

– The mitigation potential is uncertain, as it will depend on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors.

– Cost and mitigation potential estimates were extrapolated from available sectoral studies. Actual costs and potentials would vary by place, context and time.

– Beyond 2030, the relative importance of the assessed mitigation options is expected to change, in particular while pursuing long-term mitigation goals, recognising also that the emphasis for particular options will vary across regions (for specific mitigation options see SPM Sections C4.1, C5.2, C7.3, C8.3 and C9.1).

– Different options have different feasibilities beyond the cost aspects, which are not reflected in the figure (compare with SPM Section E.1).

– The potentials in the cost range USD100–200 tCO_2-eq^{-1} may be underestimated for some options.

– Costs for accommodating the integration of variable renewable energy sources in electricity systems are expected to be modest until 2030, and are not included because of complexities in attributing such costs to individual technology options.

– Cost range categories are ordered from low to high. This order does not imply any sequence of implementation.

– Externalities are not taken into account. {12.2, Table 12.3, 6.4, Table 7.3, Supplementary Material Table 9.SM.2, Supplementary Material Table 9.SM.3, 10.6, 11.4, Figure 11.13, Supplementary Material 12.SM.A.2.3}

[69] For nuclear energy, modelled costs for long-term storage of radioactive waste are included.

D. Linkages between Mitigation, Adaptation, and Sustainable Development

D.1 Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. Climate change actions can also result in some trade-offs. The trade-offs of individual options could be managed through policy design. The Sustainable Development Goals (SDGs) adopted under the UN 2030 Agenda for Sustainable Development can be used as a basis for evaluating climate action in the context of sustainable development. (*high confidence*) (Figure SPM.8) {1.6, 3.7, 17.3, Figure TS.29}

D.1.1 Human-induced climate change is a consequence of more than a century of net GHG emissions from unsustainable energy use, land-use and land use change, lifestyle and patterns of consumption and production. Without urgent, effective and equitable mitigation actions, climate change increasingly threatens the health and livelihoods of people around the globe, ecosystem health and biodiversity. There are both synergies and trade-offs between climate action and the pursuit of other SDGs. Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. (*high confidence*) {1.6, Cross-Chapter Box 5 in Chapter 4, 7.2, 7.3, 17.3; AR6 WGI SPM.A, Figure SPM.2; AR6 WGII SPM.B2, Figure SPM.3, Figure SPM.4b, Figure SPM.5}

D.1.2 Synergies and trade-offs depend on the development context including inequalities, with consideration of climate justice. They also depend on means of implementation, intra- and inter-sectoral interactions, cooperation between countries and regions, the sequencing, timing and stringency of mitigation actions, governance, and policy design. Maximising synergies and avoiding trade-offs pose particular challenges for developing countries, vulnerable populations, and Indigenous Peoples with limited institutional, technological and financial capacity, and with constrained social, human, and economic capital. Trade-offs can be evaluated and minimised by giving emphasis to capacity building, finance, governance, technology transfer, investments, and development and social equity considerations with meaningful participation of Indigenous Peoples and vulnerable populations. (*high confidence*) {1.6, 1.7, 3.7, 5.2, 5.6, 7.4, 7.6, 17.4}

D.1.3 There are potential synergies between sustainable development and energy efficiency, renewable energy, urban planning with more green spaces, reduced air pollution, and demand-side mitigation including shifts to balanced, sustainable healthy diets (*high confidence*). Electrification combined with low-GHG energy, and shifts to public transport can enhance health, employment, and can elicit energy security and deliver equity (*high confidence*). In industry, electrification and circular material flows contribute to reduced environmental pressures and increased economic activity and employment. However, some industrial options could impose high costs (*medium confidence*). (Figure SPM.8) {5.2, 8.2, 11.3, 11.5, 17.3, Figure TS.29}

D.1.4 Land-based options such as reforestation and forest conservation, avoided deforestation, restoration and conservation of natural ecosystems and biodiversity, improved sustainable forest management, agroforestry, soil carbon management and options that reduce CH_4 and N_2O emissions in agriculture from livestock and soil, can have multiple synergies with the SDGs. These include enhancing sustainable agricultural productivity and resilience, food security, providing additional biomass for human use, and addressing land degradation. Maximising synergies and managing trade-offs depend on specific practices, scale of implementation, governance, capacity building, integration with existing land use, and the involvement of local communities and Indigenous Peoples and through benefit-sharing, supported by frameworks such as Land Degradation Neutrality within the UNCCD. (*high confidence*) {3.7, 7.4, 12.5, 17.3}

D.1.5 Trade-offs in terms of employment, water use, land-use competition and biodiversity, as well as access to, and the affordability of, energy, food, and water can be avoided by well-implemented land-based mitigation options, especially those that do not threaten existing sustainable land uses and land rights, though more frameworks for integrated policy implementation are required. The sustainability of bioenergy and other bio-based products is influenced by feedstock, land management practice, climatic region, the context of existing land management, and the timing, scale and speed of deployment. (*medium confidence*) {3.5, 3.7, 7.4, 12.4, 12.5, 17.1}

D.1.6 CDR methods such as soil carbon sequestration and biochar[70] can improve soil quality and food production capacity. Ecosystem restoration and reforestation sequester carbon in plants and soil, and can enhance biodiversity and provide additional

[70] Potential risks, knowledge gaps due to the relative immaturity of use of biochar as a soil amendment and unknown impacts of widespread application, and co-benefits of biochar are reviewed in Section 7.4.3.2.

biomass, but can displace food production and livelihoods, which calls for integrated approaches to land-use planning, to meet multiple objectives including food security. However, due to limited application of some of the options today, there are some uncertainties about potential benefits. (*high confidence*) {3.7, 7.4, 7.6, 12.5, 17.3, Table TS.7}

Mitigation options have synergies with many Sustainable Development Goals, but some options can also have trade-offs. The synergies and trade-offs vary dependent on context and scale.

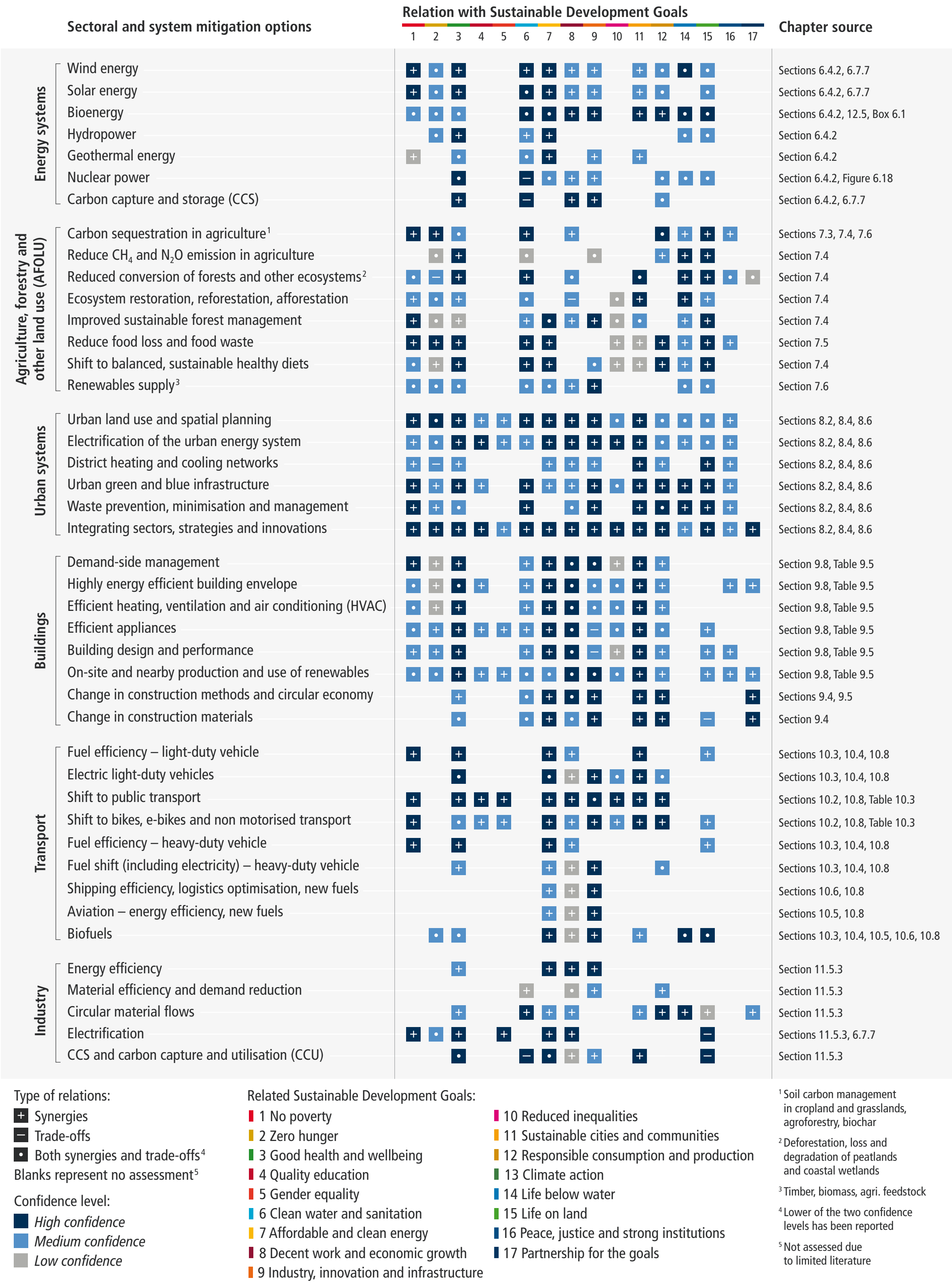

Figure SPM.8 | Synergies and trade-offs between sectoral and system mitigation options and the SDGs.

Figure SPM.8 (continued): Synergies and trade-offs between sectoral and system mitigation options and the SDGs. The sectoral chapters (Chapters 6–11) include qualitative assessments of synergies and trade-offs between sectoral mitigation options and the SDGs. Figure SPM.8 presents a summary of the chapter-level assessment for selected mitigation options (see Supplementary Material Table 17.SM.1 for the underlying assessment). The last column provides a line of sight to the sectoral chapters, which provide details on context specificity and dependence of interactions on the scale of implementation. Blank cells indicate that interactions have not been assessed due to limited literature. They do not indicate the absence of interactions between mitigation options and the SDGs. Confidence levels depend on the quality of evidence and level of agreement in the underlying literature assessed by the sectoral chapters. Where both synergies and trade-offs exist, the lower of the confidence levels for these interactions is used. Some mitigation options may have applications in more than one sector or system. The interactions between mitigation options and the SDGs might differ depending on the sector or system, and also on the context and the scale of implementation. Scale of implementation particularly matters when there is competition for scarce resources. {6.3, 6.4, 6.7, 7.3, 7.4, 7.5, 7.6, 8.2, 8.4, 8.6, Figure 8.4, Supplementary Material Table 8.SM.1, Supplementary Material Table 8.SM.2, 9.4, 9.5, 9.8, Table 9.5, 10.3, 10.4, 10.5, 10.6, 10.8, Table 10.3, 11.5, 12.5, 17.3, Figure 17.1, Supplementary Material Table 17.SM.1, Annex II.IV.12}

D.2 There is a strong link between sustainable development, vulnerability and climate risks. Limited economic, social and institutional resources often result in high vulnerability and low adaptive capacity, especially in developing countries (*medium confidence*). Several response options deliver both mitigation and adaptation outcomes, especially in human settlements, land management, and in relation to ecosystems. However, land and aquatic ecosystems can be adversely affected by some mitigation actions, depending on their implementation (*medium confidence*). Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation and adaptation (*high confidence*). {3.7, 4.4, 13.8, 17.3; AR6 WGII}

D.2.1 Sustainable urban planning and infrastructure design including green roofs and facades, networks of parks and open spaces, management of urban forests and wetlands, urban agriculture, and water-sensitive design can deliver both mitigation and adaptation benefits in settlements (*medium confidence*). These options can also reduce flood risks, pressure on urban sewer systems, urban heat island effects, and can deliver health benefits from reduced air pollution (*high confidence*). There could also be trade-offs. For example, increasing urban density to reduce travel demand, could imply high vulnerability to heat waves and flooding (*high confidence*). (Figure SPM.8) {3.7, 8.2, 8.4, 12.5, 13.8, 17.3}

D.2.2 Land-related mitigation options with potential co-benefits for adaptation include agroforestry, cover crops, intercropping, perennial plants, restoring natural vegetation and rehabilitating degraded land. These can enhance resilience by maintaining land productivity and protecting and diversifying livelihoods. Restoration of mangroves and coastal wetlands sequesters carbon, while also reducing coastal erosion and protecting against storm surges, thus, reducing the risks from sea level rise and extreme weather. (*high confidence*) {4.4, 7.4, 7.6, 12.5, 13.8}

D.2.3 Some mitigation options can increase competition for scarce resources including land, water and biomass. Consequently, these can also reduce adaptive capacity, especially if deployed at larger scale and with high expansion rates thus exacerbating existing risks, in particular where land and water resources are very limited. Examples include the large-scale or poorly planned deployment of bioenergy, biochar, and afforestation of naturally unforested land. (*high confidence*) {12.5, 17.3}

D.2.4 Coordinated policies, equitable partnerships and integration of adaptation and mitigation within and across sectors can maximise synergies and minimise trade-offs and thereby enhance the support for climate action (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a large need for financial, technical, and human resources for adaptation. Absence or limited resources in social and institutional systems can lead to poorly coordinated responses, thus reducing the potential for maximising mitigation and adaptation benefits, and increasing risk (*high confidence*). {12.6, 13.8, 17.1, 17.3}

D.3 Enhanced mitigation and broader action to shift development pathways towards sustainability will have distributional consequences within and between countries. Attention to equity and broad and meaningful participation of all relevant actors in decision-making at all scales can build social trust, and deepen and widen support for transformative changes. (*high confidence*) {3.6, 4.2, 4.5, 5.2, 13.2, 17.3, 17.4}

D.3.1 Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include social, economic, environmental, cultural, or political conditions, resource endowment, capabilities, international environment, and history. The enabling conditions for shifting development pathways towards increased sustainability will therefore also differ, giving rise to different needs. (*high confidence*) (Figure SPM.2) {1.6, 1.7, 2.4, 2.6, Cross-Chapter Box 5 in Chapter 4, 4.3.2, 17.4}

D.3.2 Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries. Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Distributional consequences within and between countries include shifting of income and employment during the transition from high- to low-emissions activities. While some jobs may be lost, low-emissions development can also open more opportunities to enhance skills and create more jobs that last, with differences across countries and sectors. Integrated policy packages can improve the ability to integrate considerations of equity, gender equality and justice. (*high confidence*) {1.4, 1.6, 3.6, 4.2, 5.2, Box 11.1, 14.3, 15.2, 15.5, 15.6}

D.3.3 Inequalities in the distribution of emissions and in the impacts of mitigation policies within countries affect social cohesion and the acceptability of mitigation and other environmental policies. Equity and just transitions can enable deeper ambitions for accelerated mitigation. Applying just transition principles and implementing them through collective and participatory decision-making processes is an effective way of integrating equity principles into policies at all scales, in different ways depending on national circumstances (*medium confidence*). This is already taking place in many countries and regions, as national just transition commissions or task forces, and related national policies, have been established in several countries. A multitude of actors, networks, and movements are engaged (*high confidence*). {1.6, 1.7, 2.4, 2.6, 4.5, 13.2, 13.9, 14.3, 14.5}

D.3.4 Broadening equitable access to domestic and international finance, technologies that facilitate mitigation, and capacity, while explicitly addressing needs can further integrate equity and justice into national and international policies and act as a catalyst for accelerating mitigation and shifting development pathways (*medium confidence*). The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, in all societies (*high confidence*). Consideration of climate justice can help to facilitate shifting development pathways towards sustainability, including through equitable sharing of benefits and burdens of mitigation, increasing resilience to the impacts of climate change, especially for vulnerable countries and communities, and equitably supporting those in need (*high confidence*). {1.4, 1.6, 1.7, 3.6, 4.2, 4.5, Box 5.10, 13.4, 13.8, 13.9, 14.3, 14.5, 15.2, 15.5, 15.6, 16.5, 17.3, 17.4; SR1.5 SPM, AR6 WGII Chapter 18}

E. Strengthening the Response

E.1 There are mitigation options which are feasible[71] to deploy at scale in the near term. Feasibility differs across sectors and regions, and according to capacities and the speed and scale of implementation. Barriers to feasibility would need to be reduced or removed, and enabling conditions[72] strengthened to deploy mitigation options at scale. These barriers and enablers include geophysical, environmental-ecological, technological, and economic factors, and especially institutional and socio-cultural factors. Strengthened near-term action beyond the NDCs (announced prior to UNFCCC COP26) can reduce and/or avoid long-term feasibility challenges of global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (*high confidence*) {3.8, 6.4, 8.5, 9.9, 10.8, 12.3, Figure TS.31, Annex II.IV.11}

E.1.1 Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand-side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective, and are generally supported by the public. This enables deployment in many regions (*high confidence*). While many mitigation options have environmental co-benefits, including improved air quality and reducing toxic waste, many also have adverse environmental impacts, such as reduced biodiversity, when applied at very large scale, for example very large scale bioenergy or large scale use of battery storage, that would have to be managed (*medium confidence*). Almost all mitigation options face institutional barriers that need to be addressed to enable their application at scale (*medium confidence*). {6.4, Figure 6.19, 7.4, 8.5, Figure 8.19, 9.9, Figure 9.20, 10.8, Figure 10.23, 12.3, Figure 12.4, Figure TS.31}

E.1.2 The feasibility of mitigation options varies according to context and time. For example, the institutional capacity to support deployment varies across countries; the feasibility of options that involve large-scale land-use changes varies across regions; spatial planning has a higher potential at early stages of urban development; the potential of geothermal is site specific; and capacities, cultural and local conditions can either inhibit or enable demand-side responses. The deployment of solar and wind energy has been assessed to become increasingly feasible over time. The feasibility of some options can increase when combined or integrated, such as using land for both agriculture and centralised solar production. (*high confidence*) {6.4, 6.6, Supplementary Material Table 6.SM, 7.4, 8.5, Supplementary Material Table 8.SM.2, 9.9, Supplementary Material Table 9.SM.1, 10.8, Appendix 10.3, 12.3, Tables 12.SM.B.1 to 12.SM.B.6}

E.1.3 Feasibility depends on the scale and speed of implementation. Most options face barriers when they are implemented rapidly at a large scale, but the scale at which barriers manifest themselves varies. Strengthened and coordinated near-term actions in cost-effective modelled global pathways that limit warming to 2°C (>67%) or lower, reduce the overall risks to the feasibility of the system transitions, compared to modelled pathways with relatively delayed or uncoordinated action.[73] (*high confidence*) {3.8, 6.4, 10.8, 12.3}

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[71] In this report, the term 'feasibility' refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent and may change over time. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

[72] In this report, the term 'enabling conditions' refers to conditions that enhance the feasibility of adaptation and mitigation options. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance, and changes in human behaviour and lifestyles.

[73] The future feasibility challenges described in the modelled pathways may differ from the real-world feasibility experiences of the past.

E.2 In all countries, mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emissions reductions (*medium confidence*). Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation responses, and enable the pursuit of synergies with development objectives (*medium confidence*). Actions can be taken now to shift development pathways and accelerate mitigation and transitions across systems (*high confidence*). {4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.2, 5.4, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5}

E.2.1 Current development pathways may create behavioural, spatial, economic and social barriers to accelerated mitigation at all scales (*high confidence*). Choices made by policymakers, citizens, the private sector and other stakeholders influence societies' development pathways (*high confidence*). Actions that steer, for example, energy and land systems transitions, economy-wide structural change, and behaviour change, can shift development pathways towards sustainability[74] (*medium confidence*). {4.3, Cross-Chapter Box 5 in Chapter 4, 5.4, 13.9}

E.2.2 Combining mitigation with policies to shift development pathways, such as broader sectoral policies, policies that induce lifestyle or behaviour changes, financial regulation, or macroeconomic policies can overcome barriers and open up a broader range of mitigation options (*high confidence*). It can also facilitate the combination of mitigation and other development goals (*high confidence*). For example, measures promoting walkable urban areas combined with electrification and renewable energy can create health co-benefits from cleaner air and benefits from enhanced mobility (*high confidence*). Coordinated housing policies that broaden relocation options can make mitigation measures in transport more effective (*medium confidence*). {3.2, 4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.3, 8.2, 8.4}

E.2.3 Institutional and regulatory capacity, innovation, finance, improved governance and collaboration across scales, and multi-objective policies enable enhanced mitigation and shifts in development pathways. Such interventions can be mutually reinforcing and establish positive feedback mechanisms, resulting in accelerated mitigation. (*high confidence*) {4.4, 5.4, Figure 5.14, 5.6, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.2.4 Enhanced action on all the above enabling conditions can be taken now (*high confidence*). In some situations, such as with innovation in technology at an early stage of development and some changes in behaviour towards low emissions, because the enabling conditions may take time to be established, action in the near term can yield accelerated mitigation in the mid-term (*medium confidence*). In other situations, the enabling conditions can be put in place and yield results in a relatively short time frame, for example the provision of energy related information, advice and feedback to promote energy saving behaviour (*high confidence*). {4.4, 5.4, Figure 5.14, 5.6, 6.7, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.3 Climate governance, acting through laws, strategies and institutions, based on national circumstances, supports mitigation by providing frameworks through which diverse actors interact, and a basis for policy development and implementation (*medium confidence*). Climate governance is most effective when it integrates across multiple policy domains, helps realise synergies and minimise trade-offs, and connects national and sub-national policymaking levels (*high confidence*). Effective and equitable climate governance builds on engagement with civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples and local communities (*medium confidence*). {5.4, 5.6, 8.5, 9.9, 13.2, 13.7, 13.9}

E.3.1 Climate governance enables mitigation by providing an overall direction, setting targets, mainstreaming climate action across policy domains, enhancing regulatory certainty, creating specialised organisations and creating the context to mobilise finance (*medium confidence*). These functions can be promoted by climate-relevant laws, which are growing in number, or climate strategies, among others, based on national and sub-national context (*medium confidence*). Framework laws set an overarching legal basis, either operating through a target and implementation approach, or a sectoral mainstreaming approach, or both, depending on national circumstance (*medium confidence*). Direct national and sub-national laws that explicitly target mitigation and indirect laws that impact emissions through mitigation-related policy domains have both been shown to be relevant to mitigation outcomes (*medium confidence*). {13.2}

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[74] Sustainability may be interpreted differently in various contexts as societies pursue a variety of sustainable development objectives.

E.3.2 Effective national climate institutions address coordination across sectors, scales and actors, build consensus for action among diverse interests, and inform strategy setting (*medium confidence*). These functions are often accomplished through independent national expert bodies, and high-level coordinating bodies that transcend departmental mandates. Complementary sub-national institutions tailor mitigation actions to local context and enable experimentation but can be limited by inequities and resource and capacity constraints (*high confidence*). Effective governance requires adequate institutional capacity at all levels (*high confidence*). {4.4, 8.5, 9.9, 11.3, 11.5, 11.6, 13.2, 13.5, 13.7, 13.9}

E.3.3 The extent to which civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples, and local communities are engaged influences political support for climate change mitigation and eventual policy outcomes. Structural factors of national circumstances and capabilities (e.g., economic and natural endowments, political systems and cultural factors and gender considerations) affect the breadth and depth of climate governance. Mitigation options that align with prevalent ideas, values and beliefs are more easily adopted and implemented. Climate-related litigation, for example by governments, private sector, civil society and individuals, is growing - with a large number of cases in some developed countries, and with a much smaller number in some developing countries - and in some cases, has influenced the outcome and ambition of climate governance. (*medium confidence*) {5.2, 5.4, 5.5, 5.6, 9.9, 13.3, 13.4}

E.4 Many regulatory and economic instruments have already been deployed successfully. Instrument design can help address equity and other objectives. These instruments could support deep emissions reductions and stimulate innovation if scaled up and applied more widely (*high confidence*). Policy packages that enable innovation and build capacity are better able to support a shift towards equitable low-emission futures than are individual policies (*high confidence*). Economy-wide packages, consistent with national circumstances, can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). {Cross-Chapter Box 5 in Chapter 4, 13.6, 13.7, 13.9, 16.3, 16.4, 16.6}

E.4.1 A wide range of regulatory instruments at the sectoral level have proven effective in reducing emissions. These instruments, and broad-based approaches including relevant economic instruments,[75] are complementary (*high confidence*). Regulatory instruments that are designed to be implemented with flexibility mechanisms can reduce costs (*medium confidence*). Scaling up and enhancing the use of regulatory instruments, consistent with national circumstances, could improve mitigation outcomes in sectoral applications, including but not limited to renewable energy, land use and zoning, building codes, vehicle and energy efficiency, fuel standards, and low-emissions industrial processes and materials (*high confidence*). {6.7, 7.6, 8.4, 9.9, 10.4, 11.5, 11.6, 13.6}

E.4.2 Economic instruments have been effective in reducing emissions, complemented by regulatory instruments mainly at the national and also sub-national and regional level (*high confidence*). Where implemented, carbon pricing instruments have incentivised low-cost emissions reduction measures, but have been less effective, on their own and at prevailing prices during the assessment period, in promoting the higher-cost measures necessary for further reductions (*medium confidence*). Equity and distributional impacts of such carbon pricing instruments can be addressed by using revenue from carbon taxes or emissions trading to support low-income households, among other approaches (*high confidence*). Practical experience has informed instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, distributional goals and social acceptance (*high confidence*). Removing fossil fuel subsidies would reduce emissions, improve public revenue and macroeconomic performance, and yield other environmental and sustainable development benefits; subsidy removal may have adverse distributional impacts especially on the most economically vulnerable groups which, in some cases can be mitigated by measures such as redistributing revenue saved, all of which depend on national circumstances (*high confidence*); fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emissions by 1–4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*). {6.3, 13.6}

E.4.3 Low-emission technological innovation is strengthened through the combination of dedicated technology-push policies and investments (e.g., for scientific training, R&D, demonstration), with tailored demand-pull policies (e.g., standards, feed-in tariffs, taxes), which create incentives and market opportunities. Developing countries' abilities to deploy low-emission technologies, seize socio-economic benefits and manage trade-offs would be enhanced with increased financial resources and capacity for innovation which are currently concentrated in developed countries, alongside technology transfer. (*high confidence*) {16.2, 16.3, 16.4, 16.5}

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[75] Economic instruments are structured to provide a financial incentive to reduce emissions and include, among others, market- and price-based instruments.

E.4.4 Effective policy packages would be comprehensive in coverage, harnessed to a clear vision for change, balanced across objectives, aligned with specific technology and system needs, consistent in terms of design and tailored to national circumstances. They are better able to realise synergies and avoid trade-offs across climate and development objectives. Examples include: emissions reductions from buildings through a mix of efficiency targets, building codes, appliance performance standards, information provision, carbon pricing, finance and technical assistance; and industrial GHG emissions reductions through innovation support, market creation and capacity building. (*high confidence*) {4.4, 6.7, 9.9, 11.6, 13.7, 13.9, 16.3, 16.4}

E.4.5 Economy-wide packages that support mitigation and avoid negative environmental outcomes include: long-term public spending commitments; pricing reform; and investment in education and training, natural capital, R&D and infrastructure (*high confidence*). They can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Infrastructure investments can be designed to promote low-emissions futures that meet development needs (*medium confidence*). {Cross-Chapter Box 5 in Chapter 4, 5.4, 5.6, 8.5, 13.6, 13.9, 16.3, 16.5, 16.6}

E.4.6 National policies to support technology development and diffusion, and participation in international markets for emission reduction, can bring positive spillover effects for other countries (*medium confidence*), although reduced demand for fossil fuels could result in costs to exporting countries (*high confidence*). There is no consistent evidence that current emission trading systems have led to significant emissions leakage, which can be attributed to design features aimed at minimising competitiveness effects, among other reasons (*medium confidence*). {13.6, 13.7, 13.8, 16.2, 16.3, 16.4}

E.5 Tracked financial flows fall short of the levels needed to achieve mitigation goals across all sectors and regions. The challenge of closing gaps is largest in developing countries as a whole. Scaling up mitigation financial flows can be supported by clear policy choices and signals from governments and the international community (*high confidence*). Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions, and can address inequities in access to finance and the costs of, and vulnerability to, the impacts of climate change (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6}

E.5.1 Average annual modelled investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Mitigation investment gaps are wide for all sectors, and widest for the AFOLU sector in relative terms and for developing countries[76] (*high confidence*). Financing and investment requirements for adaptation, reduction of losses and damages, general infrastructure, regulatory environment and capacity building, and climate-responsive social protection further exacerbate the magnitude of the challenges for developing countries to attract financing (*high confidence*). {3.2, 14.4, 15.1, 15.2, 15.3, 15.4, 15.5}

E.5.2 There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector, and in the macroeconomic headwinds facing developing regions. Barriers to the deployment of commercial finance from within the financial sector as well as macroeconomic considerations include: inadequate assessment of climate-related risks and investment opportunities; regional mismatch between available capital and investment needs; home bias factors; country indebtedness levels; economic vulnerability; and limited institutional capacities (*high confidence*). Challenges from outside the financial sector include: limited local capital markets; unattractive risk-return profiles, in particular due to missing or weak regulatory environments consistent with ambition levels; limited institutional capacity to ensure safeguards; standardisation, aggregation, scalability and replicability of investment opportunities and financing models; and, a pipeline ready for commercial investments. (*high confidence*) {15.2, 15.3, 15.5, 15.6}

E.5.3 Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance mitigation action and address inequities in access to finance, including its costs, terms and conditions, and economic vulnerability to climate change for developing countries (*high confidence*). Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, especially in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy (*high confidence*). Options for scaling up mitigation in developing regions include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD100 billion-a-year goal; increase the use of public guarantees to reduce risks and leverage private flows

[76] In modelled pathways, regional investments are projected to occur when and where they are most cost-effective to limit global warming. The model quantifications help to identify high-priority areas for cost-effective investments, but do not provide any indication on who would finance the regional investments.

at lower cost; local capital markets development; and building greater trust in international cooperation processes (*high confidence*). A coordinated effort to make the post-pandemic recovery sustainable and increased flows of financing over the next decade can accelerate climate action, including in developing regions and countries facing high debt costs, debt distress and macroeconomic uncertainty (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6, Box 15.6}

E.5.4 Clear signalling by governments and the international community, including a stronger alignment of public sector finance and policy, and higher levels of public sector climate finance, reduces uncertainty and transition risks for the private sector. Depending on national contexts, investors and financial intermediaries, central banks, and financial regulators can support climate action and can shift the systemic underpricing of climate-related risk by increasing awareness, transparency and consideration of climate-related risk, and investment opportunities. Financial flows can also be aligned with funding needs through: greater support for technology development; a continued role for multilateral and national climate funds and development banks; lowering financing costs for underserved groups through entities such as green banks existing in some countries, funds and risk-sharing mechanisms; economic instruments which consider economic and social equity and distributional impacts; gender-responsive and women-empowerment programmes as well as enhanced access to finance for local communities and Indigenous Peoples and small land owners; and greater public-private cooperation. (*high confidence*) {15.2, 15.5, 15.6}

E.6 International cooperation is a critical enabler for achieving ambitious climate change mitigation goals. The UNFCCC, Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging development and implementation of climate policies, although gaps remain. Partnerships, agreements, institutions and initiatives operating at the sub-global and sectoral levels and engaging multiple actors are emerging, with mixed levels of effectiveness. (*high confidence*) {8.5, 14.2, 14.3, 14.5, 14.6, 15.6, 16.5}

E.6.1 Internationally agreed processes and goals, such as those in the UNFCCC, Kyoto Protocol, and Paris Agreement – including transparency requirements for national reporting on emissions, actions and support, and tracking progress towards the achievement of Nationally Determined Contributions – are enhancing international cooperation, national ambition and policy development. International financial, technology and capacity building support to developing countries will enable greater implementation and encourage ambitious Nationally Determined Contributions over time. (*medium confidence*) {14.3}

E.6.2 International cooperation on technology development and transfer accompanied by capacity building, knowledge sharing, and technical and financial support can accelerate the global diffusion of mitigation technologies, practices and policies at national and sub-national levels, and align these with other development objectives (*high confidence*). Challenges in and opportunities to enhance innovation cooperation exist, including in the implementation of elements of the UNFCCC and the Paris Agreement as per the literature assessed, such as in relation to technology development and transfer, and finance (*high confidence*). International cooperation on innovation works best when tailored to specific institutional and capability contexts, when it benefits local value chains, when partners collaborate equitably and on voluntary and mutually agreed terms, when all relevant voices are heard, and when capacity building is an integral part of the effort (*medium confidence*). Support to strengthen technological innovation systems and innovation capabilities, including through financial support in developing countries would enhance engagement in and improve international cooperation on innovation (*high confidence*). {4.4, 14.2, 14.4, 16.3, 16.5, 16.6}

E.6.3 Transnational partnerships can stimulate policy development, low-emissions technology diffusion and emission reductions by linking sub-national and other actors, including cities, regions, non-governmental organisations and private sector entities, and by enhancing interactions between state and non-state actors. While this potential of transnational partnerships is evident, uncertainties remain over their costs, feasibility, and effectiveness. Transnational networks of city governments are leading to enhanced ambition and policy development and a growing exchange of experience and best practices (*medium confidence*). {8.5, 11.6, 14.5, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.6.4 International environmental and sectoral agreements, institutions, and initiatives are helping, and in some cases may help, to stimulate low-GHG emissions investment and reduce emissions. Agreements addressing ozone depletion and transboundary air pollution are contributing to mitigation, and in other areas, such as atmospheric emissions of mercury, may contribute to mitigation (*high confidence*). Trade rules have the potential to stimulate international adoption of mitigation technologies and policies, but may also limit countries' ability to adopt trade-related climate policies (*medium confidence*). Current sectoral levels of ambition vary, with emission reduction aspirations in international aviation and shipping lower than in many other sectors (*medium confidence*). {14.5, 14.6}

DOCUMENT 2

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INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Impacts, Adaptation and Vulnerability

Summary for Policymakers

WGII

Working Group II contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Summary for Policymakers

Drafting Authors: Hans-O. Pörtner (Germany), Debra C. Roberts (South Africa), Helen Adams (United Kingdom), Carolina Adler (Switzerland/Chile/Australia), Paulina Aldunce (Chile), Elham Ali (Egypt), Rawshan Ara Begum (Malaysia/Australia/Bangladesh), Richard Betts (United Kingdom), Rachel Bezner Kerr (Canada/USA), Robbert Biesbroek (The Netherlands), Joern Birkmann (Germany), Kathryn Bowen (Australia), Edwin Castellanos (Guatemala), Gueladio Cissé (Mauritania/Switzerland/France), Andrew Constable (Australia), Wolfgang Cramer (France), David Dodman (Jamaica/United Kingdom), Siri H. Eriksen (Norway), Andreas Fischlin (Switzerland), Matthias Garschagen (Germany), Bruce Glavovic (New Zealand/South Africa), Elisabeth Gilmore (USA/Canada), Marjolijn Haasnoot (The Netherlands), Sherilee Harper (Canada), Toshihiro Hasegawa (Japan), Bronwyn Hayward (New Zealand), Yukiko Hirabayashi (Japan), Mark Howden (Australia), Kanungwe Kalaba (Zambia), Wolfgang Kiessling (Germany), Rodel Lasco (Philippines), Judy Lawrence (New Zealand), Maria Fernanda Lemos (Brazil), Robert Lempert (USA), Debora Ley (Mexico/Guatemala), Tabea Lissner (Germany), Salvador Lluch-Cota (Mexico), Sina Loeschke (Germany), Simone Lucatello (Mexico), Yong Luo (China), Brendan Mackey (Australia), Shobha Maharaj (Germany/Trinidad and Tobago), Carlos Mendez (Venezuela), Katja Mintenbeck (Germany), Vincent Möller (Germany), Mariana Moncassim Vale (Brazil), Mike D Morecroft (United Kingdom), Aditi Mukherji (India), Michelle Mycoo (Trinidad and Tobago), Tero Mustonen (Finland), Johanna Nalau (Australia/Finland), Andrew Okem (SouthAfrica/Nigeria), Jean Pierre Ometto (Brazil), Camille Parmesan (France/USA/United Kingdom), Mark Pelling (United Kingdom), Patricia Pinho (Brazil), Elvira Poloczanska (United Kingdom/Australia), Marie-Fanny Racault (United Kingdom/France), Diana Reckien (The Netherlands/Germany), Joy Pereira (Malaysia), Aromar Revi (India), Steven Rose (USA), Roberto Sanchez-Rodriguez (Mexico), E. Lisa F. Schipper (Sweden/United Kingdom), Daniela Schmidt (United Kingdom/Germany), David Schoeman (Australia), Rajib Shaw (Japan), Chandni Singh (India), William Solecki (USA), Lindsay Stringer (United Kingdom), Adelle Thomas (Bahamas), Edmond Totin (Benin), Christopher Trisos (South Africa), Maarten van Aalst (The Netherlands), David Viner (United Kingdom), Morgan Wairiu (Solomon Islands), Rachel Warren (United Kingdom), Pius Yanda (Tanzania), Zelina Zaiton Ibrahim (Malaysia)

Drafting Contributing Authors: Rita Adrian (Germany), Marlies Craig (South Africa), Frode Degvold (Norway), Kristie L. Ebi (USA), Katja Frieler (Germany), Ali Jamshed (Germany/Pakistan), Joanna McMillan (German/Australia), Reinhard Mechler (Austria), Mark New (South Africa), Nick Simpson (South Africa/Zimbabwe), Nicola Stevens (South Africa)

Visual Conception and Information Design: Andrés Alegría (Germany/Honduras), Stefanie Langsdorf (Germany)

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Table of Contents

SPM.A: Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group II (WGII) contribution to the Sixth Assessment Report (AR6) of the IPCC[1]. The report builds on the WGII contribution to the Fifth Assessment Report (AR5) of the IPCC, three Special Reports[2], and the Working Group I (WGI) contribution to the AR6 cycle.

This report recognizes the interdependence of climate, ecosystems and biodiversity[3], and human societies (Figure SPM.1) and integrates knowledge more strongly across the natural, ecological, social and economic sciences than earlier IPCC assessments. The assessment of climate change impacts and risks as well as adaptation is set against concurrently unfolding non-climatic global trends e.g., biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic.

The scientific evidence for each key finding is found in the 18 chapters of the underlying report and in the 7 cross-chapter papers as well as the integrated synthesis presented in the Technical Summary (hereafter TS) and referred to in curly brackets {}. Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[4]. The WGII Global to Regional Atlas (Annex I) facilitates exploration of key synthesis findings across the WGII regions.

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[1] Decision IPCC/XLVI-3, The assessment covers scientific literature accepted for publication by 1 September 2021.

[2] The three Special Reports are: 'Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5)'; 'Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL)'; 'IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)'

[3] Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

[4] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99-100% probability, very likely 90-100%, likely 66-100%, as likely as not 33-66%, unlikely 0-33%, very unlikely 0-10%, exceptionally unlikely 0-1%. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Reports.

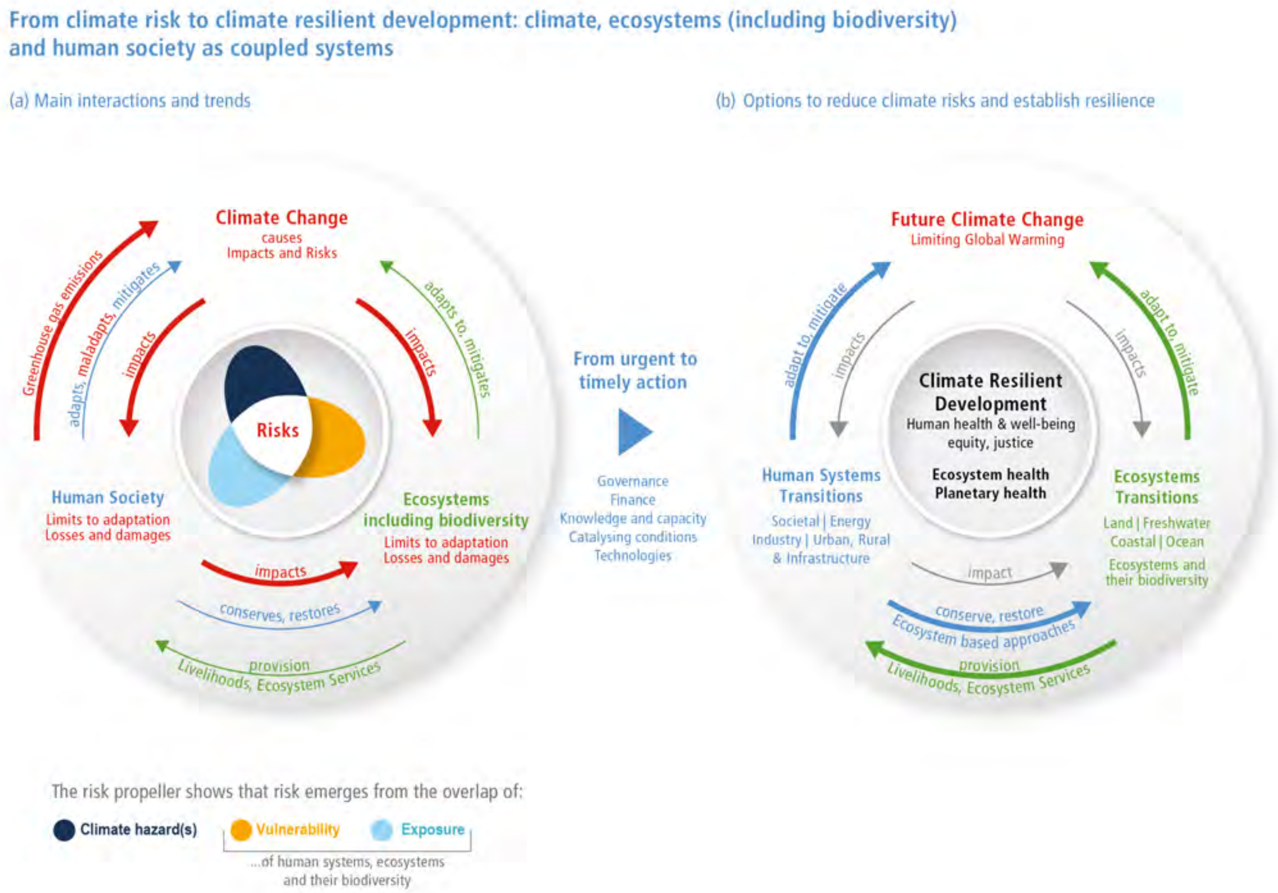

Figure SPM.1: This report has a strong focus on the interactions among the coupled systems climate, ecosystems (including their biodiversity) and human society. These interactions are the basis of emerging risks from climate change, ecosystem degradation and biodiversity loss and, at the same time, offer opportunities for the future. (a) Human society causes climate change. Climate change, through hazards, exposure and vulnerability generates impacts and risks that can surpass limits to adaptation and result in losses and damages. Human society can adapt to, maladapt and mitigate climate change, ecosystems can adapt and mitigate within limits. Ecosystems and their biodiversity provision livelihoods and ecosystem services. Human society impacts ecosystems and can restore and conserve them. (b) Meeting the objectives of climate resilient development thereby supporting human, ecosystem and planetary health, as well as human well-being, requires society and ecosystems to move over (transition) to a more resilient state. The recognition of climate risks can strengthen adaptation and mitigation actions and transitions that reduce risks. Taking action is enabled by governance, finance, knowledge and capacity building, technology and catalysing conditions. Transformation entails system transitions strengthening the resilience of ecosystems and society (Section D). In a) arrow colours represent principle human society interactions (blue), ecosystem (including biodiversity) interactions (green) and the impacts of climate change and human activities, including losses and damages, under continued climate change (red). In b) arrow colours represent human system interactions (blue), ecosystem (including biodiversity) interactions (green) and reduced impacts from climate change and human activities (grey). {1.2, Figure 1.2, Figure TS.1}

The concept of risk is central to all three AR6 Working Groups. A risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation provide alternative, overlapping, complementary, and widely used entry points to the literature assessed in this WGII report.

Across all three AR6 working groups, **risk**[5] provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse

[5] Risk is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems

consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions among climate-related **hazards**[6] (see Working Group I), the **exposure**[7] and **vulnerability**[8] of affected human and ecological systems. The risk that can be introduced by human responses to climate change is a new aspect considered in the risk concept. This report identifies 127 key risks[9]. {1.3, 16.5}

The vulnerability of exposed human and natural systems is a component of risk, but also, independently, an important focus in the literature. Approaches to analysing and assessing vulnerability have evolved since previous IPCC assessments. Vulnerability is widely understood to differ within communities and across societies, regions and countries, also changing through time.

Adaptation[10] plays a key role in reducing exposure and vulnerability to climate change. Adaptation in ecological systems includes autonomous adjustments through ecological and evolutionary processes. In human systems, adaptation can be anticipatory or reactive, as well as incremental and/ or transformational. The latter changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts. Adaptation is subject to hard and soft limits[11].

Resilience[12] in the literature has a wide range of meanings. Adaptation is often organized around resilience as bouncing back and returning to a previous state after a disturbance. More broadly the term describes not just the ability to maintain essential function, identity and structure, but also the capacity for transformation.

This report recognises the value of diverse forms of **knowledge** such as scientific, as well as Indigenous knowledge and local knowledge in understanding and evaluating climate adaptation processes and actions to reduce risks from human-induced climate change. AR6 highlights adaptation solutions which are effective, **feasible**[13], and conform to principles of **justice**[14]. The term climate justice, while used in different ways in different contexts by different communities, generally includes three principles: *distributive justice* which refers to the allocation of burdens and benefits among individuals, nations and generations; *procedural justice* which refers to who decides and participates in decision-making; and *recognition* which entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives.

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[6] Hazard is defined as the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Physical climate conditions that may be associated with hazards are assessed in Working Group I as climatic impact-drivers.

[7] Exposure is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.

[8] Vulnerability in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

[9] Key risks have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate related hazards with vulnerabilities of societies and systems exposed.

[10] Adaptation is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this.

[11] Adaptation Limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

- Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks.
- Soft adaptation limit - Options may exist but are currently not available to avoid intolerable risks through adaptive action.

[12] Resilience in this report is defined as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation.

[13] Feasibility refers to the potential for an adaptation option to be implemented.

[14] Justice is concerned with setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. *Social justice* comprises just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity and support according to principles of justice and fairness. *Climate justice* comprises justice that links development and human rights to achieve a rights-based approach to addressing climate change.

Effectiveness refers to the extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation[15].

This report has a particular focus on transformation[16] and system transitions in energy; land, ocean, coastal and freshwater ecosystems; urban, rural and infrastructure; and industry and society. These transitions make possible the adaptation required for high levels of human health and wellbeing, economic and social resilience, ecosystem health[17], and planetary health[18] (Figure SPM.1). These system transitions are also important for achieving the low global warming levels (WGIII) that would avoid many limits to adaptation[11]. The report also assesses economic and non-economic losses and damages[19]. This report labels the process of implementing mitigation and adaptation together in support of sustainable development for all as climate resilient development[20].

[START BOX SPM.1 HERE]

Box SPM.1: AR6 Common Climate Dimensions, Global Warming Levels and Reference Periods

Assessments of climate risks consider possible future climate change, societal development and responses. This report assesses literature including that based on climate model simulations that are part of the fifth and sixth Coupled Model Intercomparison Project phase (CMIP5, CMIP6) of the World Climate Research Programme. Future projections are driven by emissions and/or concentrations from illustrative Representative Concentration Pathways (RCPs)[21] and Shared Socio-economic Pathways (SSPs)[22] scenarios, respectively[23]. Climate impacts literature is based primarily on climate projections assessed in AR5 or earlier, or assumed global warming levels, though some recent impacts literature uses newer projections based on the CMIP6 exercise. Given differences in the impacts literature regarding socioeconomic details and assumptions, WGII chapters contextualize impacts with respect to exposure, vulnerability and adaptation as appropriate for their literature, this includes assessments regarding sustainable development and climate resilient development. There are many emissions and socioeconomic pathways that are consistent with a given global warming outcome. These represent a broad range of possibilities as available in the literature assessed that affect future climate change exposure and vulnerability. Where available, WGII also assesses literature that is based on an integrative SSP-RCP framework where climate projections obtained under the RCP scenarios are analysed against the backdrop of various illustrative SSPs[22]. The WGII assessment combines multiple lines of evidence including impacts modelling driven by climate projections, observations, and process understanding. {1.2, 16.5, 18.2, CCB CLIMATE, WGI SPM.C, WGI Box SPM.1, WGI 1.6, WGI Ch.12, AR5 WGI}

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[15] Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

[16] Transformation refers to a change in the fundamental attributes of natural and human systems.

[17] Ecosystem health: a metaphor used to describe the condition of an ecosystem, by analogy with human health. Note that there is no universally accepted benchmark for a healthy ecosystem. Rather, the apparent health status of an ecosystem is judged on the ecosystem's resilience to change, with details depending upon which metrics (such as species richness and abundance) are employed in judging it and which societal aspirations are driving the assessment.

[18] Planetary health: a concept based on the understanding that human health and human civilisation depend on ecosystem health and the wise stewardship of ecosystems.

[19] In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic.

[20] In the WGII report, climate resilient development refers to the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all.

[21] RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square meter, or $W\ m^{-2}$) resulting from the scenario in the year 2100.

[22] SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socio-economic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square meter, or $W\ m^{-2}$) resulting from the scenario in the year 2100.

[23] IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

A common set of reference years and time periods are adopted for assessing climate change and its impacts and risks: the reference period 1850–1900 approximates pre-industrial global surface temperature, and three future reference periods cover the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). {CCB CLIMATE}

Common levels of global warming relative to 1850-1900 are used to contextualize and facilitate analysis, synthesis and communication of assessed past, present and future climate change impacts and risks considering multiple lines of evidence. Robust geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached. {16.5, CCB CLIMATE, WGI 4.2, WGI CCB11.1, WGI Box SPM.1}

WGI assessed increase in global surface temperature is 1.09 [0.95 to 1.20][24] °C in 2011-2020 above 1850-1900. The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C).[25] Considering all five illustrative scenarios assessed by WGI, there is at least a greater than 50% likelihood that global warming will reach or exceed 1.5°C in the near-term, even for the very low greenhouse gas emissions scenario[26]. {WGI CCB 2.3, WGI SPM A1.2, WGI SPM B1.3, WGI Table SPM.1}

[END BOX SPM.1 HERE]

SPM.B: Observed and Projected Impacts and Risks

Since AR5, the knowledge base on observed and projected impacts and risks generated by climate hazards, exposure and vulnerability has increased with impacts attributed to climate change and key risks identified across the report. Impacts and risks are expressed in terms of their damages, harms, economic, and non-economic losses. Risks from observed vulnerabilities and responses to climate change are highlighted. Risks are projected for the near-term (2021-2040), the mid (2041-2060) and long term (2081-2100), at different global warming levels and for pathways that overshoot 1.5°C global warming level for multiple decades[27]. Complex risks result from multiple climate hazards occurring concurrently, and from multiple risks interacting, compounding overall risk and resulting in risks transmitting through interconnected systems and across regions.

Observed Impacts from Climate Change

SPM.B.1 Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation efforts have reduced vulnerability. Across sectors and regions the most vulnerable people and systems are observed to be disproportionately affected. The rise in weather

[24] In the WGI report, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

[25] Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

[26] Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high greenhouse gas emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high greenhouse gas emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high greenhouse gas emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low greenhouse gas emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low greenhouse gas emissions scenario (SSP1-1.9). Furthermore, for the very low greenhouse gas emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.

[27] Overshoot: In this report, pathways that first exceed a specified global warming level (usually 1.5°C, by more than 0.1°C), and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterized. The overshoot duration can vary from at least one decade up to several decades.

and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt. (*high confidence*) (Figure SPM.2) {1.3, 2.3, 2.4, 2.6, 3.3, 3.4, 3.5, 4.2, 4.3, 5.2, 5.12, 6.2, 7.2, 8.2, 9.6, 9.8, 9.10, 9.11, 10.4, 11.3, 12.3, 12.4, 13.10, 14.4, 14.5, 15.3, 16.2, CCP1.2, CCP3.2, CCP4.1, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB DISASTER, CCB MIGRATE, Figure TS.5, TS B1

SPM.B.1.1 Widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought and fire weather (*high confidence*). Increasingly since AR5, these observed impacts have been attributed[28] to human-induced climate change particularly through increased frequency and severity of extreme events. These include increased heat-related human mortality (*medium confidence*), warm-water coral bleaching and mortality (*high confidence*), and increased drought related tree mortality (*high confidence*). Observed increases in areas burned by wildfires have been attributed to human-induced climate change in some regions (*medium* to *high confidence*). Adverse impacts from tropical cyclones, with related losses and damages[19], have increased due to sea level rise and the increase in heavy precipitation (*medium confidence*). Impacts in natural and human systems from slow-onset processes[29] such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human induced climate change (*high confidence*). {1.3, 2.3, 2.4, 2.5, 3.2, 3.4, 3.5, 3.6, 4.2, 5.2, 5.4, 5.6, 5.12, 7.2, 9.6, 9.8, 9.7, 9.8, 9.11, 11.3, Box 11.1, Box 11.2, Table 11.9, 12.3, 12.4, 13.3, 13.5, 13.10, 14.2,14.5, 15.7, 15.8, 16.2, Box CCP5.1, CCP1.2, CCP2.2, CCP7.3, CCB EXTREME, CCB ILLNESS, CCB DISASTER, WG1 9, WGI 11.3-11.8, WGI SPM.3, SROCC Ch. 4}

SPM.B.1.2 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems (*high confidence*). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (*high confidence*). Widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, as well as shifts in seasonal timing have occurred due to climate change (*high confidence*), with adverse socioeconomic consequences (*high confidence*). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (*very high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*), as well as mass mortality events on land and in the ocean (*very high confidence*) and loss of kelp forests (*high confidence*). Some losses are already irreversible, such as the first species extinctions driven by climate change (*medium confidence*). Other impacts are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). (Figure SPM.2a). {2.3, 2.4, 3.4, 3.5, 4.2, 4.3, 4.5, 9.6, 10.4, 11.3, 12.3, 12.8, 13.3, 13.4, 13.10, 14.4, 14.5, 14.6, 15.3, 16.2, CCP1.2; CCP3.2, CCP4.1, CCP5.2, CCP6.1, CCP6.2, CCP7.2, CCP7.3, CCP5.2, Figure CCP5.4, CCB PALEO, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB MOVING PLATE, Figure TS.5, TS B1, SROCC 2.3}

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[28] Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence. {Annex II Glossary, CWGB ATTRIB}

[29] Impacts of climate change are caused by slow onset and extreme events. Slow onset events are described among the climatic-impact drivers of the WGI AR6 and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization (https://interactive-atlas.ipcc.ch).

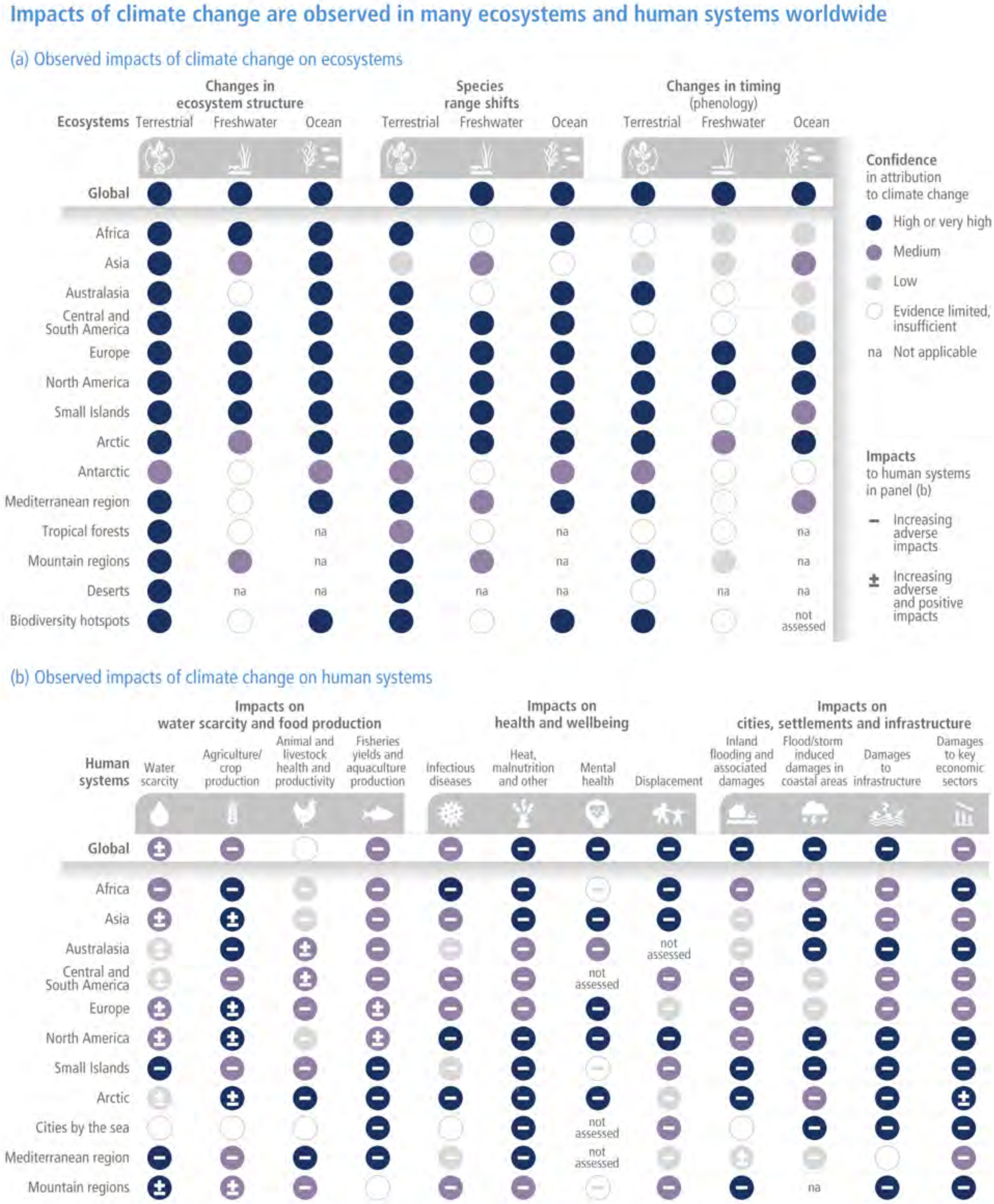

Figure SPM.2: Observed global and regional impacts on ecosystems and human systems attributed to climate change. Confidence levels reflect uncertainty in attribution of the observed impact to climate change. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. For that reason they can be assessed with higher confidence than regional studies, which may often rely on smaller studies that have more limited data. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular. (a) Climate change has already altered terrestrial, freshwater and ocean ecosystems at global scale, with multiple impacts evident at regional and local scales where there is sufficient literature to make an assessment. Impacts are evident on ecosystem structure, species geographic ranges and timing of seasonal life cycles (phenology) (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.1). (b) Climate change has already had diverse adverse impacts on human systems, including on water security and food production, health and well-being, and cities, settlements and infrastructure. The + and – symbols indicate the direction of observed impacts, with a – denoting an increasing adverse impact and a ± denoting that, within a region or globally, both adverse and positive impacts have been observed (e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item). Globally, '–' denotes an overall adverse impact; 'Water scarcity' considers, e.g., water availability in general, groundwater, water quality, demand for water, drought in cities. Impacts on food production were assessed by excluding non-climatic drivers of production increases; Global assessment for agricultural production is based on the impacts on global aggregated production; 'Reduced animal and livestock health and productivity' considers, e.g., heat stress, diseases, productivity, mortality; 'Reduced fisheries yields and aquaculture production' includes marine and freshwater fisheries/production; 'Infectious diseases' include, e.g., water-borne and vector-borne diseases; 'Heat, malnutrition and other' considers, e.g., human heat-related morbidity and mortality, labour productivity, harm from wildfire, nutritional deficiencies; 'Mental health' includes impacts from extreme weather events, cumulative events, and vicarious or anticipatory events; 'Displacement' assessments refer to evidence of displacement attributable to climate and weather extremes; 'Inland flooding and associated damages' considers, e.g., river overflows, heavy rain, glacier outbursts, urban flooding; 'Flood/storm induced damages in coastal areas' include damages due to, e.g., cyclones, sea level rise, storm surges. Damages by key economic sectors are observed impacts related to an attributable mean or extreme climate hazard or directly attributed. Key economic sectors include standard classifications and sectors of importance to regions (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.2).

SPM.B.1.3 Climate change including increases in frequency and intensity of extremes have reduced food and water security, hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (*medium confidence*), related negative impacts were mainly in mid- and low latitude regions but positive impacts occurred in some high latitude regions (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (*high confidence*). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[30] and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, Small Islands and the Arctic (*high confidence*). Jointly, sudden losses of food production and access to food compounded by decreased diet diversity have increased malnutrition in many communities (*high confidence*), especially for Indigenous Peoples, small-scale food producers and low-income households (*high confidence*), with children, elderly people and pregnant women particularly impacted (*high confidence*). Roughly half of the world's population currently experience severe water scarcity for at least some part of the year due to climatic and non-climatic drivers (*medium confidence*). (Figure SPM.2b) {3.5, Box 4.1, 4.3, 4.4, 5.2, 5.4, 5.8, 5.9, 5.12, 7.1, 7.2, 9.8, 10.4, 11.3, 12.3, 13.5, 14.4, 14.5, 15.3, 16.2, CCP5.2, CCP6.2}

SPM.B.1.4 Climate change has adversely affected physical health of people globally (*very high confidence)* and mental health of people in the assessed regions (*very high confidence*). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (*high confidence*). In all regions extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases has increased (*very high confidence*). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (*high confidence*). Animal and human diseases, including zoonoses, are emerging in new areas (*high confidence*). Water and food-borne disease risks have increased regionally from climate-sensitive aquatic pathogens, including *Vibrio* spp. (*high confidence*), and from toxic substances from harmful freshwater cyanobacteria (*medium confidence*). Although diarrheal diseases have decreased globally, higher temperatures, increased rain and flooding have increased the occurrence of diarrheal diseases, including cholera (*very high confidence*) and other gastrointestinal infections (*high confidence*). In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from weather and climate extreme events (*very high confidence*), and loss of livelihoods and culture (*high confidence*). Increased exposure to wildfire smoke, atmospheric dust, and aeroallergens have been associated with climate-sensitive cardiovascular and respiratory distress (*high confidence*). Health services have been disrupted by extreme events such as floods (*high confidence*). {4.3, 5.12, 7.2, Box 7.3, 8.2, 8.3, Figure 8.10,

[30] Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and used to assess the need for humanitarian action (IPC Global Partners, 2019).

Box 8.6, 9.10, Figure 9.33, Figure 9.34, 10.4, 11.3, 12.3, 13.7, 14.4, 14.5, Figure 14.8, 15.3, 16.2, Table CCP5.1, CCP5.2.5, CCP6.2, Figure CCP6.3, Table CCB ILLNESS.1}

SPM.B.1.5 In urban settings, observed climate change has caused impacts on human health, livelihoods and key infrastructure (*high confidence*). Multiple climate and non-climate hazards impact cities, settlements and infrastructure and sometimes coincide, magnifying damage (*high confidence*). Hot extremes including heatwaves have intensified in cities (*high confidence*), where they have also aggravated air pollution events (*medium confidence*) and limited functioning of key infrastructure (*high confidence*). Observed impacts are concentrated amongst the economically and socially marginalized urban residents, e.g., in informal settlements (*high confidence*). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to wellbeing (*high confidence*). {4.3, 6.2, 7.1, 7.2, 9.9, 10.4, 11.3, 12.3, 13.6, 14.5, 15.3, CCP2.2, CCP4.2, CCP5.2}

SPM.B.1.6 Overall adverse economic impacts attributable to climate change, including slow-onset and extreme weather events, have been increasingly identified (*medium confidence*). Some positive economic effects have been identified in regions that have benefited from lower energy demand as well as comparative advantages in agricultural markets and tourism (*high confidence*). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism (*high confidence*), and through outdoor labour productivity (*high confidence*). Some extreme weather events, such as tropical cyclones, have reduced economic growth in the short-term (*high confidence*). Non-climatic factors including some patterns of settlement, and siting of infrastructure have contributed to the exposure of more assets to extreme climate hazards increasing the magnitude of the losses (*high confidence*). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (*high confidence*). {3.5, 4.2, 5.12, 6.2, 7.2, 8.2, 9.6, 10.4, 13.10, 14.5, Box 14.6, 16.2, Table 16.5, 18.3, CCP6.2, CCB GENDER, CWGB ECONOMICS}

SPM.B.1.7 Climate change is contributing to humanitarian crises where climate hazards interact with high vulnerability (*high confidence*). Climate and weather extremes are increasingly driving displacement in all regions (*high confidence*), with small island states disproportionately affected (*high confidence*). Flood and drought-related acute food insecurity and malnutrition have increased in Africa (*high confidence*) and Central and South America (*high confidence*). While non-climatic factors are the dominant drivers of existing intrastate violent conflicts, in some assessed regions extreme weather and climate events have had a small, adverse impact on their length, severity or frequency, but the statistical association is weak (*medium confidence*). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (*medium confidence*). {4.2, 4.3, 5.4, 7.2, 9.8, Box 9.9, Box 10.4, 12.3, 12.5, CCB MIGRATE, CCB DISASTER, 16.2}

Vulnerability and Exposure of Ecosystems and People

SPM.B.2 Vulnerability of ecosystems and people to climate change differs substantially among and within regions (*very high confidence*), driven by patterns of intersecting socio-economic development, unsustainable ocean and land use, inequity, marginalization, historical and ongoing patterns of inequity such as colonialism, and governance[31] (*high confidence*). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). A high proportion of species is vulnerable to climate change (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Current unsustainable development patterns are increasing exposure of ecosystems and people to climate hazards (*high confidence*). {2.3, 2.4, 3.5, 4.3, 6.2, 8.2, 8.3, 9.4, 9.7, 10.4, 12.3, 14.5, 15.3, CCP5.2, CCP6.2, CCP7.3, CCP7.4, CCB GENDER}

[31] Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.

SPM.B.2.1 Since AR5 there is increasing evidence that degradation and destruction of ecosystems by humans increases the vulnerability of people (*high confidence*). Unsustainable land-use and land cover change, unsustainable use of natural resources, deforestation, loss of biodiversity, pollution, and their interactions, adversely affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change (*high confidence*). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (*high confidence*). {2.3, 2.5, 2.6, 3.5, 3.6, 4.2, 4.3, 4.6, 5.1, 5.4, 5.5, 5.7, 5.8, 7.2, 8.1, 8.2, 8.3, 8.4, 8.5, 9.6, 10.4, 11.3, 12.2, 12.5. 13.8, 14.4, 14.5, 15.3, CCP1.2, CCP1.3, CCP2.2, CCP3, CCP4.3, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCP7.4, CCB ILLNESS, CCB MOVING PLATE, CCB SLR}

SPM.B.2.2 Non-climatic human-induced factors exacerbate current ecosystem vulnerability to climate change (*very high confidence*). Globally, and even within protected areas, unsustainable use of natural resources, habitat fragmentation, and ecosystem damage by pollutants increase ecosystem vulnerability to climate change (*high confidence*). Globally, less than 15% of the land, 21% of the freshwater and 8% of the ocean are protected areas. In most protected areas, there is insufficient stewardship to contribute to reducing damage from, or increasing resilience to, climate change (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.6, 4.2, 4.3, 5.8, 9.6, 11.3, 12.3, 13.3, 13.4, 14.5, 15.3, CCP1.2 Figure CCP1.15, CCP2.1, CCP2.2, CCP4.2, CCP5.2, CCP 6.2, CCP7.2, CCP7.3, CCB NATURAL}

SPM.B.2.3 Future vulnerability of ecosystems to climate change will be strongly influenced by the past, present and future development of human society, including from overall unsustainable consumption and production, and increasing demographic pressures, as well as persistent unsustainable use and management of land, ocean, and water (*high confidence*). Projected climate change, combined with non-climatic drivers, will cause loss and degradation of much of the world's forests (*high confidence*), coral reefs and low-lying coastal wetlands (*very high confidence*). While agricultural development contributes to food security, unsustainable agricultural expansion, driven in part by unbalanced diets[32], increases ecosystem and human vulnerability and leads to competition for land and/or water resources (*high confidence*). {2.2, 2.3, 2.4, 2.6, 3.4, 3.5, 3.6, 4.3, 4.5, 5.6, 5.12, 5.13, 7.2, 12.3, 13.3, 13.4, 13.10, 14.5, CCP1.2, CCP2.2, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB NATURAL, CCB HEALTH}

SPM.B.2.4 Regions and people with considerable development constraints have high vulnerability to climatic hazards (*high confidence*). Global hotspots of high human vulnerability are found particularly in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Between 2010-2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (*high confidence*). Vulnerability at different spatial levels is exacerbated by inequity and marginalization linked to gender, ethnicity, low income or combinations thereof (*high confidence*), especially for many Indigenous Peoples and local communities (*high confidence*). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (*high confidence*). {4.2, 5.12, 6.2, 6.4, 7.1, 7.2, Box 7.1, 8.2, 8.3, Box 8.4, Figure 8.6, Box 9.1, 9.4, 9.7, 9.9, 10.3, 10.4, 10.6, 12.3, 12.5, Box 13.2, 14.4, 15.3, 15.6, 16.2, CCP6.2, CCP7.4}

SPM.B.2.5 Future human vulnerability will continue to concentrate where the capacities of local, municipal and national governments, communities and the private sector are least able to provide infrastructures and basic services (*high confidence*). Under the global trend of urbanization, human vulnerability will also concentrate in informal settlements and rapidly growing smaller settlements (*high confidence*). In rural areas vulnerability will be heightened by compounding processes including high emigration, reduced habitability and high reliance on climate-sensitive livelihoods (*high confidence*). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design

[32] Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-greenhouse gas emissions systems, as described in SRCCL.

standards do not account for changing climate conditions (*high confidence*). Vulnerability will also rapidly rise in low-lying Small Island Developing States and atolls in the context of sea level rise and in some mountain regions, already characterised by high vulnerability due to high dependence on climate-sensitive livelihoods, rising population displacement, the accelerating loss of ecosystem services and limited adaptive capacities (*high confidence*). Future exposure to climatic hazards is also increasing globally due to socio-economic development trends including migration, growing inequality and urbanization *(high confidence*). {4.5, 5.5, 6.2, 7.2, 8.3, 9.9, 9.11, 10.3, 10.4, 12.3, 12.5, 13.6, 14.5, 15.3, 15.4, 16.5, CCP2.3, CCP4.3, CCP5.2, CCP5.3, CCP5.4, CCP6.2, CCB MIGRATE}

Risks in the near term (2021-2040)

SPM.B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3, Box SPM.1) {WGI Table SPM.1, 16.4, 16.5, 16.6, CCP1.2, CCP5.3, CCB SLR, WGI SPM B1.3}

SPM.B.3.1 Near-term warming and increased frequency, severity and duration of extreme events will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risks of biodiversity loss (*medium to very high confidence*, depending on ecosystem). Near-term risks for biodiversity loss are moderate to high in forest ecosystems (*medium confidence*), kelp and seagrass ecosystems (*high* to *very high confidence*), and high to very high in Arctic sea-ice and terrestrial ecosystems (*high confidence*) and warm-water coral reefs (*very high confidence*). Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure (*high confidence*) and commit low-lying coastal ecosystems to submergence and loss (*medium confidence*). If trends in urbanisation in exposed areas continue, this will exacerbate the impacts, with more challenges where energy, water and other services are constrained (*medium confidence*). The number of people at risk from climate change and associated loss of biodiversity will progressively increase (*medium confidence*). Violent conflict and, separately, migration patterns, in the near-term will be driven by socio-economic conditions and governance more than by climate change (*medium confidence*). (Figure SPM.3) {2.5, 3.4, 4.6, 6.2, 7.3, 8.7, 9.2, 9.9, 11.6, 12.5, 13.6, 13.10, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCP6.3, CCB SLR, CCB MIGRATE}

SPM.B.3.2 In the near term, climate-associated risks to natural and human systems depend more strongly on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios (*high confidence*). Regional differences exist, and risks are highest where species and people exist close to their upper thermal limits, along coastlines, in close association with ice or seasonal rivers (*high confidence*). Risks are also high where multiple non-climate drivers persist or where vulnerability is otherwise elevated (*high confidence*). Many of these risks are unavoidable in the near-term, irrespective of emission scenario (*high confidence*). Several risks can be moderated with adaptation (*high confidence*). (Figure SPM.3, Section C) {2.5, 3.3, 3.4, 4.5, 6.2, 7.1, 7.3, 8.2, 11.6, 12.4, 13.6, 13.7, 13.10, 14.5, 16.4, 16.5, CCP2.2, CCP4.3, CCP5.3, CCB SLR, WGI Table SPM.1}

SPM.B.3.3 Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3b) {16.5, 16.6, CCB SLR}

Mid to Long-term Risks (2041–2100)

SPM.B.4 Beyond 2040 and depending on the level of global warming, climate change will lead to numerous risks to natural and human systems (*high confidence*). For 127 identified key risks, assessed mid- and long-term impacts are up to multiple times higher than currently observed (*high confidence*). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (*very high confidence*). (Figure SPM.3) {2.5, 3.4, 4.4, 5.2, 6.2, 7.3, 8.4, 9.2, 10.2, 11.6, 12.4, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7, 13.8, 14.6, 15.3, 16.5, 16.6, CCP1.2; CCP2.2, CCP3.3, CCP4.3, CCP5.3, CCP6.3, CCP7.3}

SPM.B.4.1 Biodiversity loss, and degradation, damages to and transformation of ecosystems are already key risks for every region due to past global warming and will continue to escalate with every increment of global warming (*very high confidence*). In terrestrial ecosystems, 3 to 14% of species assessed[33] will *likely* face very high risk of extinction[34] at global warming levels of 1.5°C, increasing up to 3 to 18% at 2°C, 3 to 29% at 3°C, 3 to 39% at 4°C, and 3 to 48% at 5°C. In ocean and coastal ecosystems, risk of biodiversity loss ranges between moderate and very high by 1.5°C global warming level and is moderate to very high by 2°C but with more ecosystems at high and very high risk (*high confidence*), and increases to high to very high across most ocean and coastal ecosystems by 3°C (*medium* to *high confidence*, depending on ecosystem). Very high extinction risk for endemic species in biodiversity hotspots is projected to at least double from 2% between 1.5°C and 2°C global warming levels and to increase at least tenfold if warming rises from 1.5°C to 3°C (*medium confidence*). (Figure SPM.3c, d, f) {2.4, 2.5, 3.4, 3.5,12.3, 12.5, Table 12.6, 13.4, 13.10, 16.4, 16.6, CCP1.2, Figure CCP1.6; Figure CCP1.7, CCP5.3, CCP6.3, CCB PALEO}

SPM.B.4.2 Risks in physical water availability and water-related hazards will continue to increase by the mid- to long-term in all assessed regions, with greater risk at higher global warming levels (*high confidence*). At approximately 2°C global warming, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20%, and global glacier mass loss of 18 ± 13% is projected to diminish water availability for agriculture, hydropower, and human settlements in the mid- to long-term, with these changes projected to double with 4°C global warming (*medium confidence*). In small islands, groundwater availability is threatened by climate change (*high confidence*). Changes to streamflow magnitude, timing and associated extremes are projected to adversely impact freshwater ecosystems in many watersheds by the mid- to long-term across all assessed scenarios (*medium confidence*). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C compared to 1.5°C global warming without adaptation (*medium confidence*). At global warming of 4°C, approximately 10% of the global land area is projected to face increases in both extreme high and low river flows in the same location, with implications for planning for all water use sectors (*medium confidence*). Challenges for water management will be exacerbated in the near, mid and long term, depending on the magnitude, rate and regional details of future climate change and will be particularly challenging for regions with constrained resources for water management (*high confidence*). {2.3, Box 4.2, 4.4, 4.5, Figure 4.20, 15.3, CCB DISASTER, CCP5.3, SROCC 2.3}

SPM.B.4.3 Climate change will increasingly put pressure on food production and access, especially in vulnerable regions, undermining food security and nutrition (*high confidence*). Increases in frequency, intensity and severity of droughts, floods and heatwaves, and continued sea level rise will increase risks to food security (*high confidence*) in vulnerable regions from moderate to high between 1.5°C and 2°C global warming level, with no or low levels of adaptation (*medium confidence*). At 2°C or higher global warming level in the mid-term, food security risks due to climate change will be more severe, leading to malnutrition and micro-nutrient deficiencies, concentrated in Sub-Saharan Africa, South Asia, Central and South America and Small Islands (*high confidence)*. Global warming will progressively weaken soil health and ecosystem

[33] Numbers of species assessed are in the tens of thousands globally.

[34] The term 'very high risks of extinction' is used here consistently with the IUCN categories and criteria and equates with 'critically endangered'.

services such as pollination, increase pressure from pests and diseases, and reduce marine animal biomass, undermining food productivity in many regions on land and in the ocean (*medium confidence*). At 3ºC or higher global warming level in the long term, areas exposed to climate-related hazards will expand substantially compared with 2ºC or lower global warming level (*high confidence*), exacerbating regional disparity in food security risks (*high confidence*). (Figure SPM.3) {1.1, 3.3, CCB SLR, 4.5, 5.2, 5.4, 5.5, 5.8, 5.9, 5.12, CCB MOVING PLATE, 7.3, 8.3, 9.11,13.5,15.3, 16.5, 16.6}

SPM.B.4.4 Climate change and related extreme events will significantly increase ill health and premature deaths from the near- to long-term (*high confidence*). Globally, population exposure to heatwaves will continue to increase with additional warming, with strong geographical differences in heat-related mortality without additional adaptation (*very high confidence*). Climate-sensitive food-borne, water-borne, and vector-borne disease risks are projected to increase under all levels of warming without additional adaptation (*high confidence*). In particular, dengue risk will increase with longer seasons and a wider geographic distribution in Asia, Europe, Central and South America and sub-Saharan Africa, potentially putting additional billions of people at risk by the end of the century (*high confidence*). Mental health challenges, including anxiety and stress, are expected to increase under further global warming in all assessed regions, particularly for children, adolescents, elderly, and those with underlying health conditions (*very high confidence*). {4.5, 5.12, Box 5.10, 7.3, Fig 7.9, 8.4, 9.10, Fig 9.32, Fig 9.35, 10.4, Fig 10.11, 11.3, 12.3, Fig 12.5, Fig 12.6, 13.7, Fig 13.23, Fig 13.24, 14.5, 15.3, CCP6.2}

SPM.B.4.5 Climate change risks to cities, settlements and key infrastructure will rise rapidly in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*). Globally, population change in low-lying cities and settlements will lead to approximately a billion people projected to be at risk from coastal-specific climate hazards in the mid-term under all scenarios, including in Small Islands (*high confidence*). The population potentially exposed to a 100-year coastal flood is projected to increase by about 20% if global mean sea level rises by 0.15 m relative to 2020 levels; this exposed population doubles at a 0.75 m rise in mean sea level and triples at 1.4 m without population change and additional adaptation (*medium confidence*). Sea level rise poses an existential threat for some Small Islands and some low-lying coasts (*medium confidence*). By 2100 the value of global assets within the future 1-in-100 year coastal floodplains is projected to be between US$7.9 and US$12.7 trillion (2011 value) under RCP4.5, rising to between US$8.8 and US$14.2 trillion under RCP8.5 (*medium confidence*). Costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy will increase with global warming level (*medium confidence*), the associated functional disruptions are projected to be substantial particularly for cities, settlements and infrastructure located on permafrost in cold regions and on coasts (*high confidence*). {6.2, 9.9, 10.4, 13.6, 13.10, 15.3, 16.5, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCB SLR, SROCC 2.3, SROCC CCB9}

SPM.B.4.6 Projected estimates of global aggregate net economic damages generally increase non-linearly with global warming levels (*high confidence*).[35] The wide range of global estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates (*high confidence*). The existence of higher estimates than assessed in AR5 indicates that global aggregate economic impacts could be higher than previous estimates (*low confidence*).[36] Significant regional variation in aggregate economic damages from climate change is projected (*high confidence*) with estimated economic damages per capita for developing countries often higher as a fraction of income (*high confidence*). Economic damages, including both those represented and those not represented in economic markets, are projected to be lower at 1.5°C than at 3°C or higher global warming levels (*high confidence*). {4.4, 9.11, 11.5, 13.10, Box 14.6, 16.5, CWGB ECONOMICS}

SPM.B.4.7 In the mid- to long-term, displacement will increase with intensification of heavy precipitation and associated flooding, tropical cyclones, drought and, increasingly, sea level rise (*high confidence*). At progressive levels of warming, involuntary migration from regions with high exposure and low adaptive

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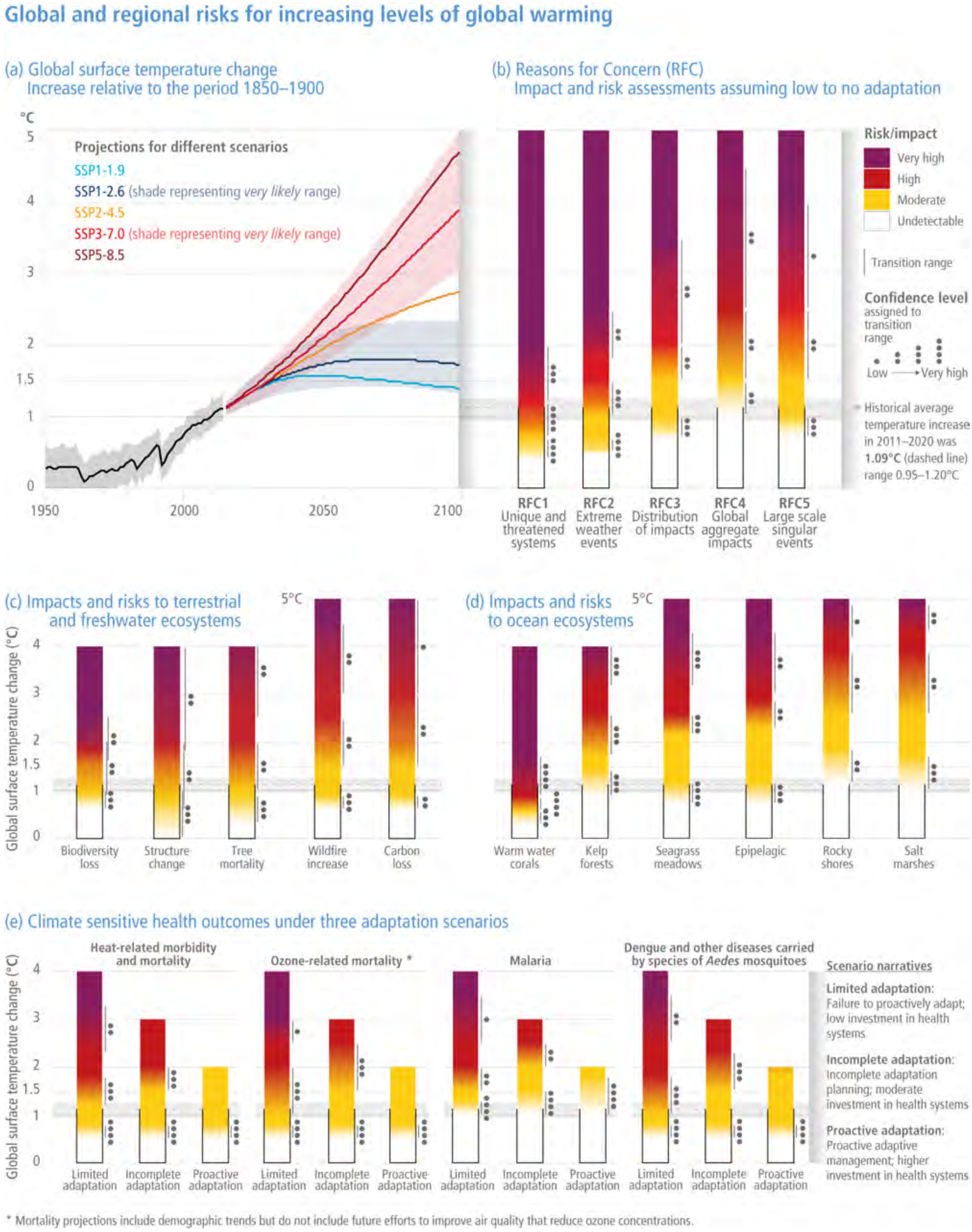
[35] The assessment found estimated rates of increase in projected global economic damages that were both greater than linear and less than linear as global warming level increases. There is evidence that some regions could benefit from low levels of warming (*high confidence*). {CWGB ECONOMICS}

[36] *Low confidence* assigned due to the assessed lack of comparability and robustness of global aggregate economic damage estimates. {CWGB ECONOMICS}

capacity would occur (*medium confidence*). Compared to other socioeconomic factors the influence of climate on conflict is assessed as relatively weak (*high confidence*). Along long-term socioeconomic pathways that reduce non-climatic drivers, risk of violent conflict would decline (*medium confidence*). At higher global warming levels, impacts of weather and climate extremes, particularly drought, by increasing vulnerability will increasingly affect violent intrastate conflict (*medium confidence*). {7.3, 16.5, CCB MIGRATE, TSB7.4}



(f) Examples of regional key risks

Absence of risk diagrams does not imply absence of risks within a region. The development of synthetic diagrams for Small Islands, Asia and Central and South America was limited due to the paucity of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socioeconomic contexts across countries within a region, and the resulting few numbers of impact and risk projections for different warming levels.

The risks listed are of at least *medium confidence* level:

Small Islands
- Loss of terrestrial, marine and coastal biodiversity and ecosystem services
- Loss of lives and assets, risk to food security and economic disruption due to destruction of settlements and infrastructure
- Economic decline and livelihood failure of fisheries, agriculture, tourism and from biodiversity loss from traditional agroecosystems
- Reduced habitability of reef and non-reef islands leading to increased displacement
- Risk to water security in almost every small island

North America
- Climate-sensitive mental health outcomes, human mortality and morbidity due to increasing average temperature, weather and climate extremes, and compound climate hazards
- Risk of degradation of marine, coastal and terrestrial ecosystems, including loss of biodiversity, function, and protective services
- Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture, other human uses, and degraded water quality
- Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access
- Risks to well-being, livelihoods and economic activities from cascading and compounding climate hazards, including risks to coastal cities, settlements and infrastructure from sea-level rise

Europe
- Risks to people, economies and infrastructures due to coastal and inland flooding
- Stress and mortality to people due to increasing temperatures and heat extremes
- Marine and terrestrial ecosystems disruptions
- Water scarcity to multiple interconnected sectors
- Losses in crop production, due to compound heat and dry conditions, and extreme weather

Central and South America
- Risk to water security
- Severe health effects due to increasing epidemics, in particular vector-borne diseases
- Coral reef ecosystems degradation due to coral bleaching
- Risk to food security due to frequent/extreme droughts
- Damages to life and infrastructure due to floods, landslides, sea level rise, storm surges and coastal erosion

Australasia
- Degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values
- Loss of human and natural systems in low-lying coastal areas due to sea-level rise
- Impact on livelihoods and incomes due to decline in agricultural production
- Increase in heat-related mortality and morbidity for people and wildlife
- Loss of alpine biodiversity in Australia due to less snow

Asia
- Urban infrastructure damage and impacts on human well-being and health due to flooding, especially in coastal cities and settlements
- Biodiversity loss and habitat shifts as well as associated disruptions in dependent human systems across freshwater, land, and ocean ecosystems
- More frequent, extensive coral bleaching and subsequent coral mortality induced by ocean warming and acidification, sea level rise, marine heat waves and resource extraction
- Decline in coastal fishery resources due to sea level rise, decrease in precipitation in some parts and increase in temperature
- Risk to food and water security due to increased temperature extremes, rainfall variability and drought

Africa
- Species extinction and reduction or irreversible loss of ecosystems and their services, including freshwater, land and ocean ecosystems
- Risk to food security, risk of malnutrition (micronutrient deficiency), and loss of livelihood due to reduced food production from crops, livestock and fisheries
- Risks to marine ecosystem health and to livelihoods in coastal communities
- Increased human mortality and morbidity due to increased heat and infectious diseases (including vector-borne and diarrhoeal diseases)
- Reduced economic output and growth, and increased inequality and poverty rates
- Increased risk to water and energy security due to drought and heat

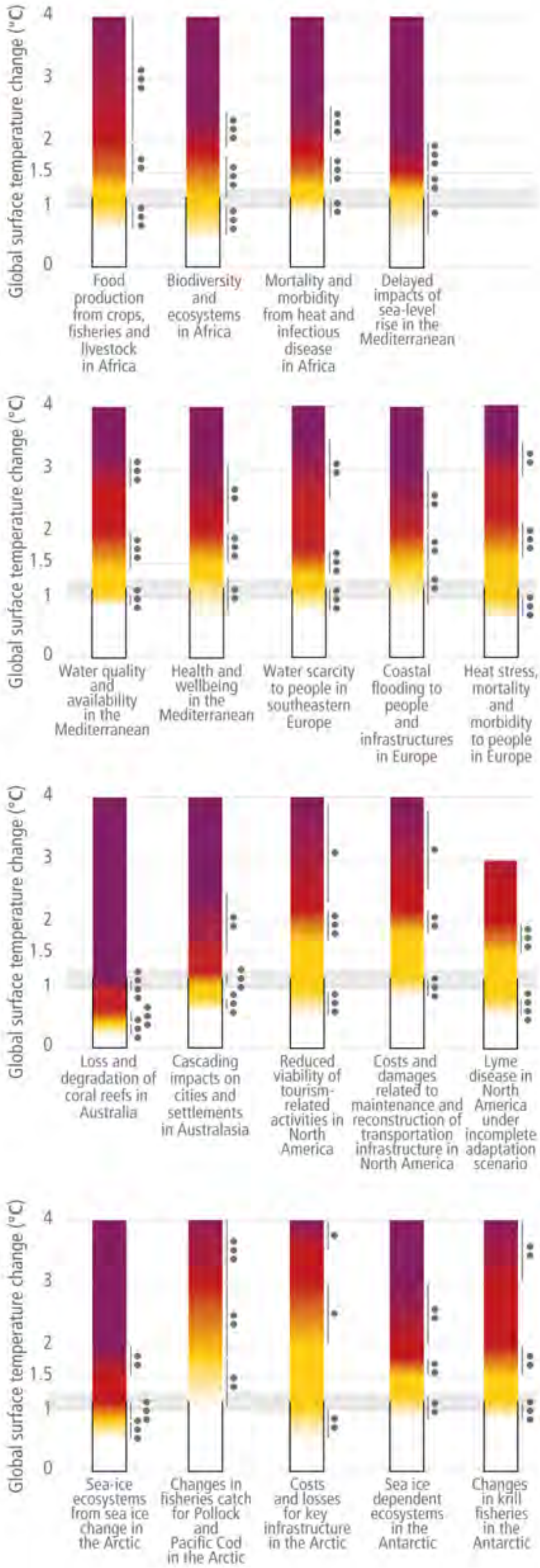


Figure SPM.3: Synthetic diagrams of global and sectoral assessments and examples of regional key risks. Diagrams show the change in the levels of impacts and risks assessed for global warming of 0-5°C global surface temperature change relative to pre-industrial period (1850-1900) over the range. (a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-

7.0 (WGI Figure SPM.8). Assessments were carried out at the global scale for (b), (c), (d) and (e). (b) The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localized and comprises incremental adjustments to existing practices). However, the transition to a very high risk level has an emphasis on irreversibility and adaptation limits. Undetectable risk level (white) indicates no associated impacts are detectable and attributable to climate change; moderate risk (yellow) indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk (red) indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level (purple) indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. The horizontal line denotes the present global warming of 1.09°C which is used to separate the observed, past impacts below the line from the future projected risks above it. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Assessment methods are described in SM16.6 and are identical to AR5, but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6. Risks for (c) terrestrial and freshwater ecosystems and (d) ocean ecosystems. For c) and d), diagrams shown for each risk assume low to no adaptation. The transition to a very high risk level has an emphasis on irreversibility and adaptation limits. (e) Climate-sensitive human health outcomes under three scenarios of adaptation effectiveness. The assessed projections were based on a range of scenarios, including SRES, CMIP5, and ISIMIP, and, in some cases, demographic trends. The diagrams are truncated at the nearest whole ºC within the range of temperature change in 2100 under three SSP scenarios in panel (a). (f) Examples of regional key risks. Risks identified are of at least *medium confidence* level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. The full set of 127 assessed global and regional key risks is given in SM16.7. Diagrams are provided for some risks. The development of synthetic diagrams for Small Islands, Asia and Central and South America were limited by the availability of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socio-economic contexts across countries within a region, and the resulting low number of impact and risk projections for different warming levels. Absence of risks diagrams does not imply absence of risks within a region. (Box SPM.1) {16.5, 16.6, Figure 16.15, SM16.3, SM16.4, SM16.5, SM16.6 (methodologies), SM16.7, Figure 2.11, Figure SM3.1, Figure 7.9, Figure 9.6, Figure 11.6, Figure 13.28, Figure CCP6.5, Figure CCP4.8, Figure CCP4.10, Figure TS.4, WGI Figure SPM.8, WGI SPM A.1.2, Box SPM.1, WGI Ch. 2}

Complex, Compound and Cascading Risks

SPM.B.5 Climate change impacts and risks are becoming increasingly complex and more difficult to manage. Multiple climate hazards will occur simultaneously, and multiple climatic and non-climatic risks will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Some responses to climate change result in new impacts and risks. (*high confidence*) {1.3, 2.4, Box 2.2, Box 9.5, 11.5, 13.5, 14.6, Box 15.1, CCP1.2, CCP2.2, CCB DISASTER, CCB INTERREG, CCB SRM, CCB COVID}

SPM.B.5.1 Concurrent and repeated climate hazards occur in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Increasing concurrence of heat and drought events are causing crop production losses and tree mortality (*high confidence*). Above 1.5°C global warming increasing concurrent climate extremes will increase risk of simultaneous crop losses of maize in major food-producing regions, with this risk increasing further with higher global warming levels (*medium confidence*). Future sea level rise combined with storm surge and heavy rainfall will increase compound flood risks (*high confidence*). Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (*high confidence*). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (*high confidence*). Risks to food safety from climate change will further compound the risks to health by increasing food contamination of crops from mycotoxins and contamination of seafood from harmful algal blooms, mycotoxins, and chemical contaminants (*high confidence*). {5.2, 5.4, 5.8, 5.9, 5.11, 5.12, 7.2, 7.3, 9.8, 9.11, 10.4, 11.3, 11.5, 12.3, 13.5, 14.5, 15.3, Box 15.1, 16.6, CCP1.2, CCP6.2, Figure TS10C, WG1 SPM A.3.1, A.3.2 and C.2.7}

SPM.B.5.2 Adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (*high confidence*), propagating impacts along coasts and urban centres (*medium confidence*) and in mountain regions (*high confidence*). These hazards and cascading risks also trigger tipping points in sensitive ecosystems and in significantly and rapidly changing social-ecological systems impacted by ice melt, permafrost thaw and changing hydrology in polar regions (*high confidence*). Wildfires, in many regions, have affected ecosystems and species, people and their built assets, economic activity, and health (*medium to high confidence*)**.** In cities and settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (*high confidence*). In Amazonia, and in some mountain regions, cascading impacts from climatic (e.g., heat) and non-climatic stressors (e.g., land use change) will result in irreversible and severe losses of ecosystem services and biodiversity at 2°C global warming level and beyond (*medium confidence*). Unavoidable sea level rise will bring cascading and compounding impacts resulting in losses of coastal ecosystems and ecosystem services, groundwater salinisation, flooding and damages to coastal infrastructure that cascade into risks to livelihoods, settlements, health, well-being, food and water security, and cultural values in the near to long-term (*high confidence*). (Figure SPM.3) {2.5, 3.4, 3.5, Box 7.3, Box 8.7, Box 9.4, Box 11.1, 11.5, 12.3, 13.9, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.2, CCP5.2, CCP5.3, CCP6.2, CCP6.3, Box CCP6.1, Box CCP6.2, CCB EXTREMES, Figure TS.10, WGI SPM Figure SPM.8d}

SPM.B.5.3 Weather and climate extremes are causing economic and societal impacts across national boundaries through supply-chains, markets, and natural resource flows, with increasing transboundary risks projected across the water, energy and food sectors (*high confidence*). Supply chains that rely on specialized commodities and key infrastructure can be disrupted by weather and climate extreme events. Climate change causes the redistribution of marine fish stocks, increasing risk of transboundary management conflicts among fisheries users, and negatively affecting equitable distribution of food provisioning services as fish stocks shift from lower to higher latitude regions, thereby increasing the need for climate-informed transboundary management and cooperation (*high confidence*). Precipitation and water availability changes increases the risk of planned infrastructure projects, such as hydropower in some regions, having reduced productivity for food and energy sectors including across countries that share river basins (*medium confidence*). {Figure TS.10e-f, 3.4, 3.5, 4.5, 5.8, 5.13, 6.2, 9.4, Box 9.5,14.5, Box 14.5, Box 14.6, CCP5.3, CCB EXTREMES, CCB MOVING PLATE, CCB INTERREG, CCB DISASTER}

SPM B.5.4 Risks arise from some responses that are intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emission reduction and carbon dioxide removal measures (*high confidence*). Deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods, especially if implemented at large scales, especially in regions with insecure land tenure (*high confidence*). {Box 2.2, 4.1, 4.7, 5.13, Table 5.18, Box 9.3, Box 13.2, CCB NATURAL, CWGB BIOECONOMY}

SPM B.5.5 Solar radiation modification approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood (*high confidence*). Solar radiation modification approaches have potential to offset warming and ameliorate some climate hazards, but substantial residual climate change or overcompensating change would occur at regional scales and seasonal timescales (*high confidence*). Large uncertainties and knowledge gaps are associated with the potential of solar radiation modification approaches to reduce climate change risks. Solar radiation modification would not stop atmospheric CO_2 concentrations from increasing or reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). {XWGB SRM}

Impacts of Temporary Overshoot

SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3) {2.5, 3.4, 12.3, 16.6, CCB SLR, CCB DEEP, Box SPM.1}

SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). {2.5, 3.4, 12.3, 13.2, 16.5, 16.6, CCP 1.2, CCP5.3, CCP6.1, CCP6.2, CCP2.2, CCB SLR, Box TS4, SROCC 2.3, SROCC 5.4, WG1 SPM B5 and C3}

SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*). {2.4, 2.5, CCP4.2, WG1 SPM B.4.3, SROCC 5.4}

SPM.C: Adaptation Measures and Enabling Conditions

Adaptation, in response to current climate change, is reducing climate risks and vulnerability mostly via adjustment of existing systems. Many adaptation options exist and are used to help manage projected climate change impacts, but their implementation depends upon the capacity and effectiveness of governance and decision-making processes. These and other enabling conditions can also support Climate Resilient Development (Section D).

Current Adaptation and its Benefits

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[37] In this report, overshoot pathways exceed 1.5°C global warming and then return to that level, or below, after several decades.

[38] Despite limited evidence specifically on the impacts of a temporary overshoot of 1.5°C, a much broader evidence base from process understanding and the impacts of higher global warming levels allows a high confidence statement on the irreversibility of some impacts that would be incurred following such an overshoot.

[39] At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere (-3.4 ± 0.9 Gt yr^{-1}) than they emit ($+1.6 \pm 0.7$ Gt yr^{-1}), a net sink of -1.9 ± 1.1 Gt yr^{-1}. However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources.

SPM.C.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). However, adaptation progress is unevenly distributed with observed adaptation gaps[40] (*high confidence*). Many initiatives prioritize immediate and near-term climate risk reduction which reduces the opportunity for transformational adaptation (*high confidence*). {2.6, 5.14, 7.4, 10.4, 12.5, 13.11, 14.7, 16.3, 17.3, CCP5.2, CCP5.4}

SPM.C.1.1 Adaptation planning and implementation have continued to increase across all regions (*very high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). Decision support tools and climate services are increasingly being used (*very high confidence*). Pilot projects and local experiments are being implemented in different sectors (*high confidence*). Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (*very high confidence*). {1.4, CCB ADAPT, 2.6, CCB NATURE, 3.5, 3.6, 4.7, 4.8, 5.4, 5.6, 5.10, 6.4.2, 7.4, 8.5, 9.3, 9.6, 10.4, 12.5, 13.11, 15.5, 16.3, 17.2, 17.3, 17.5 CCP5.4}

SPM.C.1.2 Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, designed to respond to current impacts or near-term risks, and focused more on planning rather than implementation (*high confidence*). Observed adaptation is unequally distributed across regions *(high confidence)*, and gaps are partially driven by widening disparities between the estimated costs of adaptation and documented finance allocated to adaptation (*high confidence*)*.* The largest adaptation gaps exist among lower income population groups (*high confidence*). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (*high confidence*). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in the next decade, is important to close adaptation gaps, recognising that constraints remain for some regions (*high confidence*). {1.1, 1.4, 5.6, 6.3, Figure 6.4, 7.4, 8.3, 10.4, 11.3, 11.7, 15.2, Box 13.1, 13.11, 15.5, Box16.1, Figure 16.4, Figure 16.5, 16.3, 16.5, 17.4, 18.2, CCP2.4, CCP5.4, CCB FINANCE, CCB SLR}

[40] Adaptation gaps are defined as the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities.

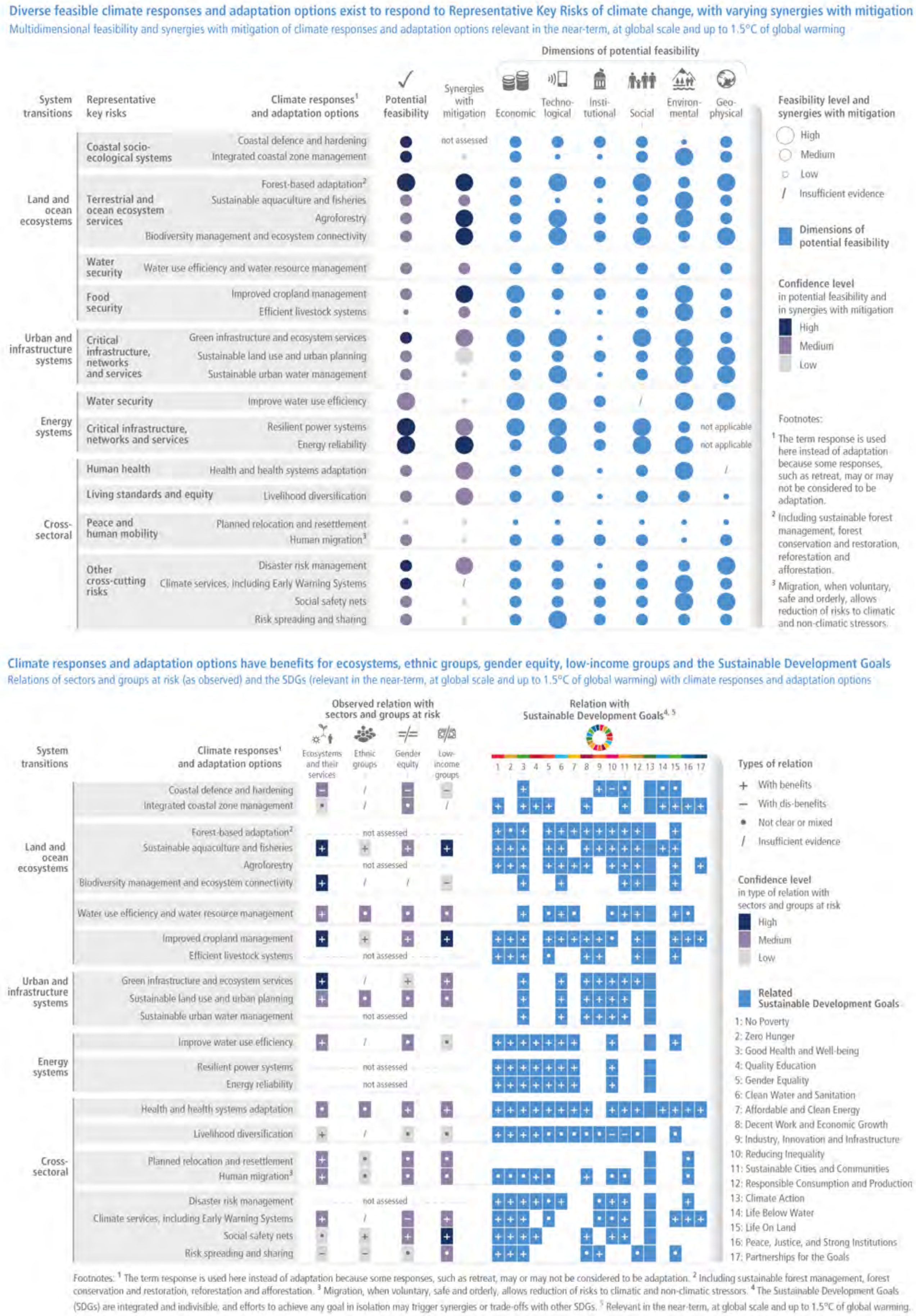

Figure SPM.4: (a) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks (RKRs), are assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. Climate responses and adaptation options at global scale are drawn from a set of options assessed in AR6 that have robust evidence across the feasibility dimensions. This figure shows the six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) that are used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. Insufficient evidence is denoted by a dash. {CCB FEASIB., Table SMCCB FEASIB.1.1; SR1.5 4.SM.4.3}

Figure SPM.4: (b) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks, are assessed at global scale for their likely ability to reduce risks for ecosystems and social groups at risk, as well as their relation with the 17 Sustainable Development Goals (SDGs). Climate responses and adaptation options are assessed for observed benefits (+) to ecosystems and their services, ethnic groups, gender equity, and low-income groups, or observed dis-benefits (-) for these systems and groups. Where there is highly diverging evidence of benefits/ dis-benefits across the scientific literature, e.g., based on differences between regions, it is shown as not clear or mixed (•). Insufficient evidence is shown by a dash. The relation with the SDGs is assessed as having benefits (+), dis-benefits (-) or not clear or mixed (•) based on the impacts of the climate response and adaptation option on each SDG. Areas not coloured indicate there is no evidence of a relation or no interaction with the respective SDG. The climate responses and adaptation options are drawn from two assessments. For comparability of climate responses and adaptation options see Table SM17.5. {17.2, 17.5; CCB FEASIB}

Future Adaptation Options and their Feasibility

SPM.C.2 There are feasible[41] and effective[42] adaptation options which can reduce risks to people and nature. The feasibility of implementing adaptation options in the near-term differs across sectors and regions (*very high confidence*). The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions (*high confidence*) and will decrease with increasing warming (*high confidence*). Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (*high confidence*). (Figure SPM.4) {Figure TS.6e, 1.4, 3.6, 4.7, 5.12, 6.3, 7.4, 11.3, 11.7, 13.2, 15.5, 17.6, CCB FEASIB, CCP2.3}

Land, Ocean and Ecosystems Transition

SPM.C.2.1 Adaptation to water-related risks and impacts make up the majority of all documented adaptation (*high confidence*). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (*medium confidence*). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (*medium confidence*). On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional or ecological benefits and reduce vulnerability (*high confidence*). Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (*medium confidence*). Large scale irrigation can also alter local to regional temperature and precipitation patterns (*high confidence*), including both alleviating and exacerbating temperature extremes (*medium confidence*). The effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming (*high confidence*). {4.1,

[41] In this report, feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

[42] Effectiveness refers to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk.

4.6, 4.7, Box 4.3, Box 4.6, Box 4.7, Figure 4.28, Figure 4.29, Table 4.9, 9.3, 9.7, 11.3, 12.5, 13.1, 13.2, 16.3, CCP5.4, Figure 4.22}

SPM.C.2.2 Effective adaptation options, together with supportive public policies enhance food availability and stability and reduce climate risk for food systems while increasing their sustainability (*medium confidence*). Effective options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture (*high confidence*). Institutional feasibility, adaptation limits of crops and cost effectiveness also influence the effectiveness of the adaptation options (*limited evidence*, *medium agreement*). Agroecological principles and practices, ecosystem-based management in fisheries and aquaculture, and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services (*high confidence*). These services include pest control, pollination, buffering of temperature extremes, and carbon sequestration and storage (*high confidence*). Trade-offs and barriers associated with such approaches include costs of establishment, access to inputs and viable markets, new knowledge and management (*high confidence*) and their potential effectiveness varies by socio-economic context, ecosystem zone, species combinations and institutional support (*medium confidence*). Integrated, multi-sectoral solutions that address social inequities and differentiate responses based on climate risk and local situation will enhance food security and nutrition (*high confidence*). Adaptation strategies which reduce food loss and waste or support balanced diets[33] (as described in the IPCC Special Report on Climate Change and Land) contribute to nutrition, health, biodiversity and other environmental benefits (*high confidence*). {3.2, 4.7, 4.6, Box 4.3, 5.4, 5.5, 5.6, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 7.4, Box 5.10, Box 5.13, 6.3, 10.4, 12.5, 13.5, 13.10, 14.5, CWGB BIOECONOMY, CCB MOVING PLATE, CCB NATURAL, CCB FEASIB, CCP5.4, CCB HEALTH}

SPM.C.2.3 Adaptation for natural forests[43] includes conservation, protection and restoration measures. In managed forests[44], adaptation options include sustainable forest management, diversifying and adjusting tree species compositions to build resilience, and managing increased risks from pests and diseases and wildfires. Restoring natural forests and drained peatlands and improving sustainability of managed forests, generally enhances the resilience of carbon stocks and sinks. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful forest adaptation in many areas. (*high confidence*) {2.6, Box 2.2, CCB NATURAL, CCB FEASIB, CCB INDIG, 5.6, 5.13, 11.4, 12.5, 13.5, Box 14.1, Box 14.2, Table 5.23, Box CCP7.1, CCP7.5}.

SPM.C.2.4 Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change, reduces the vulnerability of biodiversity to climate change (*high confidence*). The resilience of species, biological communities and ecosystem processes increases with size of natural area, by restoration of degraded areas and by reducing non-climatic stressors (*high confidence*). To be effective, conservation and restoration actions will increasingly need to be responsive, as appropriate, to ongoing changes at various scales, and plan for future changes in ecosystem structure, community composition and species' distributions, especially as 1.5°C global warming is approached and even more so if it is exceeded (*high confidence*). Adaptation options, where circumstances allow, include facilitating the movement of species to new ecologically appropriate locations, particularly through increasing connectivity between conserved or protected areas, targeted intensive management for vulnerable species and protecting refugial areas where species can survive locally (*medium confidence*). {2.3, Figure 2.1, 2,6, Table 2.6, 2.6, 3.6, Box 3.4, 4.6, Box 11.2, 12.3, 12.5, 3.3, 13.4, 14.7, Box 4.6, CCP5.4, CCB FEASIB}

SPM.C.2.5 Effective Ecosystem-based Adaptation[44] reduces a range of climate change risks to people, biodiversity and ecosystem services with multiple co-benefits (*high confidence*). Ecosystem-based Adaptation

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[43] In this report, the term natural forests describes those which are subject to little or no direct human intervention, whereas the term managed forests describes those where planting or other management activities take place, including those managed for commodity production.

[44] Ecosystem based Adaptation (EbA) is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), which includes a broader range of approaches with safeguards, including those that contribute to adaptation and mitigation. The term 'Nature-based Solutions' is widely but not universally used in the scientific literature. The term is the subject of ongoing debate, with concerns that it may lead to the misunderstanding that NbS on its own can provide a global solution to climate change.

is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (*high confidence*). Urban greening using trees and other vegetation can provide local cooling (*very high confidence*). Natural river systems, wetlands and upstream forest ecosystems reduce flood risk by storing water and slowing water flow, in most circumstances (*high confidence*). Coastal wetlands protect against coastal erosion and flooding associated with storms and sea level rise where sufficient space and adequate habitats are available until rates of sea level rise exceeds natural adaptive capacity to build sediment (*very high confidence*). {2.4, 2.5, 2.6, Table 2.7, 3.4, 3.5, 3.6, Figure 3.26, 4.6, Box 4.6, Box 4.7, 5.5, 5.14, Box 5.11, 6.3, 6.4, Figure 6.6, 7.4, 8.5, 8.6, 9.6, 9.8, 9.9, 10.2, 11.3, 12.5, 13.3, 13.4, 13.5, 14.5, Box 14.7, 16.3, 18.3, CCB HEALTH, CCB NATURAL, CCB MOVING PLATE, CCB FEASIB.3, CWGB BIOECONOMY, CCP5.4}

Urban, Rural and Infrastructure Transition

SPM.C.2.6 Considering climate change impacts and risks in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being (*high confidence*). The urgent provision of basic services, infrastructure, livelihood diversification and employment, strengthening of local and regional food systems and community-based adaptation enhance lives and livelihoods, particularly of low-income and marginalised groups (*high confidence*). Inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition (*high confidence*). Effective partnerships between governments, civil society, and private sector organizations, across scales provide infrastructure and services in ways that enhance the adaptive capacity of vulnerable people (*medium to high confidence*). {5.12, 5.13, 5.14, Box 6.3, 6.3, 6.4, Box 6.6, Table 6.6, 7.4, 12.5, 13.6, 14.5, Box14.4, Box17.4, CCB FEASIB, CCP2.3, CCP2.4, CCP5.4}

SPM.C.2.7 An increasing number of adaptation responses exist for urban systems, but their feasibility and effectiveness is constrained by institutional, financial, and technological access and capacity, and depends on coordinated and contextually appropriate responses across physical, natural and social infrastructure (*high confidence*). Globally, more financing is directed at physical infrastructure than natural and social infrastructure (*medium confidence*) and there is *limited evidence* of investment in the informal settlements hosting the most vulnerable urban residents (*medium* to *high confidence*). Ecosystem-based adaptation (e.g., urban agriculture and forestry, river restoration) has increasingly been applied in urban areas (*high confidence).* Combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (*medium confidence*). {3.6, Box 4.6, 5.12, 6.3, 6.4, Table 6.8, 7.4, 9.7, 9.9, 10.4, Table 10.3, 11.3, 11.7, Box 11.6, 12.5, 13.2, 13.3, 13.6, 14.5, 15.5, 17.2, Box 17.4, CCB FEASIB, CCP2.3, CCP 3.2, CCP5.4, CCB SLR, SROCC ES}

SPM C.2.8: Sea level rise poses a distinctive and severe adaptation challenge as it implies dealing with slow onset changes and increased frequency and magnitude of extreme sea level events which will escalate in the coming decades (*high confidence*). Such adaptation challenges would occur much earlier under high rates of sea level rise, in particular if low-likelihood, high impact outcomes associated with collapsing ice sheets occur (*high confidence*). Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation (*high confidence*)[45]. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes (*high confidence*). {CCB SLR, CCP2.3, 6.2, 10.4, 11.7, Box 11.6, 13.2.2, 14.5.9.2, 15.5, SROCC ES: C3.2, WGI SPM B5, C3}

SPM.C.2.9 Approximately 3.4 billion people globally live in rural areas around the world, and many are highly vulnerable to climate change. Integrating climate adaptation into social protection programs, including cash transfers and public works programmes, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. Social safety nets are increasingly being reconfigured to build adaptive capacities of the most vulnerable in rural and also urban communities. Social

[45] The term 'response' is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation.

safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. (*high confidence*) {5.14, 9.4, 9.10, 9.11, 12.5, 14.5, CCB GENDER, CCB FEASIB, CCP5.4}

Energy System Transition

SPM.C.2.10 Within energy system transitions, the most feasible adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Energy generation diversification, including with renewable energy resources and generation that can be decentralised depending on context (e.g., wind, solar, small scale hydroelectric) and demand side management (e.g., storage, and energy efficiency improvements) can reduce vulnerabilities to climate change, especially in rural populations (*high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {4.6, 4.7, Figure 4.28, Figure 4.29, 10.4, Table 11.8, Figure 13.19, Figure 13.16, 13.6, 18.3, CCB FEASIB, CWGB BIOECONOMY, CCP5.2, CCP5.4}

Cross-cutting Options

SPM.C.2.11 Strengthening the climate resiliency of health systems will protect and promote human health and wellbeing (*high confidence*). There are multiple opportunities for targeted investments and finance to protect against exposure to climate hazards, particularly for those at highest risk. Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (*high confidence*). Effective adaptation options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (*very high confidence*). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (*very high confidence*). Effective adaptation options for reducing mental health risks under climate change include improving surveillance, access to mental health care, and monitoring of psychosocial impacts from extreme weather events (*high confidence*). Health and well-being would benefit from integrated adaptation approaches that mainstream health into food, livelihoods, social protection, infrastructure, water and sanitation policies requiring collaboration and coordination at all scales of governance (*very high confidence*). {5.12, 6.3, 7.4, 9.10, Box 9.7, 11.3, 12.5, 13.7, 14.5, CCB FEASIB, CCB ILLNESS, CCB COVID}.

SPM.C.2.12 Increasing adaptive capacities minimises the negative impacts of climate-related displacement and involuntary migration for migrants and sending and receiving areas (*high confidence*). This improves the degree of choice under which migration decisions are made, ensuring safe and orderly movements of people within and between countries (*high confidence*). Some development reduces underlying vulnerabilities associated with conflict, and adaptation contributes by reducing the impacts of climate change on climate sensitive drivers of conflict (*high confidence*). Risks to peace are reduced, for example, by supporting people in climate-sensitive economic activities (*medium confidence*) and advancing women's empowerment (*high confidence*). {7.4, 12.5, CCB MIGRATE, Box 9.8, Box 10.2, CCB FEASIB}

SPM.C.2.13 There are a range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined (*high confidence*). For example, climate services that are inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (*high confidence*). {2.6, 3.6, 4.7, 5.4, 5.5, 5.6, 5.8, 5.9, 5.12, 5.14, 9.4, 9.8, 10.4, 12.5, 13.11, CCB MOVING PLATE, CCB FEASIB, CCP5.4}

Limits to Adaptation

SPM.C.3 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, primarily financial, governance, institutional and policy constraints (*high confidence*). Hard limits to adaptation have been reached in some ecosystems (*high confidence*). With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits (*high confidence*). {Figure TS.7, 1.4, 2.4, 2.5, 2.6, CCB SLR, 3.4, 3.6, 4.7, Figure 4.30, 5.5, Table 8.6, Box 10.7, 11.7, Table 11.16, 12.5 13.2, 13.5, 13.6, 13.10, 13.11, Figure 13.21, 14.5, 15.6, 16.4, Figure 16.8, Table 16.3, Table 16.4, CCP1.2, CCP1.3, CCP2.3, CCP3.3, CCP5.2, CCP5.4, CCP6.3, CCP7.3}

SPM.C.3.1 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, which primarily consist of financial, governance, institutional and policy constraints (*high confidence*). For example, individuals and households in low lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (*medium confidence*). Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (*high confidence*). Lack of climate literacy[46] at all levels and limited availability of information and data pose further constraints to adaptation planning and implementation (*medium confidence*). {1.4, 4.7, 5.4, Table 8.6, 8.4, 9.1, 9.4, 9.5, 9.8, 11.7, 12.5 13.5, 15.3, 15.5, 15.6, 16.4, Figure 16.8, 16.4, Box 16.1, CCP5.2, CCP5.4, CCP6.3}

SPM.C.3.2 Financial constraints are important determinants of soft limits to adaptation across sectors and all regions (*high confidence*). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient for and constrain implementation of adaptation options especially in developing countries (*high confidence*). The overwhelming majority of global tracked climate finance was targeted to mitigation while a small proportion was targeted to adaptation (*very high confidence*). Adaptation finance has come predominantly from public sources (*very high confidence*). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (*medium confidence*). {1.4, 2.6, 3.6, 4.7, Figure 4.30, 5.14, 7.4, Table 8.6, 8.4, 9.4, 9.9, 9.11, 10.5, 12.5, 13.3, 13.11, Box 14.4, 15.6, 16.2, 16.4, Figure 16.8, Table 16.4, 17.4, 18.1, CCB FINANCE, CCP2.4, CCP5.4, CCP6.3, Figure TS 7}

SPM.C.3.3 Many natural systems are near the hard limits of their natural adaptation capacity and additional systems will reach limits with increasing global warming (*high confidence*). Ecosystems already reaching or surpassing hard adaptation limits include some warm water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (*high confidence*). Above 1.5°C global warming level, some ecosystem-based adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (*high confidence*). {1.4, 2.4, 2.6, 3.4, 3.6, CCB SLR, 9.6, Box11.2, 13.4, 14.5, 15.5, 16.4, 16.6, 17.2, CCP1.2, CCP5.2, CCP6.3, CCP7.3, Figure SPM.4}

SPM.3.4 In human systems, some coastal settlements face soft adaptation limits due to technical and financial difficulties of implementing coastal protection (*high confidence*). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for Small Islands and for regions dependent on glacier and snow-melt (*medium confidence*). By 2°C global warming level, soft limits are projected for multiple staple crops in many growing areas, particularly in tropical regions (*high confidence*). By 3°C global warming level, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (*medium confidence*). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). {1.4, 4.7, 5.4, 5.8, 7.2, 7.3, 8.4, Table 8.6, 9.8, 10.4, 12.5, 13.2, 13.6, 16.4, 17.2, CCB SLR, CCP1.3. Box CCP1.1, CCP2.3, CCP3.3, CCP4.4, CCP5.3}

SPM.C.3.5 Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. With increasing global warming, losses and damages increase and become increasingly difficult to avoid, while strongly concentrated among the poorest vulnerable

[46] Climate literacy encompasses being aware of climate change, its anthropogenic causes and implications.

populations. (*high confidence*) {1.4, 2.6, 3.4, 3.6, 6.3, Figure 6.4, 8.4, 13.7, 13.2, 13.10, 17.2, CCB LOSS, CCB SLR, CCP2.3, CCP4.4, CWGB ECONOMIC}

Avoiding Maladaptation

SPM.C.4 There is increased evidence of maladaptation[15] across many sectors and regions since the AR5. Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {1.3, 1.4, 2.6., Box 2.2, 3.2, 3.6, Box 4.3, Box 4.5, 4.6, 4.7, Figure 4.29, 5.6, 5.13, 8.2, 8.3, 8.4, 8.6, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, Box 9.5, Box 9.8, Box 9.9, Box 11.6, 13.11, 13.3, 13.4, 13.5, 14.5, 15.5, 15.6, 16.3, 17.3, 17.4, 17.6, 17.2, 17.5, CCP5.4, CCB NATURAL, CCB SLR, CCB DEEP, CWGB BIOECONOMY, CCP2.3, CCP2.3}

SPM.C.4.1 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation if long-term impacts of the adaptation option and long-term adaptation commitment are not taken into account (*high confidence*). The implementation of these maladaptive actions can result in infrastructure and institutions that are inflexible and/or expensive to change (*high confidence*). For example, seawalls effectively reduce impacts to people and assets in the short-term but can also result in lock-ins and increase exposure to climate risks in the long-term unless they are integrated into a long-term adaptive plan (*high confidence*). Adaptation integrated with development reduces lock-ins and creates opportunities (e.g., infrastructure upgrading) (*medium confidence*). {1.4, 3.4, 3.6, 10.4, 11.7, Box 11.6, 13.2, 17.2, 17.5, 17.6, CCP 2.3, CCB SLR, CCB DEEP}

SPM.C.4.2 Biodiversity and ecosystem resilience to climate change are decreased by maladaptive actions, which also constrain ecosystem services. Examples of these maladaptive actions for ecosystems include fire suppression in naturally fire-adapted ecosystems or hard defences against flooding. These actions reduce space for natural processes and represent a severe form of maladaptation for the ecosystems they degrade, replace or fragment, thereby reducing their resilience to climate change and the ability to provide ecosystem services for adaptation. Considering biodiversity and autonomous adaptation in long-term planning processes reduces the risk of maladaptation. (*high confidence*) {2.4, 2.6, Table 2.7, 3.4, 3.6, 4.7, 5.6, 5.13, Table 5.21, 5.13, Box 13.2, 17.2, 17.5, Table 5.23, Box 11.2, 13.2, CCP5.4}

SPM.C.4.3 Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous Peoples, ethnic minorities, low-income households, informal settlements), reinforcing and entrenching existing inequities. Adaptation planning and implementation that do not consider adverse outcomes for different groups can lead to maladaptation, increasing exposure to risks, marginalising people from certain socio-economic or livelihood groups, and exacerbating inequity. Inclusive planning initiatives informed by cultural values, Indigenous knowledge, local knowledge, and scientific knowledge can help prevent maladaptation. (*high confidence*) (Figure SPM.4) {2.6, 3.6, 4.3, 4.6, 4.8, 5.12, 5.13, 5.14, 6.1, Box 7.1, 8.4, 11.4, 12.5, Box 13.2, 14.4, Box 14.1, 17.2, 17.5, 18.2, 17.2., CCP2.4}

SPM.C.4.4 To minimize maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret[47] and timely actions that keep options open, ensure benefits in multiple sectors and systems and indicate the available solution space for adapting to long-term climate change (*very high confidence*). Maladaptation is also minimized by planning that accounts for the time it takes to adapt (*high confidence*), the uncertainty about the rate and magnitude of climate risk (*medium confidence*) and a wide range of potentially adverse consequences of adaptation actions (*high confidence*). {1.4, 3.6, 5.12, 5.13, 5.14, 11.6, 11.7, 17.3, 17.6, CCP2.3, CCP2.4, CCB SLR, CCB DEEP; CCP5.4}

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[47] From AR5, an option *that would generate net social and/or economic benefits under current climate change and a range of future climate change scenarios*, and represent one example of robust strategies.

Enabling Conditions

SPM.C.5 Enabling conditions are key for implementing, accelerating and sustaining adaptation in human systems and ecosystems. These include political commitment and follow-through, institutional frameworks, policies and instruments with clear goals and priorities, enhanced knowledge on impacts and solutions, mobilization of and access to adequate financial resources, monitoring and evaluation, and inclusive governance processes. (*high confidence*) {1.4, 2.6, 3.6, 4.8, 6.4, 7.4, 8.5, 9.4, 10.5, 11.4, 11.7, 12.5, 13.11, 14.7, 15.6, 17.4, 18.4, CCB INDIG, CCB FINANCE, CCP2.4, CCP5.4}

SPM.C.5.1 Political commitment and follow-through across all levels of government accelerate the implementation of adaptation actions (*high confidence*). Implementing actions can require large upfront investments of human, financial and technological resources (*high confidence*), whilst some benefits could only become visible in the next decade or beyond (*medium confidence*). Accelerating commitment and follow-through is promoted by rising public awareness, building business cases for adaptation, accountability and transparency mechanisms, monitoring and evaluation of adaptation progress, social movements, and climate-related litigation in some regions (*medium confidence*). {3.6, 4.8, 5.8, 6.4, 8.5, 9.4, 11.7, 12.5, 13.11, 17.4, 17.5, 18.4, CCB COVID, CCP2.4}

SPM.C.5.2 Institutional frameworks, policies and instruments that set clear adaptation goals and define responsibilities and commitments and that are coordinated amongst actors and governance levels, strengthen and sustain adaptation actions (*very high confidence*). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (*high confidence*). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (*medium confidence*). {1.4, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 9.4, 10.4, 11.7, Box 11.6, Table 11.17, 13.10, 13.11, 14.7, 15.6, 17.3, 17.4, 17.5, 17.6, 18.4, CCB DEEP, CCP2.4, CCP5.4, CCP6.3}

SPM.C.5.3 Enhancing knowledge on risks, impacts, and their consequences, and available adaptation options promotes societal and policy responses (*high confidence*). A wide range of top-down, bottom-up and co-produced processes and sources can deepen climate knowledge and sharing, including capacity building at all scales, educational and information programmes, using the arts, participatory modelling and climate services, Indigenous knowledge and local knowledge and citizen science (*high confidence*). These measures can facilitate awareness, heighten risk perception and influence behaviours (*high confidence*). {1.3, 3.6, 4.8, 5.9, 5.14, 6.4, Table 6.8, 7.4, 9.4, 10.5, 11.1, 11.7, 12.5, 13.9, 13.11, 14.3, 15.6, 15.6, 17.4, 18.4, CCB INDIG, CCP2.4.1}.

SPMC.5.4 With adaptation finance needs estimated to be higher than those presented in AR5, enhanced mobilization of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (*high confidence*). Building capacity and removing some barriers to accessing finance is fundamental to accelerate adaptation, especially for vulnerable groups, regions and sectors (*high confidence*). Public and private finance instruments include inter alia grants, guarantee, equity, concessional debt, market debt, and internal budget allocation as well as savings in households and insurance. Public finance is an important enabler of adaptation (*high confidence*). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (*high confidence*). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (*high confidence*). {4.8, 5.14, 6.4, Table 6.10, 7.4, 9.4, Table 11.17, 12.5, 13.11, 15.6, 17.4, 18.4, BOX 18.9, CCP5.4, CCB FINANCE}.

SPM.C.5.5 Monitoring and evaluation (M&E) of adaptation are critical for tracking progress and enabling effective adaptation (*high confidence*). M&E implementation is currently limited (*high confidence*) but has increased since AR5 at local and national levels. Although most of the monitoring of adaptation is focused towards planning and implementation, the monitoring of outcomes is critical for tracking the effectiveness and progress of adaptation *(high confidence)*. M&E facilitates learning on successful and effective adaptation measures, and signals when and where additional action may be needed. M&E systems are most effective when supported by capacities and resources and embedded in enabling governance systems (*high confidence*). {1.4, 2.6, 6.4, 7.4, 11.7, 11.8, 13.2, 13.11, 17.5, 18.4, CCB PROGRESS, CCB NATURAL, CCB ILLNESS, CCB DEEP, CCP2.4}.

SPM.C.5.6 Inclusive governance that prioritises equity and justice in adaptation planning and implementation leads to more effective and sustainable adaptation outcomes (*high confidence*). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (*high confidence*). These approaches, which include multi-stakeholder co-learning platforms, transboundary collaborations, community-based adaptation and participatory scenario planning, focus on capacity-building, and meaningful participation of the most vulnerable and marginalised groups, and their access to key resources to adapt (*high confidence*). {1.4, 2.6, 3.6, 4.8, 5.4, 5.8, 5.9, 5.13, 6.4, 7.4, 8.5, 11.8, 12.5, 13.11, 14.7, 15.5, 15.7, 17.3, 17.5, 18.4, CCB HEALTH, CCB GENDER, CCB INDIG, CCP2.4, CCP5.4, CCP6.4}

SPM.D: Climate Resilient Development

Climate Resilient Development integrates adaptation measures and their enabling conditions (Section C) with mitigation to advance sustainable development for all. Climate resilient development involves questions of equity and system transitions in land, ocean and ecosystems; urban and infrastructure; energy; industry; and society and includes adaptations for human, ecosystem and planetary health. Pursuing climate resilient development focuses on both where people and ecosystems are co-located as well as the protection and maintenance of ecosystem function at the planetary scale. Pathways for advancing climate resilient development are development trajectories that successfully integrate mitigation and adaptation actions to advance sustainable development. Climate resilient development pathways may be temporarily coincident with any RCP and SSP scenario used throughout AR6, but do not follow any particular scenario in all places and over all time.

Conditions for Climate Resilient Development

SPM.D.1 Evidence of observed impacts, projected risks, levels and trends in vulnerability, and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Comprehensive, effective, and innovative responses can harness synergies and reduce trade-offs between adaptation and mitigation to advance sustainable development. (*very high confidence*) {2.6, 3.4, 3.6, 4.2, 4.6, 7.2, 7.4, 8.3, 8.4, 9.3, 10.6, 13.3, 13.8, 13.10, 14.7, 17.2, 18.3, Figure 18.1, Table 18.5, Box 18.1}

SPM.D.1.1 There is a rapidly narrowing window of opportunity to enable climate resilient development. Multiple climate resilient development pathways are still possible by which communities, the private sector, governments, nations and the world can pursue climate resilient development – each involving and resulting from different societal choices influenced by different contexts and opportunities and constraints on system transitions. Climate resilient development pathways are progressively constrained by every increment of warming, in particular beyond 1.5°C, social and economic inequalities, the balance between adaptation and mitigation varying by national, regional and local circumstances and geographies, according to capabilities including resources, vulnerability, culture and values, past development choices leading to past emissions and future warming scenarios, bounding the climate resilient development pathways remaining, and the ways in which development trajectories are shaped by equity, and social and climate justice. (*very high confidence*) {2.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 9.4, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, 18.5, CCP2.3, CCP3.4, CCP4.4, CCP5.3, CCP5.4, Table CCP5.2, CCP6.3, CCP7.5, Figure TS14.d}

SPM.D.1.2 Opportunities for climate resilient development are not equitably distributed around the world (*very high confidence*). Climate impacts and risks exacerbate vulnerability and social and economic inequities and consequently increase persistent and acute development challenges, especially in developing regions and sub-regions, and in particularly exposed sites, including coasts, small islands, deserts, mountains and polar regions. This in turn undermines efforts to achieve sustainable development, particularly for vulnerable and marginalized communities (*very high confidence*). {2.5, 4.4, 4.7, 6.3, 9.4, Box 6.4, Figure 6.5, Table 18.5, CWGB URBAN, CCB HEALTH, CCP2.2, CCP3.2, CCP3.3, CCP5.4, CCP6.2}

SPM.D.1.3 Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources (*high confidence*). Dynamic trade-offs and competing priorities exist between mitigation, adaptation, and development. Integrated and inclusive system-oriented solutions based on equity and social and climate justice reduce risks and enable climate resilient development (*high confidence*). {1.4, 2.6, 3.6, 4.7, 4.8, Box 4.5, Box 4.8, 5.13, 7.4, 8.5, 9.4, 10.6, Box 9.3, Box 2.2, 12.5, 12.6, 13.3, 13.4, 13.10, 13.11, 14.7, 18.4, CCB HEALTH, SRCCL, CCB DEEP, CCP2, CCP5.4}

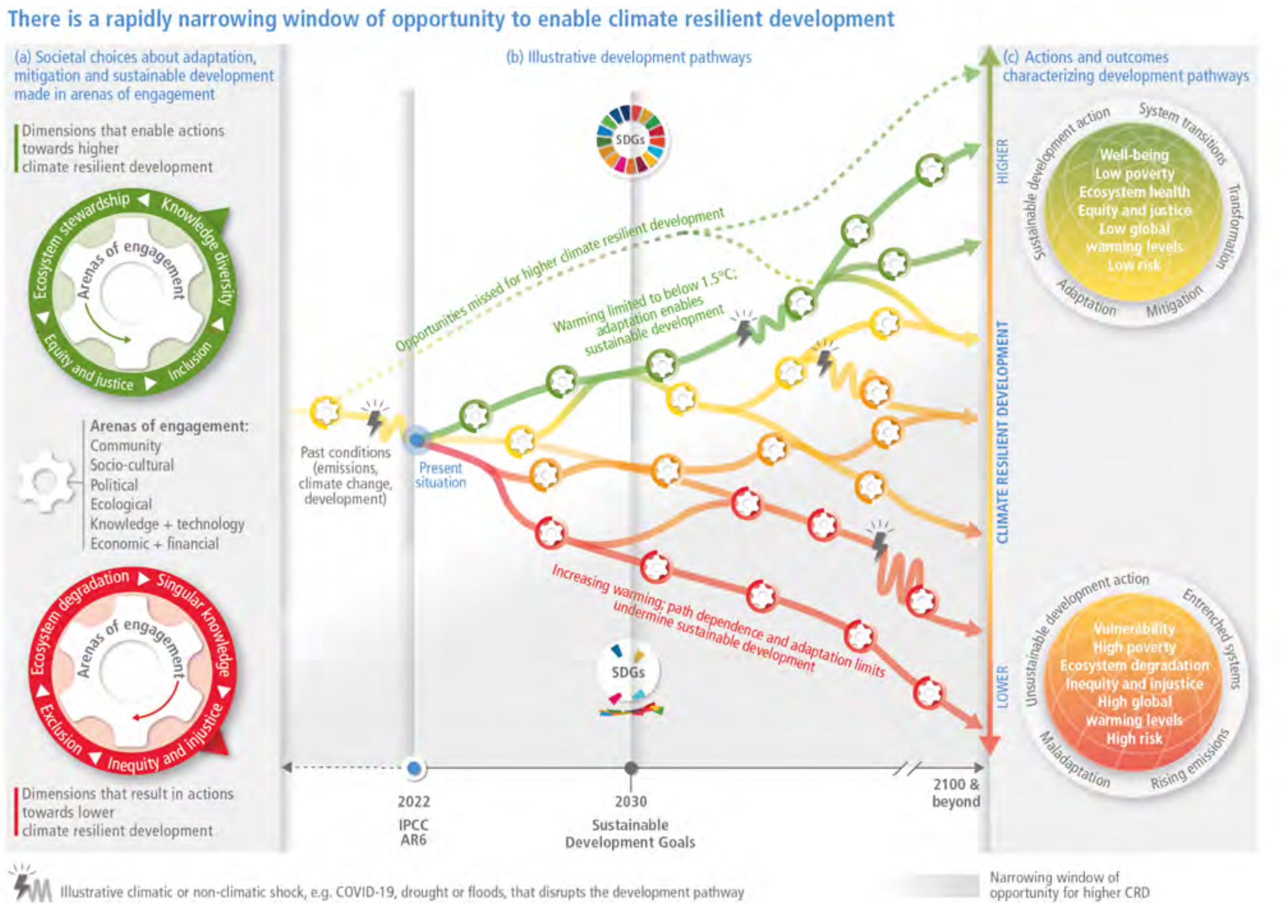

Figure SPM.5: Climate resilient development (CRD) is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. This figure builds on Figure SPM.9 in AR5 WGII (depicting climate resilient pathways) by describing how CRD pathways are the result of cumulative societal choices and actions within multiple arenas. Panel (a): Societal choices towards higher CRD (green cog) or lower CRD (red cog) result from interacting decisions and actions by diverse government, private sector and civil society actors, in the context of climate risks, adaptation limits and development gaps. These actors engage with adaptation, mitigation and development actions in political, economic and financial, ecological, socio-cultural, knowledge and technology, and community arenas from local to international levels. Opportunities for climate resilient development are not equitably distributed around the world. Panel (b): Cumulatively, societal choices, which are made continuously, shift global development pathways towards higher (green) or lower (red) climate resilient development. Past conditions (past emissions, climate change and development) have already eliminated some development pathways towards higher CRD (dashed green line). Panel (c): Higher CRD is characterised by outcomes that advance sustainable development for all. Climate resilient development is progressively harder to achieve with global warming levels beyond 1.5°C. Inadequate progress towards the Sustainable Development Goals (SDGs) by 2030 reduces climate resilient development prospects. There is a narrowing window of opportunity to shift pathways towards more climate resilient development futures as reflected by the adaptation limits and increasing climate risks, considering the remaining carbon budgets. (Figure SPM.2, Figure SPM.3) {2.6, 3.6, 7.2, 7.3, 7.4, 8.3, 8.4, 8.5, 16.4, 16.5, 17.3, 17.4, 17.5, 18.1, 18.2, 18.3, 18.4, Figure 18.1, Figure 18.2, Figure 18.3, Box 18.1, CCB COVID, CCB GENDER, CCB HEALTH, CCB INDIG, CCB SLR, AR6 WGI Table SPM.1 and Table SPM.2, SR1.5 Figure SPM.1, Figure TS.14b}

Enabling Climate Resilient Development

SPM.D.2 Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (*very high confidence*). Climate resilient development is facilitated by international cooperation and by governments at all levels working with communities, civil society, educational bodies, scientific and other institutions, media, investors and businesses; and by developing partnerships with traditionally marginalised groups, including women, youth, Indigenous Peoples, local communities and ethnic minorities (*high confidence*). These partnerships are most effective when supported by enabling political leadership, institutions, resources, including finance, as well as climate services, information and decision support tools (*high confidence*). (Figure SPM.5) {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.4, 17.6, 18.4, 18.5, CCP2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.2.1 Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (*high confidence*). These practices build on diverse knowledges about climate risk and chosen development pathways account for local, regional and global climate impacts, risks, barriers and opportunities (*high confidence*). Structural vulnerabilities to climate change can be reduced through carefully designed and implemented legal, policy, and process interventions from the local to global that address inequities based on gender, ethnicity, disability, age, location and income (*very high confidence*). This includes rights-based approaches that focus on capacity-building, meaningful participation of the most vulnerable groups, and their access to key resources, including financing, to reduce risk and adapt (*high confidence)*. Evidence shows that climate resilient development processes link scientific, Indigenous, local, practitioner and other forms of knowledge, and are more effective and sustainable because they are locally appropriate and lead to more legitimate, relevant and effective actions (*high confidence*). Pathways towards climate resilient development overcome jurisdictional and organizational barriers, and are founded on societal choices that accelerate and deepen key system transitions (*very high confidence*). Planning processes and decision analysis tools can help identify 'low regrets' options[47] that enable mitigation and adaptation in the face of change, complexity, deep uncertainty and divergent views (*medium confidence*). {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, Box 8.7, Box 9.2, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.2.2 Inclusive governance contributes to more effective and enduring adaptation outcomes and enables climate resilient development (*high confidence*). Inclusive processes strengthen the ability of governments and other stakeholders to jointly consider factors such as the rate and magnitude of change and uncertainties, associated impacts, and timescales of different climate resilient development pathways given past development choices leading to past emissions and scenarios of future global warming (*high confidence*). Associated societal choices are made continuously through interactions in arenas of engagement from local to international levels. The quality and outcome of these interactions helps determine whether development pathways shift towards or away from climate resilient development (*medium confidence*). (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG}

SPM.D.2.3 Governance for climate resilient development is most effective when supported by formal and informal institutions and practices that are well-aligned across scales, sectors, policy domains and timeframes. Governance efforts that advance climate resilient development account for the dynamic, uncertain and context-specific nature of climate-related risk, and its interconnections with non-climate risks. Institutions[48] that enable climate resilient development are flexible and responsive to emergent risks and facilitate sustained and timely action. Governance for climate resilient development is enabled by adequate and appropriate human and technological resources, information, capacities and finance. (*high confidence*) {2.7, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

Climate Resilient Development for Natural and Human Systems

SPM.D.3 Interactions between changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. However, the global trend of urbanisation also offers a critical opportunity in the near-term, to advance climate resilient development (*high confidence*). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure, including social, ecological and grey/physical infrastructures, can significantly increase the adaptive capacity of urban and rural settlements. Equitable outcomes contributes to multiple benefits for health and well-being and ecosystem services, including for Indigenous Peoples, marginalised and vulnerable communities (*high confidence*). Climate resilient development in urban areas also supports adaptive capacity in more rural places through maintaining peri-urban supply chains of goods and services and financial flows (*medium confidence*). Coastal cities and settlements play an especially important role in advancing climate resilient development (*high confidence*). {6.2, 6.3, 18.3, Table 6.6, Box 9.8, CCP6.2, CCP2.1. CCP2.2, CWGB URBAN}

SPM.D.3.1 Taking integrated action for climate resilience to avoid climate risk requires urgent decision making for the new built environment and retrofitting existing urban design, infrastructure and land use. Based on socioeconomic circumstances, adaptation and sustainable development actions will provide multiple benefits including for health and well-being, particularly when supported by national governments, non-governmental organisations and international agencies that work across sectors in partnerships with local communities. Equitable partnerships between local and municipal governments, the private sector, Indigenous Peoples, local communities, and civil society can, including through international cooperation, advance climate resilient development by addressing structural inequalities, insufficient financial resources, cross-city risks and the integration of Indigenous knowledge and Local knowledge. (*high confidence*) {6.2, 6.3, 6.4, 7.4, 8.5, 9.4, 10.5. 12.5, 17.4, 18.2, Table 6.6, Table 17.8, Box 18.1, CCP2.4, CCB GENDER, CCB INDIG, CCB FINANCE, CWGB URBAN}

SPM.D.3.2 Rapid global urbanisation offers opportunities for climate resilient development in diverse contexts from rural and informal settlements to large metropolitan areas (*high confidence*). Dominant models of energy intensive and market-led urbanisation, insufficient and misaligned finance and a predominant focus on grey infrastructure in the absence of integration with ecological and social approaches, risks missing opportunities for adaptation and locking in maladaptation (*high confidence*). Poor land use planning and siloed approaches to health, ecological and social planning also exacerbates, vulnerability in already marginalised

[48] Institutions: Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance.

communities (*medium confidence*). Urban climate resilient development is observed to be more effective if it is responsive to regional and local land use development and adaptation gaps, and addresses the underlying drivers of vulnerability (*high confidence*). The greatest gains in well-being can be achieved by prioritizing finance to reduce climate risk for low-income and marginalized residents including people living in informal settlements (*high confidence*). {5.14, 6.1, 6.2, 6.3, 6.4, 6.5, 7.4, 8.5, 8.6, 9.8, 9.9, 10.4, 18.2, Table 17.8, Table 6.6, Figure 6.5, CCB HEALTH, CCP2.2, CCP5.4, CWGB URBAN}

SPM.D.3.3 Urban systems are critical, interconnected sites for enabling climate resilient development, especially at the coast. Coastal cities and settlements play a key role in moving toward higher climate resilient development given firstly, almost 11% of the global population – 896 million people – lived within the Low Elevation Coastal Zone[49] in 2020, potentially increasing to beyond 1 billion people by 2050, and these people, and associated development and coastal ecosystems, face escalating climate compounded risks, including sea level rise. Secondly, these coastal cities and settlements make key contributions to climate resilient development through their vital role in national economies and inland communities, global trade supply chains, cultural exchange, and centres of innovation. (*high confidence*) {6.2, Box 15.2, CCP2.1, CCP2.2, Table CCP2.4, CCB SLR}

SPM.D.4 Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (*very high confidence*). Recent analyses, drawing on a range of lines of evidence, suggest that maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). {2.4, 2.5, 2.6, 3.4, Box 3.4, 3.5, 3.6, 12.5, 13.3, 13.4, 13.5, 13.10, CCB NATURAL, CCB INDIG}

SPM.D.4.1 Building the resilience of biodiversity and supporting ecosystem integrity[50] can maintain benefits for people, including livelihoods, human health and well-being and the provision of food, fibre and water, as well as contributing to disaster risk reduction and climate change adaptation and mitigation. {2.2, 2.5, 2.6, Table 2.6, Table 2.7, 3.5, 3.6, 5.8, 5.13, 5.14, 12.5, Box 5.11 CCP5.4, CCB NATURAL, CCB ILLNESS, CCB COVID, CCB GENDER, CCB INDIG, CCB MIGRATE}

SPM.D.4.2 Protecting and restoring ecosystems is essential for maintaining and enhancing the resilience of the biosphere (*very high confidence*). Degradation and loss of ecosystems is also a cause of greenhouse gas emissions and is at increasing risk of being exacerbated by climate change impacts, including droughts and wildfire *(high confidence)*. Climate resilient development avoids adaptation and mitigation measures that damage ecosystems (*high confidence*). Documented examples of adverse impacts of land-based measures intended as mitigation, when poorly implemented, include afforestation of grasslands, savannas and peatlands, and risks from bioenergy crops at large scale to water supply, food security and biodiversity (*high confidence*). {2.4, 2.5, Box 2.2, 3.4, 3.5, Box 3.4, Box 9.3, CCP7.3, CCB NATURAL, CWGB BIOECONOMY}

SPM.D.4.3 Biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, which will make climate resilient development progressively harder to achieve beyond 1.5°C warming (*very high confidence*). Consequences of current and future global warming for climate resilient development include reduced effectiveness of EbA and approaches to climate change mitigation based on ecosystems and amplifying feedbacks to the climate system (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.5, 3.6, 12.5, 13.2, 13.3, 13.10, 14.5, 14.5, 15.3, 17.3, 17.6, Box 14.3, Box 3.4, Table 5.2, CCP5.3, CCP5.4, Figure TS.14d, CCB EXTREMES, CCB ILLNESS, CCB NATURAL, CCB SLR, SR1.5, SRCCL, SROCC}

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[49] LECZ, coastal areas below 10 m of elevation above sea level that are hydrologically connected to the sea

[50] Ecosystem integrity refers to the ability of ecosystems to maintain key ecological processes, recover from disturbance, and adapt to new conditions.

Achieving Climate Resilient Development

SPM.D.5 It is unequivocal that climate change has already disrupted human and natural systems. Past and current development trends (past emissions, development and climate change) have not advanced global climate resilient development (*very high confidence*). Societal choices and actions implemented in the next decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (*high confidence*). Importantly climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near term (*high confidence*). These prospects are constrained by past development, emissions and climate change, and enabled by inclusive governance, adequate and appropriate human and technological resources, information, capacities and finance (*high confidence*). {1.2, 1.4, 1.5, 2.6, 2.7, 3.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 8.5, 8.6, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 13.11, 14.7, 15.3, 15.6, 15.7, 16.2, 16.4, 16.5, 16.6, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, Table CCP5.2, CCP5.3, CCP5.4, CCP6.3, CCP6.4, CCP7.5, CCP7.6, Figure TS.14d, CCB DEEP, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.5.1 Climate resilient development is already challenging at current global warming levels (*high confidence*). The prospects for climate resilient development will be further limited if global warming levels exceeds 1.5°C (*high confidence*) and not be possible in some regions and sub-regions if the global warming level exceeds 2°C (*medium confidence*). Climate resilient development is most constrained in regions/subregions in which climate impacts and risks are already advanced, including low-lying coastal cities and settlements, small islands, deserts, mountains and polar regions (*high confidence*). Regions and subregions with high levels of poverty, water, food and energy insecurity, vulnerable urban environments, degraded ecosystems and rural environments, and/or few enabling conditions, face many non-climate challenges that inhibit climate resilient development which are further exacerbated by climate change (*high confidence*). {1.2, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, CCP2.3, CCP3.4, CCP4.4, Box 6.6. CCP5.3, Table CCP5.2, CCP6.3, CCP7.5, Figure TS.14d}

SPM.D.5.2 Inclusive governance, investment aligned with climate resilient development, access to appropriate technology and rapidly scaled-up finance, and capacity building of governments at all levels, the private sector and civil society enable climate resilient development. Experience shows that climate resilient development processes are timely, anticipatory, integrative, flexible and action focused. Common goals and social learning build adaptive capacity for climate resilient development. When implementing adaptation and mitigation together, and taking trade-offs into account, multiple benefits and synergies for human well-being as well as ecosystem and planetary health can be realised. Prospects for climate resilient development are increased by inclusive processes involving local knowledge and Indigenous Knowledge as well as processes that coordinate across risks and institutions. Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for vulnerable regions, sectors and groups. (*high confidence*) (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.5.3 The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all. (*very high confidence*) {1.2, 1.4, 1.5, 16.2, 16.4, 16.5, 16.6, 17.4, 17.5, 17.6, 18.3, 18.4, 18.5, CWGB URBAN, CCB DEEP, Table SM16.24, WGI SPM, SROCC SPM, SRCCL SPM}

Chapter 11: Australasia

Coordinating Lead Authors: Judy Lawrence (New Zealand) and Brendan Mackey (Australia)

Lead Authors: Francis Chiew (Australia), Mark J. Costello (New Zealand/Norway/Ireland), Kevin Hennessy (Australia), Nina Lansbury (Australia), Uday Bhaskar Nidumolu (Australia), Gretta Pecl (Australia), Lauren Rickards (Australia), Nigel Tapper (Australia), Alistair Woodward (New Zealand), Anita Wreford (New Zealand)

Contributing Authors: Jason Alexandra (Australia), Anne-Gaelle Ausseil (New Zealand), Shaun Awatere (New Zealand), Douglas Bardsley (Australia), Rob Bell (New Zealand), Paula Blackett (New Zealand), Sarah Boulter (Australia), Nicholas Cradock-Henry (New Zealand), Sandra Creamer (Australia), Rebecca Darbyshire (Australia), Sam Dean (New Zealand), Alejandro Di Luca (Australia/Canada), Andrew Dowdy (Australia), Joanna Fountain (New Zealand), Michael Grose (Australia), Stefan Hajkowicz (Australia), David Hall (New Zealand), Sarah Harris (Australia), Peter Hayman (Australia), Jane Hodgkinson (Australia), Karen Hussey (Australia), Rhys Jones (New Zealand), Darren King (New Zealand), Martina Linnenluecke (Australia), Erich Livengood (New Zealand), Mary Livingston (New Zealand), Cate MacInnis-Ng (New Zealand), Belinda McFadgen (New Zealand), Celia McMichael (Australia), Bradley Moggridge (Australia), Sandy Morrison (New Zealand), Vinnitta Mosby (Australia), Esther Onyango (Australia/Kenya), Sharanjit Paddam (Australia), Grant Pearce (New Zealand), Petra Pearce (New Zealand), Rosh Ranasinghe (Netherlands), David Schoeman (Australia), Rodger Tomlinson (Australia), Michael Watt (New Zealand), Seth Westra (Australia), Russell Wise (Australia).

Review Editors: Ove Hoegh-Guldberg (Australia), David Wratt (New Zealand)

Chapter Scientists: Belinda McFadgen (New Zealand), Esther Onyango (Australia/Kenya)

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Table of Contents

Executive Summary

Observed changes and impacts

Ongoing climate trends have exacerbated many extreme events (*very high confidence*). The Australian trends include further warming and sea-level rise, with more hot days and heatwaves, less snow, more rainfall in the north, less April-October rainfall in the south-west and south-east, more extreme fire weather days in the south and east. The New Zealand trends include further warming and sea-level rise, more hot days and heatwaves, less snow, more rainfall in the south, less rainfall in the north, and more extreme fire weather in the east. There have been fewer tropical cyclones and cold days in the region. Extreme events include Australia's hottest and driest year in 2019 with a record-breaking number of days over 39ºC, New Zealand's hottest year in 2016, three widespread marine heatwaves during 2016-2020, Category 4 cyclone Debbie in 2017, seven major hailstorms over eastern Australia and two over New Zealand from 2014-2020, three major floods in eastern Australia and three over New Zealand during 2019-2021, and major fires in southern and eastern Australia during 2019-2020. {11.2.1, Table 11.2, 11.3.8}

Climate trends and extreme events have combined with exposure and vulnerabilities to cause major impacts for many natural systems, with some experiencing or at risk of irreversible change in Australia (*very high confidence*) and in New Zealand *(high confidence)*. For example, warmer conditions with more heatwaves, droughts and catastrophic wildfires have negatively impacted terrestrial and freshwater ecosystems. The Bramble Cay melomys, an endemic mammal species, became extinct due to loss of habitat associated with sea-level rise and storm surges in the Torres Strait. Marine species abundance and distributions have shifted polewards, and extensive coral bleaching events and loss of temperate kelp forests have occurred, due to ocean warming and marine heatwaves across the region. In New Zealand's Southern Alps, from 1978-2016, the area of 14 glaciers declined 21%, and extreme glacier mass loss was at least six times more likely in 2011, and ten times more likely in 2018, due to climate change. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949-2019. {11.3.1.1, 11.3.2.1, Table 11.2b, Table 11.4, Table 11.6, Table 11.9}

Climate trends and extreme events have combined with exposure and vulnerabilities to cause major impacts for some human systems (*high confidence*). Socio-economic costs arising from climate variability and change have increased. Extreme heat has led to excess deaths and increased rates of many illnesses. Nuisance and extreme coastal flooding have increased due to sea-level rise superimposed upon high tides and storm surges in low-lying coastal and estuarine locations, including impacts on cultural sites, traditions and lifestyles of Aboriginal and Torres Strait Islander Peoples in Australia and Tangata Whenua Māori in New Zealand. Droughts have caused financial and emotional stress in farm households and rural communities. Tourism has been negatively affected by coral bleaching, fires, poor ski seasons and receding glaciers. Governments, business and communities have experienced major costs associated with extreme weather, droughts and sea-level rise. {11.3, 11.4, 11.5.2, Table 11.2, Boxes 11.1-11.6}

Climate impacts are cascading and compounding across sectors and socio-economic and natural systems *(high confidence)*. Complex connections are generating new types of risks, exacerbating existing stressors and constraining adaptation options. An example is the impacts that cascade between interdependent systems and infrastructure in cities and settlements. Another example is the 2019-2020 south-eastern Australian wildfires which burned 5.8 to 8.1 million hectares, with 114 listed threatened species losing at least half of their habitat and 49 losing over 80%, over 3,000 houses destroyed, 33 people killed, a further 429 deaths and 3230 hospitalizations due to cardiovascular or respiratory conditions, \$1.95 billion in health costs, \$2.3 billion in insured losses, and \$3.6 billion in losses for tourism, hospitality, agriculture and forestry. {11.5.1, Box 11.1}

Increasing climate risks are projected to exacerbate existing vulnerabilities and social inequalities and inequities *(high confidence)*. These include inequalities between Indigenous and non-Indigenous Peoples, and between generations, rural and urban areas, incomes and health status, increasing the climate risks and adaptation challenges faced by some groups and places. Resultant climate change impacts include the displacement of some people and businesses, and threaten social cohesion and community wellbeing. {11.3.5, 11.3.6, 11.3.10, 11.4}

Projected impacts and key risks

Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (*very high confidence*[1]). Ongoing warming is projected, with more hot days and fewer cold days (*very high confidence*). Further sea-level rise, ocean warming and ocean acidification are projected (*very high confidence*). Less winter and spring rainfall is projected in southern Australia, with more winter rainfall in Tasmania, less autumn rainfall in south-western Victoria and less summer rainfall in western Tasmania (*medium confidence*), with uncertain rainfall changes in northern Australia. In New Zealand, more winter and spring rainfall is projected in the west and less in the east and north, with more summer rainfall in the east and less in the west and central North Island (*medium confidence*). In New Zealand, ongoing significant clean ice glacier retreat is projected (*very high confidenc*e). More droughts and extreme fire weather are projected in southern and eastern Australia (*high confidence*) and over most of New Zealand (*medium confidence*). Increased rainfall intensity is projected, with fewer tropical cyclones and a greater proportion of severe cyclones *(medium confidence*). {11.2.2, Table 11.3, Box 11.6}

Climate risks are projected to increase for a wide range of systems, sectors and communities, which are exacerbated by underlying vulnerabilities and exposures (*high confidence*) {11.3; 11.4}. Nine key risks were identified, based on magnitude, likelihood, timing and adaptive capacity {11.6, Table 11.14}:

Ecosystems at critical thresholds, where recent climate change has caused significant damage and further climate change may cause irreversible damage, with limited scope for adaptation

Loss and degradation of coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves, e.g. three marine heatwaves on the Great Barrier Reef during 2016-2020 caused significant bleaching and loss. {11.3.2.1, 11.3.2.2, Box 11.2}

Loss of alpine biodiversity in Australia due to less snow, e.g. loss of alpine vegetation communities (snow patch Feldmark and short alpine herb-fields) and increased stress on snow-dependent plant and animal species, {11.3.1.1, 11.3.1.2}

Key risks that have potential to be severe but can be reduced substantially by rapid, large-scale and effective mitigation and adaptation

Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires, e.g. declining rainfall in southern Australia over the past 30 years has led to drought-induced canopy dieback across a range of forest and woodland types, and death of fire-sensitive tree species due to unprecedented wildfires. {11.3.1.1, 11.3.1.2}

Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins, e.g. less than 10% of giant kelp in Tasmania was remaining by 2011 due to ocean warming. {11.3.2.1, 11.3.2.2}

Loss of natural and human systems in low-lying coastal areas due to sea-level rise, e.g. for 0.5 m sea-level rise, the value of buildings in New Zealand exposed to 1-in-100 year coastal inundation could increase by NZ$12.75 billion and the current 1-in-100 year flood in Australia could occur several times a year. {11.3.5; Box 11.6}

Disruption and decline in agricultural production and increased stress in rural communities in south-western, southern and eastern mainland Australia due to hotter and drier conditions, e.g. by 2050, a decline in median wheat yields of up to 30% in south-west Australia and up to 15% in South Australia, and increased heat stress in livestock by 31–42 days per year. {11.3.4; 11.3.5; Box 11.3}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Increase in heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves, e.g. heat-related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (low emission pathway) to 600/year (high emission pathway) during 2031-2080 relative to 142/year during 1971-2020. {11.3.1, 11.3.5.1, 11.3.5.2, 11.3.6.1, 11.3.6.2}

Key cross-sectoral and system-wide risk

Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to wildfires, floods, droughts, heatwaves, storms and sea-level rise, e.g. in New Zealand, extreme snow, heavy rainfall and wind events have combined to impact road networks, power and water supply, interdependent wastewater and stormwater services and business activities {11.3.3, 11.5.1, 11.8.1}.

Key implementation risk

Inability of institutions and governance systems to manage climate risks, e.g. the scale and scope of projected climate impacts overwhelm the capacity of institutions, organisations and systems to provide necessary policies, services, resources and coordination to address the socio-economic impacts {11.5.1.2, 11.5.1.3, 11.5.2.3, 11.6, 11.7.1, 11.7.2, 11.7.3}.

There are important interactions between mitigation and adaptation policies and their implementation *(high confidence)*. Integrated policies in interdependent systems across biodiversity, water quality, water availability, energy, transport, land use and forestry for mitigation, can support synergies between adaptation and mitigation. These have co-benefits for the management of land use, water and associated conflicts, and for the functioning of cities and settlements. For example, projected increases in fire, drought, pest incursions, storms and wind place forests at risk and affect their ongoing role in meeting New Zealand's emissions reduction goals. {11.3.4.3, 11.3.10.2, 11.3.5.3, Box 11.5}

Challenges and solutions

The ambition, scope and progress of the adaptation process has increased across governments, non-government organisations, businesses and communities (*high confidence*). This process includes vulnerability and risk assessments, identification of strategies and options, planning, implementation, monitoring, evaluation and review. Initiatives include institutional frameworks in statute for risk assessment and national adaptation planning and monitoring in New Zealand, a National Recovery and Resilience Agency and National Disaster Risk Reduction Framework in Australia, deployment of new national guidance, decision tools, collaborative governance approaches, and the introduction of climate risk and disclosure regimes for the private sector. The focus however has been on adaptation planning, rather than on implementation. {11.5.1, 11.7.1.1, Box 11.6, Table 11.15a, Table 11.15b, Table 11.17}

Adaptation progress is uneven, due to gaps, barriers and limits to adaptation, and adaptive capacity deficits (*very high confidence*). Progress in adaptation planning, implementation, monitoring and evaluation is lagging. Barriers include lack of consistent policy direction, competing objectives, divergent risk perceptions and values, knowledge constraints, inconsistent information, fear of litigation, up-front costs, and lack of engagement, trust and resources. Adaptation limits are being approached for some species and ecosystems. Adaptive capacity to address the barriers and limits can be built through greater engagement with groups and communities to build trust and social legitimacy through inclusion of diverse values, including those of Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori. {11.4, 11.5, 11.6, 11.7, 11.8, Table 11.4, Table 11.5, Table 11.6, Table 11.16, Box 11.2}

A range of incremental and transformative adaptation options and pathways is available as long as enablers are in place to implement them (*high confidence*). Key enablers for effective adaptation include shifting from reactive to anticipatory planning, integration and coordination across levels of government and sectors, inclusive and collaborative institutional arrangements, government leadership, policy alignment, nationally consistent and accessible information, decision-support tools, along with adaptation funding and finance and robust consistent and strategic policy commitment. Over three-quarters of people in Australia and New Zealand agree that climate change is occurring and over 60% believe climate change is caused by humans, giving climate adaptation and mitigation action further social legitimacy. {11.7.3, Table 11.17}

New knowledge on system complexity, managing uncertainty and how to shift from reactive to adaptive implementation is critical for accelerating adaptation (*high confidence*). Priorities include: greater understanding of impacts on natural system dynamics; the exposure and vulnerability of different groups within society, including Indigenous Peoples; the relationship between mitigation and adaptation; the effectiveness and feasibility of different adaptation options; the social transitions needed for transformative adaptation; and the enablers for new knowledge to better inform decision making, e.g. monitoring data repositories, risk and vulnerability assessments, robust planning approaches, sharing adaptation knowledge and practice. {11.7.3.3}

Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori can enhance effective adaptation through the passing down of knowledge about climate change planning that promotes collective action and mutual support across the region (*high confidence*). Supporting Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori institutions, knowledge and values, enables self-determination and creates opportunities to develop adaptation responses to climate change. Actively upholding the UN Declaration on the Rights of Indigenous Peoples and Māori interests under the Treaty of Waitangi at all levels of government enables intergenerational approaches for effective adaptation. {11.3, 11.4, 11.6, 11.7.3; Cross-Chapter Box INDIG in Chapter 18}

A step change in adaptation is needed to match the rising risks and to support climate resilient development *(very high confidence*). Current adaptation is largely incremental and reactive. A shift to transformative and proactive adaptation can contribute to climate resilient development. The scale and scope of cascading, compounding and aggregate impacts require new, larger-scale and timely adaptation. Monitoring and evaluation of the effectiveness of adaptation progress and continual adjustment is critical. The transition to climate-resilient development pathways can generate major co-benefits, but complex interactions between objectives can create trade-offs. {11.7, 11.8.1, 11.8.2}

Delay in implementing adaptation and emission reductions will impede climate resilient development, resulting in more costly climate impacts and greater scale of adjustments (*very high confidence*). The region faces an extremely challenging future. Reducing the risks would require significant and rapid emission reductions to keep global warming to 1.5-2.0ºC, as well as robust and timely adaptation. The projected warming under current global emissions reduction policies would leave many of the region's human and natural systems at very high risk and beyond adaptation limits. {11.8, Table 11.1, Table 11.14, Figure 11.6}

11.1 Introduction

This chapter assesses observed impacts, projected risks, vulnerability and adaptation, and the implications for climate resilient development for the Australasia region, based on literature published up to 1 September 2021. It should be read in conjunction with other Working Group 2 chapters, the climate science assessment in the Working Group 1 Report and the greenhouse gas emissions and mitigation assessment in the Working Group 3 Report.

11.1.1 Context

The Australasia region is defined as the Exclusive Economic Zones (EEZ) and territories of Australia and New Zealand. In both countries, climate adaptation is largely implemented at a sub-national level through devolution of functions constitutionally or by statute, alongside disaster risk reduction (COAG, 2011; Lawrence et al., 2015; Macintosh et al., 2015).

Australia's economy is dominated by financial and insurance services, education, mining, construction, tourism, health care and social assistance (ABS, 2018) with Australian exports accruing mostly from mining (ABS, 2018; ABS, 2019). In New Zealand, service industries, including tourism, collectively account for around two thirds of GDP (NZ Treasury, 2016). The primary sector contributes 6% of New Zealand's GDP and over half of the country's export earnings (NZ Treasury, 2016).

Existing vulnerabilities expose and exacerbate inequalities between rural, regional and urban areas, Indigenous and non-Indigenous Peoples, those with health and disability needs, and between generations, incomes and health status, increasing the relative climate change risk faced by some groups and places (Jones et al., 2014; Bertram, 2015; Perry, 2017; Hazledine and Rashbrooke, 2018) (*high confidence*).

Previous IPCC reports (Table 11.1) have documented observed climate impacts, projected risks, adaptation challenges and opportunities. In this chapter, there is more evidence of observed climate impacts and adaptation, better quantification of socio-economic risks, new information about cascading and compounding risks, greater emphasis on adaptation enablers and barriers, and links to climate-resilient development.

Table 11.1: Summary of key conclusions from the IPCC 5th Assessment Report (AR5) Australasia chapter (Reisinger et al., 2014) and relevant conclusions from the IPCC Special Reports on Global Warming of 1.5°C (IPCC, 2018), Climate Change and Land (IPCC, 2019a) and Oceans and Cryosphere (IPCC, 2019b)

Conclusions	Report
Our regional climate is changing (*very high confidence*) and warming will continue through the 21st century (*virtually certain*) with more hot days, fewer cold days, less snow, less rainfall in southern Australia and the northeast of both of New Zealand's islands, more rainfall in western New Zealand, more extreme rainfall, sea-level rise, increased fire weather in southern Australia and across New Zealand, and fewer cyclones but a greater proportion of intense cyclones. Key risks include changes in the structure and composition of Australian coral reefs, loss of montane ecosystems, increased flood damage, reduced water resources in southern Australia, more deaths and infrastructure damage during heatwaves, more fire-related impacts on ecosystems and settlements in southern Australia and across New Zealand, greater risk to coastal infrastructure and ecosystems, and reduced water availability in the Murray-Darling Basin and southern Australia (*high confidence*). Benefits are projected for some sectors and locations *(high confidence)*, including reduced winter mortality and energy demand for heating, increased forest growth, and enhanced pasture productivity. Adaptation is occurring and adaptation is becoming mainstreamed in some planning processes (*high confidence*). Adaptive capacity is considered generally high in many human systems, but adaptation implementation faces major barriers, especially for transformational responses (*high confidence*). Some synergies and trade-offs exist between different adaptation responses, and between mitigation and adaptation, with interactions occurring both within and outside the region (*very high confidence*).	(Reisinger et al., 2014)

Vulnerability remains uncertain due to incomplete consideration of socio-economic dimensions *(very high confidence),* including governance, institutions, patterns of wealth and aging, access to technology and information, labour force participation, and societal values.	
Emissions reductions under Nationally Determined Contributions from signatories to the Paris Agreement are consistent with a global warming of 2.5-3.0°C above pre-industrial temperatures by 2100. Much deeper emission reductions are needed prior to 2030 to limit warming to 1.5°C. There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses. Climate impacts will disproportionately affect the welfare of impoverished and vulnerable people because they lack adaptation resources. Strengthening the climate-action capacities of national and sub-national authorities, civil society, the private sector, Indigenous people and local communities can support implementation of actions.	(IPCC, 2018)
Land-related responses that contribute to climate change adaptation and mitigation can also combat desertification, land degradation, and enhance food security. Appropriate design of policies, institutions and governance systems at all scales can contribute to land-related adaptation and mitigation while facilitating the pursuit of climate-adaptive development pathways. Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration, and foster collaboration between stakeholders. Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits. Delaying action (both mitigation and adaptation) will be more costly.	(IPCC, 2019a)
The rate of global mean sea-level rise of 3.6 mm per year for 2006–2015 is unprecedented over the last century. Extreme wave heights, coastal erosion and flooding, have increased in the Southern Ocean by around 1.0 cm per year over the period 1985–2018. Some species of plants and animals have increased in abundance, shifted their range, and established in new areas as glaciers receded and the snow-free season lengthened. Some cold-adapted or snow-dependent species have declined in abundance, increasing their risk of extinction, notably on mountain summits. Many marine species have shifted their range and seasonal activities. Altered interactions between species have caused cascading impacts on ecosystem structure and functioning. Mean sea-level rise projections are higher by 0.1 m compared to AR5 under RCP8.5 in 2100. Extreme sea-level events that are historically rare (once per century) are projected to occur frequently (at least once per year) at many locations by 2050. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. Warm water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C. Governance arrangements (e.g., marine protected areas, spatial plans and water management systems) are too fragmented across administrative boundaries and sectors to provide integrated responses to the increasing and cascading risks. Financial, technological, institutional and other barriers exist for implementing responses. Enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions coupled with coordinated, sustained and increasingly ambitious adaptation actions. This includes better cooperation and coordination among governing authorities, education and climate literacy, sharing of information and knowledge, finance, addressing social vulnerability and equity, and institutional support.	(IPCC, 2019b)

11.1.2 Economic, Demographic and Social Trends

Economic, demographic and socio-cultural trends influence the exposure, vulnerability and adaptive capacity of individuals and communities (*high confidence*) (Elrick-Barr et al., 2016; Smith et al., 2016; Hayward, 2017; B. Frame et al., 2018; Plummer et al., 2018; Smith et al., 2018; Gartin et al., 2020). In the absence of proactive adaptation, climate change, impacts are projected to worsen inequalities between Indigenous and non-Indigenous people and other vulnerable groups (Green et al., 2009; Manning et al., 2014; Ambrey et al., 2017) (*high confidence*). Socio-economic inequality, low incomes and high levels of debt, poor health and disabilities increase vulnerability and limit adaptation (Hayward, 2012) (11.7.2). Lack of services, such as schools and medical services, in poorer and rural areas, and decision-making processes that privilege some voices over others, exacerbate inequalities (Kearns et al., 2009; Hinkson and Vincent, 2018).

Changes to the composition and location of different demographic groups in the region contributes to increased exposure or vulnerability to climate change (*medium confidence*). Australia's population reached 25 million in 2018 and is projected to grow to 37.4–49.2 million by 2066, with most growth in major cities (accounting for 81% of Australia's population growth from 2016–17) (ABS, 2018), although COVID-19 is expected to slow the growth rate (CoA, 2020c). Highest growth rates outside of major cities occurred mostly in coastal regions (ABS, 2017) which have built assets exposed to sea-level rise. New Zealand's population was 5.1 million at the end of 2020 and is projected to increase to 6.0–6.5 million by 2068 assuming no marked changes in migration patterns (Stats NZ, 2016; Stats NZ, 2021). Although the population densities of both countries are much lower than other OECD countries, they are highly urbanized with over 86% living in urban areas in both countries (Productivity Commission, 2017; World Bank, 2018). This proportion is projected to increase to over 90% by 2050 (UN DESA, 2019) mostly in coastal areas (Rouse et al., 2017). Consideration of climate change impacts when planning and managing such growth and associated infrastructure could help avoid new vulnerabilities being created, particularly from wildfires, sea-level rise, heat stress and flooding.

The region has an increasingly diverse population through the arrival of migrants, including those from the Pacific, whose innovations, skills and transnational networks enhance their and others' adaptive capacity (De et al., 2016; Fatorić et al., 2017; Barnett and McMichael, 2018), although language barriers and socio-economic disadvantage can create vulnerabilities for some (11.7.2).

Climate change inaction exacerbates intergenerational inequity including prospects for the current younger population (Hayward, 2012). Increasing transient worker populations (ABS, 2018) may diminish social networks and adaptive capacity (Jiang et al., 2017). The region has an aging population and increasing numbers of people living on their own who are highly vulnerable to extreme events, including heat stress and flooding (Zhang et al., 2013).

Socio-economic trends are affected by global mega trends (KPMG, 2021), which are expected to influence the region's ability to implement climate change adaptation strategies (World Economic Forum, 2014). Digital technological advances have potential benefits for building adaptive capacity (Deloitte, 2017a).

11.2 Observed and Projected Climate Change

11.2.1 Observed Climate Change

Regional climate change has continued since the Fifth Assessment Report (AR5) in 2014, with trends exacerbating many extreme events (*very high confidence*). The following changes are quantified with references in Tables 11.2a and 11.2b. The region has continued to warm (Figure 11.1), with more extremely high temperatures and fewer extremely low temperatures. Snow depths and glacier volumes have declined. Sea-level rise and ocean acidification have continued. Northern Australia has become wetter, while April-October rainfall has decreased in south-western and south-eastern Australia. In New Zealand, most of the south has become wetter while most of the north has become drier (Figure 11.2). The frequency, severity and duration of extreme fire weather conditions have increased in southern and eastern Australia and eastern New Zealand. Changes in extreme rainfall are mixed. There has been a decline in tropical cyclone frequency near Australia.

Reliable measurements are limited for some types of storms, particularly thunderstorms, lightning, tornadoes and hail (Walsh et al., 2016). Many high impact events are a combination of interacting physical processes across multiple spatial and temporal scales (e.g. fires, heatwaves and droughts), and better understanding of these extreme and compound events is needed (Zscheischler et al., 2018).

Some of the observed trends and events can be partly attributed to anthropogenic climate change, as documented in Chapter 16. Examples include regional warming trends and sea-level rise, terrestrial and marine heatwaves, declining rainfall and increasing fire weather in southern Australia, and extreme rainfall and severe droughts in New Zealand.

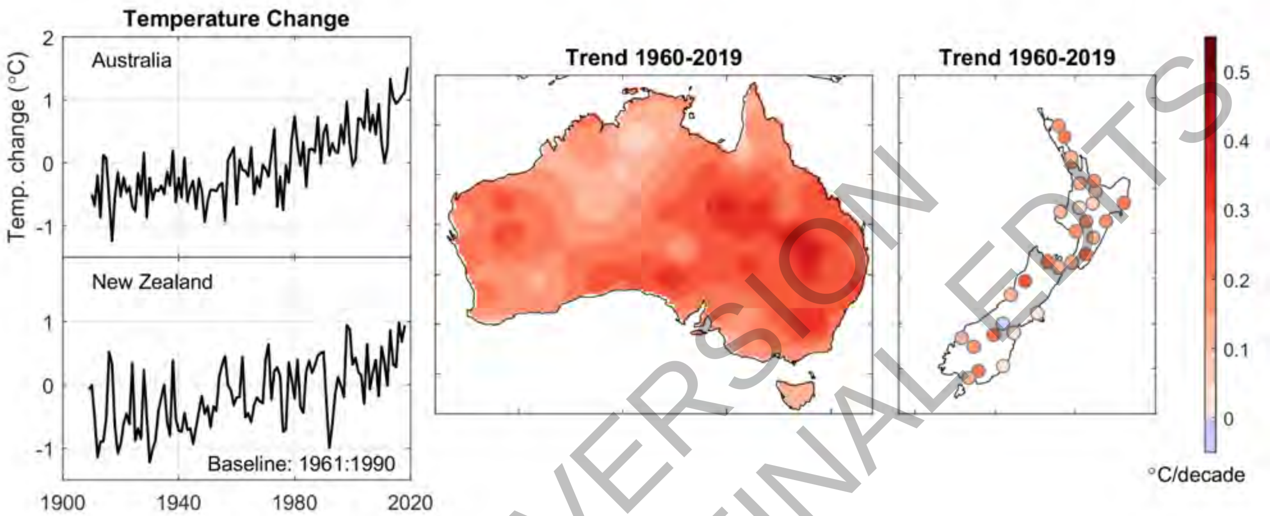

Figure 11.1: Observed temperature changes in Australia and New Zealand. Annual temperature change time-series are shown for 1910–2019. Mean annual temperature trend maps are shown for 1960–2019 using contours for Australia and individual sites for New Zealand. Data courtesy of BoM and NIWA.

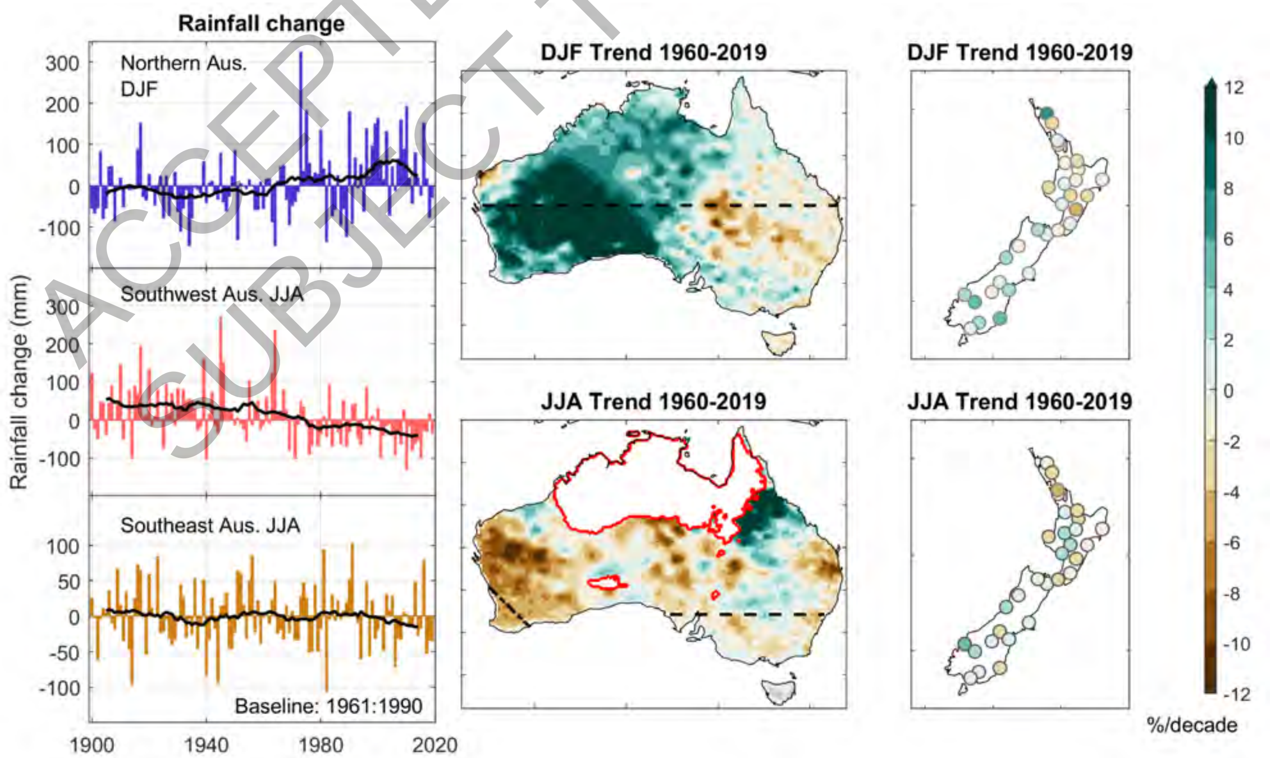

Figure 11.2: Observed rainfall changes in Australia and New Zealand. Rainfall change time-series for 1900–2019 are shown for northern Australia (December-February: DJF), southwest Australia (June-August: JJA) and southeast

Australia (JJA). Dashed lines on the maps for Australia show regions used for the time-series. Rainfall trend maps are shown for 1960–2019 (DJF and JJA) using contours for Australia and individual sites for New Zealand. Areas of low Australian rainfall (less than 0.25 mm/day) are shaded white in JJA. Data courtesy of BoM and NIWA.

Table 11.2a: Observed climate change for Australia**.**

Climate variable	Observed change	References
Air temperature over land	Increased by 1.4°C from 1910–2019. 2019 was the warmest year, and nine of the ten warmest on record occurred since 2005. Clear anthropogenic attribution.	(BoM, 2020b; BoM and CSIRO, 2020; Trewin et al., 2020; Gutiérrez et al., 2021)
Sea surface temperature	Increased by 1.0°C from 1900-2019 (0.09ºC/decade), with an increase of 0.16-0.20ºC/decade since 1950 in the south-east. Eight of the ten warmest years on record occurred since 2010.	(BoM and CSIRO, 2020)
Air temperature extremes over land	More extremely hot days and fewer extremely cold days in most regions. Weaker warming trends in minimum temperatures in southeast Australia compared to elsewhere during 1960-2016. Frost frequency in south-east and south-west Australia has been relatively unchanged since the 1980s. Very high monthly maximum or minimum temperatures that occurred around 2% of the time in the past (1960–1989) now occur 11-12% of the time (2005–2019). Multi-day heatwave events have increased in frequency and duration across many regions since 1950. In 2019, the national average maximum temperature exceeded the 99th percentile on 43 days (more than triple the number in any of the years prior to 2000) and exceeded 39°C on 33 days (more than the number observed from 1960 to 2018 combined).	(Perkins-Kirkpatrick et al., 2016; Alexander and Arblaster, 2017; Pepler et al., 2018; BoM and CSIRO, 2020; Perkins-Kirkpatrick and Lewis, 2020; Trancoso et al., 2020)
Sea temperature extremes	Intense marine heatwave in 2011 near Western Australia (peak intensity 4°C, duration 100 days) - likelihood of an event of this duration estimated to be about 5 times higher than under pre-industrial conditions. Marine heatwave over northern Australia in 2016 (peak intensity 1.5°C, duration 200 days). Marine heatwave in the Tasman Sea and around southeast mainland Australia and Tasmania from September 2015 to May 2016 (peak intensity 2.5°C, duration 250 days) - likelihood of an event of this intensity and duration has increased about 50-fold. Marine heatwave in the Tasman Sea from November 2017 to March 2018 (peak intensity 3°C, duration 100 days). Marine heatwave on the Great Barrier Reef in 2020 (peak intensity 1.2°C, duration 90 days) (BoM, 2020).	(BoM and CSIRO, 2018; BoM, 2020a; Laufkötter et al., 2020; Oliver et al., 2021)
Rainfall	Northern Australian rainfall has increased since the 1970s, with an attributable human influence. April to October rainfall has decreased 16% since the 1970s in south-western Australia (partly due to human influence) and 12% from 2000-2019 in south-eastern Australia. Australian-average rainfall was lowest on record in 2019.	(Delworth and Zeng, 2014; Knutson and Zeng, 2018; Dey et al., 2019; BoM, 2020c; BoM and CSIRO, 2020)
Rainfall extremes	Hourly extreme rainfall intensities increased by 10–20% in many locations between 1966–1989 and 1990–2013. Daily rainfall associated with thunderstorms increased 13-24% from 1979-2016, particularly in northern Australia. Daily rainfall intensity increased in the northwest from 1950–2005 and in the east from 1911–2014, and decreased in the south-west and Tasmania from 1911–2010.	(Donat et al., 2016; Alexander and Arblaster, 2017; Evans et al., 2017; Guerreiro et al., 2018; Dey et al., 2019; BoM and CSIRO, 2020; Bruyère et al., 2020; Dowdy, 2020; Dunn et al., 2020; Gutiérrez et al., 2021)

Drought	Major Australian droughts occurred in 1895-1902, 1914-1915, 1937-1945, 1965-1968, 1982-1983, 1997-2009 and 2017-2019. Fewer droughts have occurred across most of northern and central Australia since the 1970s, more droughts in the south-west since the 1970s, and mixed drought trends in the south-east since the late 1990s.	(Gallant et al., 2013; Delworth and Zeng, 2014; Alexander and Arblaster, 2017; Dai and Zhao, 2017; Knutson and Zeng, 2018; Dey et al., 2019; Spinoni et al., 2019; BoM, 2020b; Dunn et al., 2020; Rauniyar and Power, 2020; BoM, 2021; Seneviratne et al., 2021)
Windspeed	Windspeed decreased 0.067 m/s per decade over land from 1941-2016, with a decrease of 0.062 m/s per decade over land from 1979–2015, and a decrease of 0.05-0.10 m/s per decade over land from 1988-2019. Windspeed increased 0.02 m/s per year across the Southern Ocean from 1985-2018.	(Troccoli et al., 2012; Young and Ribal, 2019; Blunden and Arndt, 2020; Azorin-Molina et al., 2021)
Sea-level rise	Relative sea level rise was 3.4 mm/year from 1993-2019, which includes the influence of internal variability (e.g. ENSO) and anthropogenic greenhouse gases.	(Watson, 2020)
Fire	An increase in the number of extreme fire weather days from July 1950 to June 1985 compared to July 1985 to June 2020, especially in the south and east, partly attributed to climate change. More dangerous conditions for extreme pyro convection events since 1979, particularly in south-eastern Australia. Extreme fire weather in 2019-2020 was at least 30% more likely due to climate change.	(Dowdy and Pepler, 2018; BoM and CSIRO, 2020; van Oldenborgh et al., 2021)
Tropical cyclones and other storms	Fewer tropical cyclones since 1982, with a 22% reduction in translation speed over Australian land areas from 1949-2016. No significant trend in the number of East Coast Lows. From 1979–2016, thunderstorms and dry lightning decreased in spring and summer in northern and central Australia, decreased in the north in autumn, and increased in the south-east in all seasons. Convective rainfall intensity per thunderstorm increased by about 20% in the north and 10% in the south. An increase in the frequency of large to giant hail events across south-eastern Queensland and north-eastern and eastern New South Wales in the most recent decade. Seven major hail storms over eastern Australia from 2014-2020 and three major floods over eastern Australia from 2019-2021.	(Pepler et al., 2015b; Ji et al., 2018; Kossin, 2018; BoM and CSIRO, 2020; Dowdy, 2020; ICA, 2021) (Bruyère et al., 2020)
Snow	At Spencers Creek (1830 m elevation) in NSW, annual maximum snow depth decreased 10% and length of snow season decreased 5% during 2000–2013 relative to 1954–1999. At Rocky Valley Dam (1650 m elevation) in Victoria, annual maximum snow depth decreased 5.7 cm/decade from 1954-2011. At Mt Hotham, Mt Buller and Falls Creek (1638-1760 m elevation), annual maximum snow depth decreased 15%/decade from 1988-2013.	(Bhend et al., 2012; Fiddes et al., 2015; Pepler et al., 2015a; BoM and CSIRO, 2020)
Ocean acidification	Average pH of surface waters has decreased since the 1880s by about 0.1 (over 30% increase in acidity).	(BoM and CSIRO, 2020)

Table 11.2b: Observed climate change for New Zealand.

Climate variable	Observed change	References
Air temperature	Increased by 1.1°C from 1909–2019. Warmest year on record was 2016, followed by 2018 and 1998 as equal 2^{nd} warmest.	(MfE, 2020a; NIWA, 2020)

	Six years between 2013 and 2020 were among New Zealand's warmest on record.	
Sea surface temperature	Increased by 0.2°C/decade from 1981–2018.	(MfE, 2020a)
Air temperature extremes	Number of frost days (below 0 degrees Celsius) decreased at 12 of 30 sites, the number of warm days (over 25°C) increased at 19 of 30 sites, and the number of heatwave days increased at 18 of 30 sites during 1972–2019. Increase in the frequency of hot February days exceeding the 90th percentile between 1980–1989 and 2010–2019, with some regions showing more than a five-fold increase.	(Harrington, 2020; MfE, 2020a)
Sea temperature extremes	The eastern Tasman Sea experienced a marine heatwave in 2017/18 lasting 138 days with a maximum intensity of 4.1°C, and another marine heatwave in 2018/19 lasting 137 days with a maximum intensity of 2.8°C.	(NIWA, 2019; Salinger et al., 2019b; Salinger et al., 2020; Oliver et al., 2021)
Rainfall	From 1960–2019, almost half of the 30 sites had an increase in annual rainfall (mostly in the south) and 10 sites (mostly in the north) had a decrease, but few of the trends are statistically significant. Rainfall increased by 2.8% per decade in Whanganui, 2.1% per decade in Milford Sound and 1.3% per decade in Hokitika. Rainfall decreased by 4.3% per decade in Whangarei and 3.2% per decade in Tauranga.	(MfE, 2020a)
Rainfall extremes	The number of days with extreme rainfall increased at 14 of 30 sites and decreased at 11 sites from 1960–2019. Most sites with increasing annual rainfall had more extreme rainfall and most sites with decreasing annual rainfall had less extreme rainfall.	(MfE, 2020a)
Drought	Drought frequency increased at 13 of 30 sites from 1972–2019 and decreased at 9 sites. Drought intensity increased at 14 sites, 11 of which are in the north, and decreased at 9 sites, 7 of which are in the south.	(MfE, 2020a)
Windspeed	Since 1970, the wind belt has often been shifted to the south of New Zealand, bringing an overall decrease in wind-speed over the country. For 1980–2019, the annual maximum wind gust decreased at 11 of the 14 sites that had enough data to calculate a trend, and increased at 2 of the 14 sites	(MfE, 2020a)
Sea-level rise	Increased 1.8 mm/year from 1900–2018 and 2.4 mm/year from 1961–2018, mostly due to climate change.	(Bell and Hannah, 2019)
Fire	Six of 28 sites (Napier, Lake Tekapo, Queenstown, Gisborne, Masterton, and Gore) had an increase in days with very high or extreme fire danger from 1997–2019 and 6 sites (Blenheim, Christchurch, Nelson, Tara Hills, Timaru, and Wellington) had a decrease. An increase in fire impacts from 1988–2018 included homes lost, damaged, threatened and evacuated.	(Pearce, 2018; MfE, 2020a)
Tropical cyclones and other storms	No significant change in storminess. Three major floods and two major hail-storms during 2019-2021.	(MfE, 2020a; ICNZ, 2021)

Snow and ice	From 1978-2019, the snowline rose 3.7 m/year. From 1977 to 2018, glacier ice volume decreased from 26.6 km^3 to 17.9 km^3 (a loss of 33%). From 1978-2016, the area of 14 glaciers in the Southern Alps declined 21%. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949-2019. In the Southern Alps, extreme glacier mass loss was at least six times more likely in 2011, and ten times more likely in 2018, due to climate change.	(Baumann et al.; Salinger et al., 2019a; Chinn and Chinn, 2020; MfE, 2020a; Salinger et al., 2021) (Vargo et al., 2020)
Ocean acidification	Sub-Antarctic ocean off the Otago coast became 7% more acidic from 1998–2017.	(MfE, 2020a)

11.2.2 Projected Climate Change

There are three main sources of uncertainty in climate projections: emission scenarios, regional climate responses, and internal climate variability (CSIRO and BOM, 2015). Emission scenario uncertainty is captured in four Representative Concentration Pathways (RCPs) for greenhouse gases and aerosols. RCP2.6 represents low emissions, RCP4.5 medium emissions and RCP8.5 high emissions. Regional climate response uncertainty and internal climate variability uncertainty are captured in climate model simulations driven by the RCPs.

Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (IPCC, 2021) (*very high confidence*). Preliminary projections based on CMIP6 models are described in the IPCC Working Group I Atlas. For Australia, the CMIP6 projections broadly agree with CMIP5 projections except for a group of CMIP6 models with greater warming and a narrower range of summer rainfall change in the north and winter rainfall change in the south (Grose et al., 2020). For New Zealand, the CMIP6 projections are similar to CMIP5, but the CMIP6 models indicate greater warming, a smaller increase in summer precipitation and a larger increase in winter precipitation (Gutiérrez et al., 2021).

Dynamical and/or statistical downscaling offers the prospect of improved representation of regional climate features and extreme weather events (IPCC 2021: Working Group I Chapter 10), but the added value of downscaling is complex to evaluate (Ekström et al., 2015; Rummukainen, 2015; Virgilio et al., 2020). Downscaled simulations are available for New Zealand (MfE, 2018) and various Australian regions (Evans et al., 2020) (IPCC 2021: Working Group I Atlas). Further downscaling was recommended by the Royal Commission into National Natural Disaster Arrangements (CoA, 2020e). Projections for rainfall, thunderstorms, hail, lightning and tornadoes have large uncertainties (Walsh et al., 2016; MfE, 2018).

Future changes in climate variability are affected by the El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM), Indian Ocean Dipole (IOD) and Interdecadal Pacific Oscillation (IPO). An increase in strong El Niño and La Niña events is projected (Cai, 2015), along with more extreme positive phases of the IOD (Cai et al., 2018) and a positive trend in SAM (Lim et al., 2016), but potential changes in the IPO are unknown (NESP ESCC, 2020). There is uncertainty about regional climate responses to projected changes in ENSO (King et al., 2015; Perry et al., 2020; Virgilio et al., 2020).

Australian climate projections are quantified with references in Table 11.3a. Further warming is projected, with more hot days, fewer cold days, reduced snow cover, ongoing sea-level rise and ocean acidification (*very high confidence*). Winter and spring rainfall and soil moisture are projected to decrease with more droughts in southern Australia, increased extreme rainfall intensity, higher evaporation rates, decreased wind over southern mainland Australia, increased wind over Tasmania, and more extreme fire weather in southern and eastern Australia (*high confidence*). Increased winter rainfall is projected over Tasmania, with decreased rainfall in south-western Victoria in autumn and in western Tasmania in summer, fewer tropical cyclones with a greater proportion of severe cyclones and decreased soil moisture in the north (*medium confidence*). Hailstorm frequency may increase (*low confidence*).

New Zealand climate projections are quantified with references in Table 11.3b. Further warming is projected, with more hot days, fewer cold days, less snow and glacial ice, ongoing sea-level rise and ocean acidification (*very high confidence*). Increases in winter and spring rainfall are projected in the west of the North and South Islands, with drier conditions in the east and north, caused by stronger westerly winds (*medium confidence*). In summer, wetter conditions are projected in the east of both islands, with drier conditions in the west and central North Island (*medium confidence*). Fire weather is projected to increase in most areas, except for Taranaki-Manawatū, West Coast and Southland (*medium confidence*). Extreme rainfall is projected to increase over most regions, with increased extreme wind-speeds in eastern regions, especially in Marlborough and Canterbury, and reduced relative humidity almost everywhere, except for the West Coast in winter (*medium confidence*). Drought frequency may increase in the north (*medium confidence*).

Table 11.3a: Projected climate change for Australia. Projections are given for different Representative Concentration Pathways (RCP2.6 is low, RCP4.5 is medium, RCP8.5 is high) and years (e.g. 20–year period centered on 2090). Uncertainty ranges are generally 10–90th percentile, and median projections are given in square brackets where possible. The four Australian regions are shown in Chapter 2 of (CSIRO and BOM, 2015). Preliminary projections based on CMIP6 models are included for some climate variables from the IPCC (2021) Working Group 1 report.

Climate variable	Projected change (year, RCP) relative to 1986-2005	References
Air temperature	Annual mean temperature • +0.5–1.5°C (2050, RCP2.6), +1.5–2.5°C (2050, RCP8.5), +0.5–1.5°C (2090, RCP2.6), +2.5–5.0°C (2090, RCP8.5) • Weaker increase in the south, stronger increase in the centre. • Preliminary CMIP6 projections: +0.6-1.3ºC (2050, SSP1-RCP2.6), +1.2-2.0ºC (2050, SSP5-RCP8.5), +0.6-1.5ºC (2090, SSP1-RCP2.6), +2.8-4.9ºC (2090, SSP5-RCP8.5) relative to 1995-2014	(NESP ESCC, 2020; IPCC, 2021)
Sea surface temperature	• + 0.4–1.0°C (2030, RCP8.5), • +2–4°C (2090, RCP8.5).	(CSIRO and BOM, 2015)
Air temperature extremes	• Annual frequency of days over 35°C may increase 20–70% by 2030 (RCP4.5), and 25–85% (RCP2.6) to 80–350% (RCP8.5) by 2090 • Heatwaves may be 85% more frequent if global warming increases from 1.5 to 2.0°C, and four times more frequent for a 3°C warming • Annual frequency of frost days may decrease by 10–40% (2030, RCP4.5), 10–40% (2090, RCP2.6) and 50–100% (2090, RCP8.5).	(CSIRO and BOM, 2015; Trancoso et al., 2020)
Rainfall	Annual mean rainfall • South: –15 to +2% (2050, RCP2.6), –14 to +3% (2050, RCP8.5), –15 to +3% (2090, RCP2.6), –26 to +4% (2090, RCP8.5) • East: –13 to +7% (2050, RCP2.6), –17 to +8% (2050, RCP8.5), –19 to +6% (2090, RCP2.6), –25 to +12% (2090, RCP8.5) • North: –12 to +5% (2050, RCP2.6), -8 to +11% (2050, RCP8.5), -12 to +3% (2090, RCP2.6), -26 to +23% (2090, RCP8.5) • Rangelands: -18 to +3% (2050, RCP2.6), -15 to +8% (2050, RCP8.5), -21 to +3% (2090, RCP2.6), -32 to +18% (2090, RCP8.5).	(Liu et al., 2018; NESP ESCC, 2020)
Rainfall extremes	Intensity of daily-total rain with 20-year recurrence interval • +4 to +10% (2050, RCP2.6), • +8 to +20% (2050, RCP8.5), • +4 to +10% (2090, RCP2.6), • +15 to +35% (2090, RCP8.5).	(NESP ESCC, 2020)
Drought	Time in drought (Standardized Precipitation Index below -1) • Southern Australia: 32-46% [39%] (1995), 38-68% [54%] (2050, RCP8.5), 41-81% [60%] (2090, RCP8.5) • Eastern Australia: 25-46% [37%] (1995), 24-67% [47%] (2050, RCP8.5), 19-76% [56%] (2090, RCP8.5) • Northern Australia: 26-44% [34%] (1995), 18-54% [40%] (2050, RCP8.5), 9-81% [39%] (2090, RCP8.5)	(Kirono et al., 2020)

	• Australian Rangelands: 29-43% [34%] (1995), 26-58% [42%] (2050, RCP8.5), 23-70% [46%] (2090, RCP8.5).	
Windspeed	0-5% decrease over southern mainland Australia and 0-5% increase over Tasmania (2090, RCP8.5)	(CSIRO and BOM, 2015)
Sea-level rise	• South (Port Adelaide): 13-29 cm [21 cm] (2050, RCP2.6), 16-33 cm [25 cm] (2050, RCP8.5), 23-55 cm [39 cm] (2090, RCP2.6), 40-84 cm [61 cm] (2090, RCP8.5) • East (Newcastle): 14-30 cm [22 cm] (2050, RCP2.6), 19-36 cm [27 cm] (2050, RCP8.5), 22-54 cm [38 cm] (2090, RCP2.6), 46-88 cm [66 cm] (2090, RCP8.5) • North (Darwin City Council, 2011): 13-28 cm [21 cm] (2050, RCP2.6), 17-33 cm [25 cm] (2050, RCP8.5), 22-55 cm [38 cm] (2090, RCP2.6), 41-85 cm [62 cm] (2090, RCP8.5) • West (Port Hedland): 13-28 cm [20 cm] (2050, RCP2.6), 16-33 cm [24 cm] (2050, RCP8.5), 22-55 cm [38 cm] (2090, RCP2.6), 40-84 cm [61 cm] (2090, RCP8.5). These projections have not been updated to include an Antarctic dynamic ice sheet factor which increased global sea level projections for RCP8.5 by ~10 cm. Preliminary CMIP6 projections indicate +40-50 cm (2090, SSP1-RCP2.6) and +70-90 cm (2090, SSP5-RCP8.5).	(McInnes et al., 2015; Zhang et al., 2017; IPCC, 2019b) (IPCC, 2021)
Sea-level extremes	Increase in the allowance for a storm tide event with 1% annual exceedance probability (100-year return period) • South (Port Adelaide): 21 cm (2050, RCP2.6), 25 cm (2050, RCP8.5), 41 cm (2090, RCP2.6), 66 cm (2090, RCP8.5) • East (Newcastle): 24 cm (2050, RCP2.6), 30 cm (2050, RCP8.5), 49 cm (2090, RCP2.6), 86 cm (2090, RCP8.5) • North (Darwin): 21 cm (2050, RCP2.6), 26 cm (2050, RCP8.5), 43 cm (2090, RCP2.6), 71 cm (2090, RCP8.5) • West (Port Hedland): 21 cm (2050, RCP2.6), 26 cm (2050, RCP8.5), 43 cm (2090, RCP2.6), 70 cm (2090, RCP8.5).	(McInnes et al., 2015)
Fire	• East: annual number of severe fire weather days 0 to +30% (2050, RCP2.6), 0 to +60% (2050, RCP8.5), 0 to +30% (2090, RCP2.6), 0 to +110% (2090, RCP8.5) • Elsewhere: number of severe fire weather days +5 to +35% (2050, RCP2.6), +10 to +70% (2050, RCP8.5), +5 to +35% (2090, RCP2.6) +20 to +130% (2090, RCP8.5).	(Clarke and Evans, 2019; Dowdy et al., 2019, {Clark, 2021 #2658; Virgilio et al., 2019; NESP ESCC, 2020)
Tropical cyclones and other storms	• Eastern region tropical cyclones: -8 to +1% (2050, RCP2.6), -15 to +2% (2050, RCP8.5), -8 to +1% (2090, RCP2.6), -25 to +5% (2090, RCP8.5) • Western region tropical cyclones: -10 to -2% (2050, RCP2.6), -20 to -4% (2050, RCP8.5), -10 to -2% (2090, RCP2.6), -30 to -10% (2090, RCP8.5) • East coast lows: -15 to -5% (2050, RCP2.6), -30 to -10% (2050, RCP8.5), -15 to -5% (2090, RCP2.6), -50 to -20% (2090, RCP8.5). • Hailstorm frequency may increase, but there are large uncertainties.	(NESP ESCC, 2020; Raupach et al., 2021)

Snow and ice	• Maximum snow depth at Falls Creek and Mt Hotham may decline 30–70% (2050, B1) and 45–90% (2050, A1FI) relative to 1990. • Maximum snow depth at Mt Buller and Mt Buffalo may decline 40–80% (2050, B1) and 50–100% (2050, A1FI) relative to 1990. • Length of Victorian ski-season may contract 65–90% and mean annual snowfall may decline 60–85% (2070–2099, RCP8.5) relative to 2000–2010. • The snowpack may decrease by about 15% (2030, A2) to 60% (2070, A2).	(Bhend et al., 2012; Harris et al., 2016; Di Luca et al., 2018)
Ocean acidification	pH is projected to drop by about 0.1 (2090, RCP2.6) to 0.3 (2090, RCP8.5).	(CSIRO and BOM, 2015; Hurd et al., 2018)

Table 11.3b: Projected climate change for New Zealand. Projections are given for different Representative Concentration Pathways (RCP2.6 is low, RCP4.5 is medium, RCP8.5 is high) and years (e.g. 20–year period centered on 2090). Uncertainty ranges are 5–95^{th} percentile, and median projections are given in square brackets where possible. Preliminary projections (10-90th percentile) based on CMIP6 models are included for some climate variables from the IPCC (2021) Working Group 1 report.

Climate variable	Projected change (year, RCP) relative to 1986-2005	References
Air temperature	Annual mean temperature • +0.2–1.3°C [0.7°C] (2040, RCP2.6), +0.5–1.7°C [1.0°C] (2040, RCP8.5), +0.1–1.4°C [0.7°C] (2090, RCP2.6), +2.0–4.6°C [3.0°C] (2090, RCP8.5) • More warming in summer and autumn, less in winter and spring. • More warming in the north than the south. • Preliminary CMIP6 projections: +0.4-1.1ºC (2050, SSP1-RCP2.6), +0.9-1.7ºC (2050, SSP5-RCP8.5), +0.5-1.5ºC (2090, SSP1-RCP2.6), +2.2-4.1ºC (2090, SSP5-RCP8.5) relative to 1995-2014	(MfE, 2018) (IPCC, 2021)
Sea surface temperature	• +1.0°C (2045, RCP8.5), • +2.5°C (2090, RCP8.5).	(Law et al., 2018b)
Air temperature extremes	• Annual frequency of days over 25°C may increase 20–60% (2040, RCP2.6) to 50–100% (2040, RCP8.5), and 20–60% (2090, RCP2.6) to 130–350% (2090, RCP8.5) • Annual frost frequency may decrease 20–60% (2040, RCP2.6) to 30–70% (2040, RCP8.5), and 20–60% (2090, RCP2.6) to 70–95% (2090, RCP8.5).	(MfE, 2018)

Rainfall	Annual mean rainfall • Waikato, Auckland and Northland: -7 to +7% (2040, RCP2.6), -8 to +5% (2040, RCP8.5), -5 to +11% [+2%] (2090, RCP2.6), -15 to +12% [-2%] (2090, RCP8.5) • Hawke's Bay and Gisborne: -8 to +8% [-1%] (2040, RCP2.6), -12 to +7% [-2%] (2040, RCP8.5), -9 to +4% [-2%] (2090, RCP2.6), -15 to +15% [-3%] (2090, RCP8.5) • Taranaki, Manawatū and Wellington: -4 to +9% [+1%] (2040, RCP2.6), -6 to +10% [+1%] (2040, RCP8.5), -6 to +15% [+3%] (2090, RCP2.6), -14 to +14% [+2%] (2090, RCP8.5) • Tasman-Nelson and Marlborough: -3 to +5% [+1%] (2040, RCP2.6), -3 to +8% [+1%] (2040, RCP8.5), -4 to +8% [+2%] (2090, RCP2.6), -3 to +15% [+5%] (2090, RCP8.5) • West Coast and Southland: -4 to +12% [+3%] (2040, RCP2.6), -4 to +12% [+4%] (2040, RCP8.5), -2 to +18% [+5%] (2090, RCP2.6), -8 to +23% (2090, RCP8.5) • Canterbury and Otago: -7 to +15% [+3%] (2040, RCP2.6), -7 to +19% [+3%] (2040, RCP8.5), -6 to +18% (2090, RCP2.6), -9 to +28% [+8%] (2090, RCP8.5).	(Liu et al., 2018; MfE, 2018)
Rainfall extremes	Intensity of daily rain with 20-year recurrence interval • +2.8 to 7.2% [5%] (2040, RCP2.6) • +4.2 to 10.4% [7%] (2040, RCP8.5) • +2.8 to 7.2% [5%] (2090, RCP2.6) • +12.6 to 31.5% [2%] (2090, RCP8.5).	(MfE, 2018)
Drought	Increase in potential evapotranspiration deficit • Northern and eastern North Island: 100-200 mm (2090, RCP8.5) • Western North Island: 50-100 mm (2090, RCP8.5) • Eastern South Island: 50-200 mm (2090, RCP8.5) • Western South Island: 0-50 mm (2090, RCP8.5).	(MfE, 2018)
Windspeed	99th percentile of daily mean wind speed • Northern North Island: 0 to -5% (2090, RCP8.5) • Southern North Island: 0 to +5% (2090, RCP8.5) • South Island: 0 to +10% (2090, RCP8.5).	(MfE, 2018)
Sea-level rise	• 23 cm (2050, RCP2.6) • 28 cm (2050, RCP8.5) • 42 cm (2090 RCP2.6) • 67 cm (2090 RCP8.5). These projections have not been updated to include an Antarctic dynamic ice sheet factor which increased global sea-level projections for RCP 8.5 by ~10 cm. Preliminary CMIP6 projections indicate 40-50 cm (2090, SSP1-RCP2.6) and 70-90 cm (2090, SSP5-RCP8.5).	(MfE, 2017a; IPCC, 2019b)
Sea-level extremes	For a rise in sea level of 30 cm, the 1-in-100-year high water levels may occur about: • Every 4 years at the port of Auckland • Every 2 years at the port of Dunedin • Once a year at the port of Wellington • Once a year at the port of Christchurch.	(PCE, 2015)

Fire	• Seasonal Severity Rating (SSR) increases 50-100% in coastal Marlborough and Otago, 40-50% in Wellington and 30-40% in Taranaki and Whanganui, 0-30% elsewhere (2050, A1B). • Number of days with very high or extreme fire weather increase >100% in coastal Otago, Marlborough and the lower North Island, 50-100% in Taupō and Rotorua, 20-50% in the rest of the North Island, and little change in the rest of the South Island (2050, A1B).	(Pearce et al., 2011)
Tropical cyclones and other storms	Poleward shift of mid-latitude cyclones and potential for a small reduction in frequency.	(MfE, 2018)
Snow and ice	• Maximum snow depth on 31 August may decline by 0-10% (2040, A1B) and 26-54% (2090, A1B). • Annual snow days may be reduced by 5-15 days (2040, RCP2.6), 10-25 days (2040, RCP8.5), 5-15 days (2090, RCP2.6) and 15-45 days (2090 RCP8.5). • Relative to 2015, New Zealand glaciers are projected to lose 36%, 53% and 77 % of their mass by the end of the century under RCP2.6, RCP4.5 and RCP8.5, respectively. • Over the period 2006-2099, New Zealand glaciers are projected to lose 50 to 92% of their ice volume for RCP2.6 to RCP8.5.	(Hendrikx et al., 2013; MfE, 2018; Marzeion et al., 2020) (Anderson et al. 2021)
Ocean acidification	pH is projected to drop by about 0.1 (2090, RCP2.6) to 0.3 (2090 RCP8.5).	(CSIRO and BOM, 2015; Hurd et al., 2018; Law et al., 2018b)

11.3 Observed Impacts, Projected Impacts and Adaptation

This section assesses observed impacts, projected risks, and adaptation for 10 sectors and systems. Boxes provide more detail on specific issues. Risk is considered in terms of vulnerability, hazards (impact driver), exposure, reasons for concern, complex and cascading risks (Chapter 1 Figure 1.2).

11.3.1 Terrestrial and Freshwater Ecosystems

11.3.1.1 Observed Impacts

Widespread and severe impacts on ecosystems and species are now evident across the region (*very high confidence*) (Table 11.4). Climate impacts reflect both on-going change and discrete extreme weather events (Harris et al., 2018) and the climatic change signal is emerging despite confounding influences (Hoffmann et al., 2019). Fundamental shifts are observed in the structure and composition of some ecosystems and associated services (Table 11.4). Impacts documented for species include global and local extinctions, severe regional population declines, and phenotypic responses (Table 11.4). In terrestrial and freshwater ecosystems, land use impacts are interacting with climate, resulting in significant changes to ecosystem structure, composition and function (Bergstrom et al., 2021) with some landscapes experiencing catastrophic impacts (Table 11.4). Some of observed changes may be irreversible where projected impacts on ecosystems and species persist (Table 11.5). Of note is the global extinction of an endemic mammal species, the Bramble Cay melomys (*Melomys rubicola*), from the loss of habitat attributable in part to sea-level rise and storm surges in the Torres Strait (Table 11.4).

Natural forest and woodland ecosystem processes are experiencing differing impacts and responses depending on the climate zone (*high confidence*). In Australia, an overall increase in the forest fire danger index, associated with warming and drying trends (Table 11.2a), has been observed particularly for southern and eastern Australia in recent decades (Box 11.1). The 2019-2020 mega wildfires of south eastern Australia burnt between 5.8 - 8.1 million hectares of mainly temperate broadleaf forest and woodland, but with substantial areas of rainforest also impacted, and were unprecedented in their geographic location, spatial extent, and forest types burnt (Boer et al., 2020; Nolan et al., 2020; Abram et al., 2021; Collins et al., 2021; Godfree et al., 2021). The human influence on these events is evident (Abram et al., 2021; van Oldenborgh et al., 2021) (Box 11.1). The fires had significant consequences for wildlife (Hyman et al., 2020; Nolan et al., 2020; Ward et al., 2020) (Box 11.1) and flow-on impacts for aquatic fauna (Silva et al., 2020). In southern Australia, deeply rooted native tree species can access soil and ground-water resources during drought, providing a level of natural resilience (Bell and Nikolaus Callow, 2020; Liu et al., 2020). However, the Northern Jarrah forests of south western Australia have experienced tree mortality and dieback from long term precipitation decline and acute heatwave-compounded drought (Wardell-Johnson et al., 2015; Matusick et al., 2018). While there is limited information on observed impacts for New Zealand, increased mast seeding events in beech forest ecosystems that stimulate invasive population irruptions have been recorded (Schauber et al., 2002; Tompkins et al., 2013).

Table 11.4: Observed impacts on terrestrial and freshwater ecosystems and species in the region where there is documented evidence that these are directly (e.g. a species thermal tolerances are exceeded) or indirectly (e.g. through changed fire regimes) the result of climate change pressures.

Ecosystem	Climate-related Pressure	Impact	Source
Australia			
Forest and woodlands of southern and southwestern Australia	30-year declining rainfall	Drought-induced canopy dieback across a range of forest and woodland types (e.g. northern jarrah)	(Matusick et al., 2018; Hoffmann et al., 2019)
	Multiple wildfires in short succession resulting from increased fire risk conditions including declining winter rainfall and increasing hot days	Local extirpations and replacement of dominant canopy tree species and replacement by woody shrubs due to seeders having insufficient time to reach reproductive age (Alpine Ash) or vegetative regeneration capacity is exhausted (Snow Gum woodlands)	(Slatyer, 2010; Bowman et al., 2014; Fairman et al., 2016; Harris et al., 2018; Zylstra, 2018)
	Background warming and drying created soil and vegetation conditions that are conducive to fires being ignited by lightning storms in regions that have rarely experienced fire over the last few millennia	Death of fire sensitive trees species from unprecedented fire events (Palaeo-endemic pencil pine forest growing in sphagnum, Tasmania, killed by lightning-ignited fires in 2016)	(Hoffmann et al., 2019)
Australia Alps Bioregion and Tasmanian alpine zones	Severe winter drought; warming and climate-induced biotic interactions	Shifts in dominant vegetation with a decline in grasses and other graminoids and an increase in forb and shrub cover in Bogong High Plains, Victoria, Australia	(Bhend et al., 2012; Hoffmann et al., 2019)

	Snow loss, fire, drought and temperature changes	Changing interactions within and among three key alpine taxa related to food supply and vegetation habitat resources: The mountain pygmy-possum (Burramys parvus), the mountain plum pine (Podocarpus lawrencei) and the bogong moth (Agrostis infusia)	(Hoffmann et al., 2019)
	Retreat of snow line	Increased species diversity in alpine zone	(Slatyer, 2010)
	Reduced snow cover	Loss of snow-related habitat for alpine zone endemic and obligate species	(ACE CRC, 2010; Pepler et al., 2015a; Thompson, 2016; Mitchell et al., 2019)
Wet Tropics World Heritage Area	Warming and increasing length of dry season	Some vertebrate species have already declined in both distribution area and population size, both earlier and more severely than originally predicted	(Moran et al., 2014; Hoffmann et al., 2019)
Sub-Antarctic Macquarie island	Reduced summer water availability for 17 consecutive summers, and increases in mean wind speed, sunshine hours and evapotranspiration over four decades	Dieback in the critically endangered habitat-forming cushion plant Azorella macquariensis in the fellfield and herb field communities	(Bergstrom et al., 2015; Hoffmann et al., 2019)
Mass mortality of wildlife species (flying foxes, freshwater fish)	Extreme heat events; rising water temperatures, temperature fluctuations, altered rainfall regimes including droughts and reduced in-flows	flying foxes - thermal tolerances of species exceeded; fish - amplified extreme temperature fluctuations, increasing annual water basin temperatures, extreme droughts and reduced runoff after rainfall	(AAS, 2019; Ratnayake et al., 2019; Vertessy et al., 2019)
Bramble Cay melomys (mammal) *Melomys rubicola*	Sea-level rise and storm surges in Torres Strait	Loss of habitat and global extinction	(Lunney et al., 2014; Gynther et al., 2016; Waller et al., 2017; CSIRO, 2018)
Koala, *Phascolarctos cinereus*	Increasing drought and rising temperatures, compounding impacts of habitat loss, fire and increasing human population	Population declines and enhanced risk of local extinctions	(Lunney et al., 2014)
Tawny dragon lizard, *Ctenophorus decresii*	Desiccation stress driven by higher body temperatures and declining rainfall	Population decline and potential local extinction in Flinders Ranges, South Australia	(Walker et al., 2015)

Birds	Changing thermal regimes including increasing thermal stress and changes in plant productivity are identified causal	Changes in body size, mass and condition and other traits linked to heat exchange	(Gardner et al., 2014a; Gardner et al., 2014b; Campbell-Tennant et al., 2015; Gardner et al., 2018; Hoffmann et al., 2019)
New Zealand			
Forest Birds	Warming	Increasing invasive predation pressure on endemic forest birds surviving in cool forest refugia, particularly larger-bodied bird species that nest in tree cavities and are poor dispersers	(Walker et al., 2019)
Coastal ecosystems	More severe storms and rising sea levels	Erosion of coastal habitats including dunes and cliffs is reducing habitat	(Rouse et al., 2017)
Beech forest ecosystems	Increasing mean temperatures and indirectly through effects of events like El Niño–Southern Oscillation (ENSO)	Increased beech mast seeding events that stimulate population irruptions for invasive rodents and mustelids which then prey on native species	(Schauber et al., 2002; Tompkins et al., 2013)

11.3.1.2 Projected Impacts

In the near-term (2030-2060), climate change is projected to become an increasingly dominant stress on the region's biodiversity, with some ecosystems experiencing irreversible changes in composition and structure and some threatened species becoming extinct (*high confidence*). Climate change will interact with current ecological conditions, threats and pressures, with cascading ecological impacts, including population declines, heat-related mortalities, extinctions and disruptions for many species and ecosystems (*high confidence*) (Table 11.5)**.** These include inadequate allocation of environmental flows for freshwater fish (Vertessy et al., 2019), native forest logging for old-growth forest-dependent fauna (Lindenmayer et al., 2015; Lindenmayer and Taylor, 2020a; Lindenmayer and Taylor, 2020b), and invasive species (Scott et al., 2018). Climate change has synergistic and compounding impacts particularly in bioregions already experiencing ecosystem degradation, threatened endemics, collapse of keystone species, including those of value to Indigenous Peoples, and high extinction rates as a consequence of human activities (Table 11.4) (Gordon, 2009; Australia SoE, 2016; Weeks et al., 2016; Cresswell and Murphy, 2017; Hare et al., 2019; MfE, 2019; Lindenmayer and Taylor, 2020a; Lindenmayer and Taylor, 2020b; Bergstrom et al., 2021). Some native species are projected to have potentially greater geographic range if they can colonise new areas, while other species may be resilient to projected climate change impacts (Bulgarella et al., 2014; K. Lawrence et al., 2017; Conroy et al., 2019; Rizvanovic et al., 2019).

In southern Australia, some forest ecosystems (alpine ash, snowgum woodland, pencil pine, northern jarrah) are projected to transition to a new state or collapse due to hotter and drier conditions with more fires (Table 11.5) (*high confidence*). In Australia, most native Eucalyptus forest plants have a range of traits that enable them to persist with recurrent fire through recovery buds (sprouters) or regenerate through seeding (Collins, 2020), affording them a high level of resilience. For high end projected 2060-2080 fire weather conditions in south east Australia (Clarke and Evans, 2019), stand-killing wildfires could occur at a severity and frequency greater than the regenerative capacity of seeders (Enright et al., 2015; Clarke and Evans, 2019). Most New

Zealand native plants are not fire resistant and are projected to be replaced by fire-resistant introduced species following climate-change related fires (Perry et al., 2014).

A loss of alpine biodiversity in the south-east Australian Alps Bioregion is projected in the near-term due to less snow on snow patch Feldmark and short alpine herb-fields as well as increased stress on snow-dependent plant and animal species (*high confidence*) (Table 11.3, Table 11.5). In Australia, invasive plants and weeds response rates are expected to be faster than for native species, and climate change could foster the appearance of a new set of weed species, with many bioregions facing increased impacts from non-native plants (*medium confidence)* (Gallagher et al., 2013; Scott et al., 2014; March-Salas and Pertierra, 2020) (Table 11.5), along with declines in some listed weeds (Duursma et al., 2013; Gallagher et al., 2013). In New Zealand, climate change is projected to enable invasive species to expand to higher elevations and southwards (Giejsztowt et al., 2020; MfE, 2020a) (Table 11.5) (*medium confidence*).

Projected responses of ecosystem processes are uncertain in part due to complex interactions of climate change with soil respiration, plant nutrient availability (Hasegawa et al., 2015; Orwin et al., 2015; Ochoa-Hueso et al., 2017) and changing fire regimes (Scheiter et al., 2015; Dowdy et al., 2019) (Table 11.5). For aquatic biota, responses will reflect seasonal differences in water temperature (Wallace et al., 2015), and changes in rainfall intensity, productivity and biodiversity (Jardine et al., 2015). Extreme floods may impact negatively on New Zealand river biota by mobilising nutrients, sediments and toxic chemicals, and aiding dispersal of invasive species. These effects are compounded by homogenisation of rivers through channelization (Death et al., 2015).

Improved coastal modelling, experiments and *in situ* studies are reducing uncertainties at a local scale about the impact of future sea-level rise on coastal freshwater terrestrial wetlands *(medium confidence)* (Shoo et al., 2014; Bayliss et al., 2018; Grieger et al., 2019). Low-lying coastal wetlands are susceptible to saltwater intrusion from sea-level rise (Shoo et al., 2014; Kettles and Bell, 2015; Finlayson et al., 2017) with consequences for species dependent on freshwater habitats (Houston et al., 2020). Saline habitat conditions will move inland and new coastal ecosystem states may emerge, including the World Heritage listed Kakadu's freshwater wetland (Bayliss et al., 2018) (Table 11.5). Increasingly, sea-level rise will shrink the intertidal zone, having implications for wading birds which use this zone (Tait and Pearce, 2019) (Box 11.6). The ecology of freshwater wetlands in New Zealand are projected to be impacted by the intersection of warming, drought and heavy rainfall (Pingram et al., 2021) (Table 11.5).

The impacts on species from projected global warming depend on their physiological and ecological responses for which knowledge is limited (Table 11.5) (Bulgarella et al., 2014; Carter et al., 2018; Green et al., 2021). Knowledge of projected impacts is constrained by uncertainties about the influence of physiological limits, barriers to dispersal, competition, the availability of habitat resources (Worth et al., 2014) and disruptions to ecological interactions (Lakeman-Fraser and Ewers, 2013; Parida et al., 2015; Porfirio et al., 2016). Gaps in ecological modelling of future climate impacts include consideration of long term rainfall and temperature changes (Grimm-Seyfarth et al., 2017; Grimm-Seyfarth et al., 2018), species dispersal rates, evolutionary capacity and phenotypic plasticity and the thresholds at which they are considered adequate to counter the impacts of climate change (Ofori et al., 2017b), as well as indirect effects including sea-level rise and altered fire regimes (Shoo et al., 2014; Cadenhead et al., 2016; He et al., 2016).

Table 11.5: An indicative selection of projected climate-change impacts on terrestrial and freshwater ecosystems and species in Australia and New Zealand respectively.

Ecosystem, species	Climate-related pressure	Projected Impact	Source
Australia			

Floristic composition of vegetation communities	Increases in temperature and reductions in annual precipitation by 2070. Many plant species based on median projection from five global climate models (ACCESS1.0, CNRM-CM5, HADGEM2-CC, MIROC5, NorESM1-M) centred on the decade 2070 under RCP8.5.	47% of vegetation types have characteristic plant species at risk of their climatic tolerances being exceeded from increasing mean annual temperature by 2070 with only 2% at risk from reductions in annual precipitation by 2070	(Gallagher et al., 2019)
Some south east Australian temperate forests	Reduction in winter rainfall and rising spring temperatures resulting in an increase in the frequency of very high fire weather conditions and increased risk of catastrophic wildfires; based on output from 15 CMIP5 GCMs using RCP 8.5 for years for 2060–2079 as compared to 1990–2009	Increase in fire frequency prevents recruitment of obligate seeder resulting in changing dominant species and vegetation structure including long lasting or irreversible shift in formation from tall wet temperate eucalypt forests dominated by obligate seeder trees (e.g. Alpine Ash) to open forest or in worst case to shrubland.	(Doherty et al., 2017; Zylstra, 2018; Bowman et al., 2019; Dowdy et al., 2019; Naccarella et al., 2020)
		Declining rainfall and regolith drying, more unplanned, intense fires and declining productivity places stress on tree growth and compromises biodiversity in northern jarrah forest.	(Wardell-Johnson et al., 2015)
		Tree line stasis or regression (Snow Gum)	(Doherty et al., 2017) (Bowman et al., 2019; Naccarella et al., 2020)
	Increase in lightning-ignited landscape fires along with contracting palaeoendemic refugia due to warmer and drier climates	Population collapse and severe range contraction of slow-growing, fire-sensitive palaeoendemic temperate rainforest species (e.g. Pencil Pine)	(Doherty et al., 2017) (Bowman et al., 2019)
	Rhizosphere responses or accelerated rates of soil organic matter decomposition	Plant nutrient availability may be enhanced	(Hasegawa et al., 2015; Ochoa-Hueso et al., 2017)
Alpine ecosystems	Increasing global warming and rising temperatures ongoing reduction in snow cover and winter rain, and increasing frequency and magnitude of wildfires	Loss of alpine vegetation communities (snow patch Feldmark and short alpine herb-fields) and increased stress on snow-dependent plant and animal species; changing suitability for invasive species	(Slatyer, 2010; Morrison and Pickering, 2013; Pepler et al., 2015a; Williams et al., 2015; Harris et al., 2017)
Northern tropical savannahs	Rainfall and CO_2 effects	Potentially resulting in an in increase in ecosystem carbon storage	(Scheiter et al., 2015)
Murray-Darling River Basin	Drought	Reduced river flow; mass fish kills	(Grafton et al., 2014; AAS, 2019)
Unimpaired river basins	Elevated CO_2 levels	Increase plant water use reduces stream flow	(Ukkola et al., 2016)

Bearded dragons (lizards), *Pogona spp.*	Changes in precipitation	P. henrylawsoni and P. microlepidota to gain suitable habitat, P. nullarbor and P. vitticeps showing the most potential loss	(Wilson and Swan, 2017; Silva et al., 2018)
Xeric bees	Broad temperate tolerances, arid climate adapted	Climate resilient, only small response	(Silva et al., 2018)
Great desert skink Liopholis kintorei	Buffering capacity of underground microclimates, for nocturnal and crepuscular ectotherms	Warming impacts projected to be indirect	(Moore et al., 2018)
22 narrow range fish species in imminent risk of extinction	Projected changes in rainfall, run-off, air temperatures and the frequency of extreme events (drought, fire, flood) compound risk from other key threats especially invasive species	Extinction likely within next 20 years	(Lintermans et al., 2020)
Freshwater taxa (freshwater fish, crayfish, turtles and frogs)	Changed hydrological regimes	Substantial changes to the composition of faunal assemblages in Australian rivers well before the end of this century, with gains/losses balanced for fish but suitable habitat area predicted to decrease for many crayfish and turtle species and nearly all frog species	(James et al., 2017)
New Zealand			
Modified lowland wetlands	Intersection of warming, drought and heavy rainfall (ex-tropical cyclones)	Prolonged anoxic conditions in waterways (blackwater events) leading to mortality of fish (e.g. shortfin eels) and invertebrates, while botulism outbreaks can lead to impacts on waterfowl	(Pingram et al., 2021)
Native forests and lands	Elevated CO_2 levels, warming, increased precipitation.	Short-term beneficial effects on carbon storage. Droughts in eastern areas would decrease productivity and rates of carbon storage in the medium term	(Ausseil et al., 2019b)
	Increased fire intensity and frequency in hot and dry parts of New Zealand	Much of the native vegetation has no fire adaptations causing vulnerability to local extinction due to 'interval squeeze'	(Perry et al., 2014)
Freshwater rivers	Rainfall variation	Cascading effects of warming, drought, floods, and algal blooms compounded by water abstraction	(Macinnis-Ng et al., 2021)
Three species of naturalized woody weeds	Warming and increased CO_2 levels	Increased geographic range	(Sheppard and Stanley, 2014)

Kauri tree, *Agathis australis*	Lower than average rainfall stimulates a drought-deciduous response in this evergreen species	Increased litter fall	(Macinnis-Ng and Schwendenmann, 2015)
Windmill palm	Warming	Increased geographic range	(Aguilar et al., 2017)
New Zealand tussock grasslands	Warming	Enhanced respiration	(Graham et al., 2014)
Invasive species	Warming	Increased invasive species abundance & increased predation on native species	(Tompkins et al., 2013; Macinnis-Ng et al., 2021)
	Warming	Expanded ranges of invasive species in higher/cooler areas	(Sheppard and Stanley, 2014; Walker et al., 2019)
	Warming	Change in flowering phenology and pollination competition	(Giejsztowt et al., 2020)
	Warming	Increase in invasive plants, insects, and pathogens from subtropical/tropical climates	(Macinnis-Ng et al., 2021)
Tuatara (reptile), *Sphenodon punctatus*	Warming	Temperature-dependent sex determination with more males hatch threatening small isolated populations	(Grayson et al., 2014)
	Warming	Increased geographic range	(Carter et al., 2018)
Cattle tick	Warming	Increased geographic range and risk of tick-spread anaemia in cattle	(K. Lawrence et al., 2017)
Brown mudfish, *Neochanna apoda*	Drought	Reduced flow regimes associated with drought interact with reduced habitat due to land use change, leading to population declines and potential local extinction	(White et al., 2016b; White et al., 2017)
Suter's skink (lizard) *Oligosoma suteri*	Warming	Increased suitable range but unclear if dispersal is possible because habitats are isolated	(Stenhouse et al., 2018)
Threatened endemic passerine bird, *Notiomystis cincta*	Fluctuations in total precipitation, particularly increased and more variable rainfall	Heavy rainfall can flood nests and kill fledglings while droughts can cause population-wide reproductive failure	(Correia et al., 2015)
Feral cats	Warming	Increased geographic range	(Aguilar et al., 2015b)

11.3.1.3 Adaptation

Managing climate change risks to ecosystems is primarily based on reducing the impact of other anthropogenic pressures, including invasive species, and facilitating natural adaptation (*high confidence*). This approach is most feasible within protected areas on public, private and Indigenous land and sea (Bellard et al., 2014; Liu et al., 2020) but is also applicable elsewhere (Barnes et al., 2015). Effective strategies promote ecosystem resilience through changing unsustainable land uses and management practices, increasing habitat connectivity, controlling introduced species, restoring habitats, implementing appropriate fire management, integrated risk assessment and adaptation planning (B. Frame et al., 2018; Lindenmayer et al., 2020; Macinnis-Ng et al., 2021). Complementary approaches include *ex situ* seed banks (Morrison and Pickering, 2013; Christie et al., 2020).

Best practice conservation adaptation planning is informed by data on key habitats, including refugia, and restoration that facilitates species movements and employs adaptive pathways (*very high confidence*) (Guerin and Lowe, 2013; Reside et al., 2014; Shoo et al., 2014; Keppel et al., 2015; Andrew and Warrener, 2017; Baumgartner et al., 2018; Harris et al., 2018; Jacobs et al., 2018a; Das et al., 2019; Walker et al., 2019; Molloy et al., 2020). Landscape planning (Bond et al., 2014; McCormack, 2018) helps reduce habitat loss and facilitates species dispersal and gene flow (McLean et al., 2014; Shoo et al., 2014; Lowe et al., 2015; Harris et al., 2018; McCormack, 2018) and allows for new ecological opportunities (Norman and Christidis, 2016). Coastal squeeze is a threat to freshwater wetlands and requires planning for the potential inland shift (Grieger et al., 2019). Adaptations that maintain critical volumes and periodicity of environmental flows will help protect freshwater biodiversity (Yen et al., 2013; Barnett et al., 2015; Wang et al., 2018b) (Box 11.3).

Adaptation planning for ecosystems and species requires monitoring and evaluation to identify trigger points and thresholds for new actions to be implemented *(high confidence)* (Tanner-McAllister et al., 2017; Williams et al., 2020). Best planning practice includes keeping options open (Barnett et al., 2015; Dunlop et al., 2016; Finlayson et al., 2017) and updating management plans in light of new information. New insights are emerging into how species' natural adaptive capacities can inform adaptation planning (Llewelyn et al., 2016; Steane et al., 2017; Hoeppner and Hughes, 2019). Physiological limits to adaptation in some species are being identified (Barnett et al., 2015; Sorensen et al., 2016) and where natural responses are not feasible, human-assisted translocations may be warranted (Becker et al., 2013; Chauvenet et al., 2013; Innes et al., 2019) for some species (Ofori et al., 2017a; Ofori et al., 2017b). Legal reform may be needed to better enable climate adaptation for biodiversity conservation that recognises species' natural adjustments to their distributions, and the difficulties in predicting the consequences for ecological interactions and ecosystem services (McCormack, 2018; McDonald et al., 2019).

Adaptation research priorities include understanding of the interactions and cumulative impacts of existing stressors and climate change, and the implications for managing ecosystems and natural resources (Williams et al., 2020). For Australia, research on implementation strategies for conservation and managing threats, stress and natural assets is a priority (Williams et al., 2020). For New Zealand, understanding how terrestrial ecosystems and species respond to climate change is a priority and where existing stressors are affecting freshwater quantity and quality, in-situ monitoring to detect and evaluate projections of climate change impacts on biodiversity, and a national data repository are lacking (MfE, 2020a). The projected increase in invasive species indicates the importance of a step up in pest management effort to ensure native species persistence as invasive species spread from climate change (Firn et al., 2015). There remains a gap between the knowledge generated, potential adaptation strategies, and their incorporation into conservation instruments (*medium confidence*) (Graham et al., 2019; Hoeppner and Hughes, 2019), though there is increasing recognition of the need to improve governance and management structures for their implementation (Christie et al., 2020).

[START BOX 11.1 HERE]

Box 11.1: Escalating Impacts and Risks of Wildfire

Fire activity depends on weather, ignition sources, land management practices, and fuel flammability, availability and continuity (Bradstock et al., 2014). Increased fire activity in southeast Australia associated with climate change has been observed since 1950 (Abram et al., 2021) but trends vary regionally (Bradstock et al., 2014) (*medium confidence*). In New Zealand, there has been an increased frequency of major wildfires in plantations (FENZ, 2018) and at the rural-urban interface (Pearce, 2018) (*medium confidence*). In northern Australia, increased wet season rainfall (Gallego et al., 2017) has increased dry season fuel loads (Harris et al., 2008).

In Australia, the frequency and severity of dangerous fire weather conditions is increasing, with partial attribution to climate change (*very high confidence*) (Dowdy and Pepler, 2018; Abram et al., 2021) (11.2.1,

Figure Box 11.1.1), especially in southern and eastern Australia during spring and summer (Harris and Lucas, 2019). Although Australia's eucalypt forests and woodlands are fire adapted (Collins, 2020), increasing intensity and frequency of fires may exceed their resilience due to shorter intervals between high-severity fires (Bowman et al., 2014; Etchells et al., 2020; Lindenmayer and Taylor, 2020a). Recent fires have severely impacted eastern rainforests, including significant Gondwana refugia (Abram et al., 2021). In New Zealand, the trends in very high and extreme fire weather (1997–2019) have not yet been attributed to climate change (MfE, 2020a).

Fire weather is projected to increase in frequency, severity and duration for southern and eastern Australia (*high confidence*) and most of New Zealand (*medium confidence*) (11.2.2), with projected increases in pyro-convection risk for parts of southern Australia (Dowdy et al., 2019) and increased dry-lightning and fire ignition for southeast Australia (Mariani et al., 2019; Dowdy, 2020). Increased fire risk in spring may reduce opportunities for prescribed fuel-reduction burning in some regions (Harris and Lucas, 2019; Di Virgilio et al., 2020). Fuel dryness is a key constraint on wildfire occurrence (Ruthrof et al., 2016). Vegetation change will affect fuel load and fire risk in different areas in complex ways (Watt et al., 2019; Alexandra and Max Finlayson, 2020; Clarke et al., 2020; Sanderson and Fisher, 2020).

Direct effects of wildfire include death and injury to people and animals, and damage to ecosystems, property, agriculture, water supplies and other infrastructure (Brodison, 2013; Pearce, 2018; de Jesus et al., 2020; Johnston et al., 2020; Maybery et al., 2020). Indirect effects include electricity and communication blackouts leading to cascading impacts on services, infrastructure and communities (Bowman, 2012; Schavemaker and van der Sluis, 2017).

For New Zealand, there has been recent increased frequency and magnitude of property losses due to wildfire (Pearce, 2018). The 1660ha Port Hills fire in 2017 resulted in the greatest house losses (9) in almost 100 years (Langer et al., 2018), but the subsequent 5540ha Lake Ohau fire destroyed 53 houses in 2020 (Waitaki District Council, 2020).

In Australia, between 1987 and 2016, there were 218 deaths, 1,000 injuries, 2,600 people left homeless and 69,000 people affected by wildfire (Deloitte, 2017b). Wildfires cost about \$1.1 billion per year on average (11.5.2).

The Australian wildfires of 2019–2020 resulted in 33 deaths, over 3,000 houses destroyed, \$2.3 billion in insured losses, and \$3.6 billion in losses for tourism, hospitality, agriculture and forestry (CoA, 2020e; Filkov et al., 2020) (Figure Box 11.1.2). Smoke caused a further 429 deaths and 3230 hospitalizations as a result of respiratory distress and illness, with health costs totalling \$1.95 billion (Johnston et al., 2020). These fires burnt about 5.8 to 8.1 million hectares of forest in eastern Australia (Ward et al., 2020; Godfree et al., 2021) resulting in the loss or displacement of nearly 3 billion vertebrate animals (CoA, 2020e; Wintle et al., 2020). 114 listed threatened species lost at least 50% of their habitat, and 49 lost 80% (Wintle et al., 2020) among other severe ecological impacts (Hyman et al., 2020). Smoke carried over 4,000 km to New Zealand where it increased snow/glacier melt through darkening surfaces and produced detectable odour (Pu et al. 2021)(Filkov et al., 2020). The fire season of 2019–20 was at least 30% more likely than a century ago due to the influence of climate change (van Oldenborgh et al., 2021). Following the fires, a Royal Commission into National Natural Disaster Arrangements made 80 recommendations, most of which were accepted by government, including establishing a disaster advisory body and a resilience and recovery agency (11.5.2.3) (CoA, 2020e).

In the face of climate change and the increased cost of fire damage and suppression, there has been considerable investment in fire risk reduction (Table Box 11.1.1). Recent analysis of 8,800 fires in Australia shows resource constraints in response capacity are a barrier to effectively containing fires (Collins et al., 2018b), compounded by lengthened and more extreme fire seasons.

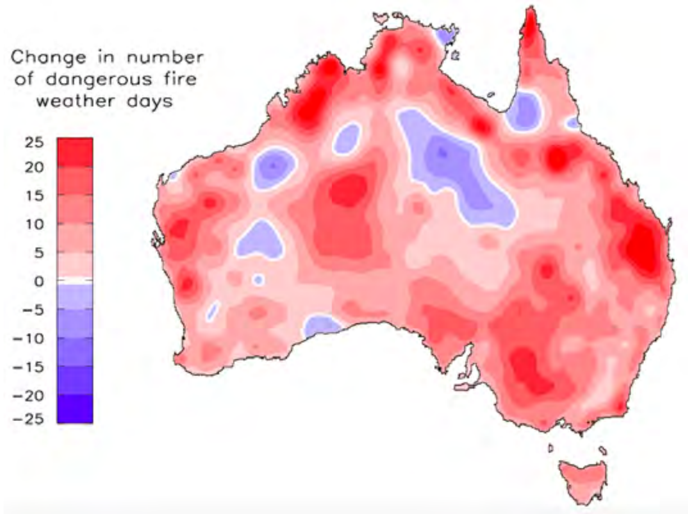

Figure Box 11.1.1: Change in the annual (July to June) number of days that the Forest Fire Danger Index (FFDI) exceeds its 90th percentile from July 1985 to June 2020 relative to July 1950 to June 1985 (BoM and CSIRO, 2020; Abram et al., 2021).

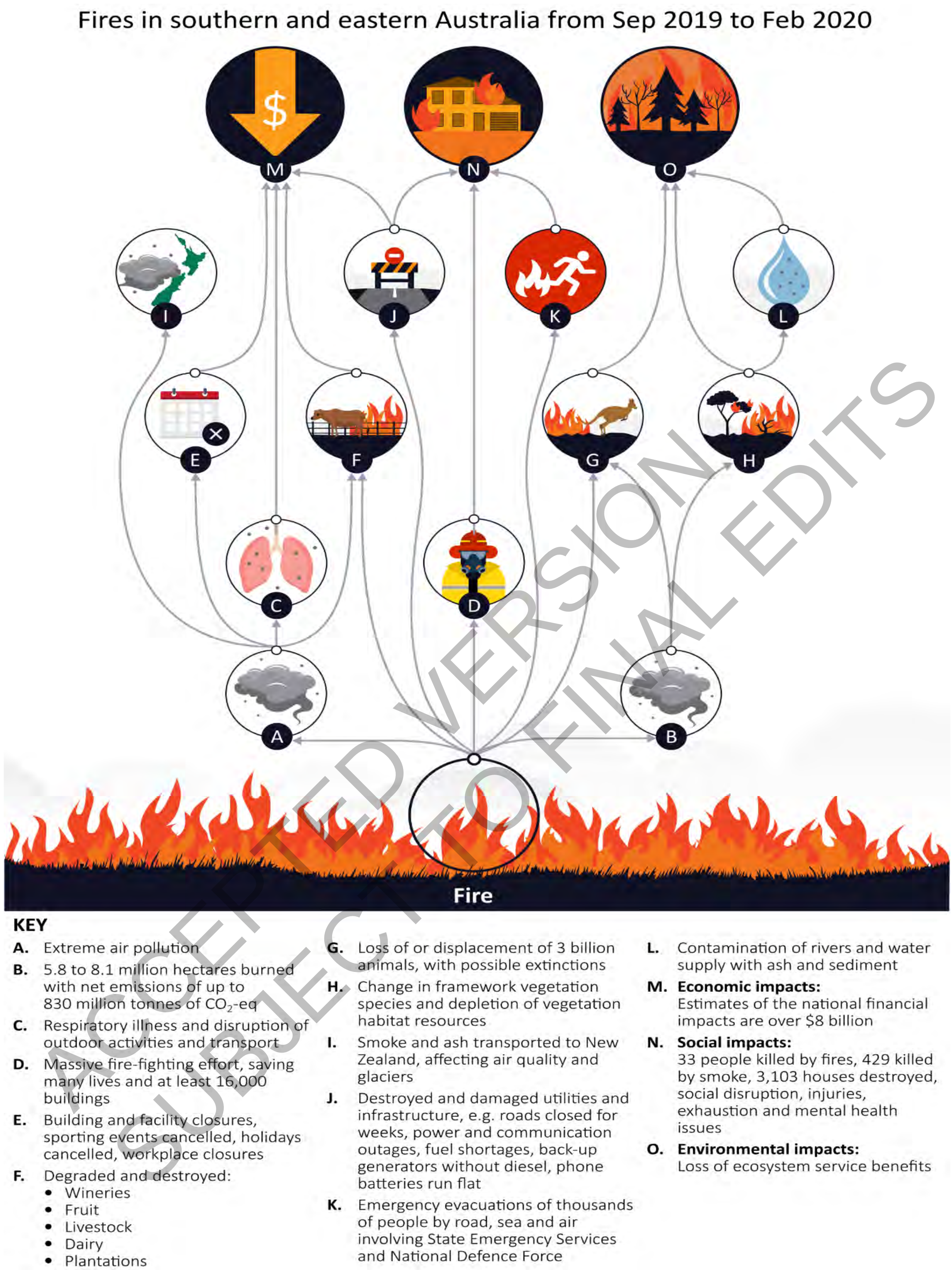

Figure Box 11.1.2: Cascading impacts on people, economic activity, built assets, ecosystems and species arising from the Black Summer fires of 2019–2020 in eastern and southern Australia (Boer et al., 2020; CoA, 2020e; CoA, 2020b; CoA, 2020a; CSIRO, 2020; Filkov et al., 2020; Johnston et al., 2020; Ward et al., 2020; Wintle et al., 2020; Abram et al., 2021; Godfree et al., 2021).

Table Box 11.1.1: Examples of adaptation options and enablers to reduce wildfire risk (Hart and Langer, 2011; Mitchell, 2013; Price et al., 2015; Tolhurst and McCarthy, 2016; Deloitte, 2017b; Miller et al., 2017; Steffen et al., 2017; Kornakova and Glavovic, 2018; Newton et al., 2018; Pearce, 2018; CoA, 2020e; McKemey et al., 2020).

Land management
Prescribed burning to reduce fuel load close to built assets.
Engagement with Australia's Aboriginal and Torres Strait Islander Peoples to utilise and learn from their fire management knowledge and skills to assist in management of the landscape and greenhouse gas mitigation.
Locating power lines appropriately or underground and decentralizing power supply to reduce ignitions.
Preventative, community-based interventions to reduce ignitions from arson and accidental fires.
Reduced exposure of new assets through statutory spatial planning and land use regulations, building codes and building design standards.
Communications
Clearer communication of existing exposure and vulnerability to enable informed decisions about risk tolerance and management. This should include sites of key biodiversity that are sensitive or susceptible to fire.
Increased research to understand interactions between fire, fuel, weather, climate and human factors to enhance projections of fire occurrence and behaviour.
Community education and engagement, encouraging house and property maintenance, improving early warning systems, more targeted messaging, and increased emergency evacuation planning and sheltering options.
Infrastructure
Enhanced training and support for fire-fighters and aerial fire-fighting assets, including sharing of resources nationally and internationally to address the increasing overlap of fire seasons which are lengthening across the world.
Nationally consistent response to exceedance of air quality standards.
Improved governance arrangements to ensure greater accountability and coordination between agencies, sharing of data and resources for emergency planning, and greater understanding of risks to critical infrastructure and supply chains.
Development of new systems to augment capability of fire services and technological advances to detect and respond to fires.

[END BOX 11.1 HERE]

11.3.2 Coastal and Ocean Ecosystems

Australia's EEZ covers over 8.1 million km^2 of marine territory, including 50,000 km of coastline (Dhanjal-Adams et al., 2016), spanning sub-Antarctic islands in the south to tropical waters in the north. New Zealand's marine territory extends from the sub-tropics to sub-Antarctic waters, encompassing an EEZ of 4 million km^2, 18,000 km of coastline and 700 smaller islands and islets, in addition to the two main islands (Costello et al., 2010a; MfE, 2016).

The marine environment is important to the culture, health and well-being of the region's diverse Indigenous Peoples, including those who had sovereign ownership, governance, resource rights, and stewardship over 'Sea Country' for many thousands of years before the current sea level stabilised approximately 6000 years ago and before current coastal ecosystems were established (Rist et al., 2019). Marine environments contribute A$69 billion per year to Australia's economy (Eadie et al., 2011), and NZ$4 billion per year to New Zealand's economy (MfE, 2016). They have a high proportion of rare and endemic species (Croxall et al., 2012) and provide ecosystem services including food production, coastal protection, tourism and carbon sequestration (Croxall et al., 2012; Kelleway et al., 2017). Half of the species within New Zealand's seas are endemic (Costello et al., 2010b).

11.3.2.1 Observed Impacts

Climate change is having major impacts on the region's oceans (*very high confidence*) (Table 11.6) (Law et al., 2016; Sutton and Bowen, 2019). Rising sea surface temperatures have exacerbated marine heatwaves, notably near Western Australia in 2011, the Great Barrier Reef in 2016, 2017 and 2020, and the Tasman Sea in 2015/2016, 2017/2018 and 2018/19 (Table 11.2) (BoM and CSIRO, 2018; AMS, 2019; NIWA, 2019; Salinger et al., 2019b; Sutton and Bowen, 2019; BoM, 2020a; Salinger et al., 2020; Oliver et al., 2021). Temperature anomalies ranged from 1.2-4.0˚C and durations ranged from 90-250 days (Table 11.2).

Ocean carbon storage and acidification has led to decreased surface pH in the region (Table 11.2) including the sub-Antarctic waters off the East Coast of New Zealand's South Island (*very high confidence*) (Law et al., 2016). The depth of the Aragonite Saturation Horizon has shallowed by 50–100 m over much of New Zealand, which may limit and/or increase the energetic costs of growth of calcifying species (Anderson et al., 2015; Bostock et al., 2015; Mikaloff-Fletcher et al., 2017) (*low confidence*).

In the estuaries of south-western Australia, sustained warming and drying trends have caused dramatic declines in freshwater flows of up to 70% since the 1970s, and increased frequency and severity of hypersaline conditions; enhanced water column stratification and hypoxia; and reduced flushing and greater retention of nutrients (Hallett et al., 2017).

Extensive changes in the life history and distribution of species have been observed in Australia's (*very high confidence*) (Gervais et al., 2021) and New Zealand's marine systems (*medium confidence*) (Table 11.6) (Cross-Chapter box MOVING SPECIES in Chapter 5). New occurrences or increased prevalence of disease, toxins and viruses are evident (de Kantzow et al., 2017; Condie et al., 2019), along with heat stress mortalities and changes in community composition (Wernberg et al., 2016; Zarco-Perello et al., 2017; Thomsen et al., 2019). Extreme climatic events in Australia from 2011 to 2017 led to abrupt and extensive mortality of key habitat-forming organisms – corals, kelps, seagrasses, and mangroves – along over 45% of the continental coastline of Australia (*high confidence*) (Babcock et al., 2019).

In 2016 and 2017, the Great Barrier Reef (GBR) experienced consecutive occurrences of the most severe coral bleaching in recorded history (*very high confidence*) (Box 11.2), with shallow-water reef in the top two thirds of the GBR affected and the severity of bleaching on individual reefs tightly correlated with the level of local heat exposure (Hughes et al., 2018b; Hughes et al., 2019c). Mass mortality of corals from these two unprecedented events resulted in larval recruitment in 2018 declining by 89% compared to historical levels (Hughes et al., 2019b). Southern reefs were also affected by warming, although significantly less than in the north (Kennedy et al., 2018). Coral reefs in Australia are at very high risk of continued negative effects on ecosystem structure and function (Hughes et al., 2019b) (*very high confidence*), cultural well-being (Goldberg et al., 2016; Lyons et al., 2019) (*very high confidence*), food provision (Hoegh-Guldberg et al., 2017) (*medium confidence*), coastal protection (Ferrario et al., 2014) (*high confidence*) and tourism (Deloitte Access Economics, 2017; Prideaux and Pabel, 2018; GBRMPA, 2019) (*high confidence*). If bleaching persists, an estimated 10,000 jobs and A$1 billion in revenue would be lost per year from declines in tourism alone (Swann and Campbell, 2016).

11.3.2.2 Projected Impacts

Future ocean warming, coupled with periodic extreme heat events, is projected to lead to the continued loss of ecosystem services and ecological functions (*high confidence*) (Smale et al., 2019), as species further shift their distributions and/or decline in abundance (Day et al., 2018). Compounding climate-driven changes in the distribution of habitat forming species, invasive macroalgae are predicted to exhibit higher growth under all higher pCO_2 and lower pH conditions (Roth-Schulze et al., 2018). Corals and mangroves around northern Australia and kelp and seagrass around southern Australia are of critical importance for ecosystem structure and function, fisheries productivity, coastal protection and carbon sequestration; these ecosystem services are therefore *extremely likely*[2] to decline with continued warming. Equally, many species provide important ecosystem structure and function in New Zealand's seas including in the deep sea (Tracey and Hjorvarsdottir, 2019). The future level of sustainable exploitation of fisheries is dependent on how climate change impacts these ecosystems. Native kelp is projected to further decline in south-eastern New Zealand with warming seas (Table 11.6). Climate change could affect New Zealand fisheries' productivity (Cummings et al., 2021), and both ocean warming and acidification may directly affect shellfish culture (Cunningham et al., 2016; Cummings et al., 2019), and indirectly through changes in phytoplankton production (Pinkerton, 2017).

Climate change related temperature and acidification may affect species sex ratios and thus population viability (*medium confidence*) (Table 11.3) (Law et al., 2016; Tait et al., 2016; Mikaloff-Fletcher et al., 2017). Acidification may alter sex determination (e.g., in the oyster *Saccostrea glomerate*), resulting in changes in sex ratios (Parker et al., 2018), and may thus affect reproductive success (*low confidence*). Decreasing river flows (Chiew et al., 2017) are projected to cause periodically open estuaries across south-west Australia to remain closed for longer periods, inhibiting the extent to which marine taxa can access these systems (Hallett et al., 2017) and with warming predicted to constrain activity in some large fish (Scott et al., 2019b). Major knowledge gaps include environmental tolerances of key life stages, sources of recruitment, population linkages, critical ecological (e.g., predator–prey interactions) or phenological relationships, and projected responses to lowered pH (Fleming et al., 2014; Fogarty et al., 2019).

Black-browed albatrosses breeding on Macquarie Island may be more vulnerable to future climate-driven changes to weather patterns in the Southern Ocean, and potential latitudinal shifts in the sub-Antarctic Front (Cleeland et al., 2019). New Zealand coastal ecosystems face risks from sea-level rise and extreme weather events (MfE, 2020a).

Nutrient availability and productivity in sub-tropical waters of New Zealand are projected to decline due to increased sea surface temperature and strengthening of the thermocline, but may increase in sub-Antarctic waters, potentially bringing some benefit to fish and other species (*low confidence*) (Law et al., 2018b). For New Zealand waters as a whole, declines in net primary productivity of 1.2% and 4.5% are projected under RCP4.5 and RCP8.5 respectively by 2100, and declines in primary production of surface waters by an average 6% from the present day under RCP8.5, with sub-tropical waters experiencing the largest decline (Tait et al., 2016).

The pH of surface waters around New Zealand is projected to decline by 0.33 under RCP 8.5 by 2090 (Tait et al., 2016), and the depth at which carbonate dissolves is projected to be significantly shallower (Mikaloff-Fletcher et al., 2017) affecting the distribution of some species of calcifying cold water corals (Law et al., 2016) (*medium confidence*). However, model projections suggest that the top of the Chatham Rise may provide temporary refugia for scleractinian stony corals from ocean acidification because the Chatham Rise sits above the aragonite saturation horizon (Anderson et al., 2015; Bostock et al., 2015). For sub-tropical corals, skeletal formation will be vulnerable to the changes in ocean pH with implications for their longer-term growth and resilience (Foster et al., 2015).

11.3.2.3 Adaptation

Climate change adaptation opportunities and pathways have been identified across aquaculture, fisheries, conservation and tourism sectors in the region (MacDiarmid et al., 2013; Fleming et al., 2014; MPI, 2015; Jennings et al., 2016; MfE, 2016; Royal Society Te Apārangi, 2017; Ling and Hobday, 2019) and some stakeholders are already autonomously adapting (Pecl et al., 2019). Some fishing and aquaculture industries use seasonal forecasts of environmental conditions, to improve decision making, risk management, and business planning (Hobday et al., 2016) with potential to use 5-yearly forecasts similarly (Champion et al., 2019). Shifts in the distribution, and availability of target species (e.g., oceanic tuna) would impact the

[2] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

ability of domestic fishing vessels to continue current fishing practices, with potential social and economic adjustment costs (Dell et al., 2015), including disruption to supply chains (Fleming et al., 2014; Plagányi et al., 2014) (Cross-Chapter Box MOVING SPECIES in Chapter 5). Species abundance data are insufficient to enable projections of climate impacts on fishery productivity. However, fishery and aquaculture industries are considering adaptation strategies, such as changing harvests and relocating farms (Pinkerton, 2017). Thus, while climate change is *extremely likely* to affect the abundance and distribution of marine species around New Zealand, insufficient monitoring means there is limited evidence of ecosystem level change in biodiversity to date, and no quantitative projections of which species may win and lose to climate change (Table 11.6) (Law et al., 2018a; Law et al., 2018b).

Table 11.6: Observed climate-change related changes in the marine ecosystems of Australia and New Zealand. Climate-related impacts have been documented at a range of scales from single species or region-specific studies, to multi-species or community-level changes.

Type of change	Examples	Climate-related Pressure	Source
Australia			
Reduced activity and increased energetic demands	Coral trout (*Plectropomus leopardus*) one of Australia's most important commercial and recreational tropical finfish species	Increased temperature (experimental laboratory study) and ocean warming	(Johansen et al., 2014; Scott et al., 2017)
Estuaries warming and freshening	Australian lagoons and rivers warming and decreasing pH at a faster rate than predicted by climate models	Warming and reduction in rainfall (leading to reduced flows and therefore being less frequently open to the sea)	(Scanes et al., 2020)
Changes in life-history traits, behaviour or recruitment	Reduced size of Sydney rock oysters (for commercial sale)	Limited capacity to bio mineralize under acidification conditions	(Fitzer et al., 2018)
	Reduced growth in tiger flathead fish in equatorward range	Ocean warming	(Morrongiello and Thresher, 2015)
	55% of 335 fish species became smaller and 45% became larger as seas warmed around Australia	Ocean warming (over three decades)	(Audzijonyte et al., 2020)
	Rock lobster display reduced avoidance of predators at 23°C compared to 20°C	Increased temperature (experimental laboratory study)	(Briceño et al., 2020)
	Analysis of stress rings in cores of corals from the Great Barrier Reef dating back to 1815, found that following bleaching events, the coral was less affected by subsequent marine heatwaves.	Heat events	(DeCarlo et al., 2019)
	Mortality and reductions in spawning stocks of fishery important abalone, prawns, rock lobsters	2011 marine heatwave	(Caputi et al., 2019)

	Recruitment of coral on GBR reduced to 11% of long-term average	Warming-driven back-to-back global bleaching events	(Hughes et al., 2019b)
	Green turtle hatchlings from southern GBR 65-69% female and hatchlings from northern GBR 100% female for last two decades	Increased sand temperatures	(Jensen et al., 2018)
New diseases, toxins	First occurrence of the virulent virus causing Pacific Oyster Mortality Syndrome (POMS), up to 90% of all farmed oysters died in impacted areas	Detected during heatwave	(de Kantzow et al., 2017)
	Mussels, scallops, oysters, clams, abalone and rock lobsters on the east coast of Tasmania found to have high levels of Paralytic Shellfish Toxins, originating from a bloom of the harmful *Alexandrium tamarense*	Warming and extension of the East Australian Current	(Hallegraeff and Bolch, 2016)
	Range expansion of phytoplankton *Noctiluca* which can be toxic	Warming and extension of the East Australian Current	(Hallegraeff et al., 2020)
	Mortality fish following algal blooms in South Australia	2013 marine heatwave	(Roberts et al., 2019)
Changes in species distributions	Range extensions at the poleward range limit have been detected in: Fish, Cephalopods, Crustaceans, Nudibranchs, Urchins, Corals.	Ocean warming	(Baird et al., 2012; Robinson et al., 2015; Sunday et al., 2015; Ling et al., 2018; Nimbs and Smith, 2018; Ramos et al., 2018; Smith et al., 2019; Caswell et al., 2020)
	Contractions in range at the equatorward range edge have been detected in: Anemones, Asteroids, Gastropods, Mussels, Algae.	Ocean warming	(Pitt et al., 2010; Poloczanska et al., 2011; Smale et al., 2019)
	Australia's most southern dominant reef building coral, *Plesiastrea versipora* in eastern Bass Strait, increasing in abundance at the poleward edge of the species' range, and also in Western Australia	Ocean warming	(Tuckett et al., 2017; Ling et al., 2018)
	South-west Australia fish assemblages- warm water fish increasing in density at poleward edge of distributions and cool-water species decrease in density at equatorward edge of distributions; increase in warm-water habitat forming species leading to reduced habitat for invertebrate assemblages	Combination of increased temperatures and changes in habitat-forming algal species	(Shalders et al., 2018; Teagle et al., 2018)
	Predicted reduction range of rare W*ilsonia humilis* herb in Tasmanian saltmarsh but no change in rest of community	Wetter and drier climate	(Prahalad and Kirkpatrick, 2019)

Changes in abundance	Shift towards a zooplankton community dominated by warm-water small copepods in south-east Australia	Ocean warming	(Kelly et al., 2016)
	Diebacks of tidal wetland mangroves	2015–2016 heatwaves combined with moisture stress	(Duke et al., 2017)
	Decline in giant kelp in Tasmania, Australia. Less than 10% remaining. Loss of kelp Australia-wide totalling at least 140,187 ha	Ocean warming & change in East Australian Current (lower nutrients)	(Wahl et al., 2015; Butler et al., 2020; Filbee-Dexter and Wernberg, 2020)
	Regional loss of seagrass in Shark Bay World Heritage Area, Western Australia	High air and water temperatures during 2011 heatwave	(Strydom et al., 2020)
	Increased annual dugong and inshore dolphin mortality across Queensland	Sustained low air temperature and increased freshwater discharge during high SOI (ENSO) index	(Meager and Limpus, 2014)
	Predict equatorward decline and poleward shift of sea urchin in eastern Australia	Ocean warming	(Castro et al., 2020)
	Increasing mortality of Australian fur seal pups in low-lying colonies	Storm surges and high tides amplified by ongoing sea-level rise	(McLean et al., 2018) (Box 11.6)
Rapid shifts in community composition, structure and integrity	Community-wide tropicalization in Australian temperate reef communities. Temperate species replaced by seaweeds, invertebrates, corals, and fishes characteristic of subtropical and tropical waters	Extreme marine heatwaves led to a 100-km range contraction of extensive kelp forests	(Vergés et al., 2016; Wernberg et al., 2016)
	On-going declines in habitat-forming seaweeds	Climate-driven shift of tropical herbivores	(Thomson et al., 2015; Nowicki et al., 2017; Zarco-Perello et al., 2017) (Wernberg et al., 2016)
	Dieback of temperate seagrass in Shark Bay, Australia, subsequently replaced by a tropical early successional seagrass with seagrass-associated megafauna (sea turtles) declining in health status	2011 Marine heatwave	(Strydom et al., 2020)
	Increased herbivory by fish on tropicalized reefs of Western Australia	Change in species composition due to ocean warming	(Zarco-Perello et al., 2019)
	No recovery two years after coral bleaching and macro alga mortality in western Australia	2011 marine heatwave	(Bridge et al., 2014)

	Mass mortality of particular coral species on affected reefs during heatwaves on the Great Barrier Reef (eastern Australia) led to altered coral reef structure and species composition 8 months later.	2016 marine heatwave	(Hughes et al., 2018c)
	Community-wide restructuring along the Great Barrier Reef, one year after the 2016 mass bleaching event.	2016 Marine heatwave	(Stuart-Smith et al., 2018)
New Zealand			
Changes in life-history	Alteration of the shell of pāua (black footed abalone, *Haliotis iris*) under lowered pH (calcite layer thinner, greater etching of external shell surface)	Lowered pH (experimental laboratory study)	(Cummings et al., 2019)
	Decline in maximum swimming performance of kingfish and snapper	Elevated CO_2 (experimental laboratory study)	(Watson et al., 2018; McMahon et al., 2020)
	Increased mortality and faster growth in juvenile kingfish	Increased temperature	(Watson et al., 2018)
	Earlier spawning of snapper in South Island	2017–2018 heatwave	(Salinger et al., 2019b)
Increase in mortality	Heat stress mortality in salmon farms off Marlborough, New Zealand, where 20 % of the salmon stocks died	2017–18 marine heatwave	(Salinger et al., 2019b)
Changes in species distributions	Species increasingly caught further south, e.g. snapper and kingfish	Ocean warming and 2017–2018 marine heatwave	(Salinger et al., 2019b)
	Non-breeding distribution of New Zealand nesting seabird (Antarctic Prion) shifting south with long term climate inferred from stable isotopes	Climate warming	(Grecian et al., 2016)
	Less phytoplankton production in Tasman Sea but more on subtropical front	Ocean warming	(Chiswell and Sutton, 2020)
	Loss of bull kelp (*Durvillaea*) populations in southern New Zealand subsequently replaced by the introduced kelp *Undaria*	2017-18 heatwave when sea and air temperatures exceeded 23 and 30 °C respectively	(Salinger et al., 2019b; Thomsen et al., 2019; Salinger et al., 2020)

[START BOX 11.2 HERE]

Box 11.2: The Great Barrier Reef in Crisis

The Great Barrier Reef ("GBR") is the world's largest coral reef system, comprising 3,863 reefs over an area of 348,700 km^2, stretching for 2,300 km. The GBR is a central cornerstone of the beliefs, knowledges, Lores, languages and ways of living for over 70 geographically and culturally diverse Traditional Owner groups spanning the length of the GBR (Dale et al., 2018), and contributes an estimated A$6.4 billion per year (pre COVID) to the Australian economy, mainly via tourism. As the world's most extensive coral reef ecosystem, GBR is a globally outstanding and significant entity, with practically the entire ecosystem inscribed as World Heritage in 1981 (UNESCO, 2021).

The GBR is already severely impacted by climate change, particularly ocean warming, through more frequent and severe coral bleaching (Hughes et al., 2018b; Hughes et al., 2019c) (*very high confidence*). The worst coral bleaching event on record affected over 90% of reefs in 2016 (Hughes et al., 2018b). In the most northern 700-km-long section of the GBR in which the heat exposure was the most extreme, 50% of the coral cover on reef crests was lost within eight months (Hughes et al., 2018c). Throughout the entire GBR, including the southern third where heat exposure was minimal, the cover of corals declined by 30% between March and November 2016 (Hughes et al., 2018b). In 2017, the central third of the reef was the most severely affected and the back-to-back regional-scale bleaching events has led to an unprecedented shift in the composition of GBR coral assemblages, transforming the northern and middle sections of the reef system (Hughes et al., 2018c) to a highly degraded state *(very high confidence)*. Coral recruitment to the GBR in 2018 was reduced to only 11% of the long-term average (Hughes et al., 2019b). A mass bleaching event also occurred in 2020, making it the third event in five years (BoM, 2020a) (Figure Boxes 11.2.1 and 11.2.2).

Increased heat exposure also affects the abundance and distribution of associated fish, invertebrates and algae *(high confidence)* (Stuart-Smith et al., 2018). Thus, coral bleaching is an indicator of thermal effects on coral habitat, fauna and flora. Bleaching is expected to continue for the GBR, and Australia's other coral reef systems (*virtually certain*). Bleaching conditions are projected to occur twice each decade from 2035 and annually after 2044 under RCP8.5, and annually after 2051 under RCP4.5 (Heron et al., 2017). Three degrees of global warming would result in over six times the 2016 level of thermal stress (Lough et al., 2018).

Increases in cyclone intensity projected for this century, and other extreme weather events, will greatly accelerate coral reef degradation (Osborne et al., 2017). Additionally, through interactions between elevated ocean temperature and coastal runoff (nutrient and sediment), extreme weather events may contribute to an increased frequency and/or amplitude of crown of thorn starfish outbreaks (Uthicke et al., 2015), further reducing the spatial distribution of coral.

Recovery of coral reefs following repeated disturbance events is slow (Hughes et al., 2019b; IPCC, 2019b), and it takes at least a decade after each bleaching event for the very fastest growing corals to recover (*high confidence*) (Gilmour et al., 2013; Osborne et al., 2017). Estimates of future levels of thermal stress, measured as 'degree heating months' which incorporates both the magnitude and duration of warm season sea surface temperatures (SST) anomalies, suggest that achieving the 1.5°C Paris Agreement target would be insufficient to prevent more frequent mass bleaching events (*very high confidence*) (Lough et al., 2018), although it may reduce their occurrence (Heron et al., 2017), and occurrences of warming events similar to 2016 bleaching could be reduced by 25% (King et al., 2017).

Tourist motivations for visiting the GBR are changing, with a recent survey finding that two-thirds of tourists were visiting 'before it was gone' and a similar number were reporting damage to the reef – an example of 'last chance tourism' (Piggott-McKellar and McNamara, 2016). The Australian Government is investing A$1.9 billion to support the Great Barrier Reef through science and practical environmental outcomes including reducing other anthropogenic pressures which can suppress natural adaptive capacity (CoA, 2019b; GBRMPA, 2019). However, adaptation efforts on the Great Barrier Reef aimed specifically at climate impacts, for example, coral restoration following marine heatwave impacts (Boström-Einarsson et al., 2020) may slow the impacts of climate change in small discrete regions of the reef, or reduce short-term socio-economic ramifications, but will not prevent widespread bleaching (Condie et al. 2021).

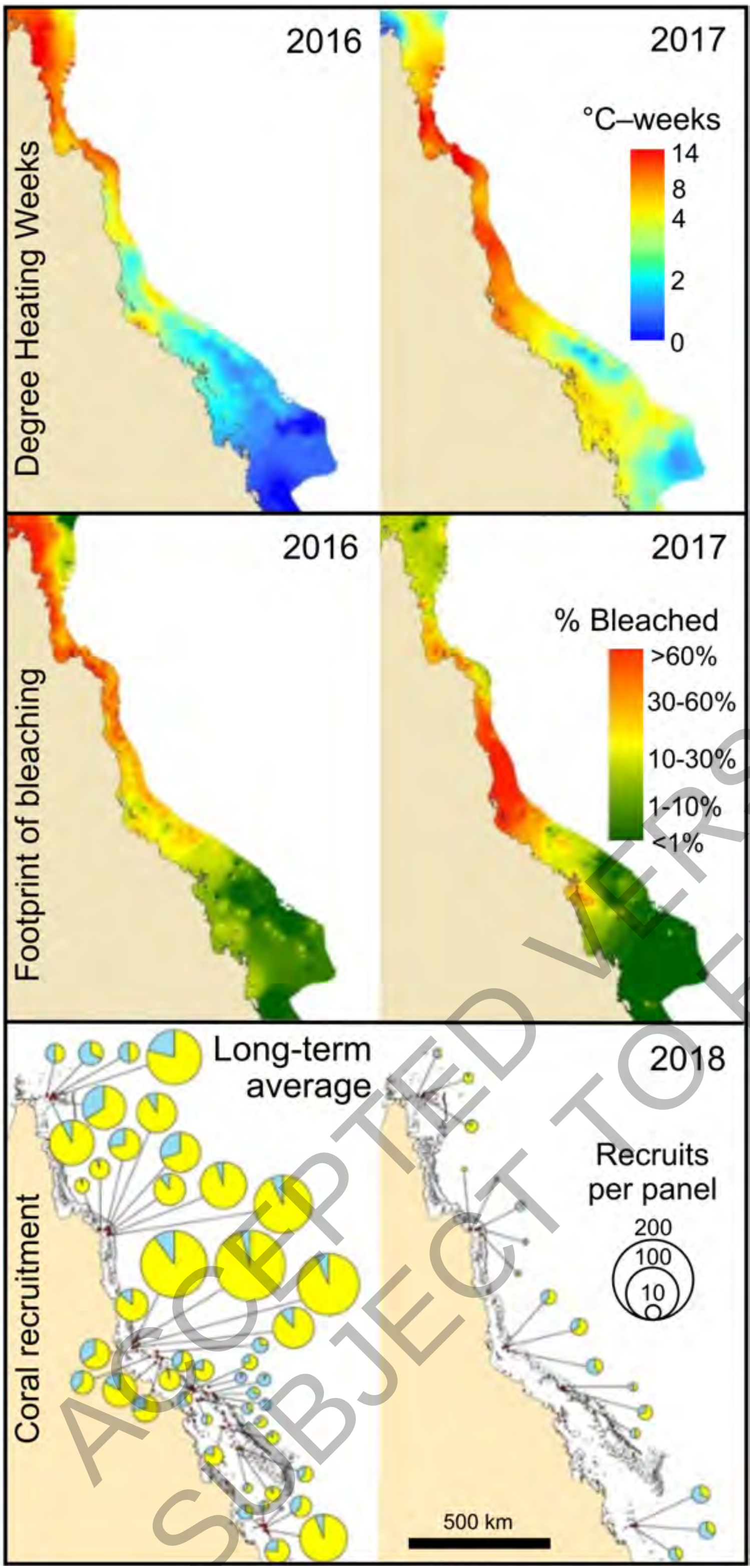

Figure Box 11.2.1: Top panels show spatial patterns in heat exposure along the Great Barrier Reef in 2016 (left) and 2017 (right), measured from satellites as Degree Heating Weeks (DHW, ºC-weeks). Middle panels show the geographic footprint of recurrent coral bleaching in 2016 (left) and again in 2017 (right), measured by aerial assessments of individual reefs (adapted from (Hughes et al., 2019c)). Bottom panels display the density of coral recruits (mean per recruitment panel on each reef), measured over three decades, from 1996 to 2016 (*n* = 47 reefs, 1,784 panels) (left), compared to the density of coral recruits in 2018 after the mass mortality of corals in 2016 and 2017 due to the back-to-back bleaching events (*n* = 17 reefs, 977 panels) (right). The area of each circle is scaled to the overall recruit density of spawners and brooders combined. Yellow and blue indicate the proportion of spawners and brooders, respectively (from (Hughes et al., 2019b)).

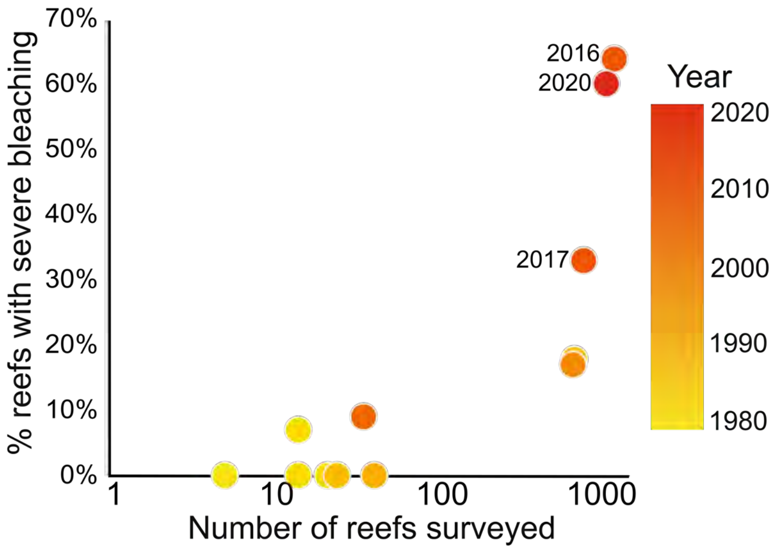

Figure Box 11.2.2: Variation in the severity of mass-bleaching episodes recorded on Australia's Great Barrier Reef over the last four decades (1980–2020). The overall number of reefs surveyed was substantially higher in 1998, 2002, 2016, 2017 and 2020 when aerial surveys were undertaken, whereas the severity of other more localised bleaching episodes was documented with in-water surveys (adapted from (Pratchett et al., 2021). Extent of bleaching in 2020 was similar in severity to 2016, but more geographically widespread and included southern reefs.

[END BOX 11.2 HERE]

11.3.3 Freshwater Resources

Climate change impacts on freshwater resources cascade across people, agriculture, industries and ecosystems (Boxes 11.3 and 11.5). The challenge of satisfying multiple demands with a finite resource is exacerbated by high inter-annual and inter-decadal variability of river flows, particularly in Australia (Chiew and McMahon, 2002; Peel et al., 2004; McKerchar et al., 2010).

11.3.3.1 Observed Impacts

Streamflow has generally increased in northern Australia and decreased in southern Australia since the mid-1970s (Zhang et al., 2016) (*high confidence*). Declining river flows since the mid-1970s in southwest Australia have led to changed water management (WA Government, 2012; WA Government, 2016). The large decline in river flows during the 1997–2009 'Millennium' drought in south-east Australia resulted in low irrigation water allocations, severe water restrictions and major environmental impacts (Potter et al., 2010; Chiew and Prosser, 2011; Leblanc et al., 2012; van Dijk et al., 2013). The drying in southern Australia highlighted the need for hydrological models that adequately account for climate change (Vaze et al., 2010; Chiew et al., 2014; Saft et al., 2016; Fowler et al., 2018). The decline in streamflow was largely due to the decline in cool season rainfall (which has been partly attributed to climate change) (Figure 11.2) (Timbal and Hendon, 2011; Post et al., 2014; Hope et al., 2017; DELWP, 2020) when most of the runoff in southern Australia occurs.

In New Zealand, precipitation has generally decreased in the north and increased in the southwest (Figure 11.2) (Harrington et al., 2014), but it is difficult to ascertain trends in the relatively short streamflow records. Glaciers in New Zealand's southern alps have lost one third of their mass since 1977 (Mackintosh et al., 2017; Salinger et al., 2019b), and glacier mass loss in 2018 was at least ten times more likely to occur with anthropogenic forcing than without (Vargo et al., 2020).

11.3.3.2 Projected Impacts

Projections indicate that future runoff in south-east and south-west Australia are *likely* to decline (median estimate of 20% and 50% respectively, under 2.2°C global average warming) (Figure 11.3) (Chiew et al., 2017; Zheng et al., 2019). These projections are broadly similar to those reported previously and in AR5 (Teng et al., 2012; Reisinger et al., 2014). The range of estimates arises mainly from the uncertainty in projected future precipitation (Table 11.2a).

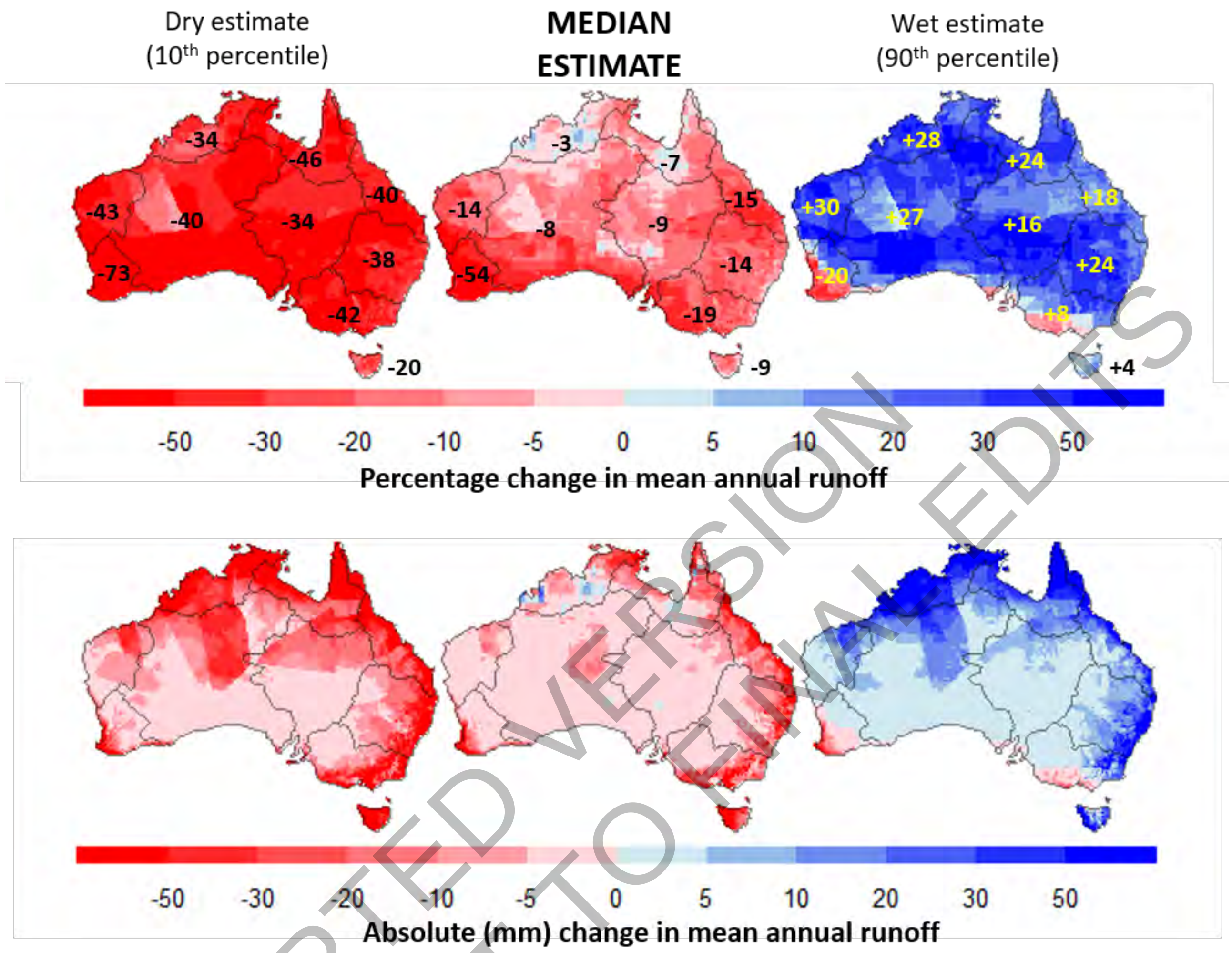

Figure 11.3: Projected changes in mean annual runoff for 2046–2075 relative to 1976–2005 for RCP8.5 from hydrological modelling with future climate projections informed by 42 CMIP5 GCMs. Projections for RCP4.5 are about three quarters of the above projections. Plots show median projection, and the 10th and 90th percentile range of estimates. The boundaries are based on hydroclimate regions and major drainage basins. Source: (Zheng et al., 2019).

The runoff decline in southern Australia is projected to be further accentuated by higher temperature and potential evapotranspiration (Potter and Chiew, 2011; Chiew et al., 2014), transpiration from tree regrowth following more frequent and severe wildfires (Brookhouse et al., 2013) (Box 11.1), interceptions from farm dams (Fowler et al., 2015), and reduced surface-groundwater connectivity (limiting groundwater discharge to rivers) in long dry spells (Petrone et al., 2010; Hughes et al., 2012; Chiew et al., 2014) (*high confidence*). In the longer-term, runoff will also be affected by changes in vegetation and surface-atmosphere feedback in a warmer and higher CO_2 environment, but the impact is uncertain because of the complex interactions including changes in climate inputs, fire patterns (Box 11.1) and nutrient availability (Raupach et al., 2013; Ukkola et al., 2016; Cheng et al., 2017).

Climate change is projected to affect groundwater recharge and the relationship between surface waters and aquifers, and through rising sea-levels where groundwater has a tidal signature (PCE, 2015; MfE, 2017a). Groundwater recharge across southern Australia has decreased in recent decades (Fu et al., 2019) and this trend is expected to continue (Barron et al., 2011; Crosbie et al., 2013) (*high confidence*). Climate change is also projected to impact water quality in rivers and water bodies, particularly through higher temperature and low flows (Jöhnk et al., 2008) (Box 11.5) and increased sediment and nutrient load following wildfires (Biswas et al., 2021) (Box 11.1) and floods (Box 11.4) (*high confidence*).

The projected changes in river flows in New Zealand are consistent with the precipitation projections (Table 11.2), with increases in the west and south of the South Island and decreases in the east and north of the North Island (Figure 11.4). In the South Island, the runoff increase occurs mainly in winter due to increasing moisture-bearing westerly airflow, with more precipitation falling as rain and snow melting earlier. In the North Island, the runoff decrease occurs in spring and summer (Caruso et al., 2017; Collins et al., 2018a; Jobst et al., 2018; D. Collins, 2020).

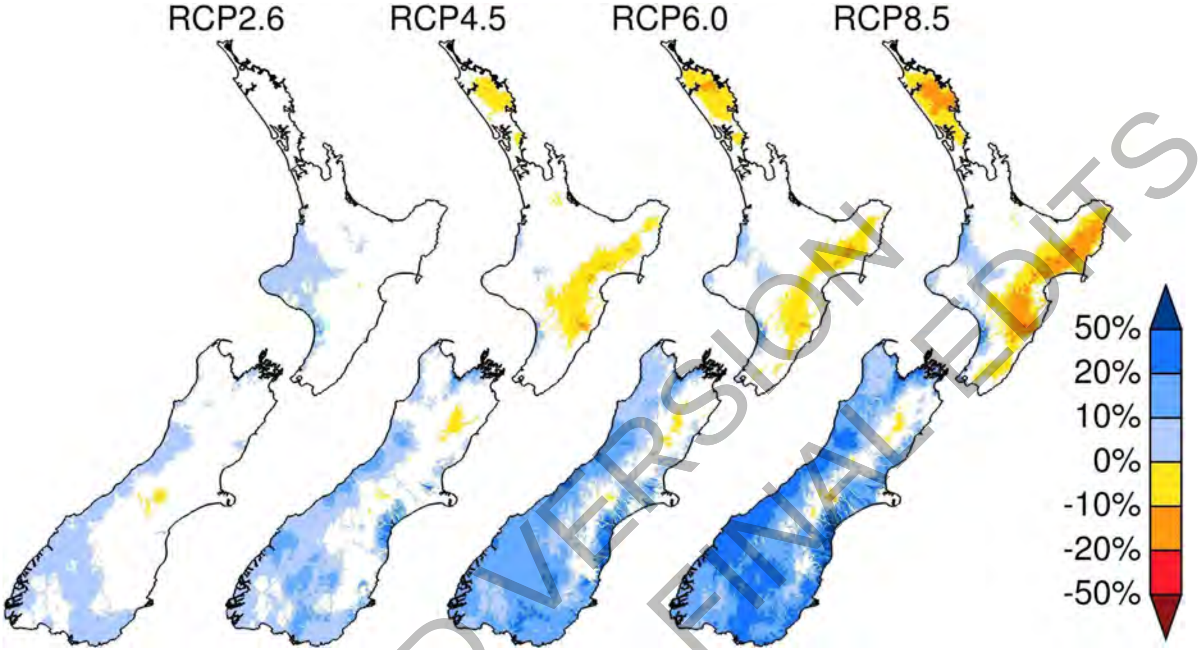

Figure 11.4: Projected percentage change in mean annual runoff for 2086–2099 relative to 1986–2005 from hydrological modelling informed by six CMIP5 GCMs for four RCPs. Maps show median projection from the six modelling runs. White indicates that the change is not statistically significant. Source: (D. Collins, 2020).

11.3.3.3 Adaptation

In Australia, prolonged droughts and projections of a drier future have accelerated policy and management change in urban and rural water systems. Adaptation initiatives and mechanisms, like significant government investment to enhance the Bureau of Meteorology online water information (Vertessy, 2013; BoM, 2016), funding to improve agriculture water use and irrigation efficiency (Koech and Langat, 2018), enhanced supply through inter-basin transfers and upgrading water infrastructure, and an active water trading market (Wheeler et al., 2013; Kirby et al., 2014; Grafton et al., 2016) are helping to buffer regional systems against droughts, and facilitating some adaptation to climate change (*medium confidence*). However, these measures could also be maladaptive as they may perpetuate unsustainable water and land uses under ongoing climate change (Boxes 11.3 and 11.5).

The widespread 2017-2019 drought across eastern Australia (BoM, 2019) has led to the Australian Government establishing a Future Drought Fund (Australian Government, 2019) to enhance drought resilience, and a National Water Grid Authority to develop regional water infrastructure to support agriculture. Nevertheless, the ability to adapt to climate change is compounded by uncertainties in future water projections, complex interactions between science, policy, community values and political voice, and competition between different sectors dependent on water (Boxes 11.3 and 11.5). The impact of declining water resource on agricultural, ecosystems and communities in south-eastern Australia would escalate with ongoing climate change (Hart, 2016; Moyle et al., 2017) (*medium confidence*), highlighting the importance of more ambitious, anticipatory, participatory and integrated adaptation responses (Bettini et al., 2015; Abel et al., 2016; Marshall and Lobry de Bruyn, 2021).

Altered water regimes resulting from the combined effects of climatic conditions and water policies carry uneven and far-reaching implications for communities (*high confidence*). Acting on Indigenous Peoples' claims to cultural flows (to maintain connection to Country) is increasingly recognised as an important water management and social justice issue (Taylor et al., 2017; Hartwig et al., 2018; Jackson, 2018; Jackson and Moggridge, 2019; Moggridge et al., 2019). Compounding stressors such as coal and coal seam gas developments can also severely impact local communities, water catchments and water-dependent ecosystems and assets, exacerbating their vulnerability to climate change (Navi et al., 2015; Tan et al., 2015; Chiew et al., 2018).

In Australian capital cities and regional centres, water planning has focused on securing new supplies that are resilient to climate change. This includes increasing use of stormwater and sewage recycling and managed aquifer recharge (Bekele et al., 2018; Page et al., 2018; Gonzalez et al., 2020). All major coastal Australian cities have desalination plants. Household scale adaptation like rainwater harvesting, water smart gardens, dual flush toilets, water-efficient showerheads and voluntary residential use targets can help reduce water demand by up to 40% (Shearer, 2011; Rhodes et al., 2012; Moglia et al., 2018). Water utilities across Australia have established climate change adaptation guidelines (WSAA, 2016). Coordinated efforts to reduce demand, design and retrofit infrastructure to reduce flood risk and harvest water, and water sensitive urban design, are evident (WSAA, 2016; Kunapo et al., 2018; Rogers et al., 2020b). Transitioning centralised water systems to a more sustainable basis represents adaptation progress but is complex and faces many barriers and limits (Morgan et al., 2020) (*medium confidence*). Developing multiple redundant or decentralised systems can enhance community resilience and promote autonomous adaptations that may be more sustainable and cost effective in the longer term (Mankad and Tapsuwan, 2011; WSAA, 2016; Iwanaga et al., 2020).

In New Zealand, many water supplies are at risk from drought, extreme rainfall events and sea-level rise, exacerbated by underinvestment in existing water infrastructure (in part due to funding constraints), and urban densification (CCATWG, 2017; MfE and StatsNz, 2021) (*high confidence*). Lessons can be learned from global experience (e.g. Cape Town, South Africa; Chapter 4.3.4). Water quality has diminished, with hotter conditions and drought causing algal blooms, combined with intensification of agricultural land uses in some areas, and heavy rainfall and sea-level rise causing flooding and sedimentation of water sources and health impacts (11.3.6; Box 11.5). Some towns are only partially metered or not metered at all, which exacerbates the adaptation challenge (Hendy et al., 2018; WaterNz, 2018; Paulik et al., 2019b). Unregulated or absent water supplies accentuate risks to vulnerable groups of people (MfE, 2020b). Māori view water as the essence of all life, which makes any impacts on water, of governance and stewardship concern, and increasingly, the subject of legal claims (MfE, 2020a; MfE, 2020b; MfE, 2020c) (11.4.2). Māori understanding of time can also open up new spaces for rethinking freshwater management in a climate change context that does not reinforce or rearticulate multiple environmental injustices (Parsons et al., 2021).

Water resource adaptation in New Zealand is variable across local government and water authorities but they all actively monitor water availability, demand and quality, and most have drought management plans. The 2019/20 drought led to water shortages in the most populated areas of Waikato, Auckland and Northland, resulting in water reduction advisories and five to eight weeks waiting time for water tank refills and water rationing. The Havelock North water supply contamination that arose after an extreme rainfall event (DIA, 2017a; DIA, 2017b) was exacerbated by fragmented governance, and led to the Taumata Arawai-Water Services Regulator Act 2020 and the Water Services Bill 2020 to protect source water. The 2017 update to the National Policy Statement for Freshwater Management with guidelines for implementation at the regional level (MfE, 2017b), including consideration of climate change which creates opportunities for adaptation. However, there remain tensions between land, water and people which are exacerbated by climate changes and yet to be addressed (Box 11.5). The first National Adaptation Plan and the Resource Management law reform have potential for helping to resolve these tensions (11.7.1) (CCATWG, 2017; MfE, 2020a).

[START BOX 11.3 HERE]

Box 11.3: Drought, Climate Change, and Water Reform in the Murray-Darling Basin

The Murray-Darling Basin (MDB) is Australia's largest, most economically important and politically complex river system (Figure Box 11.3.1). The MDB supports agriculture worth A$24 billion/year, 2.6 million people in diverse rural communities, and important environmental assets including 16 Ramsar listed wetlands (DAWE, 2021). Climate change is projected to substantially reduce water resources in the MDB (*high confidence*), with the median projection indicating a 20% decline in average annual runoff under 2.2˚C average global warming (Figure 11.3) (Whetton and Chiew, 2020). This reduction, plus increased demand for water in hot and dry conditions, would increase the already intense competition for water (*high confidence*) (CSIRO, 2008; Hart, 2016).

The economic, environmental and social impacts of the 1997–2009 'Millennium Drought' in the MDB (Chiew and Prosser, 2011; Leblanc et al., 2012; van Dijk et al., 2013), and projections of a drier future under climate change, have accelerated significant water policy reforms, costing more than A$12 billion (Bark et al., 2014; Docker and Robinson, 2014; Hart, 2016). These reforms included the development of a Basin Plan (MDBA, 2011; MDBA, 2012) requiring consistent regional water resource plans (MDBA, 2011; MDBA, 2012; MDBA, 2013) and environmental watering strategies (MDBA, 2014) across the MDB. Despite contestation, the reforms have resulted in some substantive achievements, including returning an equivalent of about one fifth of consumptive water to the environment through the purchase of irrigation water entitlements and infrastructure projects (Hart, 2016; Gawne et al., 2020; MDBA, 2020) (*medium confidence*). However, the overall impacts of these water management initiatives are difficult to measure due to hydroclimatic variability, time lags and environmental, social and institutional complexity (Crase, 2011; Bark et al., 2014; Docker and Robinson, 2014; MDBA, 2020).

Reform initiatives such as water markets, improving agriculture water use efficiency (Koech and Langat, 2018), and increasing environmental water are helping buffer the system against droughts (Moyle et al., 2017) (*medium confidence*) but they can also be maladaptive by perpetuating unsustainable water and land use under ongoing climate change. While water markets can allow users to adapt and shift water to higher value uses, they can also have adverse impacts unless supported by wider policy goals and planning processes (Wheeler et al., 2013; Kirby et al., 2014; Grafton et al., 2016; Qureshi et al., 2018).

Adapting MDB management to climate risks is an escalating challenge, with the projected decline in runoff being potentially greater than the water recovered for the environment (Chiew et al., 2017). While the Basin Plan includes mechanisms for climate risks management (Neave et al., 2015), it does not require altering pre-existing rules that distribute the impacts of anticipated reductions in water resource between users (Hart, 2016; Capon and Capon, 2017; Alexandra, 2020). The intense drought conditions in 2017-2019 (BoM, 2019), the South Australian Royal Commission into the MDB reforms (SA Government, 2019b), and major fish kills in the lower Darling River in the summer of 2018/2019 (AAS, 2019; Vertessy et al., 2019) have increased concerns about the Basin Plan's climate adaptation deficit (*medium confidence*). The Murray Darling Basin Authority (MDBA) consequently is undertaking an assessment of climate change risks and developing adaptation mechanisms (MDBA, 2019) that can feed into the revisions to the Basin Plan scheduled for 2026. The MDB reforms to date illustrate the difficulties in integrating climate change science and projections into management (Alexandra, 2018; Alexandra, 2020). Anticipatory and participatory governance and adaptive management approaches supported by structural and institutional reforms would support the effectiveness of the reforms (Abel et al., 2016; Alexandra, 2019; Hassenforder and Barone, 2019; Marshall and Lobry de Bruyn, 2021).

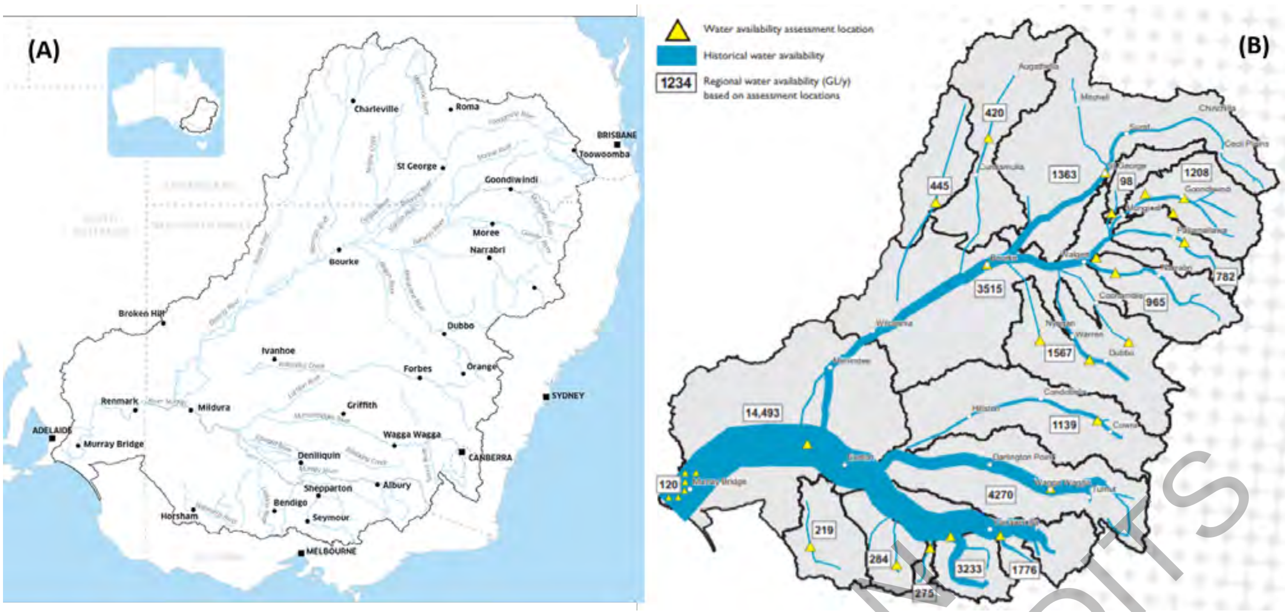

Figure Box 11.3.1: (A) The Murray-Darling Basin, and (B) average annual river flows in the Basin under pre-development conditions (from (CSIRO, 2008) showing that most of the runoff comes from the south-eastern highlands. The borders show key drainage basins.

[END BOX 11.3 HERE]

[START BOX 11.4 HERE]

Box 11.4: Changing Flood Risk

Pluvial (flash flood from high intensity rainfall) and fluvial (river) flooding are the most costly natural disasters in Australia, averaging A$8.8 billion per year (Deloitte, 2017b). In New Zealand, insured damages for the 12 costliest flood events from 2007-2017 exceeded NZ$472 million of which NZ$140 million has been attributed to anthropogenic climate change (Frame et al., 2020). Extreme rainfall intensity in northern Australia and New Zealand has been increasing, particularly for shorter (sub-daily) duration and more extreme high rainfall (*high confidence*) (Westra and Sisson, 2011; Griffiths, 2013; Laz et al., 2014; Rosier et al., 2015). Changes are also occurring in spatial and temporal patterns and seasonality (Wasko and Sharma, 2015; Zheng et al., 2015; Wasko et al., 2016).

Extreme rainfall is projected to become more intense (*high confidence*) but the magnitude of change is uncertain (Evans and McCabe, 2013; Bao et al., 2017) (Table 11.3). The insured damage in New Zealand from more intense extreme rainfall under RCP8.5 is projected to increase 25% by 2080–2100 (Pastor-Paz et al., 2020). In urban areas, extreme rainfall intensity is projected to increase pluvial flood risk (*high confidence*). In New Zealand, 20,000km^2 of land, 675,000 people, and 411,000 buildings with a NZ$135 billion replacement value are exposed to 1-in-100 year flood risk (Paulik et al., 2019a).

In non-urban areas, where the flood response is also dependent on antecedent catchment conditions (Johnson et al., 2016; Sharma et al., 2018), there is no evidence of increasing flood magnitudes in Australia (Ishak et al., 2013; Zhang et al., 2016; Bennett et al., 2018) except for the most extreme events (Sharma et al., 2018; Wasko and Nathan, 2019). Modelling studies project increases in flood magnitudes in northern and eastern Australia, and in western and northern New Zealand (*high confidence*) (Hirabayashi et al., 2013; Collins et al., 2018a; Do et al., 2020). The change in flood magnitude in southern Australia is uncertain because of the compensating effect of more intense extreme rainfall, versus projected drier antecedent conditions (Johnson et al., 2016; Pedruco et al., 2018; Wasko and Nathan, 2019). Higher rainfall intensity and peak flows also increase erosion, sediment and nutrient loads in waterways (Lough et al., 2015) and exacerbate problems from aging stormwater and wastewater infrastructure (Jollands et al., 2007; WSAA, 2016; Hughes et al., 2021).

There is some recognition of the need for flood management and planning to adapt to climate change (COAG, 2011; CCATWG, 2018; CoA, 2020d) (*medium confidence*). Australian flood estimation guidelines recommend a 5% increase in design rainfall intensity per degree global average warming (Bates et al., 2015). In New Zealand, the recommended increase ranges from 5% to more than 10% for shorter duration and longer return period storms (MfE, 2010; Carey-Smith et al., 2018). Both guidelines also indicate the potential for higher increases in extreme rainfall intensity.

Adaptation to reduce flooding and its impacts have included: improved flood forecasting (Vertessy, 2013; BoM, 2016) and risk management (AIDR, 2017); accommodating risk through raising floor levels and sealing external doors (Queensland Government, 2011; Wang et al., 2015), deployment of temporary levee structures; and risk reduction through spatial planning and relocation. Adaptation options in urban areas include improved stormwater management (Hettiarachchi et al., 2019; Matteo et al., 2019), ecosystem-based approaches such as maintaining floodplains, restoring wetlands and retrofitting existing flood control systems to attenuate flows, and water sensitive urban design (WSAA, 2016; Radcliffe et al., 2017; Radhakrishnan et al., 2017; Rogers et al., 2020b).

Adaptation to changing flood risks is currently mostly reactive and incremental in response to flood and heavy rainfall events (*high confidence*). For example, the 2010-2011 flooding in eastern Australia resulted in changes to reservoir operations to mitigate floods (QFCI, 2012) and insurance practice to cover flood damages (Phelan, 2011; Phelan et al., 2011; QFCI, 2012; Schuster, 2013). Nevertheless, adaptation planning that is pre-emptive and incorporates uncertainties into flood projections is emerging (Schumacher, 2020) (*medium confidence*). Examples from New Zealand include the use of Dynamic Adaptive Pathways Planning (Lawrence and Haasnoot, 2017) with Real Options assessment (Infometrics and PSConsulting, 2015) and design of decision signals and triggers to monitor changes before physical and coping thresholds are reached (Stephens et al., 2018). Implementing adaptive flood risk management relies upon an understanding of how such risks change in uncertain and ambiguous ways necessitating adaptive and robust decision making processes. These can enable learning through participatory adaptive pathways approaches (Lawrence and Haasnoot, 2017; Bosomworth and Gaillard, 2019) and through coordination across different levels of government and statutory mandates, adaptation funding, and individual and community adaptations (Glavovic et al., 2010; Boston and Lawrence, 2018; McNicol, 2021).

[END BOX 11.4 HERE]

11.3.4 Food, Fibre, Ecosystem Products

The food, fibre and ecosystem products sectors are economically important in the region. Agriculture contributes around 4% of New Zealand GDP and 2% of Australian GDP, and over 50% of New Zealand's and 11% of Australia's exports (NZ Treasury, 2016; Jackson et al., 2020). Forestry contributes 1% of New Zealand GDP and 0.5% Australian GDP (NZ Treasury, 2016; Whittle, 2019). With the processing and indirect effects, the primary sector of New Zealand contributes 25% of GDP (Saunders et al., 2016). The region has the lowest level of agricultural subsidies across the OECD (OECD, 2017), and highly responsive producers to market drivers but limited strategic, longer-term approaches to environmental challenges and adaptation (Wreford et al., 2019). Both countries receive government financial drought assistance (Pomeroy, 2015; Downing et al., 2016).

Impacts resulting from climate change are observed across sectors and the region (*high confidence*). While more intense changes are observed in Australia, New Zealand is also experiencing impacts, including the economic impacts of drought attributable to climate change (Frame et al. 2020). Overall, modelling indicates that negative impacts will intensify with increased levels of warming in both countries, with declining crop yield and quality, and negative effects on livestock production and forestry. Although benefits are identified, particularly in the short term for New Zealand (MfE, 2020a), an absence of studies that consider the totality of climatic variables, including extremes, moderate the benefits identified from considering only selected variables and systems in isolation.

Incremental adaptation is occurring (Hochman et al., 2017; Hughes and Lawson, 2017; Hughes and Gooday, 2021). In the longer term, transformative adaptation, including land-use change, will be required (Cradock-Henry et al., 2020a), both as a result of sectoral adaptations and mitigation (Grundy et al., 2016) (*medium confidence*). Specific changes are context specific and challenging to project (Bryan et al., 2016). Future adaptive capacity may be limited by declining institutional and community capacity resulting from high debt, unavailability of insurance, increasing regulatory requirements, and funding mechanisms that lock-in ongoing exposure to climate risk, creating mental health impacts (Rickards et al., 2014; Wiseman and Bardsley, 2016; McNamara and Buggy, 2017; McNamara et al., 2017; Moyle et al., 2017; Robinson et al., 2018; Ma et al., 2020; Yazd et al., 2020).

11.3.4.1 Field Crops and Horticulture

11.3.4.1.1 Observed impacts

Drought, heat and frost in recent decades have shown the vulnerability of Australian field crops and horticulture to climate change (Cai et al., 2014; Howden et al., 2014; CSIRO and BOM, 2015; Lobell et al., 2015; Hughes and Lawson, 2017; King et al., 2017; Webb et al., 2017; Harris et al., 2020) as recognised by policy makers (CoA, 2019a) (*high confidence*). Drought has caused economic losses attributable to climate change of at least NZ$800M in New Zealand (Frame et al., 2020). Northern Australia's agricultural output losses are on average 19% each year due to drought (Thi Tran et al., 2016). In southern Australia, the frequency of frost has been relatively unchanged since the 1980s (Dittus et al., 2014; Pepler et al., 2018; BoM and CSIRO, 2020). Drier winters have increased the irrigation requirement for wine grapes (Bonada et al., 2020) while smoke from the 2019/20 fires, which occurred early in the season, caused significant taint damage (Jiang et al., 2021). In New Zealand, reduced winter chill has a compounded impact on the kiwifruit industry, resulting in early harvest and increased energy demand for refrigeration and port access problems (Cradock-Henry et al., 2019) (11.5).

Across all types of agriculture, drought and its physical flow-on effects have caused financial and emotional disruption and stress in farm households and communities (Austin et al., 2018; Bryant and Garnham, 2018; Yazd et al., 2019) (11.3.6). Severe and uncertain climate conditions are statistically associated with increases in farmer suicide (Crnek-Georgeson et al., 2017; Perceval et al., 2019). Rural women often carry extra stress and responsibilities, including increased unpaid and paid work and emotional load (Whittenbury, 2013; Hanigan et al., 2018; Rich et al., 2018).

11.3.4.1.2 Projected impacts

Australian crop yields are projected to decline due to hotter and drier conditions, including intense heat spikes (Anwar et al., 2015; Lobell et al., 2015; Prokopy et al., 2015; Dreccer et al., 2018; Nuttall et al., 2018; Wang et al., 2018a) (*high confidence*). Interactions of heat and drought could lead to even greater losses than heat alone (Sadras and Dreccer, 2015; Hunt et al., 2018). Australian wheat yields are projected to decline by 2050, with a median yield decline of up to 30% in south-west Australia and up to 15% in South Australia, with possible increases and decreases in the east (Taylor et al., 2018, Wang, #1599; Wang et al., 2018a). In temperate fruit, accumulated winter chill for horticulture is projected to further decline (Darbyshire et al., 2016). Winegrape maturity is projected to occur earlier due to warmer temperatures (Webb et al., 2014; van Leeuwen and Darriet, 2016; Jarvis et al., 2018; Ausseil et al., 2019b) (*high confidence*) leading to potential changes in wine style (Bonada et al., 2015). Rice is susceptible to heat stress and average grain yield losses across rice varieties range from 83% to 53% in experimental trials when heat stress was applied during plant emergence and grain fill stages (Ali et al., 2019). In Tasmania, wheat yields are projected to increase, particularly at sites presently temperature-limited (Phelan et al., 2014).

New Zealand evidence on impacts across crops is very limited. Considering precipitation and temperature changes alone show minor effects on crop yield, and winter yields of some crops may increase (e.g. wheat, maize) (Ausseil et al., 2019b). For temperate fruit, loss of winter chill may reduce yields in some regions and trigger impacts across supply chains (Cradock-Henry et al., 2019) (11.5.1). Increased pathogens could damage the cut flower, guava and feijoa fruit growing, and the honey industries (Lawrence et al., 2016). The combined effects of changes in seasonality, temperature, precipitation, water availability and extremes, such as drought, have the potential to escalate impacts, but understanding of these effects is limited.

Other climate-change related factors complicate crop climate responses. When CO_2 was elevated from present-day levels of 400 ppm to 550 ppm in trials, yields of rainfed wheat, field pea and lentil increased approximately 25% (0-70%). However, there was a 6% reduction in wheat protein that could not be offset by additional nitrogen fertilizer (O'Leary et al., 2015; Fitzgerald et al., 2016; Tausz et al., 2017). Elevated CO2 will worsen some pest and disease pressures, e.g. Barley Yellow Dwarf Virus impacts on wheat (Trębicki et al., 2015). Warmer temperatures are also expanding the potential range of the Queensland fruit fly, including into New Zealand (Aguilar et al., 2015a) threatening the horticulture industry (Sultana et al., 2017; Sultana et al., 2020). Some crop pests (e.g. the oat aphid) are projected to be negatively affected by climate change (Macfadyen et al., 2018), but so too are beneficial insects. There is large uncertainty in rainfall and crop projections for northern Australia (Table 11.3). For sugarcane, impact assessment for CO_2 at 734ppm using the A2 emission scenario at Ayr in Queensland projected modest yield increases (Singels et al., 2014). Climate change are projected to adversely impact tropical fruit crops such as mangoes through higher minimum and maximum temperatures reducing the number of inductive days for flowering (Clonan et al., 2020).

Climate change is projected to shift agro-ecological zones (Lenoir and Svenning, 2015; Scheffers et al., 2016) (*high confidence*). This includes the climatically determined cropping strip bounded by the inner arid rangelands and the wetter coast or mountain ranges in mainland Australia (Nidumolu et al., 2012; Eagles et al., 2014; Tozer et al., 2014). A narrowing of grain growing regions is projected with a shift of the inner margin towards the coast under drier and warmer conditions (Nidumolu et al., 2012; Fletcher et al., 2020). The economic impact of the shift depends on adaptation (Sanderson et al., 2015; Hunt et al., 2019) and how resources, support industries, infrastructure and settlements adapt. Shifts in agro-ecological zones present some opportunities, for example, warming is projected to be beneficial for wine production in Tasmania (Harris et al., 2020).

11.3.4.1.3 Adaptation

Some farmers are adapting to drier and warmer conditions through more effective capture of non-growing season rainfall (e.g. stubble retention to store soil water), improved water use efficiency, and matching sowing times and cultivars to the environment (Kirkegaard and Hunt, 2011; Fitzer et al., 2019; Haensch et al., 2021) (*high confidence*). Observed adaptations include new technologies that improve resource efficiencies, professional knowledge and skills development, new farmer and community networks, and diversification of business and household income (Ghahramani et al., 2015; De et al., 2016). For Australian wheat, earlier sowing and longer season cultivars may increase yield by 2-4% by 2050, with a range of -7 to +2% by 2090 (Wang et al., 2018a). In the wheat industry, breeding for improved reproductive frost tolerance remains a priority (Lobell et al., 2015). Modelling suggests that, since 1990, farm management has held Australian wheat yields constant, but declining rainfall and increasing temperature may have contributed to a 27% decline in simulated potential Australian wheat yield (Hochman et al., 2017).

Other observed incremental adaptations include later pruning in the grape industry to spread harvest period and partially restore wine balance, with neutral effects on yield and cost (Moran et al., 2019; Ausseil et al., 2021). The cotton sector increasingly requires shifts in sowing dates to avoid financial impacts (Luo et al., 2017). During years of low water availability, rice growers have been trading water and/or shifting to dry land farming (Mushtaq, 2016).

Growers in New Zealand are changing the timing of their operations, growing crops within covered enclosures, and purchasing insurance (Cradock-Henry and McKusker, 2015)(Teixeira et al. 2018). Investment of capital in irrigation infrastructure has increased (Cradock-Henry et al., 2018a), although its effectiveness as an adaptation depends on water availability (Box 11.5). In industries based on long-lived plants, such as the kiwifruit and grape industries, many of the adaptations (e.g. breeding and growing heat-adapted and disease-resistant varieties) have long-lead times and require greater investment than in the cropping sector (Cradock-Henry et al., 2020a). While breeding programmes for traits with enhanced resilience to future climates are beginning, there is little evidence of strategic industry planning (Cradock-Henry et al., 2018a).

For drought management, balancing near-term needs with long-term adaptation to increasing aridity is essential (Downing et al., 2016). Insufficient and maladaptive decisions can have far-reaching effects, including changes to resources, infrastructure, services and supply chains to which others have to adapt

(Fleming et al., 2015; Graham et al., 2018). While there is potential for greater proportion of agriculture to be located to northern Australia, there are significant and complex agronomic, environmental, institutional, financial and social challenges for successful transformation including the risk of disruption (Jakku et al., 2016) (*medium confidence*).

11.3.4.2 Livestock

11.3.4.2.1 Observed impacts

Both the seasonality and annual production of pasture is changing (*high confidence*). In many regions, warming is increasing winter pasture growth (Lieffering, 2016); effects on spring growth are more mixed with some regions experiencing increased growth {(Newton et al. 2014)} and others experiencing reduced spring growth (Perera et al., 2020). Droughts are causing economic damage to livestock enterprises with drought and market prices significantly affecting profit (Hughes et al., 2019a), in addition to the impacts on animal health and the livelihoods of pastoralists, periods of drought contribute to land degradation, particularly in the cattle regions of northern Australia (Marshall, 2015). Heat load in cattle leads to reduced growth rates and reproduction, and extreme heat waves can lead to death (Lees et al., 2019; Harrington, 2020). Temperatures over 32ºC reduce ewe and ram fertility along with the birth weight of lambs (van Wettere et al., 2021).

11.3.4.2.2 Projected impacts

Some areas may experience increased pasture growth, but others may experience a decrease that cannot be fully offset by adaptation (Moore and Ghahramani, 2013; Lieffering, 2016; Kalaugher et al., 2017) (*high confidence*). Climate change may modify the seasonality of pasture growth rates more than annual yields in New Zealand (Lieffering, 2016). In eastern parts of Queensland, climate change impacts on pasture growth are equivocal, with simple empirical models suggesting a decrease in net primary productivity (Liu et al., 2017), whilst mechanistic models that include increases in length of the growing season and the beneficial effects of CO_2 fertilisation indicate increases in pasture growth (Cobon et al., 2020). In Tasmania, annual pasture production is projected to increase by 13–16%, even with summer growth projected to reduce with increased inter-annual variability, resulting in projected increase of milk yields by 3–16% per annum (Phelan et al., 2015).

Extreme climatic events (droughts, floods and heatwaves) are projected to adversely impact productivity for livestock systems (*medium confidence*). This includes reduced pasture growth rates between 3-23% by 2070 from late spring to autumn, and elevated growth in winter and early spring (Cullen et al., 2009; Hennessy et al., 2016; Chang-Fung-Martel et al., 2017). Heavy rainfall and storms are projected to lead to increased erosion, particularly in extensively grazed systems on steeper land, reducing productivity for decades, reducing soil carbon (Orwin et al., 2015), and increasing sedimentation. Increased heat stress in livestock is projected to decrease milk production and livestock reproduction rates (high confidence) (Nidumolu et al., 2014; Ausseil et al., 2019b; Lees et al., 2019). In Australia, the average number of moderate to severe heat stress days for livestock is projected to increase 12-15 days by 2025 and 31–42 days by 2050 compared to 1970-2000 (Nidumolu et al., 2014). In New Zealand, an extra 5 (RCP2.6) to 7 (RCP8.5) moderate heat stress days per year are projected for 2046-2060 (Ausseil et al., 2019b) (*high confidence*) especially affecting animals transported long distances (Zhang and Phillips, 2019) and strain the cold chains needed to deliver meat and dairy products safely. The distribution of existing and new pests and diseases are projected to increase, for example, new tick and mosquito-borne diseases such as Bovine ephemeral fever (Kean et al., 2015).

11.3.4.2.3 Adaptation

Adaptations in both grazing and confined beef cattle systems require enhanced decision-making skills capable of integrating biophysical, social and economic considerations (*high confidence*). Social learning networks that support integration of lessons learned from early adopters and involvement with science-based organizations can help enhance decision-making and climate adaptation planning (Derner et al., 2018). Pasture management adaptations for livestock production include deeper rooted pasture species in higher rainfall regions (Cullen et al., 2014) and drought tolerant species (Mathew et al., 2018). Soil and land management practices are important in ensuring soils maintain their supporting and regulating services (Orwin et al., 2015). Adaptations in the primary sector in New Zealand are now positioned within the requirements of the National Policy Statement on Freshwater (MfE, 2020b). Adaptations to manage heat stress in livestock include altering the breeding calendar, providing shade and sprinklers, altering nutrition and feeding times, and more heat-tolerant animal breeds (Chang-Fung-Martel et al., 2017; Lees et al., 2019; van Wettere et al., 2021).

Beef rangeland systems in Queensland are projected to have benefits in the south-east through higher CO_2 and temperatures extending the growing season and reducing frost, but a warmer and drier climate in the south-west may reduce pasture and livestock production (Cobon et al., 2020). Northern Queensland is most resilient to temperature and rainfall changes (production limited by soil fertility) while western/central west Queensland is most sensitive to rainfall changes. i.e. low rainfall associated with lower productivity (Cobon et al., 2020). The social context of climate change impacts and the processes shaping vulnerability and adaptation, especially at the scale of the individual, are critical to successful adaptation efforts.(Marshall and Stokes, 2014)

11.3.4.3 Forestry

11.3.4.3.1 Observed impacts

Climate change may have increased tree mortality in Australia's commercial *Eucalyptus globulus* and *Pinus radiata* plantation forests (Crous et al., 2013; Pinkard et al., 2014). Climate warming decreased fine root biomass of *E. globulus* (Quentin et al., 2015) and enhanced tree water use and vulnerability to heat (Crous et al., 2013). Increases in fire frequency and intensity in forests of southern Australia are leading to diminishing resources available for timber production (Pinkard et al., 2014) [Box 11.1].

11.3.4.3.2 Projected impacts

The projected declines in rainfall in far southwest and far southeast mainland Australia are projected to reduce plantation forest yields (*high confidence*). Warmer temperatures are projected to reduce forest growth in hotter regions (between 7-25%), especially where species are grown at the upper range of their temperature tolerances, and increase plantation forest growth (>15%) in cooler margins like Tasmania and the Victorian highlands (2030, A2); emission scenario A2 creates a warming trajectory slightly higher than the RCP6.0 warming scenario, but less than RCP8.5 (Rogelj et al., 2012; Battaglia and Bruce, 2017). Elevated CO_2 is projected to increase forest growth if other biophysical factors are not limiting (*medium confidence*) (Quentin et al., 2015; Duan et al., 2018).

Forestry plantations are projected to be negatively impacted from increases in fire weather (Box 11.1), particularly in southern Australia (Pinkard et al., 2014) (*high confidence*). Increased pest damage due to temperature increases may reduce eucalypt and pine plantation growth by as much as 40% in some Australian environments by 2050) (Pinkard et al., 2014). Increased heat and water stress may enhance insect pest defoliation for *P. radiata* in Australia (e.g. *Sirex noctilio, Ips grandicollis and Essigella californica*) (Mead, 2013; Pinkard et al., 2014).

Combined impacts from heavy rainfall, soil erosion, drought, fire and pest incursions are projected to increase risks to the permanence of carbon offset and removal strategies in New Zealand for meeting its climate change targets (PCE, 2019; Watt et al., 2019; Anderegg et al., 2020; Schenuit et al., 2021). Effective management of the interactions between mitigation and adaptation policies can be achieved through governance and institutions, including Māori tribal organisations and sectoral adaptation, to ensure effective and continued carbon sequestration and storage as the climate changes (Lawrence et al., 2020b) (11.4.2) (Box 11.5) (*medium confidence*). The productivity of radiata pine (*P. radiata D. Don*) in New Zealand due to higher CO_2 is projected to increase by 19% by 2040 and 37% by 2090, but greater wind damage to trees is expected (Watt et al., 2019). Changes in the distribution of existing weeds, pests and diseases with potential establishment of new subtropical pests and seasonal invasions are projected (Kean et al., 2015; Watt et al., 2019; MfE, 2020a). Increased pathogens such as pitch canker, red needle cast and North American bark beetles could damage plantations (Hauraki Gulf Forum, 2017; Lantschner, 2017; Watt et al., 2019).

11.3.4.3.3 Adaptation

Adaptation options include: increased investment in monitoring forest condition and functioning; early detection and management of insect pests, diseases and invasive species; improved selection of land with appropriate growing conditions for plantation timber production under current and future conditions; trialling new species and genetic varieties; changing timing and frequency of planned fuel reduction fires, introducing more fire-tolerant tree species where appropriate, reducing ignition sources and maintaining access and emergency response capacity (Boulter, 2012; Pinkard et al., 2014; Keenan, 2017).

11.3.4.4 Marine Food

11.3.4.4.1 Observed impacts

Ecological impacts of climate change on fisheries species have already emerged (Morrongiello and Thresher, 2015; Gervais et al., 2021)(*high confidence*). This includes loss of habitats for fisheries species (Vergés et al., 2016; Babcock et al., 2019), and poleward shifts in distribution of barrens-forming urchins (Ling and Keane, 2018) impacting abalone and rock lobster fisheries. The percentage of reef as barrens across eastern Tasmania grew from 3.4% to 15.2% from 2001/02 to 2016/17, a ~10.5% increase per annum over the 15-year period (Ling and Keane, 2018). Oysters farmed from wild spat (Sydney rock oysters *Saccostrea glomerata*) are most at risk from climate change, primarily due to observed increases in summer temperatures and heat wave-related mortalities (Doubleday et al., 2013). The exceptional 2017/18 summer heatwave caused significant losses of farmed salmon in New Zealand, with farm owners seeking consent to move operations to cooler water (Salinger et al., 2019b).

11.3.4.4.2 Projected impacts

Aquaculture is projected to be more easily adapted than wild fisheries to avoid excessive exposure to the physio-chemical stresses from acidification, warming and extreme events (Richards et al., 2015). In New Zealand, wild and cultured shellfish are identified as most at risk from climate change (Capson and Guinotte, 2014). Changes in ocean temperature and acidification, and the downstream impacts on species distribution, productivity and catch are projected concerns (Law et al., 2016) (*medium confidence*) that impact Māori harvesting of traditional seafood, and the social, cultural and educational elements of food gathering (mahinga kai) (MfE, 2016). Warm temperate hatchery-based finfish species (yellowtail kingfish *Seriola lalandi*) are projected to be the least at risk, because of well controlled environmental conditions in hatcheries, and temperature increases which are expected to increase growth rates and productivity during the grow-out stage (Doubleday et al., 2013). For wild fisheries, multi-model projections suggest temperate and demersal systems, especially invertebrate shallow water species, would be more strongly affected by climate change than tropical and pelagic systems (Pecl et al., 2014; Fulton et al., 2018; Pethybridge et al., 2020) (*medium confidence*). In New Zealand waters, available habitat for both albacore tuna and oceanic tuna (Cummings et al., 2021) is expected to widen and shift.

11.3.4.4.3 Adaptation

Selective breeding in oysters is projected to be an important global adaptation strategy for sustainable shellfish aquaculture which can withstand future climate-driven change to habitat acidification (Fitzer et al., 2019). Less than a quarter of fisheries management plans for 99 of Australia's most important fisheries considered climate change, and only to a limited degree (Fogarty et al., 2019; Fogarty et al., 2021). Implementation of management and policy responses to climate change have lagged in part because climate change has not been considered as the most pressing issue (Hobday and Cvitanovic, 2017; Fogarty et al., 2019; Fogarty et al., 2021) (Cross-Chapter Box MOVING SPECIES in Chapter 5).

[START BOX 11.5 HERE]

Box 11.5: New Zealand's Land, Water and People Nexus under a changing climate

New Zealand's economy, dominated by the primary sector and the tourist industry (pre-COVID), relies upon a "clean green" image of water, natural ecosystems and pristine landscapes (Foote et al., 2015; Roche and Argent, 2015; Hayes and Lovelock, 2017). Water is highly valued by Māori for its mauri or life force and for its intrinsic values and multiple uses (Harmsworth et al., 2016). Increasingly, these diverse values are in conflict (Hopkins et al., 2015) due to increasing pressures from how land is used and managed and the effects on water availability and quality. Such tensions will be further challenged as temperatures rise and extreme events intensify beyond what has been experienced, thus stressing current adaptive capacities (Hughey and Becken, 2014; Cradock-Henry and McKusker, 2015; Hopkins et al., 2015; MfE and StatsNz, 2021) (11.2.2; 11.3.4) (*high confidence*).

Irrigation has increasingly been used to enhance primary sector productivity and regional economic development (Srinivasan et al., 2017; Fielke and Srinivasan, 2018; MfE and StatsNz, 2021). Pressure for long-term access to groundwater or large-scale water storage is increasing to ensure the ongoing viability of the primary sector as the climate changes. While investment in irrigation infrastructure may reduce climate change impacts in the short-term, maladaptive outcomes cannot be ruled out longer-term which means that focusing attention now on adaptive and transformational measures can help increase climate resilience in areas exposed to increasing drought and climate extremes that disrupt production (Abel et al., 2016; Cradock-Henry et al., 2019) (Yletyinen et al., 2019) (*medium confidence*).

Furthermore, over-allocation raises further tensions from competing uses of water such as for horticulture and urban water supplies, as well as for ecological requirements. The deterioration of water quality and loss of places of social, economic, cultural, and spiritual significance creates increasing tension for Māori especially (Harmsworth et al., 2016; Salmon, 2019; MfE and StatsNz, 2021). Public concern has increased about the deterioration of New Zealand's waterways and the profiting of some land uses at the expense of environmental quality and human health - tensions that make adaptation to climate change more challenging (Duncan, 2014; Foote et al., 2015; Scarsbrook and Melland, 2015; McDowell et al., 2016; McKergow et al., 2016; Greenhalgh and Samarasinghe, 2018). A lack of precautionary governance of water resources linked to unsustainable land use practices degrading water quality (Scarsbrook and Melland, 2015; Salmon, 2019) highlights the role that foresight could play in managing the nexus between land, water and people in a changing climate (11.3.3). Adaptive planning has potential for navigating these multi-dimensional challenges (Sharma-Wallace et al., 2018; Cradock-Henry and Fountain, 2019; Hurlbert et al., 2019) (11.7).

Furthermore, land and particularly plantation and native forests play a critical role in meeting New Zealand's emissions reduction goals. However, the persistence of land and forests as a carbon sink is uncertain and the sequestered carbon is at risk from future loss resulting from climate change impacts, including from increased fire, drought and pest incursions, storms and wind (IPCC, 2019a; PCE, 2019; Watt et al., 2019; Anderegg et al., 2020) (11.3.4.3), emphasising the importance of interactions between mitigation and adaptation policy and implementation. Integrated climate change policies across biodiversity, water quality, water availability, land use and forestry for mitigation can support the management of land use, water and people conflicts, but there is little evidence of such coordinated policies (Cradock-Henry et al., 2018b; Wreford et al., 2019). Implementation of the National Policy Statement for Freshwater Management 2020 (MfE, 2020b) and the National Adaptation Plan (due August 2022) present opportunities for such interconnections and diverse values to be addressed, as well as enabling sector and community benefits to be realised across New Zealand (Awatere et al., 2018; Lawrence et al., 2020b).

[END BOX 11.5 HERE]

11.3.5 Cities, Settlements and Infrastructure

Almost 90% of the population of Australia and New Zealand is urban (World Bank, 2019). Each country has vibrant and diverse urban, rural and remote settlements, with some highly disadvantaged areas isolated by distance and limited infrastructure and services (Argent et al., 2014; Charles-Edwards et al., 2018; Spector et al., 2019). Some areas in northern Australia and New Zealand, especially those with higher proportions of Indigenous inhabitants, face severe housing, health, education, employment and services issues (Kotey, 2015) which increases their vulnerability to climate change.

Infrastructure within and between cities and settlements is critical for activity across all sectors, with interdependencies increasing exposure to climate hazards (11.5.1). Previous planning horizons for existing infrastructure are compromised by now having to accommodate ongoing sea-level rise, warming, and increasing frequency of extreme rainfall and storm events (Climate Institute, 2012; MfE, 2017a). There is almost no information on the costs and benefits of adapting vulnerable and exposed infrastructure in Australia or New Zealand. Given the value of the infrastructure and the rising damage costs, this represents a large knowledge gap leading to an adaptation investment deficit.

11.3.5.1 Observed Impacts

Critical infrastructure, cities and settlements are being increasingly affected by chronic and acute climate hazards including heat, drought, fire, pluvial and fluvial flooding and sea-level rise, with consequent effects for many sectors (Instone et al., 2014; Loughnan et al., 2015; Zografos et al., 2016; Hughes et al., 2021) (*high confidence*). Risks and impacts vary with physical characteristics, location, connectivity and socio-economic status of settlements because of the ways these influence exposure and vulnerability (Loughnan et al., 2013; MfE, 2020a) (*high confidence*).

Weather-related disasters are causing significant disruption and damage (Paulik et al., 2019a; CSIRO, 2020; Paulik et al., 2020). In Australia, during 1987-2016, natural disasters caused an estimated 971 deaths and 4,370 injuries, 24,120 people were made homeless and about 9 million people were affected (Deloitte, 2017a). More than 50% of these deaths and injuries came from heatwaves in cities and 22% from fires. During 2007-2016, Australia natural disaster costs averaged A$18.2 billion per year with largest contributions from floods (A$8.8 billion), followed by cyclones (A$3.1 billion), hail (A$2.9 billion), storms (A$2.3 billion) and fires (A$1.1 billion) (Deloitte, 2017a). The Australian fires in 2019-2020 cost over A$8 billion, with devastating impacts on settlements and infrastructure (Box 11.1)

Sea-level rise affects many interdependent systems in cities and settlements which increase the potential for compounding and cascading impacts (11.5.1). Seaports, airports, water treatment plants, desalination plants, roads and railways are increasingly exposed to sea-level rise (*very high confidence*), impacting their longevity, levels of service and maintenance (*high confidence*) (McEvoy and Mullett, 2014; Woodroffe et al., 2014; PCE, 2015; Ranasinghe, 2016; Newton et al., 2018; Paulik et al., 2020) (Box 11.6). Compounding coastal hazards in New Zealand, such as elevated water tables associated with rising sea-level and intense rainfall (Morgan and Werner, 2015; McBride et al., 2016; White et al., 2017; Hughes et al., 2021) are exerting pressure on stormwater and wastewater infrastructure and drinking water supply and quality (MfE, 2020a).

Extreme heat events exacerbate problems for vulnerable people and infrastructure in urban Australia where urban heat is superimposed upon regional warming, and there are adverse impacts for population and vegetation health, particularly for socio-economically disadvantaged groups (Tapper et al., 2014; Heaviside et al., 2017; Filho et al., 2018; Gebert et al., 2018; Rogers et al., 2018; Longden, 2019; Marchionni et al., 2019; Tapper, In Press) (11.3.6), energy demand, energy supply and infrastructure (Newton et al., 2018) (11.3.10) (*very high confidence*). Extreme heat is increasingly threatening liveability in some rural areas in Australia (Turton, 2017), particularly given their reliance on outside physical work and older populations. Settlement design and the level of greening interact with climate change to influence local heating levels (Tapper et al., 2014; Wong et al., 2020; Tapper, In Press).

Floods cause major damage. The floods of early 2019 in north Queensland cost A$5.68 billion (Deloitte, 2019), while Cyclone Yasi and the Queensland floods of 2011 cost A$6.9 billion (Deloitte, 2016). Floodplains in New Zealand have considerably higher overall national exposure of buildings and population than coasts (Paulik et al., 2019a) (Box 11.4). The insured loss from the 12 costliest floods in New Zealand from 2007-2017 totalled NZ$471.56 million, of which NZ$140.48 million could be attributed to climate change (Frame et al., 2020).

Climatic extremes are exacerbating existing vulnerabilities *(high confidence)*. Long supply chains, poorly maintained infrastructure, social disadvantage and poor health, and lack of skilled workers (Eldridge and Beecham, 2018; Mathew et al., 2018; Rolfe et al., 2020) are contributing to serious stress and disruption (Smith and Lawrence, 2014; Kiem et al., 2016). In many rural settlements, population ageing and reliance on an over-stretched volunteer base for recovery from extreme events are increasing vulnerability to climate change (Astill and Miller, 2018; Davies et al., 2018). Recovery from long, intense, more frequent and compounding climatic events in rural areas has been disrupted by the erosion of natural, financial, built, human and social capital (De et al., 2016; Sheng and Xu, 2019). Delayed recovery from extreme climatic events has been compounded by long-term displacement which in turn prolongs the impacts (Matthews et al., 2019). Severe droughts have contributed to poor health outcomes for rural communities, including extreme stress and suicide (Beautrais, 2018; Perceval et al., 2019). In Australia, competition between water users has left some rural communities experiencing extreme water shortage and insecurity with associated health impacts (Wheeler et al., 2018; Judd, 2019) (Box 11.3).

11.3.5.2 Projected Impacts

Changes in heat waves, droughts, fire weather, heavy rainfall, storms and sea-level rise are projected to increase negative impacts for cities, settlements and infrastructure (Tables 11.3a and 11.3b; Boxes 11.1, 11.3, 11.4) (*high confidence*).

Increased floods, coastal inundation (assuming a sea-level rise of 1.6 m by 2100), wildfires, windstorms and heatwaves may cause property damage in Australia estimated at A$91 billion per year by 2050 and A$117 billion per year by 2100 for RCP8.5, while damage-related loss of property value is estimated at A$611 billion by 2050 and A$770 billion by 2100 for RCP8.5 (Steffen et al., 2019). For 1.0 m sea-level rise, the value of exposed assets in New Zealand would be NZ$25.5 billion (Box 11.6). For 1.1 m sea-level rise, the value of exposed assets in Australia would be A$164-226 billion (Box 11.6). These cost estimates exclude impacts on personal livelihood, well-being or lifestyle.

Extreme heat risks are projected to exacerbate existing heat-related impacts on human health, vegetation and infrastructure (Tapper et al., 2014; Tapper, In Press) (11.3.6). In Australia, the annual frequency of days over 35ºC is projected to increase 20-70% by 2030 (RCP4.5), and 25–85% (RCP2.6) to 80–350% (RCP8.5) by 2090 (Table 11.3a). For example, Perth may average 36 days over 35ºC by 2030 (RCP4.5). In New Zealand, the annual frequency of days over 25ºC may increase 20-60% (RCP2.6) to 50-100% (RCP8.5) by 2040, and 20–60% (RCP2.6) to 130-350% (RCP8.5) by 2090 (Table 11.3b). For example, Auckland may average 39 days over 25ºC by 2040 (RCP8.5). Unprecedented extreme temperatures, as high as 50ºC in Sydney or Melbourne, could occur with global warming of 2.0ºC (Lewis et al., 2017). Heat-related costs for Melbourne during 2012-2051 are estimated at A$1.9 billion, of which A$1.6 billion is human health/mortality costs (AECOM, 2012). Extreme heat is threatening liveability in some rural areas in Australia (Turton, 2017), particularly given their reliance on outside physical work and older populations.

Key infrastructure and services face major challenges. Structural metal corrosion rates are projected to increase significantly at coastal locations but decrease inland (Trivedi et al., 2014). A drier climate may decrease the rate of deterioration of road pavements but extreme rainfall events and heat pose a significant risk (Taylor and Philp, 2015), especially to unsealed roads in northern Australia (CoA, 2015). Critical infrastructure on coasts is at risk from sea-level rise and storm surges (Box 11.6). Facilities such as hospitals face weather-related hazards exacerbated by climate change and not originally anticipated in building and infrastructure design (Loosemore et al., 2011; Loosemore et al., 2014). By 2050, increased risks are projected for the availability and quality of potable water supplies, delivery of wastewater and stormwater services to communities, transport systems, electricity infrastructure, operating municipal landfills, and contaminated sites located near rivers and the coast (Gilpin et al., 2020; MfE, 2020a; Hughes et al., 2021). These then create risks to social cohesion and community wellbeing from displacement of individuals, families and communities, with inequitable outcomes for vulnerable groups (Boston and Lawrence, 2018).

11.3.5.3 Adaptation

In cities and settlements, climate adaptation is underway and is being led and facilitated by state and local government leadership and facilitation, particularly in Australia (Hintz et al., 2018; Newton et al., 2018) (Table 11.7, Supplementary Material Table SM11.1a) (*high confidence*).

Effective adaptations to urban heat include spatial planning, expanding tree canopy and greenery, shading, sprays and heat-resistant and energy-efficient building design, including cool materials and reflective or green roofs (*very high confidence*) (Broadbent et al., 2018; Jacobs et al., 2018b; Haddad et al., 2019; Haddad et al., 2020a; Yenneti et al., 2020; Bartesaghi-Koc et al., 2021; Tapper, In Press). Reducing urban heat not only benefits human health but reduces demand for, and cost of, air conditioning (Haddad et al., 2020b) and the risk of electricity blackouts (11.3.10).

Adaptation progress is being hampered by current urban redevelopment practice and statutory planning guidelines that are leading to removal of critical urban green space (Newton and Rogers, 2020). Reform of approaches to urban redevelopment would facilitate adaptation (Newton and Rogers, 2020). Several cities in Australia and New Zealand are part of the 100 Resilient Cities global network which helped facilitate the metropolitan Melbourne Urban Forest Strategy across councils (Fastenrath et al., 2019; Coenen et al., 2020) and in New Zealand, restoration of the urban forest in Hamilton is reducing heat stressors (Wallace and Clarkson, 2019). In peri-urban zones, adapting to fire risk is a contested issue, raising difficult trade-offs between heat management, ecological values and fuel reduction in treed landscapes (Robinson et al., 2018).

The resilience of Australia's major cities to flooding and drought has been advanced through a range of economic and physical interventions. Water sensitive urban design irrigates vegetation with harvested storm water that improves water security, flood risk, carbon sequestration, biodiversity, air and water quality, and delivers cooling that can save human lives in heatwaves (Wong et al., 2020). Storm water harvesting is supported by some councils in New Zealand and can deliver recycled water for households (Attwater and Derry, 2017), improving climate resilience and reducing water demand (White et al., 2017). Addressing infrastructure vulnerability is essential given the long lifetime of the assets, criticality of services and high costs of maintenance (Chester et al., 2020; Hughes et al., 2021).

Climate risk management is developing, but adaptive capacity, implementation, monitoring and evaluation are uneven across all scales of cities, settlements and infrastructure (*very high confidence*) (Tables 11.15a and 11.15b; Supplementary Material Tables SM11.1a, and SM11.1b). There is increasing awareness of the need to move from incremental coping and defensive coastal strategies (Jongejan et al., 2016) to transformational adaptation, for example, managed retreat (Torabi et al., 2018; Hanna, 2019), and to consider the flow-on effects (e.g. for housing and employment) (Fatorić et al., 2017; Torabi et al., 2018). Strategies limited to building household and community self-reliance (Astill and Miller, 2018) are increasingly inadequate given systemic and interconnected stressors and cascading impacts across interdependent systems (Lawrence et al., 2020b). Integrated approaches to climate change adaptation and emissions reduction have potential for addressing interdependent systems (e.g. nature-based approaches, climate-sensitive urban design, energy and transport systems) (Norman et al., 2021). Climate risk assessment and adaptation guidelines have been prepared for transport infrastructure authorities and organisations (Finlayson et al., 2017; Byett et al., 2019; Yenneti et al., 2020).

Table 11.7: Cities, settlements and infrastructure: key risks and adaptation options.

Sector	Key Risks	Adaptation Options	Inter-Sector Dependencies	Sources
Road	Heat; sea-level rise; coastal surges; floods and high intensity rainfall impacts on road foundations	Re-routing; coastal protection; improved drainage	Ports (fuel supply); rail (fuel supply); electricity	(NCCARF, 2013; CoA, 2018a; MfE, 2020a)
Rail	Extreme temperatures; flooding; sea-level rise; high intensity rainfall impacts on track foundations	Drainage and ventilation improvements; systematic risk assessments; overhead wire and rail/sleeper upgrades; rerouting	Electricity; telecommunications; fuel supply (transport, ports)	(CoA, 2018a; MfE, 2020a)
Urban and Rural Built Environment[1]	Extreme temperatures; floods; extreme weather events; wildfire (at urban-rural interface); sea-level rise	Multiple options from the building-to-city scale to reduce heat impacts and improve climate resilience; behavioural change; coastal defences and managed retreat	Road; rail; electricity; air and seaports; telecommunications; water and wastewater	(CoA, 2018a; Newton et al., 2018; Haddad et al., 2019; MfE, 2020a; Paulik et al., 2020; Tapper, In Press) (Box 11.4) (Box 11.4)

Electricity	High wind/ temperature events; wildfire; lightning; dust storms; drought (hydro)	Demand management; re-engineering and new technology; network intelligence; smart metering; improved planning for outages	Road; rail; water	(CoA, 2017; MfE, 2020a) (11.3.10.)
Ports: Air and Sea	Sea-level rise; coastal surges; wind; heat; extreme weather events	Air; improved coastal, pluvial and fluvial flood protection, on-site services. Sea; widening operational limits, raising wharfs, roads and breakwaters.	Electricity; road; rail, water	(McEvoy and Mullett, 2014; MfE, 2020a)
Telecommunications	Floods; wildfires; extreme wind	Protect; place underground; wireless systems	Electricity; digital connectivity; all sectors serviced; rural communities	(NCCARF, 2013)
Stormwater Wastewater and Water supply[1.]	High intensity rainfall; increased and extreme temperatures; flooding; drought; sea-level rise	Large investments in upgrading centralized infrastructure and capacity; increasing investment in decentralized infrastructure and capacity (e.g. Water Sensitive Urban Design); demand management; fewer options in smaller communities; governance at scale	Electricity; telecommunications; urban and rural built environment	(White et al., 2017; CoA, 2018a; Gilpin et al., 2020; MfE, 2020a; Wong et al., 2020; Hughes et al., 2021) (Box 11.4)

Table Notes:
[1.] Water supply safety and security and exposure of buildings have been identified as the most significant risks for New Zealand in terms of urgency and consequence (MfE, 2020a). No such ranking of risk has been done for Australia.

Infrastructure service vulnerability in New Zealand is supported by new institutional adaptations including the Infrastructure Commission to develop a 30-year national infrastructure strategy. The Climate Change Commission (Climate Change Commission, 2020) has issued six principles for climate-relevant infrastructure investments and is mandated to monitor the National Climate Change Adaptation Plan based on the first National Climate Change Risk Assessment (MfE, 2020a). A National Disaster Resilience Strategy addresses integrated planning for risk reduction and awareness-raising in New Zealand (Department of the Prime Minister and Cabinet, 2019).

Successive inquiries and reviews highlight potential synergies between disaster risk management and climate resilience (11.5.1) (Smith and Lawrence, 2018; Ruane, 2020). In Australia, there is a National Disaster Risk Reduction Framework (CoA, 2018b) and a National Recovery and Resilience Agency (CoA, 2021) that help underpin the development of national support systems for rural and regional emergency management and associated volunteer sectors (McLennan et al., 2016) and wildfire smoke impacts (CoA, 2020e). The National Heatwave Framework Working Group uses a Heatwave Forecast Service, and heatwave early warning and adaptation systems that operate in Adelaide, Melbourne, Sydney and Brisbane have reduced potential death rates (Nitschke et al., 2016).

Infrastructure planning is lagging behind international standards for climate resilience evaluation and guidance for adaptation to climate risk (CSIRO, 2020; Kool et al., 2020; Hughes et al., 2021) *(high* *confidence)*. Some companies have examined their exposure to climate risk and developed strategies to minimise their vulnerability (Climate Institute, 2012) (11.3.8). Climate risk assessments have been conducted for the electricity sector in both Australia and New Zealand (11.3.10). Climate change is considered in Australian infrastructure plans for national and regional water supply security, water for irrigated agriculture, a coastal hazards adaptation strategy, and the Tanami Road upgrade (Infrastructure Australia, 2016; Infrastructure Australia, 2019; Infrastructure Australia, 2021).

Industry associations are beginning to facilitate climate adaptation for infrastructure, including the Australian Green Infrastructure Council (CoA, 2015), the Green Building Council of Australia, Green Star Programme (GBCA, 2020), the Water Services Association of Australia, Climate Change Adaptation Guidelines (WSAA, 2016) and the Australian Sustainable Built Environment Council, Built Environment Adaptation Framework (ASBEC, 2012). The Infrastructure Sustainability Rating Scheme measures the social, environmental, governance and cultural outcomes delivered by more than $160 billion worth of infrastructure, and it is projected to deliver a cost-benefit ratio of 1:1.6 to 1:2.4 during 2020-2040 (RPS, 2020). There is scope for engagement of industry in transitioning to a low carbon green economy that is adapted to climate change, but less certainty on how to develop appropriate business cases (Newton and Newman, 2015).

There are tensions between settlement-scale adaptation options such as managed retreat that focus on the long term, and people's values, place attachments, needs and capacities (Gorddard et al., 2016; Fatorić et al., 2017; Graham et al., 2018; O'Donnell, 2019; Norman et al., 2021). Tensions also exist between climate change adaptation and mitigation goals (e.g. current energy efficiency standards in Australian buildings can worsen their heat resistance and increase dependence on air-conditioning) (Hatvani-Kovacs et al., 2018). Where there is a lack of coordination between jurisdictions, there can be flow-on effects from failure to adapt, for example in coastal local government areas (Dedekorkut-Howes et al., 2020) (Box 11.6). There is limited information across the region on climate change impacts and adaptation options for telecommunications (NCCARF, 2013) (Table 11.7). There is an emerging recognition that implementing and evaluating the adaptation process (vulnerability and risk assessments, identification of options, planning, implementation, monitoring, evaluation and review) in local contexts can advance more effective adaptation (Moloney and McClaren, 2018). For example, the Victorian State Government has built monitoring, evaluation and adaptation components into its adaptation plan (Table 11.15a).

[START BOX 11.6 HERE]

Box 11.6: Rising to the Sea-Level Challenge

Many of the region's cities and settlements, cultural sites and place attachments are situated around harbours, estuaries and lowland rivers (Black, 2010; PCE, 2015; Australia SoE, 2016; Rouse et al., 2017; Hanslow et al., 2018; Birkett-Rees et al., 2020) exposed to ongoing relative sea-level rise (RSLR). RSLR includes regional variability in oceanic conditions (Zhang et al., 2017) and vertical land movement along New Zealand's tectonically dynamic coasts (Levy et al., 2020) and some Australian hotspots for subsidence (Denys et al., 2020; King et al., 2020; Watson, 2020).

Table Box 11.6.1: Observed and projected impacts from higher mean sea level

Impacts from increase in mean sea level	References
Nuisance and extreme coastal flooding have increased from higher mean sea level in New Zealand. Projected sea level rise will cause more frequent flooding in Australia and New Zealand before mid-century (*very high confidence*)	(Hunter, 2012; McInnes et al., 2016; Stephens et al., 2017; Stephens et al., 2020) (Steffen et al., 2014; PCE, 2015; MfE, 2017a; Hague et al., 2019; Paulik et al., 2020)
Squeeze in intertidal habitats (*high confidence)*	(Steffen et al., 2014; Peirson et al., 2015; Mills et al., 2016a; Mills et al., 2016b; Pettit et al., 2016; Rouse et al., 2017; Rayner et al., 2021)

Significant property and infrastructure damage (*high confidence*)	(Steffen et al., 2014; PCE, 2015; Harvey, 2019; LGNZ, 2019; Paulik et al., 2020) (Table Box 11.5.2) (Table Box 11.6.2)
Loss of significant cultural and archaeological sites and projected to compound with several hazards over this century (*medium confidence*)	(Bickler et al., 2013; Birkett-Rees et al., 2020; NZ Archaeological Association, 2020)
Increasing flood risk and water insecurity with health and well-being impacts on Torres Strait Islanders (*high confidence*)	(Steffen et al., 2014; McInnes et al., 2016; McNamara et al., 2017)
Degradation and loss of freshwater wetlands (*high confidence*)	(Pettit et al., 2016; Bayliss and Ligtermoet, 2018; Tait and Pearce, 2019; Grieger et al., 2020; Swales et al., 2020)

Coastal shoreline position is driven by a complex combination of natural drivers, past and present human interventions, climate variability (Bryan et al., 2008; Helman and Tomlinson, 2018; Allis and Murray Hicks, 2019) and variation in sediment flux (Blue and Kench, 2017; Ford and Dickson, 2018). RSLR, to date, is a secondary factor influencing shoreline stability (*medium confidence*), and in Australia no definitive sea-level rise signature is yet observed in shoreline recession, nor documented in New Zealand, due to variability in shoreline position responding to storms and seasonal, annual and decadal climate drivers (Australian Government, 2009; McInnes et al., 2016; Sharples et al., 2020).

The primary impacts of rising mean sea level (Table Box 11.6.1) are being compounded by climate-related changes in waves, storm surge, rising water tables, river flows and alterations in sediment delivery to the coast (*medium confidence*). The net effect is projected to increase erosion on sedimentary coastlines and flooding in low-lying coastal areas(McInnes et al., 2016; MfE, 2017a; Hanslow et al., 2018; Wu et al., 2018). Waves are projected to be higher in southern Australasia and lower elsewhere (Morim et al., 2019) and storm surge slightly higher in the south, slightly lower further north in New Zealand (Cagigal et al., 2019) and small robust declines along southern Australia, with potentially larger changes in the Gulf of Carpentaria (Colberg et al., 2019).

The cumulative direct and residual risk from RSLR and associated impacts are projected to continue for centuries, necessitating on-going adaptive decisions for exposed coastal communities and assets (MfE, 2017c; Oppenheimer et al., 2019; Tonmoy et al., 2019) (*high confidence*).

Table Box 11.6.2: Observed relative sea-level rise (variance-weighted average) with uncertainty range (standard deviation) and projected impacts on infrastructure and population of 1.1 m in Australia and 1 m in New Zealand. Sea-level rise projections for 2050 and 2090 are given in Table 11.3a and Table 11.3b.

Country	Observed relative sea-level rise	Projected impacts of sea-level rise (1.1m Australia; 1.0m New Zealand)			
		Value of coastal urban infrastructure	Number of buildings exposed	Number of residents exposed	Public council assets exposed

Australia	2.2±1.8 mm/year to 2018 for four >75-year records (or an average of 0.17 m over 75 years). 3.4 mm/year from 1993-2019 (Watson, 2020)	A$164 to >226 billion (DCCEE, 2011; Steffen et al., 2019) 111% rise in inundation cost from 2020-2100 (Mallon et al., 2019)	187,000 to 274,000 residential buildings, 5,800 to 8,600 commercial buildings, 3,700 to 6,200 light industrial buildings (DCCEE, 2011)	N/A	27,000 to 35,000 km of roads, and 1,200 to 1,500 km of rail lines and tramways (DCCEE, 2011)
New Zealand	1.8 mm/year from 1900-2018, 1.2 mm/year from 1900-1960 and 2.4 mm/year from 1961-2018 (Bell and Hannah, 2019)	NZ$25.5 billion (Paulik et al., 2020)	75,890 (Paulik et al., 2020)	105,580 (Paulik et al., 2020)	4000 km pipelines, 1440 km roads, 101 km rail, 72 km electricity transmission lines (Paulik et al., 2020) NZ$5 billion (2018) (reserves, buildings, utility networks, roads) (LGNZ, 2019)

Prevailing decision-making assumes shorelines can continue to be maintained and protected from extreme storms, flooding and erosion, even with RSLR (Lawrence et al., 2019a). Rapid coastal development has increased exposure of coastal communities and infrastructure (*high confidence*) (Helman and Tomlinson, 2018; Paulik et al., 2020) reinforcing perceptions of safety (Gibbs, 2015; Lawrence et al., 2015) and creating barriers to retreat and nature-based adaptations (Schumacher, 2020) (*very high confidence*). The efficacy and increasing costs of protection and accommodation risk reduction approaches, and rebuilding after extreme events have been questioned and have limits (PCE, 2015; MfE, 2017a; Harvey, 2019; LGNZ, 2019; Paulik et al., 2020; Haasnoot et al., 2021). Future shoreline erosion is often signalled by using defined coastal setback lines(s) and using probabilistic approaches to signal uncertainty (Ramsay et al., 2012; Ranasinghe, 2016).

Flooding from high spring ("king") tides or storm tides during extreme weather events are raising public awareness of sea-level rise (Green Cross Australia, 2012) including through media coverage (Priestley et al., 2021). The use of adaptive decision tools (11.7.3.1; Table 11.17) is increasing the understanding of changing coastal risk (Bendall, 2018; Lawrence et al., 2019b; Palutikof et al., 2019b) and how dynamic adaptive pathways and monitoring of them can aid implementation (Stephens et al., 2018; Lawrence et al., 2020b). Collaborative governance between local governments and their communities, including with Māori tribal organisations, is emerging in New Zealand (OECD, 2019b) assisted by national direction (DoC NZ, 2010) and guidance on adaptive planning (Table 11.15b). This shift from reactive to pre-emptive planning is better suited to ongoing RSLR (Lawrence et al., 2020b).

In Australia, adaptation to sea-level rise remains uneven across jurisdictions in the absence of clear Federal or State guidance, rendering Australia unprepared for flooding from sea-level rise (Dedekorkut-Howes et al., 2020). Risk-averse coastal governance at the local level has led to shifts in liabilities to other actors and to future generations (Jozaei et al., 2020). Managed retreat has emerged as an adaptation option in New Zealand (Rouse et al., 2017; Hanna, 2019; Kool et al., 2020; Lawrence et al., 2020c) where protective measures are transitional (DoC NZ, 2010) and where managed retreat has arisen from collaborative governance (Owen et al., 2018). Remaining adaptation barriers are social or cultural (the absence of licence and legitimacy) and institutional (the absence of regulations, policies and processes that support changes to existing property rights and the funding of retreat) (O'Donnell and Gates, 2013; Tombs et al., 2018; Grace et al., 2019; O'Donnell et al., 2019) (*high confidence*).

Legacy development, competing public and private interests, trade-offs among development and conservation objectives, policy inconsistencies, short and long-term objectives, and the timing and scale of impacts, compound to create contestation over implementation of coastal adaptation (Mills et al., 2016b; McClure and Baker, 2018; Dedekorkut-Howes et al., 2020; McDonald, 2020; Schneider et al., 2020) (*high confidence*). Legal barriers to coastal adaptation remain (Schumacher, 2020) with a risk that the courts become decision makers (Iorns Magallanes et al., 2018) due to legislative fragmentation, status quo leadership, lack of coordination between governance levels and agreement about who pays for what adaptation (Waters et al., 2014; Boston and Lawrence, 2018; Palutikof et al., 2019a; Noy, 2020) (*very high confidence*). The nexus of climate, law, place and property rights continues to expose people and assets to ongoing sea-level rise (Johnston and France-Hudson, 2019; O'Donnell, 2019), especially where the risks of sea-level rise are not being reflected in property valuations (Cradduck et al., 2020). Risk signalling through land use planning, flooding events, and changes in insurance availability and costs, are projected to increase recognition of coastal risks (Storey and Noy, 2017; CCATWG, 2018; Lawrence et al., 2018a; Harvey and Clarke, 2019; Steffen et al., 2019; Cradduck et al., 2020; ICNZ, 2021) (*medium confidence*). Proactive local-led engagement and strategy are key to effective adaptation and incentivising and supporting communities to act(Gibbs, 2020; Schneider et al., 2020). Adopting 'fit for purpose' decision tools that are flexible as sea levels rise (11.7.3) can build adaptive capacity in communities and institutions (*high confidence*).

[END BOX 11.6 HERE]

11.3.6 Health and Wellbeing

11.3.6.1 Observed Impacts

There is ample evidence of health loss due to extreme weather in Australia and New Zealand, and rising temperatures, changing rainfall patterns and increasing fire weather have been attributed to anthropogenic climate change (11.2.1). Extreme heat leads to excess deaths and increased rates of many illnesses (Hales et al., 2000; Nitschke et al., 2011; Lu et al., 2020). Between 1991 and 2011 it is estimated that 35-36% of heat-related mortality in Brisbane, Sydney and Melbourne was attributable to climate change, amounting to about 106 deaths a year on average over the study period (Vicedo-Cabrera et al., 2021). Exposure to high temperatures at work is common in Australia, and the health consequences may include more accidents, acute heat stroke and chronic disease (Kjellstrom et al., 2016). Long-term rise in temperatures is changing the balance of summer and winter mortality in Australia (Hanigan et al., 2021). The Black Summer wildfires in Australia in 2019/2020 (Box 11.1) caused 33 deaths directly (Davey and Sarre, 2020) and exposed millions of people to heavy particulate pollution (Vardoulakis et al., 2020). In the Australian States most heavily affected by the fires, 417 deaths, 3151 hospital admissions for cardiovascular or respiratory conditions, and about 1300 emergency department presentations for asthma are attributed to wildfire smoke exposure (Borchers Arriagada et al., 2020). Immediate smoke-related health costs from the 2019-20 fires are estimated at A$1.95 billion (Johnston et al., 2020).

Extreme heat is associated with decreased mental well-being, more marked in women than men (Ding et al., 2016). Changing climatic patterns in Western Australia have undermined farmers' sense of identity and place, heightened anxiety and increased self-perceived risks of depression and suicide (Ellis and Albrecht, 2017). Following the Black Saturday wildfires in Victoria in 2009, 10-15% of the population in the most severely affected areas reported persistent fire-related post-traumatic stress disorder, depression and psychological distress (Bryant et al., 2014). Repeated exposure to the threat of wildfires in Australia, either directly (Box 11.1) or through media coverage (Looi et al., 2020) may compound effects on mental health. In March 2017, 31,000 people in New South Wales and Queensland were displaced by Tropical Cyclone Debbie. Six months post-cyclone, adverse mental health outcomes were more common among those whose access to health and social care was disrupted (King et al., 2020).

Dengue fever remains a threat in northern Australia and variations in rainfall and temperature are related to disease outbreaks and patterns of spread, although most outbreaks are sparked by travellers bringing the virus into the country (Bannister-Tyrrell et al., 2013; Hall et al., 2021). Cases of dengue fever and other arboviral diseases have been increasing amongst recent arrivals to New Zealand from overseas, but to date there have been no reports of local transmission (Ammar et al., 2021).

In 2016 in New Zealand, it is estimated 6-8,000 people became ill due to contamination of the Havelock North water supply with the bacteria *Campylobacter* (Gilpin et al., 2020). The infection was traced to sheep faeces washed into the underground aquifer that feeds the town's (untreated) water supply after an extraordinarily heavy rainfall event. This is not an isolated finding: increases in pediatric hospital admissions are seen across New Zealand two days after heavy rainfall events (Lai et al., 2020).

11.3.6.2 Projected impacts

Climate change is projected to have detrimental effects on human health due to heat stress, changing rainfall patterns including floods and drought, and climate-sensitive air pollution (including that caused by wildfires) (*high confidence*). Vulnerability to detrimental effects of climate change will vary with socio-economic conditions (*high confidence*).

The greatest number of people affected by compounding effects of heat, wildfires and poor air quality will be in urban and peri-urban areas of Australia. By 2100 the proportion of all deaths attributable to heat in Melbourne, Sydney and Brisbane may rise from about 0.5% to 0.8% (under RCP 2.6), or 3.2% (under RCP 8.5) (Gasparrini et al., 2017). Heat-wave related excess deaths in Melbourne, Sydney and Brisbane are projected to increase to 300/year (RCP2.6) or 600/year (RCP8.5) during 2031-2080 relative to 142/year during 1971-2020, assuming no adaptation and high population growth (Guo et al., 2018). High temperatures amplify the risks due to local air pollution: without adaptation, ozone-related deaths in Sydney may increase by 50-60 per year by 2070 (Physick et al., 2014).

Unless there is more effective control of nutrient run-off, bacterial contamination of drinking water supplies is projected to increase due to more intense rainfall events, exacerbating risks to human health (Gilpin et al., 2020, Lai, 2020 #2680), and higher temperatures will increase freshwater toxic blooms (Hamilton et al., 2016).

Less certain climate change impacts include: surges in vector-borne diseases (*medium confidence*); threats to mental health (*medium confidence*); reduction in winter mortality (*medium confidence*); emergence of new or poorly understood weather-related threats (such as thunderstorm asthma or interactions between rising heat and air pollution) (*low confidence*); and spill-over effects on health from global impacts of climate change (e.g., on trade, conflict, migration) (*low confidence*).

In general, the area of Australia suitable for transmission of dengue is projected to increase (Zhang and Beggs, 2018; Messina et al., 2019) but estimates of local disease risk vary considerably according to climate change scenario and socio-economic pathways (Williams et al., 2016). The spread of *Wolbachia* amongst *Aedes* mosquitoes in northern Australia has already reduced dengue transmission and may decrease the influence of climate in the future (Ryan et al., 2019). In New Zealand, the risk of dengue remains low for the remainder of this century (Messina et al., 2019). Higher temperatures and more intense rainfall may also increase pollen production and the risk of allergic illness throughout the region (Haberle et al., 2014).

11.3.6.3 Adaptation

Strengthening basic public health services can rapidly reduce vulnerability to death and ill-health caused by climate change, however this opportunity is often missed (*very high confidence*). The 2020 New Zealand Health and Disability System Review pointed to short-comings in leadership and governance, structures that embed health inequity, lack of transparency in planning and reporting, and under-investment in public health personnel and systems (HDSR, 2020). An Australian study found that without deliberate planning the health system 'would only be able to deal with climate change in an expensive, *ad hoc* crisis management manner' (Burton, 2014). In both Australia and New Zealand the COVID-19 epidemic has highlighted weaknesses in information systems, primary care for marginalized groups and inter-sectoral planning (Salvador-Carulla et al., 2020; Skegg and Hill, 2021): all these deficiencies are relevant to climate adaptation.

Underlying health and economic trends affect the vulnerability of the population to extreme weather (*high confidence*). Poor housing quality is a risk factor for climate-related health threats (Alam et al., 2016). Homeless people lack access to temperature-controlled or structurally safe housing, and often are excluded from disaster preparation and responses (Every, 2016). These inequalities are reversible. For example, a government partnership with social housing providers in Australia improved the thermal performance of housing for low-income tenants (Barnett et al., 2014a). A postcode-level analysis of the vulnerability of urban populations to extreme heat in Australian capital cities (Loughnan et al., 2013) led to the development of an interactive website for purposes of planning and emergency preparedness (Figure 11.5) as well as subsequent work on green urban design for cooler, more liveable cities (Tapper, In Press).

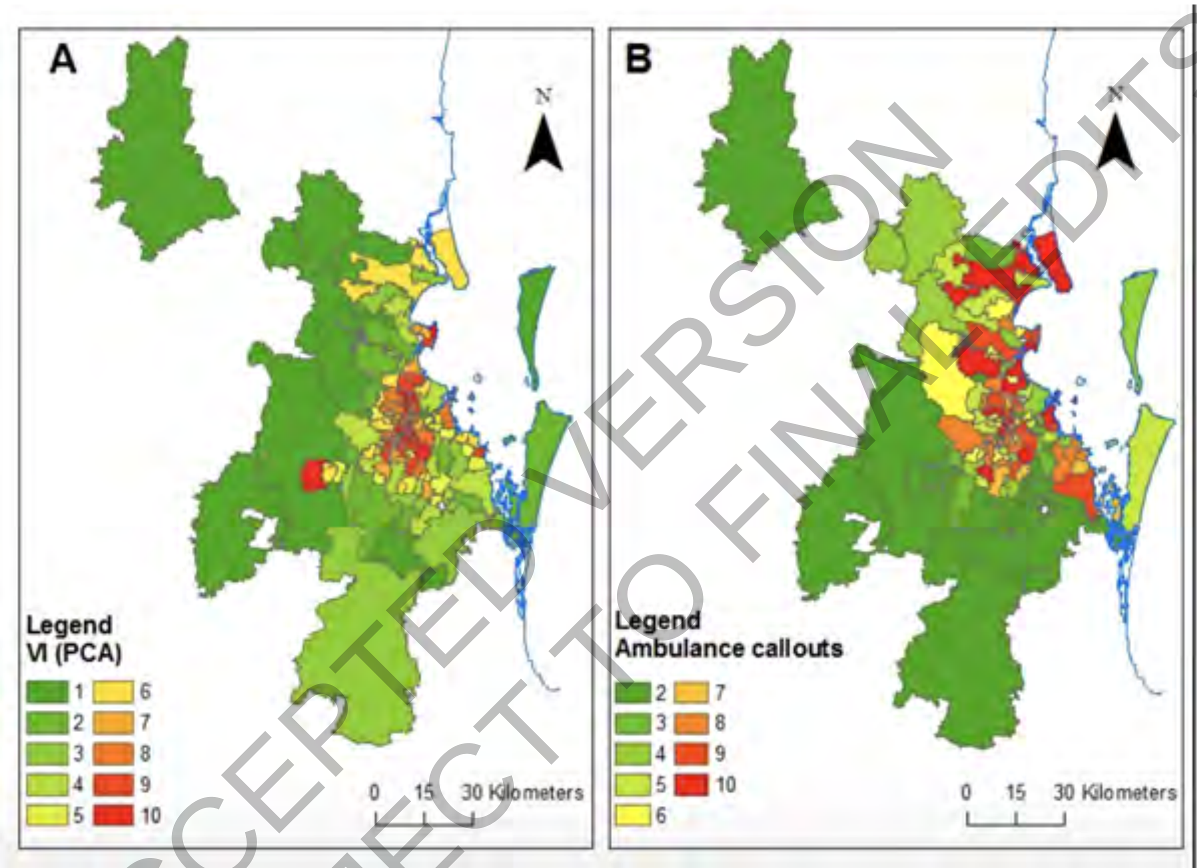

Figure 11.5: Housing and socio-economic disadvantage is correlated with the use of emergency services on hot days (rho = 0.55, p<0.01). The spatial distribution of (A) a community vulnerability index (VI (PCA) by deciles and (B) ambulance call-outs on days above daily mean of 34ºC, in Brisbane, Australia. Ambulance call-out data are expressed as deciles based on per-capita calls during 2003-2011 (Loughnan et al., 2013).

Heat-wave responses, from public education to formal heat-warning systems, are the best-developed element of adaptation planning for health in Australia, but many metropolitan centres are still not covered (Nicholls et al., 2016; Nitschke et al., 2016) (*high confidence*). Air conditioning (AC) in Australian homes reduces mortality in heat-waves by up to 80% (Broome and Smith, 2012) but heavy reliance on AC carries risks. It is estimated that a power outage on the third day of extreme heat-waves would result in an additional 10–21 deaths in Adelaide, 24–47 in Melbourne and 7–13 in Brisbane (Nairn and Williams, 2019). Multiple interventions at the landscape, building and individual scale are available to reduce the negative health effects of extreme heat (Jay et al., 2021)

Heat extremes receive most policy attention, but the numbers of deaths are less than those resulting from more frequent exposures to moderately high temperatures (Longden, 2019). Melbourne provides a case study in long-term planning for cooler cities, with its Urban Forest Strategy (Gulsrud et al., 2018). Australian workers' perceptions of heat and responses to high temperatures show that heat policies on their own are insufficient for full protection; workers also require knowledge and agency to slow down or take breaks on their own initiative (Singh et al., 2015; Lao et al., 2016).

The first national climate change risk assessment in New Zealand (MfE, 2020a) highlighted the risk to potable water supplies. An inquiry into the Havelock North outbreak recommended that all registered drinking water supplies (which supply about 80% of the national population) in New Zealand should be disinfected and have stronger oversight by a national regulatory body (Government Inquiry into Havelock North Drinking Water, 2017). The use of local and Indigenous knowledge strengthens interventions to protect water supplies to remote settlements that may be affected by climatic changes (Henwood, 2019).

Adaptation requires better protection of health facilities and supply chains, but hospital managers seldom have capacity to invest in long-term improvements in infrastructure (Loosemore et al., 2014). However, health services in the region are required to prepare disaster plans: these could be expanded to explicitly cover health adaptation and local threats from climate change, including flooding events (Rychetnik et al., 2019).

11.3.7 Tourism

11.3.7.1 Observed Impacts

Tourism is a major economic driver in the region, accounting for 3% (Australia) and 6% (New Zealand) of GDP pre-COVID-19 (WTTC, 2018). Climate change is having significant impacts on tourism due to the heavy reliance of the sector on natural heritage and outdoor attractions (11.3.1; Box 11.2). Furthermore, as Australia and New Zealand are both long-haul destinations, a global increase in 'flygskam' (flight shame) will to impact travel patterns (Becken et al., 2021).

Impacts of climate change are being observed across the tourism system (Scott et al., 2019a) (*high confidence*), most notably the Great Barrier Reef (Box 11.2) (Ma and Kirilenko, 2019). Australia's ski industry is very sensitive to climatic change, due to reduction in snow depth and the length of the snow season (Table 11.2) (Steiger et al., 2019; Knowles and Scott, 2020). The 2019-2020 summer wildfires (Box 11.1), impacted tourism and travel infrastructure, affecting air quality, vineyards and wineries (CoA, 2020e; Filkov et al., 2020). Global media coverage of the wildfires, alongside Australia's climate change policy response, profoundly and negatively, affected Australia's destination image (Schweinsberg et al., 2020; Wen et al., 2020). In New Zealand's South Island, Fox and Franz Josef Glaciers have retreated approximately 700m since 2008, with ice melt and retreat resulting in increased rock fall risks and negatively affecting the tourist experience (Purdie, 2013; Stewart et al., 2016; Wang and Zhou, 2019). The West Coast of New Zealand is extremely prone to flooding events impacting amenity values and access (Paulik et al., 2019b). Damage to tracks, huts and bridges have closed popular destinations, including the Hooker Glacier and the popular Routeburn and Heaphy Tracks during heavy rainfall events (Christie et al., 2020). Climate-driven damage is motivating 'last chance' tourism to see key natural heritage and outdoor attractions, e.g. Great Barrier Reef (Piggott-McKellar and McNamara, 2016) and Franz and Fox Glaciers (Stewart et al., 2016).

11.3.7.2 Projected Impacts

Widespread impacts from projected climate change are *very likely* across the tourism sector. The World Heritage listed Kakadu National Park in Australia is projected to experience increasing severity of cyclones (Turton, 2014) and sea-level rise is projected to affect freshwater wetlands (11.3.1.2; Table 11.5) (McInnes et al., 2015) and Indigenous rock art (Higham et al., 2016; Hughes et al., 2018a). The projected increase in the number of hot days in northern and inland Australia may impact the attractiveness of the region for tourists (Amelung and Nicholls, 2014; Webb and Hennessy, 2015). Coastal erosion and flooding of Australasian beaches due to sea-level rise and intensifying storm activity is estimated to increase by 60% on the Sunshine Coast by 2030 causing significant damage to tourist-related infrastructure (Hughes et al., 2018a). Urgent 'hard' and 'soft' adaptation strategies are projected to help reduce sea-level rise impacts (Becken and Wilson, 2016).

Glacier tourism, a multimillion-dollar industry in New Zealand, is potentially under threat because glacier volumes are projected to decrease (Purdie, 2013) (*very high confidence).* Glacier volume reductions of 50–92% by 2099 relative to present reflect the large range of temperature projections between RCP2.6 and RCP8.5. Under RCP2.6 at 2099, the glaciers retain a similar configuration to present, although clean-ice glaciers will retreat significantly. For RCP4.5, RCP6.0 and RCP8.5, the clean-ice glaciers will retreat to become small remnants in the high mountains (Anderson et al. 2021).

Snow skiing faces significant challenges from climate change (*high confidence*). In Australia, the annual maximum snow depth is estimated to decrease from current levels by 15% (2030) and 60% by 2070 (SRES A2) (Di Luca et al., 2018). By 2070-2099, relative to 2000-2010, the length of the Victorian ski-season is projected to contract by 65-90% under RCP8.5 (Harris et al., 2016). The New Zealand tourism destination of Queenstown is expected to experience declining snowfall, increased wind and more severe weather events (Becken and Wilson, 2016). Ski tourism stakeholders have been responding to longer-term climate risks with an increase in snow-making machines in New Zealand since 2013 (Hopkins, 2015) and in Australia (Harris et al., 2016).

11.3.7.3 Adaptation

Current snow-making technologies are expected to sustain the ski industry until mid-century. However, with warmer winter temperatures and declining water availability, snow-making is projected to decrease to half at most resorts by 2030 (Harris et al., 2016). New Zealand's ski industry may benefit from Australian skiers visiting New Zealand, due to lower relative vulnerability (Hopkins, 2015). However, tourists may substitute destinations or ski less in the absence of snow (*medium agreement, limited evidence*) (Cocolas et al., 2015; Walters and Ruhanen, 2015).

With the exception of the ski industry (Becken, 2013; Hopkins, 2015), tourism stakeholders generally focus on coping with short-term weather events, rather than longer-term climate risks, but do exhibit high adaptive capacity by diversifying their activities (Stewart et al., 2016). Post Covid-19 pandemic economics and recovery policies challenge this sector's prospects, and the combination of COVID-19 and climate change (e.g. fires, floods) has also highlighted the need for the tourism sector to be able to respond to multiple, overlapping crises.

There is limited evidence that research into the impact of climate change on tourism in Australia and New Zealand is translating into policy or action (Moyle et al., 2017). New Zealand government tourism sector strategies acknowledge this and the need for greater understanding of climate change for the sector, (TIA, 2019), but do not offer solutions (MBIE, 2019b; MfE, 2020a). The COVID-19 pandemic and the global pause of international travel offers an opportunity to potentially 'reset' tourism to account for the impacts of climate change (Prideaux et al., 2020).

11.3.8 Finance

11.3.8.1 Observed Impacts

The finance sector has significant exposure to climate variability and extreme events (*high confidence*). Aggregated insured losses from weather-related hazard events from 2013-2020 were almost A$15 billion for Australia (1.2% of GDP) and almost NZ$1 billion for New Zealand (0.4% of GDP) (ICA, 2020a; NIWA, 2020). However, there is no trend in normalised losses because the rising insurance costs are being driven by more people living in vulnerable locations with more to lose (McAneney et al., 2019). In New Zealand, two major hailstorms during 2014-2020 and three major floods during 2019-2021 caused significant insurance losses (ICNZ, 2021). Insured losses exceeded NZ$472 million for the 12 costliest floods from 2007-2017, of which NZ$140 million could be attributed to anthropogenic climate change (Frame et al., 2020). In Australia, insured damage was almost A$1.0 billion for the Queensland hailstorm in 2020, A$1.7 billion for east coast flooding in 2020, A$2.3 billion for the 2019-2020 fires, A$2.3 billion for the Queensland hailstorm in 2019, A$1.2 billion for the north Queensland floods in 2019, A$1.4 billion for the NSW hailstorm in 2018, A$1.8 billion for Cyclone Debbie in 2017 and A$1.5 billion for the Brisbane hailstorm in 2014 (ICA, 2020b). The insured loss from the seven costliest hailstorms in Australia from 2014-2021 totalled A$7.6 billion (ICA, 2021).

Some homes in the highest risk areas tend to be in lower socio-economic groups that may not buy insurance (Actuaries Institute, 2020). For example, one quarter of residents that experienced loss or damage in the 2019 Townsville floods did not have insurance (ACCC, 2020). Under-insurance reduces people's capacity to recover from adverse events, while over-reliance on private insurance undermines collective disaster recovery efforts (Lucas and Booth, 2020). In Australia, those in high-risk areas minimise house and contents insurance for financial reasons (Booth and Harwood, 2016; Osbaldison et al., 2019; Actuaries Institute, 2020). Insurance premiums in northern Australia are almost double those in the rest of Australia, and rising, mainly due to cyclone damage (ACCC, 2020).

11.3.8.2 Projected Impacts

Risks for the finance sector are projected to increase (*medium confidence*). The potential impact of increased coastal and inland flooding, soil desiccation and contraction, fire and wind could lead to higher insurance costs, reduced property values and difficulty for some customers to service loans (CBA, 2018). Under a high emission scenario (RCP8.5), estimated annual losses to home-lending customers may increase 27% by 2060, and the proportion of properties with high credit risk may rise from 0.01% in 2020 to 1% in 2060, assuming no change in the portfolio (CBA, 2018). In New Zealand, weather-related insurance claims between 2000–2017 totaled NZ$450 million, 40% of which were due to extreme rainfall. Using six climate model projections of extreme rainfall, the insured damage is projected to increase by 7% (RCP2.6) to 8% (RCP8.5) by 2020–2040 and 9% (RCP2.6) to 25% (RCP8.5) by 2080–2100, relative to 2000–2017 (Pastor-Paz et al., 2020). By 2050–2070, tropical cyclone risk for properties not in flood plains or storm surge zones in south-east Queensland may increase by 33% under a 2°C scenario, and by 317% under a 3°C scenario for properties in flood plains and storm surge zones (IAG, 2019).

11.3.8.3 Adaptation

Banks, insurers and investors increasingly recognise the risks posed by climate change to their businesses (Paddam and Wong, 2017) (*high confidence*). Collaborations between banks, insurers and superannuation funds in Australia and New Zealand are driving efforts aimed at achieving the Paris Agreement goals, including the New Zealand Centre for Sustainable Finance and Australian Sustainable Finance Initiative (AFSI, 2020; TAO, 2020; NZCFSF, 2021). Company directors including superannuation fund directors have legal obligations to disclose and appropriately manage material financial risks (Barker et al., 2016; Hutley and Davis, 2019). Financial regulators are aware of climate risks for financial stability and financial institutions (RBNZ, 2018; RBA, 2019) and are closely supervising climate risk disclosure practices (TCFD, 2017; RBNZ, 2018; APRA, 2019; CMSI, 2020; IGCC, 2021b). In Australia, regulatory action (APRA, 2021) includes issuing prudential guidelines for financial institutions on managing climate risk, aligned with guidelines developed by the Climate Measurement Standards Initiative (NESP ESCC, 2020). In New Zealand, the Financial Sector (Climate-related Disclosure and Other Matters) Amendment Bill aims to ensure that the effects of climate change are routinely considered in business, investment, lending, and insurance underwriting decisions
(NZ Government, 2021).

Banks and insurers are beginning to undertake climate risk analyses (CRO Forum, 2019; Bruyère et al., 2020) and disclose their risks (Paddam and Wong, 2017; ANZ, 2018; CBA, 2018). For example, the agricultural banking sector has analysed climate risk and embedded climate adaptation financing into its risk scoring and lending practices (CBA, 2019). However, the overall number of disclosures continues to lag expectations, suggesting the need for mandatory climate risk disclosure in Australia (IGCC, 2021a).

Climate adaptation finance is not evident (*medium confidence*). There is an adaptation finance gap (Mortimer et al. 2020). Private sector initiatives are beginning to emerge through large scale projects or public-private partnerships, such as the Queensland Betterment Fund (Banhalmi-Zakar et al., 2016; Ware and Banhalmi-Zakar, 2020). Addressing investor pressure (IGCC, 2017) could increase investment in adaptation. However, ongoing policy uncertainty in Australia continues to be the key barrier to allocating further capital to invest in climate solutions for 70% of investors (IGCC, 2021a).

Current and future insurance affordability pressures could be addressed by increased mitigation, revisions to building codes and standards, and better land-use planning (ACCC, 2020; Actuaries Institute, 2020). In New Zealand, insurance signals are motivating the government to address adaptation funding mechanisms (Boston and Lawrence, 2018; CCATWG, 2018). Some insurers offer premium discounts to customers with reduced risk (Drill et al., 2016) with increasing premiums reflecting known risk and no cover for some hazards in risky locations (CCATWG, 2017). Special excess payments are available for flood hazard so customers take responsibility for part of the claim, with increasing premiums to reflect known and foreseeable risk, and downgrading cover from replacement value to market value (Bruyère et al., 2020). Retreat by private insurers from risky locations could increase the unfunded fiscal risk to the government (Storey and Noy, 2017) creating moral hazard (Boston and Lawrence, 2018). The litigation risk from failing to take adaptation action (Hodder, 2019) could affect financial markets and government policy settings, creating cascading impacts across society (Lawrence et al., 2020b)(CRO Forum, 2019). For some climate risks, national governments act as "last resort" insurers (CCATWG, 2017), but this could become unsustainable (CRO Forum, 2019).

11.3.9 Mining

Many mines are exposed and sensitive to climate extremes (*high confidence*), but there is little available research on climate change impacts (Odell et al., 2018). Most Australian mines face higher temperatures, cyclones, erosion and landslides, and hazards such as sea-level rise and storms across their supply chains, including ports (Cahoon et al., 2016). Impacts include operational disruptions such as acute drainage problems (Loechel and Hodgkinson, 2014) and heat-induced illness, irritation and absenteeism among workers (McTernan et al., 2016), lost revenue and increased costs (Pizarro et al., 2017).

Damage and disruption from climate impacts can cost operators billions of dollars (Cahoon et al., 2016). Climatic extremes increase the risk and impact of spillages along transportation routes (Grech et al., 2016) exacerbate mining's effects on hydrology, ecosystems, and air quality (Phillips, 2016; Ali et al., 2018); increase contamination risks (Metcalfe and Bui, 2016); and disrupt and slow mine site rehabilitation (Wardell-Johnson et al., 2015; Hancock et al., 2017). Adaptations such as improved water management are emerging slowly (Gasbarro et al., 2016; Becker et al., 2018). Some companies are spatially diversifying and relocating (Hodgkinson et al., 2014). Others are replacing workers with automation and remote operations (Halteh et al., 2018; Keenan et al., 2019).

11.3.10 Energy

Australia's energy generation is a mix of coal (56%), gas (23%) and renewables (21%) (DISER, 2020), with ageing coal-fired infrastructure being replaced with a growing proportion of renewable and distributed energy resources (AEMO, 2018). In New Zealand, 60% of energy generation comes from hydro-electricity and 15% from geothermal (MBIE, 2021), with coal (2%) and gas (13%) generation capacity to be retired, and total renewable energy to increase from 82% in 2017 to around 95% by 2050, mostly through wind generation (MBIE, 2019a).

11.3.10.1 Observed Impacts

The energy sector is highly vulnerable to climate change (*high confidence*). Oil and gas systems are vulnerable to storms, fires, drought, floods, sea-level rise, extreme heat and fires which can damage infrastructure, slow production, and add to operational costs (Smith, 2013). The electricity system is vulnerable to high temperatures reducing generator and network capacity and increasing failure rates and maintenance costs(AEMO, 2020a). Fires (including those sparked by electrical distribution lines) pose risks to assets, smoke can cause electricity transmission to trip, high winds reduce wind-energy capacity and threaten the integrity of transmission lines, low rainfall reduces hydro-energy capacity and increases the demand for desalination energy, higher sea-level may affect some low-lying generation, distribution and transmission assets, and compound extreme weather events can cause outages (Vose and Applequist, 2014; Lawrence et al., 2016; AEMO, 2020b; AEMO, 2020a; ESCI, 2021). For example, in September 2016, a major windstorm in South Australia damaged 23 transmission towers and cut power to over 900,000 households. In February 2017, the South Australian energy system failed to cope with a heatwave-related jump in demand, causing power cuts to 40,000 homes (Steffen et al., 2017). In April 2018, a storm over

Auckland New Zealand left 182,000 properties without power (Bell, 2018). The 2019/20 Australian heatwaves and fires caused widespread blackouts that disrupted communications, transport, and emergency response capacity (Box 11.1).

11.3.10.2 Projected Impacts

Risks for the energy sector are projected to increase with climate change (*medium confidence*). Projected increases in the frequency and intensity of heatwaves, fires, droughts and wind-storms would increase risks for energy supply and demand (AEMO, 2020b; ESCI, 2021). Households are unevenly vulnerable to energy sector risks due to varying housing quality and health dependencies (11.3.6). In New Zealand, a warmer climate and increasing energy efficiency is projected to marginally reduce annual average peak electricity heating demand (Stroombergen et al., 2006; MBIE, 2019a). Winter and spring inflows to main hydro lakes are projected to increase 5-10% and may reduce hydroelectric energy vulnerability (McKerchar and Mullan, 2004; Poyck et al., 2011; Stevenson et al., 2018). However, major electricity supply disruptions are projected to increase as dependence on electricity grows from 25% of total energy in 2016 to 58% in 2050 (Transpower, 2020).

In Australia, the total heating and cooling energy demand of 5-star energy-rated houses is projected to change by 2100 (Wang et al., 2010). At 2°C global warming, the estimated change in demand is –27% in Hobart, –21% in Melbourne, +61% in Darwin, +67% in Alice Springs and +112% in Sydney. For a 4°C global warming, the changes are –48%, –14%, +135%, +213% and +350% respectively.

11.3.10.3 Adaptation

Options to manage risks include adaptation of energy markets, integrated planning, improved asset design standards, smart-grid technologies, energy generation diversification, distributed generation (e.g. roof-top solar, micro-grids), energy efficiency, demand management, pumped hydro storage, battery storage, and improved capacity to respond to supply deficits and balance variable energy resources across the network (Table 11.8) (*high confidence*). With increasing electrification, diversification and resilience can contribute to security of supply as fossil fuels are retired from the energy mix (AEMO, 2020b). In Australia, the AEMO (2020) Integrated System Plan has evaluated various options, costs and benefits. Risks associated with an increasing reliance on weather-dependent renewable energy (e.g. solar, wind, hydro) (ESCI, 2021) can be managed through strong long-distance interconnection via high voltage powerlines and storage (Blakers et al., 2017; Blakers et al., 2021; Lu et al., 2021). However, implementation of adaptation options remains inadequate (Gasbarro et al., 2016).

Table 11.8: Adaptation options for the energy sector.

Adaptation options	References
Diversification of electricity supplies geographically and technically, including distributed energy resources and variable renewable energy	(AEMO, 2020b)
Integrated planning, improved asset design and management, and disaster recovery to build resilience to more extreme weather	(AEMO, 2020b; Transpower, 2020)
Augmentation of transmission grid to support change in generation mix using interconnectors and renewable energy zones, coupled with energy storage, adds capacity and helps balance variable resources across the network	(Blakers et al., 2017; ICCC, 2019; AEMO, 2020b)
Climate change risks included in the design, location, and rating of future infrastructure and consideration of the implications for future transmission developments	(Bridge et al., 2018; AEMO, 2020b)
Increased design and construction standards, flood defence measures, insurance, improved water efficiency, improved insulation of super-cooled LNG processes, more efficient air conditioning and creating fire breaks for the oil and gas sector	(Smith, 2013; Gasbarro et al., 2016)

Technological developments to strengthen existing resilience under climate change that reinforces the relative advantage of Western Australia and Tasmania for new wind energy installations	(Evans et al., 2018)
Energy generation diversity, demand management, pumped hydro storage and battery storage	(Keck et al., 2019; Transpower, 2020)
Tools and strategies to manage winter energy deficits and dry years alongside renewable electricity generation deployment	(Transpower, 2020)
Improved insulation and heating of buildings, and flexible electricity consumption to reduce the significance of winter electricity demand peak	(Stroombergen et al., 2006; MBIE, 2019a; Transpower, 2020)

11.3.11 Detection and Attribution of Observed Climate Impacts

Detection and attribution of observed climate trends and events is called 'climate attribution'. This has been assessed by IPCC Working Group I (Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021) and summarised in IPCC Working Group 2 Chapter 16. Trends that have been formally attributed in part to anthropogenic climate change include regional warming trends and sea-level rise, decreasing rainfall and increasing fire risk in southern Australia. Events include extreme rainfall in New Zealand during 2007-2017, the 2007/8 and 2012/13 droughts in New Zealand, high temperatures in Australia during 2013-2020, the 2016 northern Australian marine heatwave, the 2016/2017 and 2017/18 Tasman Sea marine heatwaves, and 2019/2020 fires in Australia.

Detection and attribution of climate impacts on natural and human systems is called 'impact attribution'. This often involves a two-step approach (joint attribution) that links climate attribution to observed impacts. Impact attribution is complicated by confounding factors, e.g. changes in exposure arising from population growth, urban development and underlying vulnerabilities.

Impact attribution has been considered in Sections 11.3.1 to 11.3.10 and summarised in Table 11.9. More literature is available for natural systems than human systems, which represents a knowledge gap rather than an absence of impacts that are attributable to anthropogenic climate change. Fundamental shifts in the structure and composition of some ecosystems are partly due to anthropogenic climate change (*high confidence*). In human systems, the costs of droughts and floods in New Zealand, and heat-related mortality and fire damage in Australia, are partly attributed to anthropogenic climate change (*medium confidence*).

Table 11.9: Examples of observed impacts that can be partly attributed to climate change.

Impact	Source
Mass bleaching of the Great Barrier Reef in 2016/2017 due to a marine heatwave	Box 11.2
In the New Zealand Southern Alps, extreme glacier mass loss was at least six times more likely in 2011, and ten times more likely in 2018, due to warming	11.2.1, 11.3.3
In the Australian Alps bioregion, loss of habitat for endemic and obligate species due to snow loss and increases in fire, drought and temperature	Table 11.4
In the Australian wet tropics world heritage area, some vertebrate species have declined in distribution area and population size due to increasing temperatures and length of dry season	Table 11.4
Extinction of Bramble Cay melomys due to loss of habitat caused by storm surges and sea-level rise in Torres Strait	Table 11.4
In New Zealand, increasing invasive predation pressure on endemic forest birds surviving in cool forest refugia due to anthropogenic warming	Table 11.4
In New Zealand, erosion of coastal habitats due to more severe storms and sea-level rise	Table 11.4, Box 11.6

In Australia, estuaries warming and freshening with decreasing pH	Table 11.6
Changes in life-history traits, behaviour or recruitment of fish and invertebrates due to ocean acidification or warming, severe decline in recruitment of coral on the Great Barrier Reef due to ocean warming, aquaculture stock deaths due to heat stress	Table 11.6
New diseases and toxins due to warming and extension of East Australian Current	Table 11.6
Changes in almost 200 marine species distributions and abundance due to ocean warming	Table 11.6
Temperate marine species replaced by seaweeds, invertebrates, corals and fishes characteristic of subtropical and tropical waters	Table 11.6
River flow decline in southern Australia is largely due to the decline in cool season rainfall partly attributed to anthropogenic climate change	11.3.3
In New Zealand, the 2007/08 drought and the 2012/13 drought were 20% attributed to anthropogenic climate change	11.3.3
In New Zealand, about 30% of the insured damage for the 12 costliest flood events from 2007-2017 can be attributed to anthropogenic climate change	11.3.8
In Australia, 35-36% of heat-related excess mortality in Melbourne, Sydney and Brisbane from 1991-2018 can be attributed to anthropogenic climate change	11.3.6

11.4 Indigenous Peoples

Indigenous perspectives of well-being embrace physical, social, emotional and cultural domains, collectiveness and reciprocity, and more fundamentally connections between all elements across the past, present and future generations (Australia. NAHS Working Party, 1989; MfE, 2020a). Changing climate conditions are expected to exacerbate many of the social, economic and health inequalities faced by Aboriginal and Torres Strait Islander Peoples in Australia and Māori in New Zealand (Bennett et al., 2014; Hopkins et al., 2015; AIHW, 2016; Lyons et al., 2019) (*high confidence*). As a consequence, effective policy responses are those that take advantage of the interlinkages and dependencies between mitigation, adaptation and Indigenous Peoples' wellbeing (Jones, 2019) and those that address the transformative change needed from colonial legacies (Hill et al., 2020) (*high confidence)*. There is a central role for Indigenous Peoples in climate change decision making that helps address the enduring legacy of colonisation through building opportunities based on Indigenous governance regimes, cultural practices to care for land and water, and intergenerational perspectives (Nursey-Bray et al., 2019; Petzold et al., 2020) (Cross-Chapter Box INDIG in Chapter 18) (*very high confidence*).

11.4.1 Aboriginal and Torres Strait Islander Peoples of Australia

The highly diverse Aboriginal and Torres Strait Islander Peoples of Australia have survived and adapted to climate changes such as sea-level rise and extreme rainfall variability during the late Pleistocene era, through intimate place-based Indigenous Knowledge in practice and while losing traditional land and sea Country ownership (Liedloff et al., 2013) (Cross-Chapter-Box INDIG in Chapter 18) including during the Late Pleistocene era (Golding and Campbell, 2009; Nunn and Reid, 2016). They belong to the world's oldest living cultures, continually resident in their own ancestral lands, or 'country', for over 65,000 years (Kingsley et al., 2013; Marmion et al., 2014; Nagle et al., 2017; Tobler et al., 2017; Nursey-Bray and Palmer, 2018). The majority of the Australian Indigenous Peoples live in urban areas in southern and eastern Australia, but are the predominant population in remote areas.

Climate-related impacts on Aboriginal and Torres Strait Islander Peoples, Countries (traditional estates) and cultures have been observed across Australia and are pervasive, complex and compounding(Green et al., 2009) (11.5.1) (*high confidence*). For example, loss of bio-cultural diversity, nutritional changes through availability of traditional foods and forced diet change, water security, and loss of land and cultural resources through erosion and sea-level rise (Table 11.10)](TSRA, 2018). Moreover, these impacts are being experienced now particularly in low-lying geographical areas- especially in the Torres Strait Islands (Mosby, 2012; Kelly, 2014; Murphy, 2019; Hall et al., 2021). Estimates of the loss from fire impacts on ecosystem services that contribute to the wellbeing of remotely-located Indigenous Australians were found to be higher than the financial impacts from the same fires on pastoral and conservation lands (Sangha et al., 2020) and could increase with both financial and non-financial impacts (Box 11.1).

Table 11.10: Climate-related impacts on Aboriginal and Torres Strait Islander Peoples, country and cultures.

Impacts	Implications
Loss of bio-cultural diversity (land, water and sky) (*medium confidence*)	Healthy country is critical to Indigenous Australians' livelihoods, caring for country responsibilities, health and wellbeing. Damage to land can magnify the loss of spiritual connection to land from dispossession from traditional Country and leads to disruption of cultural structures. Climate change impacts can exacerbate and/or accelerate existing threats of habitat degradation and biodiversity loss, and create challenges for traditional stewardship of landscapes (Mackey and Claudie, 2015)
Climate-driven loss of native title and other customary lands (*medium confidence*)	Traditional coastal lands lost through erosion and rising sea level, with associated mental health implications from loss of cultural and traditional artefacts and landscapes, including the destruction and exhumation of ancestral graves and burial grounds. This is also occurring and predicted to intensify in the low-lying islands of the Torres Strait (TSRA, 2018; Hall et al., 2021) and was also noted during the extreme bushfires in Eastern Australia in late 2019 and early 2020.
Changing availability of traditional foods and forced diet change (*medium confidence*)	Human health impacts can be exacerbated by climate change through changing availability of traditional foods and medicines, while outages and high costs of electricity can limit storage of fresh food and medication (Kingsley et al., 2013; Spurway and Soldatic, 2016; Hall and Crosby, 2020)
Changing climatic conditions for subsistence food harvesting (*medium confidence*)	Climate change-induced sea-level rise and saltwater intrusion can limit the capacity for traditional Indigenous floodplain pastoralism, and also affect food security, access and affordability to healthy, nutritional food (Ligtermoet, 2016; Spurway and Soldatic, 2016)
Extreme weather events triggering disasters (*high confidence*)	Increasing frequency or intensity of extreme weather events (floods, droughts, cyclones, heatwaves) can cause disaster responses in remote communities, including infrastructure damage of essential water and energy systems and health facilities (TSRA, 2018; Hall and Crosby, 2020)
Heatwave impacts on human health (*high confidence*)	Heatwaves can occur in many regions. Tropical regions can experience prolonged seasons of high temperatures and humidity levels, resulting in extreme heat stress risks. For example, the Torres Strait Island are already categorised under the U.S. National Oceanic and Atmospheric Administration (NOAA) Heat Index as a danger zone for extreme human health risk during Summer (TSRA, 2018)
Health impacts from changing conditions for vector-borne diseases (*high confidence*)	Climate change can change exposure and increase risk for remote Indigenous Peoples to infection from waterborne and insect-borne diseases, especially if medical services are limited or damaged by extreme weather events. For example, in the Torres Strait Islands the changing climate is affecting the range and extension of the Aedes albopictus and Aedes aegypti mosquitoes that can carry and transmit dengue and other viruses (Horwood et al., 2018; TSRA, 2018)
Unadaptable infrastructure for changing environmental conditions (*high confidence*)	Poorly-designed, inferior quality and unmaintained housing can create health challenges for tenants in extreme heat (Race et al., 2016). Essential community-scale water and energy service infrastructure, unpaved roads, sea walls and storm water drains can fail in extreme weather events (McNamara et al., 2017)

Drinking water security (*medium confidence*)	Predicted continued increases in arid conditions in Australia are expected to reduce the recharge rate of finite groundwater supplies (Barron et al., 2011). For remote communities reliant on groundwater for drinking supplies, this water insecurity creates vulnerabilities from over-extraction and lack of access (Jackson et al., 2019; Hall and Crosby, 2020). This groundwater can also have microbial contamination from sewage and chemicals supporting bacterial growth, such as high iron levels supporting the growth of *Burkholderia pseudomallei* that causes melioidosis in humans and animals (Kaestli et al., 2019). In the Torres Strait, increasing reliance on desalination for drinking water raises costs for fuel and its associated transport (Beal et al., 2018)

Due to ongoing impacts of colonisation, Aboriginal and Torres Strait Islander Peoples have, on average, lower income, poorer nutrition, lower school outcomes and employment opportunities, and higher incarceration and removal of children than non-Indigenous Australians, represented in high comorbidities of chronic diseases and mental health impacts (Marmot, 2011; Green and Minchin, 2014; AIHW, 2015). This relative poverty can reduce climate-adaptive capacities while exacerbating climate change vulnerabilities (Nursey-Bray and Palmer, 2018). In remote Country, this can combine with lack of security for food and water, non-resilient housing and extreme weather events, contributing to migration off traditional Country and into towns and cities- with flow-on social impacts such as homelessness, dislocation from community and family, and disconnection from country and spirituality (Mosby, 2012; Brand et al., 2016).

Recognition of the role Aboriginal and Torres Strait Islander Peoples in identifying solutions to the impacts of climate change is slowly emerging (UN, 2018) having been largely excluded from meaningful representation from the conception of climate change dialogue, through to debate and decision-making (Nursey-Bray et al., 2019). Honouring the United Nations' Declaration on the Rights of Indigenous Peoples and social justice values would support self-determination and the associated opportunity for Indigenous Australians to develop adaptation responses to climate change (Langton et al., 2012; Nursey-Bray and Palmer, 2018; Nursey-Bray et al., 2019), including the adaptive capacity opportunities available through Indigenous Knowledge (Liedloff et al., 2013; Petheram et al., 2015; Stewart et al., 2019) (Cross-Chapter Box INDIG in Chapter 18). The Uluru Statement from the Heart proposes a pathway and roadmap forward for enhanced representation of Aboriginal and Torres Strait Islander Peoples in decision-making in Australia (Ululru Statement, 2017). Table 11.11 provides examples of traditional Indigenous practices of adaptation to a changing climate. However, due to Indigenous methods of knowledge sharing and knowledge holding, such knowledge relies disproportionately on elders and seniors, who form a very small portion of the total Aboriginal and Torres Strait Islander Peoples of Australia, and is limited in the formal literature (ABS, 2016).

Table 11.11: Examples of Aboriginal and Torres Strait Islander Peoples' practices of adaptation to a changing climate

'Caring for Country': Traditional Practices for Holistic Land and Cultural Protection and Adaptation in a Changing Climate	Source
Indigenous Protected Area (IPA) management plans enable culturally and ecologically compatible development that contribute to local Indigenous economies	(Mackey and Claudie, 2015).
IPAs can avoid the potential for 'nature–cultures dualism' that locks out Indigenous access in some protected area legislation, as they are based on relational values informed by local Indigenous Knowledge	(Lee, 2016)
Fire management using cultural practices can achieve greenhouse gas emission targets while also maintaining Indigenous cultural heritage.	(Robinson et al., 2016)
Indigenous Ranger programmes provide a means for Indigenous-guided land management, including for fire management and carbon abatement, fauna studies, medicinal plant products, weed management and recovery of threatened species	(Mackey and Claudie, 2015)

Faunal field surveys can engage local, bounded and fine-scale intuitive species location by Indigenous knowledge holders and their knowledge used for conservation planning	(Wohling, 2009; Ziembicki et al., 2013)
Cultural flows in waterways are a demonstration of cultural knowledge, values and practice in action as they are informed by Indigenous knowledge, bound by water-dependent values, and define when and where water is to be delivered - particularly in a changing climate.	(Bark et al., 2015; Taylor et al., 2017)

11.4.2 Tangata Whenua – New Zealand Māori

Māori society faces diverse impacts, risks and opportunities from climate change (Table 11.12). Studies exploring climate change impacts, scenarios, policy implications, adaptation options and tools for Māori society have increased substantially e.g. (King et al., 2012; Bargh et al., 2014; Jones et al., 2014; Bryant et al., 2017; Awatere et al., 2018; Colliar and Blackett, 2018). Māori priorities surrounding climate change risks and natural resource management have been articulated in planning documents by many Māori kin-groups e.g. (Ngāti Tahu- Ngāti Whaoa Rūnanga Trust, 2013; Raukawa Settlement Trust, 2015; Ngai-Tahu, 2018; Te Urunga Kea - Te Arawa Climate Change Working Group, 2021) reflecting the importance of reducing vulnerability and enhancing resilience to climate impacts and risks through adaptation and mitigation.

Māori have long-term interests in land and water and are heavily invested in climate sensitive sectors (agriculture, forestry, fishing, tourism and renewable energy) (King et al., 2010). Large proportions of collectively owned land already suffer from high rates of erosion (Warmenhoven et al., 2014; Awatere et al., 2018) which are projected to be exacerbated by climate change induced extreme rainfalls (RSNZ, 2016; Awatere et al., 2018) (*high confidence*). Changing drought occurrence, particularly across eastern and northern New Zealand, is also projected to affect primary sector operations and production (King et al., 2010; Smith et al., 2017; Awatere et al., 2018) (*medium confidence*). Further, many Māori-owned lands and cultural assets such as marae and urupa are located on coastal lowlands vulnerable to sea-level rise impacts (Manning et al., 2014; Hardy et al., 2019) (*high confidence*). Māori tribal investment in fisheries and aquaculture faces substantial risks from changes in ocean temperature and acidification, and the downstream impacts for species distribution, productivity and yields (Law et al., 2016) (*medium confidence*). A clearer understanding of climate change risks and the implications for sustainable outcomes can enable more informed decisions by tribal organisations and governance groups.

Changing climate conditions are projected to exacerbate health inequities faced by Māori (Bennett et al., 2014; Jones et al., 2014; Hopkins, 2015) (*medium confidence*). The production and ecology of some keystone cultural flora and fauna may be impacted by projected warming temperatures and reductions in rainfall (RSNZ, 2016; Bond et al., 2019; Egan et al., 2020) (*medium confidence*). Obstruction of access to keystone species is expected to adversely impact customary practice, cultural identity and well-being (Jones et al., 2014; Bond et al., 2019)(*medium confidence*). Social-cultural networks and conventions that promote collective action and mutual support are central features of many Māori communities, and these practices are invaluable for initiating responses to, and facilitating recovery from, climate stresses and extreme events (King et al., 2011; Hopkins et al., 2015). Māori tribal organisations have a critical role in defining climate risks and policy responses (Bargh et al., 2014; Parsons et al., 2019) as well as entering into strategic partnerships with business, science, research and government to address these risks (Manning et al., 2014; Beall and Brocklesby, 2017; CCATWG, 2017) (*high confidence*).

More integrated assessments of climate change impacts, adaptation and socio-economic risk for different Māori groups and communities, in the context of multiple stresses, inequities and different ways of knowing and being (King et al., 2013; Schneider et al., 2017; Henwood, 2019) would assist those striving to evaluate impacts and risks, and how to integrate these assessments into adaptation plans (*high confidence*). Better understanding of the social, cultural and fiscal implications of sea-level rise is urgent (PCE, 2015; Rouse et al., 2017; Colliar and Blackett, 2018), including what duties local and central Government might have with respect to actively upholding Māori interests under the Treaty of Waitangi (Iorns Magallanes, 2019) (*high confidence*). Intergenerational approaches to climate change planning will become increasingly important, elevating political discussions about conceptions of rationality, diversity and the rights of non-human entities (Ritchie, 2013; Carter et al., 2018; Ruru, 2018; Munshi et al., 2020) (*high confidence*).

Table 11.12: Climate-related impacts and risks for Tangata Whenua New Zealand Māori

Impact	Risks
Changes in drought occurrence and extreme weather events	Risks to Māori tribal investment in forestry, agriculture and horticulture sector operations and production, particularly across eastern and northern New Zealand (King et al., 2010; Awatere et al., 2018; Hardy et al., 2019)(*medium confidence*)
Changes in rainfall, temperature, drought, extreme weather events and ongoing sea-level rise	Risks to potable water supplies (availability and quality) for remote Māori populations (RSNZ, 2016; Henwood, 2019)(*medium confidence*)
Changes in rainfall, temperature, drought, extreme weather events and ongoing sea-level rise	Risks of exacerbating existing inequities (e.g. health, economic, education and social services), social cohesion and well-being (Bennett et al., 2014; Jones et al., 2014)(*medium confidence*)
Changes in rainfall regimes and more intense drought combined with degradation of lands and water	Risks to the distribution and survival of cultural keystone flora and fauna, as well as cascading risks for Māori customary practice, cultural identity and well-being (King et al., 2010; RSNZ, 2016; Bond et al., 2019)(*high confidence*)
Changes in ocean temperature and acidification	Risks to nearshore and ocean species productivity and distribution, as well as cascading risks for Māori tribal investment in the fisheries and aquaculture sectors (King et al., 2010; Law et al., 2016)(*medium confidence*)
Sea-level rise induced erosion, flooding and saltwater intrusion	Risks to Māori-owned coastal lands and economic investment as well as risks to community wellbeing from displacement of individuals, families and communities (Manning et al., 2014; Smith et al., 2017; Hardy et al., 2019)(*high confidence*)
Sea-level rise induced erosion, inundation and saltwater intrusion	Risks to Māori cultural heritage as well as cascading risks for tribal identity and spiritual well-being (King et al., 2010; Manning et al., 2014; RSNZ, 2016)(*medium confidence*)
Impacts of climate change, adaptation and mitigation actions	Risks that governments are unable to uphold Māori interests, values and practices under the Treaty of Waitangi, creating new, modern-day breaches of the Treaty of Waitangi (Iorns Magallanes, 2019; MfE, 2020a)(*high confidence*)

11.5 Cross-Sectoral and Cross-Regional Implications

The impacts and adaptation processes described in sections 11.3 and 11.4 are focused on specific sectors, systems and Indigenous Peoples. Added complexity, risk and adaptation potential stem from cross-sectoral and cross-regional inter-dependencies.

11.5.1 Cascading, compounding and aggregate impacts

11.5.1.1 Observed Impacts

Climate impacts are cascading, compounding and aggregating across sectors and systems due to complex interactions (*high confidence*) (Pescaroli and Alexander, 2016; Challinor et al., 2018; Zscheischler et al., 2018; Steffen et al., 2019; AghaKouchak et al., 2020; CoA, 2020e; Lawrence et al., 2020b; Simpson et al., 2021) (Box 11.1; Box 11.3; Box 11.4; Box 11.5; Box 11.6). Cascading impacts propagate via interconnections and systemic factors, including supply chains, shared reliance on connected biophysical systems (e.g. water catchments and ecosystems), infrastructure and essential goods and services, and the exercise of governance, leadership, regulation, resources and standard practices (e.g. in planning and building codes), including lock-in of past decisions and experience (CSIRO, 2018; Lawrence et al., 2020b). The capacity of critical systems such as Information, Communication and Technology, water infrastructure, health care, electricity and transport networks are being stretched, with impacts cascading to other systems and places, exacerbating existing hazards and generating new risks (Cradock-Henry, 2017) (11.3.6;11.3.10; Box 11.1). Temporal or spatial overlap of hazards (e.g. drought, extreme heat and fire; drought followed by extreme rainfall) are compounding impacts (Zscheischler et al., 2018) and affecting multiple sectors.

In Australia, extreme events such as heatwaves, droughts, floods, storms and fires have caused deaths and injuries (Deloitte, 2017a) (11.3.5.1), and affected many households, communities and businesses via impacts on ecosystems, critical infrastructure, essential services, food production, the national economy, valued places and employment. This has created long-lasting impacts (e.g. mental health, homelessness, health incidents and reduced health services) (Brown et al., 2017; Brookfield and Fitzgerald, 2018; Rychetnik et al., 2019) and reduced adaptive capacity (Friel et al., 2014; O'Brien et al., 2014; Ding et al., 2015; CoA, 2020e) (Box 11.1, Box 11.3, 11.3.1-11.3.10).

In New Zealand, extreme snow, rainfall and wind events have combined to impact road networks, power and water supply, and have impeded interdependent wastewater and stormwater services and business activities (Deloitte, 2019; Lawrence et al., 2020b; MfE, 2020a) (Box 11.4). Community and infrastructure services are periodically disrupted during extreme weather events, triggering impacts from the interdependencies across enterprises and individuals (Glavovic, 2014; Paulik et al., 2021).

Slow onset climate change impacts have also had cascading and compounding effects. For example, degradation of the Great Barrier Reef by ocean heating, acidification and non-climatic pressures (Marshall et al., 2019), repeated pluvial, fluvial and coastal flooding of some settlements (Paulik et al., 2019a; Paulik et al., 2020), long droughts and water insecurity in rural communities (Tschakert et al., 2017), and the gradual loss of species and ecological communities, have caused substantial ecological, social and economic losses. Indigenous peoples have especially been impacted by multiple and complex losses (Johnson et al., 2021) (11.4).

11.5.1.2 Projected Impacts

Cascading, compounding and aggregate impacts are projected to grow due to a concurrent increase in heatwaves, droughts, fires, storms, floods and sea level (*high confidence*) (CSIRO, 2020; Lawrence et al., 2020b). Urban wastewater, stormwater and water supply systems are particularly vulnerable in New Zealand (Paulik et al., 2019a; Hughes et al., 2021) to pluvial flooding (Box 11.4) and to sea-level rise (Box 11.6), with flow-on effects to settlements, insurance and finance sectors, and governments (Lawrence et al., 2020b). Furthermore, consecutive heavy rainfall events in late summer and autumn, following drought conditions in low-lying modified wetland areas, have implications for the operation of flood control infrastructure as increased rainfall intensity, land subsidence, and sea-level rise compound and result in the retention of floodwaters (Pingram et al., 2021).

In Australia, the aggregate loss of wealth due to climate-induced reductions in productivity across agriculture, manufacturing and service sectors is projected to exceed A$19 billion by 2030, A$211 billion by 2050 and A$4 trillion by 2100 for RCP8.5 (Steffen et al., 2019) (Table 11.13). Projected impacts also cascade across national boundaries via value chains, markets, movement of humans and other organisms, and geopolitics (e.g. migration from near-neighbours as a pathway for adaptation, mobile climate-sensitive diseases and changes in production and trade patterns) (Lee et al., 2018; Nalau and Handmer, 2018; Schwerdtle et al., 2018; Dellink et al., 2019). The scale of impacts is projected to challenge the adaptive capacity of sectors, governments and institutions (Steffen et al., 2019), including the insurability of assets and risks to lenders (Storey and Noy, 2017).

11.5.1.3 Adaptation

Coordinating adaptation strategies and addressing underlying exposure and vulnerability can increase resilience to cascading, compounding and aggregate impacts (Table 11.17; 11.7.3) (*high confidence*). Systems understanding, network analysis, stress testing, spatial mapping, collaboration, information sharing and interoperability across states, sectors, agencies and value chains, as well as national scale facilitation, can increase adaptive capacity (Espada et al., 2015; CoA, 2020e; Cradock-Henry et al., 2020b; Jozaei et al., 2020). Greater system diversity, modularity, redundancy, adaptability and decentralised control can reduce the risk of cascading failures and system breakdown (Sinclair et al., 2017; Sellberg et al., 2018). Addressing existing vulnerabilities in systems can reduce susceptibility and improve the resilience of interdependent systems (11.7.3). Multi-level leadership, including national and sub-national policies, laws and finance can reduce and manage aggregate risks supported by the enablers in Table 11.17.

Anticipatory governance and agile decision making can build resilience to cascading, compounding and aggregate impacts (Boston, 2016; Deloitte, 2016; Steffen et al., 2019; CoA, 2020e; CSIRO, 2020; Lawrence et al., 2020b; MfE, 2020c) (*high confidence*). There is uncertainty about whether standard integrated assessment models can estimate cascading and compounding impacts across systems and sectors, but systems methodologies and social network analysis hold promise (Stoerk et al., 2018; Cradock-Henry et al., 2020b). Interventions at the landscape, building and individual scale can reduce the negative health effects of current and future extreme heat, if integrated in well-communicated heat action plans with robust surveillance and monitoring (Jay et al., 2021).

In Australia, the National Disaster Risk Reduction Framework (CoA, 2018b), National Recovery and Resilience Agency, and Australian Climate Service (CoA, 2021) can provide some support for adaptation across multiple sectors. New Zealand has effective partnerships across critical infrastructure through lifelines groups, but organisational silos and lack of stress testing of plans hamper coordinated decision making during crises and for adaptation (Brown et al., 2017; Lawrence et al., 2020b). The New Zealand national risk assessment, national adaptation plan, forthcoming Climate Change Adaptation Act, and monitoring of adaptation progress by the Climate Change Commission, provide a framework for anticipating climate change risks (MfE, 2020a).

11.5.2 Implications for National Economies

The implications of climate change for national economies are significant (*high confidence*). The costs associated with lost productivity, disaster relief expenditure and unfunded contingent liabilities represent a major risk to financial system stability (MfE, 2020a). Costs include significant and often long-term social impacts, temporary dislocation, business disruption, and impacts on employment, education, community networks, health and wellbeing (Deloitte, 2017a). Climate change disrupts international patterns of agricultural production and trade in ways that may be negative, but may also lead to new opportunities for agriculture (Mosnier et al., 2014; Nelson et al., 2014; Lee et al., 2018). Net exports may increase following global climate shocks (Lee et al., 2018), but the longer term effects on GDP are *likely* to be negative (Dellink et al., 2019).

11.5.2.1 Observed Impacts

In Australia, during 2007-2016, total economic costs from natural disasters averaged A$18.2 billion per year (Deloitte, 2017a). Individual weather-related disaster costs across multiple sectors have exceeded A$4 billion, such as the 2009 fires in Victoria (Parliament of Victoria, 2010), the 2010-2011 floods in south-east Queensland (Deloitte, 2017b), the 2019 floods in northern Queensland (Deloitte, 2019) and the 2019-2020 fires in southern and eastern Australia (Box 11.1).

In New Zealand, the annual cost of rural fire to the economy has been estimated at NZ$67 million, with indirect 'costs' potentially 2–3 times direct costs (Scion, 2018). Insured losses from weather-related disasters cost almost NZ$1 billion during 2015-2021 (ICNZ, 2021). Floods cost the New Zealand economy at least NZ$120 million for privately insured damages between 2007 and 2017 (D. Frame et al., 2018). The 2007/08 drought cost NZ$3.2 billion and the 2012/13 drought cost NZ$1.6 billion, of which about 20% could be attributed to anthropogenic climate change (Frame et al., 2020) (11.5.3.1).

The intangible costs of climate impacts - including death and injury, impacts on health and wellbeing, education and employment, community connectedness, and the loss of ancestral lands, cultural sites and ecosystems (Barnett et al., 2016; Warner et al., 2019) - affect multiple sectors and systems and exacerbate existing vulnerabilities. While often incommensurable, intangible costs may be far higher than the tangible costs. For example, following the Victorian fires in 2009, the tangible costs were A$3.1 billion while the intangible costs were A$3.4 billion; following the Queensland floods in 2010/11, the tangible costs were A$6.7 billion while the intangible costs were A$7.4 billion (Deloitte, 2016).

11.5.2.2 Projected Impacts

The economic impact increases with higher levels of warming (*high confidence*) but there is a wide range in projections. Conservative estimates for the impacts of a 1, 2 or 3°C global warming (relative to 1986-2005) on Australian GDP growth are -0.3%/year, -0.6%/year and -1.1%/year, respectively, while for New Zealand the estimates are -0.1%, -0.4%/year and -0.8%/year, respectively (Kompas et al., 2018). More detailed modelling indicates a loss in Australia's GDP of 6% by 2070 for 3°C global warming, while a 2.6% GDP rise by 2070 is possible for 1.5°C global warming (Deloitte, 2020). The potential for much more severe effects on GDP is shown in recent estimates which attempt to account for the increased severity of uncertain effects (e.g. up to 18.5% reduction in Australia's GDP by mid-Century) (Swiss Re, 2021).

In Australia, the total annual cost of damage due to floods, coastal inundation, forest fires, subsidence and wind (excluding cyclones) is estimated to increase 55% between 2020 and 2100 for RCP8.5 (Mallon et al., 2019). National damage costs and impacts on asset values could be significant (Table 11.13). The macro-economic shocks induced from climate change, including reduced agricultural yields, damage to property and infrastructure and commodity price increases, could lead to significant market corrections and potential financial instability (Steffen et al., 2019). Under a 'slow decline' scenario by 2060 where Australia fails to adequately address climate change and sustainability challenges, GDP is projected to grow at 0.7% less per year and real wages would be 50% lower than under an 'outlook scenario' where Australia meets climate change and sustainability challenges (CSIRO, 2019).

In New Zealand, the value of buildings exposed to coastal inundation could increase by NZ$2.55 billion for every 0.1 m increment in sea level, i.e. $25.5 billion for a 1.0 m sea-level rise (Paulik et al., 2020). Greater understanding is required of the distributional impacts, the rate of change of costs over time and the economic implications of delayed action (Warner et al., 2020).

Table 11.13: Economy-wide projected costs (A$) of climate change in Australia. (Estimates are not comparable across studies because different methods have been used. Estimates for later in the century are speculative as both impacts and adaptation are uncertain).

Impact	2030	2050	2090	Reference
Damage-related loss of property value in Australia	$571 billion	$611 billion	$770 billion	(Steffen et al., 2019)
Property damage in Australia		$91 billion per year	$117 billion per year	(Steffen et al., 2019)
Loss of asset value of road infrastructure (including freeways, main roads and unsealed roads) in Australia at risk of a sea-level rise of 1.1 metres by 2100			$46-60 billion	(DCCEE, 2011)
Loss of asset value of rail and tramway infrastructure in Australia at risk of a sea-level rise of 1.1 metres by 2100			$4.9-6.4 billion	(DCCEE, 2011)
Loss of asset value of residential buildings in Australia at risk of a sea-level rise of 1.1 metres by 2100 (2008 replacement value)			$51-72 billion	(DCCEE, 2011)
Loss of asset value of light industrial buildings (used for warehousing, manufacturing, and assembly activities and services) in Australia at risk of a sea-level rise of 1.1 metres by 2100			$4.2-6.7 billion	(DCCEE, 2011)

Loss of asset value of commercial buildings (used for wholesale, retail, office and transport activities) in Australia at risk of a sea-level rise of 1.1 metres by 2100 (2008 replacement value)			$58-81 billion	(DCCEE, 2011)
Accumulated loss of wealth due to reduced agricultural productivity and labour productivity	$19 billion	$211 billion	$4.2 trillion	(Steffen et al., 2019)
Wind damage to dwellings in Cairns, Townsville, Rockhampton and south-east Queensland (assuming a 4 per cent discount rate)	$3.8 billion	$9.7 billion	$20 billion	(Stewart and Wang, 2011)
Damage to Australian coastal residential buildings due to sea-level rise (A1B scenario, 3.5°C global warming)			$8 billion	(Wang et al., 2016)

11.5.2.3 Adaptation

Investments in mitigation and adaptation can help reduce or prevent economic losses now and in the coming decades (IPCC, 2018; Steffen et al., 2019), however the costs and the benefits of mitigation and adaptation are not well understood in the region (CSIRO, 2019; MfE, 2020a) (*high confidence*).

In New Zealand, the emphasis has been on rebuilding after climate disasters, rather than anticipatory adaptation (Boston and Lawrence, 2018). Australia is similarly focused on disaster response and recovery, even though investment in disaster resilience can provide a cost:benefit ratio of 1:2 to 1:11 through reduced post-disaster recovery and reconstruction (GCA, 2019). Recent Australian and state government spending on direct recovery from disasters was around A$2.75 billion per year, compared to funding for natural disaster resilience of approximately A$0.1 billion per year (Deloitte, 2017b). The Australian Government is supporting most of the 80 recommendations from the Royal Commission into National Natural Disaster Arrangements, including establishing a disaster advisory body and a resilience and recovery agency (CoA, 2020e; CoA, 2020b). Australia and New Zealand provide humanitarian and disaster assistance across the Pacific, which is increasingly focused on climate adaptation and the Sustainable Development Goals (Brolan et al., 2019) as cyclones and floods become amplified by climate change (Fletcher et al., 2013) (Table 11.3). Climate change may increase current migration flows to and impacts on diaspora in Australia and New Zealand from near neighbour island nations, as they become increasingly stressed by rising seas, higher temperatures, more droughts and stronger storms (Nalau and Handmer, 2018).

Delaying adaptation to climate risks may result in higher overall costs in future when adaptation is more urgent and impacts more extreme (Boston and Lawrence, 2018; IPCC, 2018) (*medium confidence*). Estimates of the magnitude of adaptation costs and benefits in the region are localised and sectoral, e.g. (Thamo et al., 2017) or regionally aggregated (Joshi et al., 2016). Adaptation costs are expected to increase markedly for higher RCPs, e.g. a tripling of expected costs between RCP2.6 and RCP8.5 for sea-level rise protection in Australia (Ware et al., 2020). Existing governance arrangements for funding adaptation are inadequate for the scope and scale of climate change impacts anticipated; dedicated funding mechanisms that can be sustained over generations can enable more timely adaptation (Boston and Lawrence, 2018).

11.6 Key Risks and Benefits

Nine key risks have been identified (Table 11.14) based on four criteria: magnitude, likelihood, timing and adaptive capacity (Chapter 16). Most of the key risks are similar to those in the IPCC AR5 Australasia chapter (Reisinger et al., 2014), but the emphasis here is on specific systems affected by multiple hazards rather than specific hazards affecting multiple systems. The selection of key risks reflects what has been observed, projected and documented, noting that there are gaps in knowledge, and a lack of knowledge does not imply a lack of risk (11.7.3.3). Key risks are grouped into four categories:

Ecosystems at critical thresholds where recent climate change has caused significant damage and further climate change may cause irreversible damage, with limited scope for adaptation

1. Loss and degradation of coral reefs in Australia and associated biodiversity and ecosystem service values due to ocean warming and marine heatwaves (11.3.2.1, 11.3.2.2, Box 11.2).
2. Loss of alpine biodiversity in Australia due to less snow (11.3.1.1, 11.3.1.2).

Key risks that have potential to be severe but can be reduced substantially by rapid, large-scale and effective mitigation and adaptation

3. Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires (11.3.1.1, 11.3.1.2)
4. Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins (11.3.2.1, 11.3.2.2).
5. Loss of natural and human systems in low-lying coastal areas due to sea level rise (11.3.5, Box 11.6).
6. Disruption and decline in agricultural production and increased stress in rural communities in south-western, southern and eastern mainland Australia due to hotter and drier conditions (11.3.4, 11.3.5, Box 11.3).
7. Increase in heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves (11.3.5.1, 11.3.5.2, 11.3.6.1, 11.3.6.2).

Key cross-sectoral and system-wide risk

8. Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to wildfires, floods, droughts, heatwaves, storms and sea-level rise (11.5.1.1, 11.5.1.2, Box 11.1, Box 11.4, Box 11.6).

Key implementation risk

9. Inability of institutions and governance systems to manage climate risks. (11.5; 11.7.1, 11.7.2, 11.7.3).

At higher levels of global warming, adaptation costs increase, options become limited and risks grow. The 'burning embers' diagram in Figure 11.6 has four IPCC risk categories: "undetectable", "moderate", "high" and "very high", with transition points defined by different global warming ranges. The embers are indicative, based on an assessment of available literature and expert judgement (Supplementary Material SM 11.2). Outcomes for low and moderate adaptation have been compared, with the latter including both incremental and transformative options. Illustrative examples of adaptation pathways are shown in Figure 11.7 for low-lying coastal areas and Figure 11.8 for heat-related mortality. These figures highlight thresholds at which adaptation options become ineffective, and possible combinations of strategies and options implemented at different times to manage emerging risks and changing risk profiles.

Caveats: (a) key risks are assessed at regional scales, so they do not include other risks for finer scales or specific groups; (b) non-climatic vulnerabilities are held constant for simplicity; (c) the assessment of risk ratings at different levels of global warming is limited by available literature; (d) risks increase with global warming, despite the lack of an IPCC risk rating beyond "very high"; and (e) the feasibility and effectiveness of adaptations options were not assessed due to limited literature (11.7.3.3).

The New Zealand National Climate Change Risk Assessment (MfE, 2020a) identified the priority risks from climate change for New Zealand based on a literature review and expert elicitation. The top two risks in each of five domains are: *Natural environment* (1) risks to coastal ecosystems due to ongoing sea-level rise and extreme weather events, (2) risks to indigenous ecosystems and species from invasive species; *Human environment* (1) risks to social cohesion and community well-being from displacement of people, (2) risks of exacerbating existing inequities and creating new and additional inequities from distribution impacts; *Economy* (1) risks to governments from economic costs associated with lost productivity, disaster relief expenditure and unfunded contingent liabilities, (2) risks to the financial system from instability; *Built environment* (1) risk to potable water supplies due to changes in rainfall, temperature, drought, extreme weather events and ongoing sea-level rise,(2) risks to buildings due to extreme weather events, drought, increased fire weather and ongoing sea-level rise; *Governance* (1) risk of maladaptation due to practices, processes and tools that do not account for uncertainty and change over long timeframes, and (2) risk that climate change impacts across all domains will be exacerbated, because current institutional arrangements are not fit for adaptation. Not all of these risks feature as key risks for the wider Australasia region; nonetheless they are reflected across Chapter 11 and remain priorities for New Zealand to address through the National Adaptation Plan, its implementation and monitoring.

Short-term benefits from climate change may include reduced winter mortality, reduced energy demand for winter heating, increased agriculture productivity and forest growth in south and west New Zealand, and increased forest and pasture growth in southern Australia except where rainfall and soil nutrients are limiting (11.3.4; 11.3.6; 11.3.10) (*medium confidence*).

Table 11.14: Key risks from climate change based on assessment of the literature and expert judgement (Supplementary Material SM 11.2**)**. Assessment criteria are magnitude, timing, likelihood and adaptive capacity. Risk drivers are hazards, exposure and vulnerability. Adaptation options describe ways in which risks can be reduced. Confidence ratings are based on the amount of evidence and agreement between lines of evidence**.**

Key risk (*confidence rating*) (Chapter reference)	Consequences influenced by hazards, exposure, vulnerability and adaptation options
1. Loss and degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves (*very high confidence*) (11.3.2, Box 11.2)	Consequences: Widespread destruction of coral reef ecosystems and dependent socio-ecological systems. Three mass bleaching events from 2016-2020 have already caused significant loss of corals in shallow-water habitats across the Great Barrier Reef. Globally, bleaching is projected to occur twice each decade from 2035 and annually after 2044 under RCP 8.5 and annually after 2051 under RCP4.5. A 3ºC global warming could cause over six times the 2016 level of thermal stress. Hazards: Increase in background warming and marine heatwave events degrade reef-building corals by triggering coral bleaching events at a frequency greater than the recovery time. Fish populations also decline during and following heat wave events. Exposure: Increasing geographic area affected by rate and severity of ocean warming Vulnerability: Vulnerability to increases in sea temperature is already very high because of other stressors on the ecosystem, including sediment, pollutants, and overfishing. Adaptation options: Minimising other stressors. Efforts on the Great Barrier Reef may slow the impacts of climate change in small sections or reduce short-term socio-economic ramifications, but will not prevent widespread bleaching.
2. Loss of alpine biodiversity in Australia due to less snow (*high confidence*) (11.3.1, Tables 11.2, 11.3, 11.4, 11.5)	Consequences: Loss of endemic and obligate alpine wildlife species and plant communities (feldmark and short alpine herb-fields) as well as increased stress on snow-dependent plant and animal species. Hazards: Projected decline in annual maximum snow depth by 2050 is 30-70% (low emissions) and 45-90% (high emissions); projected increases in temperature and decreases in precipitation. Exposure: Alpine species face elevation squeeze due to lack of nival zone and alpine environments have restricted geographic extent. Vulnerability: Narrow ecological niche of species including snow-related habitat requirements; encroachment from sub-Alpine woody shrubs; vulnerability generated by non-climatic stressors including weeds and feral animals, especially horses Adaptation options: Reducing pressure on alpine biodiversity from land uses that degrade vegetation and ecological condition, along with weed and pest management.

3. Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires (*high confidence*) (11.2, 11.3.1, 11.3.2, Box 11.1)	Consequences: If regenerative capacities of the dominant (framework) canopy tree species are exceeded, a long lasting or irreversible transition to a new ecosystem state is projected with loss of characteristic and framework species including loss of some narrow range endemics. Hazards: Hotter and drier conditions have increased extreme fire weather risk since 1950, especially in southern and eastern Australia. The number of severe fire weather days is projected to increase 5-35% (RCP2.6) and 10-70% (RCP8.5) by 2050 Exposure: Shift in landscape fire regimes to larger, more intense and frequent wildfires over extensive areas (~10 million hectares) of forests and woodlands from longer fire seasons and more hazardous fire conditions and increasing human-sourced ignitions from urbanisation and projected increase in frequency of lightning strikes Vulnerability: The resilience and adaptive capacity of the forests is being reduced by ongoing land clearing and degrading land management practices Adaptation options: Increased capacity to extinguish wildfires during extreme fire weather conditions; avoiding and reducing forest degradation from inappropriate forest management practices and land use.
4. Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins (*high confidence*) (11.3.2)	Consequences: Observed decline in giant kelp in Tasmania since 1990, with less than 10% remaining by 2011 due to ocean warming. Extensive loss of kelp -140,187 hectares across Australia. Loss of bull kelp in southern New Zealand, replaced by the introduced kelp following the 2017/18 marine heatwave. Further loss of native kelp is projected with warming oceans. Hazards: Ocean warming and marine heatwave events Exposure: Coastal waters around Australia and New Zealand Vulnerability: Giant kelp are already Federally listed in Australia as an endangered marine community type. In Australia, kelp forests are vulnerable to nutrient poor East Australian Current waters pushing further south, warming waters and increased herbivory from range-extending species. Adaptation options: Minimizing other stressors, local restoration, and transplantation of heat-tolerant phenotypes.
5. Loss of human and natural systems in low-lying coastal areas from ongoing sea-level rise (*high confidence*) (11.2, 11.3.2, 11.3.5, 11.3.10, 11.4, Table 11.3; Box 11.6)	Consequences: Nuisance and extreme coastal flooding are already occurring due to sea-level rise (SLR). For 0.2-0.3 m SLR, coastal flooding is projected to become more frequent, e.g. current 1-in-100 year flood would occur every year in Wellington and Christchurch. For 0.5 m SLR, the value of buildings in New Zealand exposed to coastal inundation could increase by NZ$12.75 billion and the current 1-in-100 year flood in Australia could occur several times a year. For 1.0 m SLR, the value of exposed assets in New Zealand would be NZ$25.5 billion. For 1.1 m SLR, the value of exposed assets in Australia would be A$164-226 billion. This would be associated with displacement of people, disruption and reduced social cohesion, degraded ecosystems, loss of cultural heritage and livelihoods, and loss of traditional lands and sacred sites. Hazards: Rising sea level (0.2-0.3 m by 2050, 0.4-0.7 m by 2090), storm surges, rising ground water tables. Exposure: Population growth, new and infill urbanization, tourism developments in low-lying coastal areas. Buildings, roads, railways, electricity and water infrastructure. Torres Strait Island and remote Māori communities are particularly exposed and sensitive. Vulnerability: Ineffective planning regulations, reduced availability and increased cost of insurance, and costs to governments as insurers of last resort. Inadequate investment in avoidance and preparedness exacerbating underlying social vulnerabilities. Financial and physical capacities to cope and adapt are uneven across populations, creating equity issues. Adaptation options: Risk reduction coordinated across all levels of government with communities. Statutory planning frameworks, decision tools and funding mechanisms that can address the changing risk. Planning and land use decisions, including managed retreat where it is inevitable. Improved capacity of emergency services, early warning systems,

	improved planning and regulatory practice and building and infrastructure design standards. Options that anticipate risk and adjust as conditions change.
6. Disruption and decline in agricultural production and increased stress in rural communities across south western, southern and eastern mainland Australia due to hotter and drier conditions. (*high confidence*) (11.2, 11.3.4, 11.3.6.3, 11.4.1, Table 11.11, Boxes 11.1, 11.3)	Consequences: Projected decline in crop, horticulture and dairy production. e.g. decline in median wheat yields by 2050 of up to 30% in south-west Australia and up to 15% in South Australia. Increased heat stress in livestock by 31–42 days per year by 2050. Reduced winter chilling for horticulture. Increased smoke impacts for viticulture. Flow-on effects for agricultural supply chains, farming families and rural communities across south-western, southern and south-eastern Australia, including the Murray-Darling Basin (MDB). Hazards: Hotter and drier conditions with constraints on water resources and more frequent and severe droughts in south-western, southern and eastern Australia. Exposure: Across south western, southern and eastern Australia, many production regions are exposed including the MDB which supports agriculture worth A$24 billion/year, 2.6 million people in diverse rural communities, and important environmental assets containing 16 Ramsar listed wetlands. Vulnerability: Existing financial, social, health and environmental pressures on rural, regional and remote communities. Existing competition for water resources among communities, industries and environment, and uncertainty about sharing of water under a drying climate. Adaptation options: Improved governance and collaboration to build rural resilience, including regional and basin-scale initiatives. Improved water policies and initiatives (e.g. MDB Plan) and changes in management and technologies. Resilience-focused planning for rural settlements, land-use, industry, infrastructure and value chains. Adoption of information, tools and methods to better manage uncertainty, variability and change. Incremental changes in farm management practices (e.g. stubble retention, weed control, water-use efficiency, sowing dates, cultivars). In some regions, major changes may be necessary, e.g. diversification in agricultural enterprises, transition to different land-uses (e.g. carbon sequestration, renewable energy production, biodiversity conservation) or migration to another area. Flows in waterways based on Indigenous knowledge to protect cultural assets.
7. Increase in heat-related mortality and morbidity for people and wildlife in Australia (*high confidence*) (11.2, 11.3.1, 11.3.5, 11.3.6, 11.4)	Consequences: During 1987-2016, natural disasters caused 971 deaths and 4,370 injuries, with more than 50% due to heatwaves. Annual increases are projected for excess deaths, additional hospitalisations and ambulance callouts. Heatwave related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (RCP2.6) to 600/year (RCP8.5) during 2031-2080 relative to 142/year during 1971-2020, assuming no adaptation. Significant heat-related mortality of wildlife species (flying foxes, freshwater fish) has been observed and is projected to increase. Hazards: Increased frequency, intensity and duration of extreme heat events Exposure: Pervasive, but differentially affecting some wildlife species depending on their thermal tolerances and occupational groups (e.g. outdoor workers) and those living in high exposure areas (e.g. urban heat islands). Health risks multiply with other harmful exposures, e.g. to wildfire smoke. Vulnerability: Lower adaptive capacity for young/old/sick people, those in low quality housing and lower socio-economic status, and areas served by fragile utilities (power, water). Remote locations with extreme heat and inadequate cooling in housing infrastructure (such as remote indigenous communities). For wildlife, impacts of extreme heat events are being amplified by habitat loss and degradation. Adaptation options: Urban cooling interventions including irrigated green infrastructure and increased albedo, education to reduce heat stress, heatwave/fire early-warning systems, battery/generator systems for energy system security, building standards that improve insulation/cooling, accessible / well-resourced primary health care. For wildlife, removing human stressors, reducing pressures from ferals and weeds, and ensuring there is suitable habitat.
8. Cascading, compounding and	Consequences: Widespread and pervasive damage and disruption to human activities generated by interdependencies and interconnectedness of physical, social and natural

aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to extreme events (*high confidence*) (11.2, 11.3.4, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.9, 11.3.10, 11.4, 11.5.1, Boxes 11.1, 11.4, 11.6)	systems. Examples include: Failure of transport, energy and communication infrastructure and services, heat-stress, injuries and deaths, air pollution, stress on hospital services, damage to agriculture and tourism, insurance loss from heatwaves and fires; failure of transport, stormwater and flood-control infrastructure and services from floods and storms; water restrictions, reduced agricultural production, stress for rural communities, mental health issues, lack of potable water from droughts; damage to buildings, roads, railways, electricity and water infrastructure, loss of assets and lives, displacement of people, reduced social cohesion, and degraded ecosystems from extreme sea-level rise. Large aggregate costs due to lost productivity and major disaster relief expenditure, creating unfunded liabilities and supply chain disruption, e.g., the 2019-2020 Australian fires cost A$8 billion. The impact of a 1, 2 or 3˚C global warming (relative to 1986-2005) on Australian GDP growth is estimated at -0.3%/year, -0.6%/year and -1.1%/year, respectively, while for New Zealand estimates are -0.1%/year, -0.4%/year and -0.8%/year, respectively. Impacts on Māori tribal investments in forestry, agriculture, horticulture, fisheries and aquaculture. Hazards: Heatwaves, droughts, fires, floods, storms and sea-level rise. This includes cascading and compound events such as heatwaves with fires, storms with floods, or droughts followed by heavy rainfall and extreme sea levels. Exposure: Highly populated areas, rural and remote settlements, traditional lands and sacred sites. Greater urban density and population growth increases exposure in high-risk areas. Different exposure for different hazards, e.g. heatwaves: urban and peri-urban areas; fire: peri-urban areas and settlements near forests; floods: people, property and infrastructure from pluvial floods in cities and settlements and fluvial floods on floodplains; storms: buildings and infrastructure in cities and settlements. Vulnerability: Existing social and economic challenges (e.g. those caused by COVID-19) and socio-economic and cultural inequalities; competing resource and land use demands across sectors; inadequate planning, policy, governance, decision making and disaster resilience capacity; and non-climatic stresses on ecosystems. Vulnerabilities generated by interdependencies and interconnectedness of physical, social and natural systems. Adaptation options: Flexible and timely adaptation strategies that prepare socio-economic and natural systems for surprises and unexpected threats. Multi-sector coordinated actions that address widespread impacts, redress existing vulnerabilities and building adaptive capacity and systemic resilience. Improved coordination between and within levels of governments, communities and private sector. Greater use of dynamic decision frameworks and suitable economic and social assessment tools. Improved emergency services and early warning systems; use of climate resilient standards for buildings and infrastructure. Transformational adaptations e.g. managed retreat, that can be planned in stages.
9. Inability of institutions and governance systems to manage climate risks (*high confidence*) (11.2, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.10, 11.4, 11.5.1, 11.7.2, Boxes 11.1-11.6)	Consequences: Climate hazards overwhelm the capacity of institutions, organisations, systems and leaders to provide necessary policies, services, resources, coordination and leadership. Failed adaptation at the institutional and governance level has widespread, pervasive impacts for all areas of society. This includes a reliance on reactive, short-term decision making that locks in existing exposures, leaves perverse incentives and interconnected and systemic impacts unaddressed, and generates high costs, fiscal impacts. This worsens vulnerability and leads to maladaptation, inequities and injustices within and across generations, as well as actions that do not uphold the rights, interests, values and practices of Indigenous Peoples. Resultant failure to take adaptation action generates litigation risk. Hazards: The increasing frequency, duration, severity and complexity of extreme weather events, droughts and sea-level rise Exposure: All sectors, communities, organisations, and governments Vulnerability: Fragmented institutional and legal arrangements, under-resourcing of services, lack of dedicated adaptation funding instruments and resources to support communities and local government, uneven capability to manage uncertainty, and conflicting values and competing policy and political interests. Adaptation options: Pre-emptive options that avoid and reduce risks. Redesign of policy and statutory frameworks, and funding instruments for addressing changing risks and uncertainties that enable just and collaborative governance across scales and domains. Addressing existing vulnerabilities, and capacity, capability and leadership deficits within

	and across all levels of government, all sectors, Indigenous peoples and communities. Risk and vulnerability assessment methodologies and decision-making tools that build resilience and address changing risks and vulnerabilities. Co-designed adaptation approaches implemented with communities, including Māori tribal organisations and Australian Aboriginal and Torres Strait Island peoples.

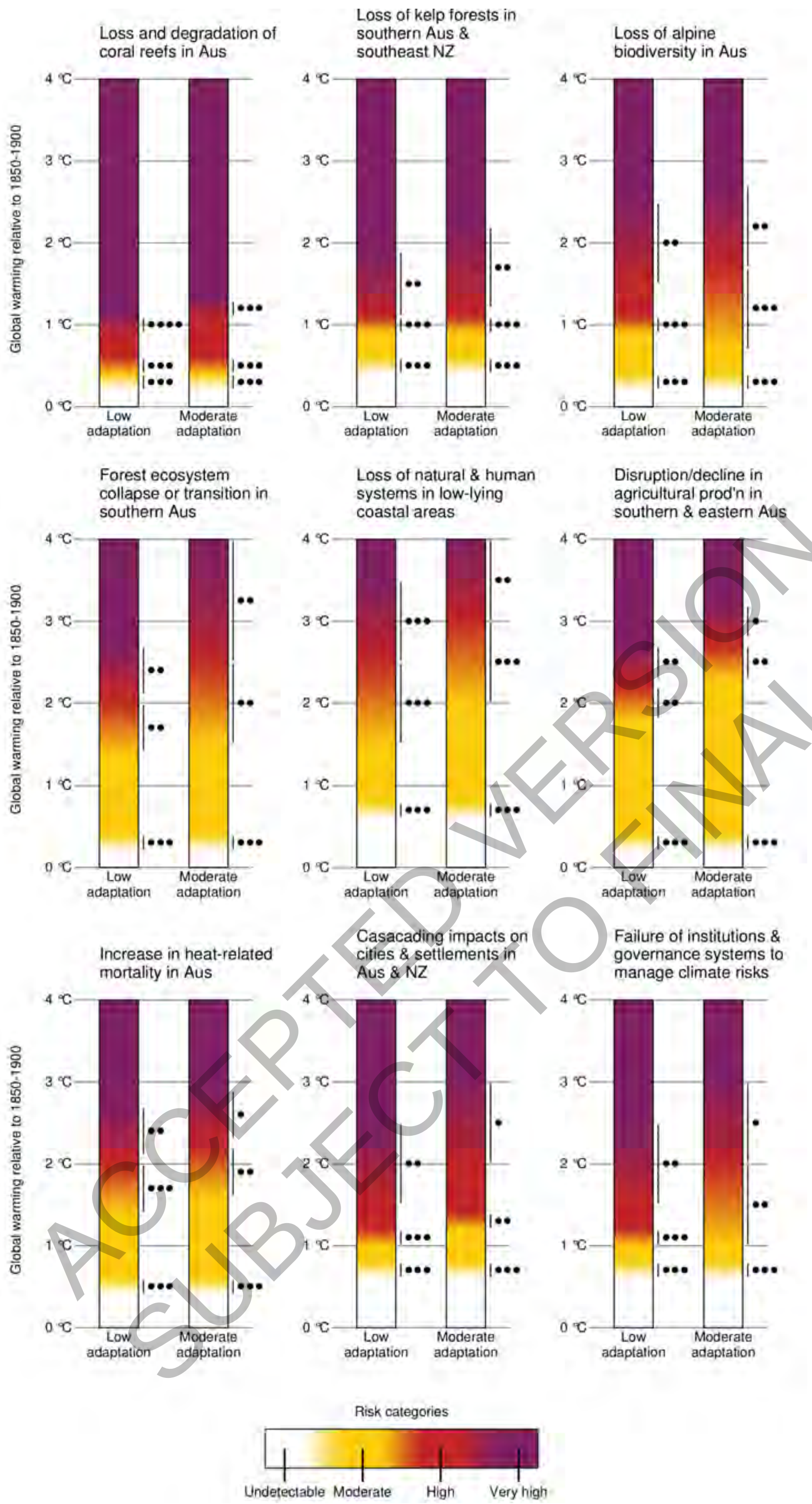

Figure 11.6: Burning embers diagram for each of the nine key risks for low and moderate adaptation. The risk categories are undetectable, moderate, high and very high. While there is no risk category beyond very high, risks obviously get worse with further global warming, and the risk for coral reefs is already very high. The assessment is based on available literature and expert judgement, summarised in Table 11.14 and described in Supplementary Material SM 11.2. The global warming range associated with each risk transition has a confidence rating (**** *very high,* *** *high,* ** *moderate,* * *low*) based on the amount of evidence and level of agreement between lines of evidence.

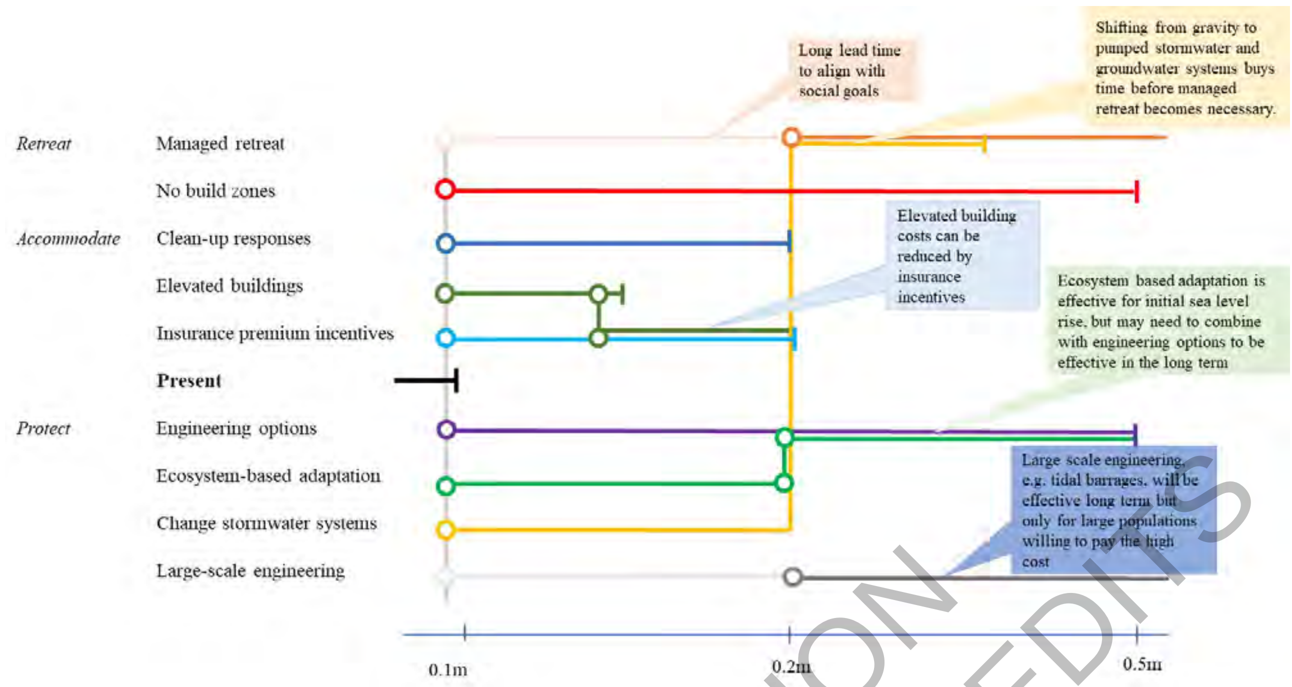

Figure 11.7: Illustrative adaptation pathway for risk to natural and human systems in low-lying coastal areas due to sea-level rise.

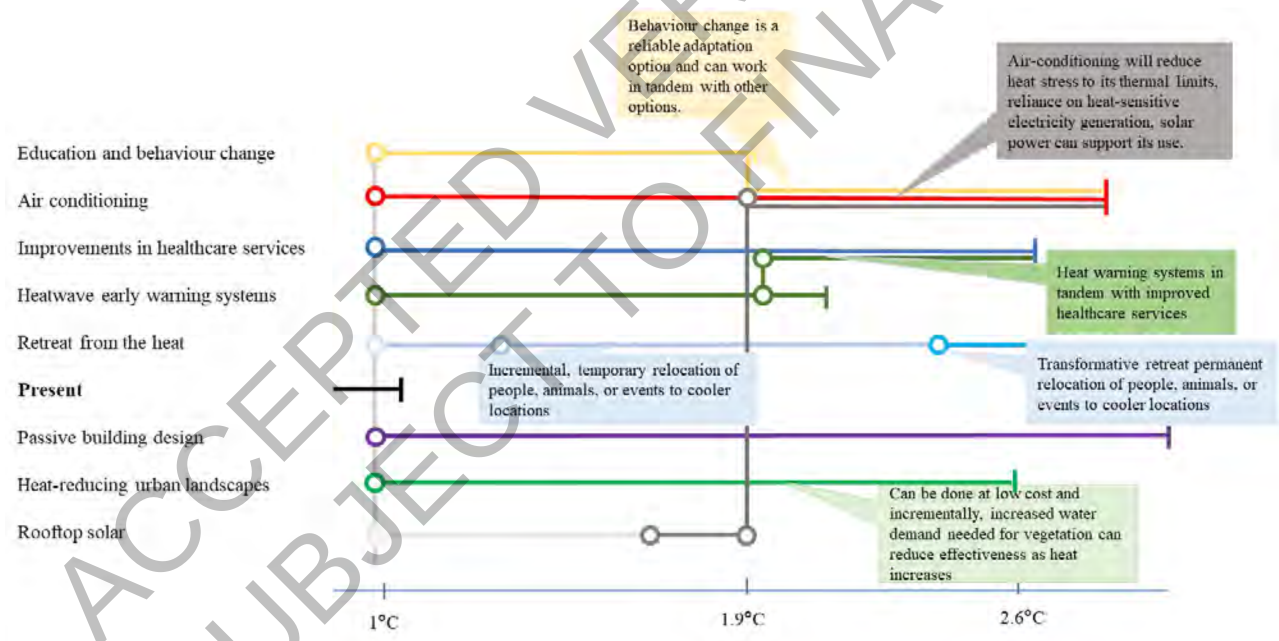

Figure 11.8: Illustrative adaptation pathway for risk of heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves.

11.7 Enabling Adaptation Decision-making

11.7.1 Observed Adaptation Decision-Making

The ambition, scope and progress on adaptation by governments has risen, but is uneven with a focus on high level strategies at national level adaptation planning at sub-national levels and new enabling legislation (Tables 11.15a and 11.15b; (Lawrence et al., 2015; Macintosh et al., 2015; MfE, 2020a) (*very high confidence*). The adaptation process comprises vulnerability and risk assessments, identification of options, planning, implementation, monitoring, evaluation and review. Large gaps remain, especially in effective implementation, monitoring and evaluation (Supplementary Material SM 11.1) (CCATWG, 2017; Warnken and Mosadeghi, 2018) and current adaptation is largely incremental and reactive (Box 11.4, Box 11.6, Table 11.14) (*very high confidence*).

Australia has a National Climate Resilience and Adaptation Strategy, and a National Recovery and Resilience Agency (11.5.2.3), the first National Action Plan to implement the Disaster Risk Reduction Framework acknowledges climate change as a disaster risk driver (Home Affairs, 2020). States and territories have climate change adaptation strategies with plans to address them (Table 11.15a).with some adaptation implementation at state level and increasingly at local government level (Jacobs et al., 2016; Warnken and Mosadeghi, 2018) (Table 11.15a). In coastal zones, however, few local government planning instruments are being applied (Warnken and Mosadeghi, 2018; Harvey, 2019; Robb et al., 2019; Elrick-Barr and Smith, 2021). Some businesses and industry sectors are recognizing climate-related risks and adaptation planning (11.3.4; 11.3.7; 11.3.10) (Harris et al., 2016; Hennessy et al., 2016; CBA, 2019). There is an opportunity for Australia to undertake a national risk assessment and to develop a national climate adaptation implementation plan that is aligned with Paris Agreement expectations of a national level system for adaptation planning, monitoring and reporting (Morgan et al., 2019).

New Zealand's Climate Change Response Act in 2019 creates a legal mandate for National Climate Change Risk Assessments (first one completed) (MfE, 2020a) and National Adaptation Plans (first in preparation) and a Climate Change Commission to monitor and report on adaptation implementation. Preparation of Natural and Built Environment, Strategic Planning and Climate Change Adaptation Acts is underway, including provision for funding and managed retreat (MfE, 2020c). National coastal guidance is available for adaptation planning to address changing climate risks (MfE, 2017a) (Table 11.15b). Meanwhile, several local authorities have developed integrated climate change strategies and plans and revised policies and rules to enable adaptation (Table 11.15b). Different adaptation approaches continue to create confusion and inertia while development pressures continue (Schneider et al., 2017). Opportunities for integrated adaptation and mitigation planning in regional policies and plans have arisen through the Resource Management Amendment Act 2020 (Dickie, 2020), the National Policy Statement on Freshwater Management (MfE, 2020b), and the revised national coastal guidance (MfE, 2017a), but rely on funding instruments to be in place and statutes are aligned for their effectiveness (Boston and Lawrence, 2018; CCATWG, 2018) (*very high confidence*).

There is a growing awareness of the need for more proactive adaptation planning at multiple scales and across sectors, and a better understanding of future risks and limits to adaptation is emerging (Evans et al., 2014; Archie et al., 2018; Christie et al., 2020; MfE, 2020a) (*medium confidence*). Disaster risk reduction is being positioned as part of climate change adaptation (Forino et al., 2017; CDEM, 2019; Forino et al., 2019; CoA, 2020e; CSIRO, 2020). Public and private climate adaptation services are informing climate risk assessments, but are characterized by fragmentation, duplication, inconsistencies, poor governance and inadequate funding - addressing these gaps presents adaptation opportunities (CCATWG, 2018; Webb et al., 2019; NESP ESCC, 2020) (Tables 11.15a; 11.15b). Large infrastructure asset planning is starting to factor in climate risks, but implementation is variable (Gibbs, 2020). Local governments in Australia are increasingly implementing adaptation plans but few monitor or evaluate actual outcomes or know how to (Scott and Moloney, 2021).

Observed and projected rates of sea-level rise (Box 11.6) and increased flood frequency (11.3.3) are challenging established uses of modelling, risk assessment, and cost benefit analysis, where climate change damage functions cannot be projected or are unknown (deep uncertainty), or impacts on communities are ambiguous (Infometrics and PSConsulting, 2015; Lawrence et al., 2019a; MfE, 2020a). New tools are available in the region (Table 11.17) but uptake cannot be assumed (Lawrence and Haasnoot, 2017; Palutikof et al., 2019c) (*high confidence*).

Resilience and adaptation approaches are beginning to converge (White and O'Hare, 2014; Aldunce et al., 2015) (Supplementary Material SM 11.1) but widespread "bounce back" resilience-driven responses that lock in risk by discounting ongoing and changing climate risk (Leitch and Bohensky, 2014; O'Hare et al., 2016; Wenger, 2017; Torabi et al., 2018) can create maladaptation and impede long-term adaptation goals (Glavovic and Smith, 2014; Dudney et al., 2018) (*high confidence*).

Local government engagement with communities on adaptation is starting to motivate a change towards more collaborative engagement practices (Archie et al., 2018; Bendall, 2018; MfE, 2019; Schneider et al., 2020). Nature-based adaptations (Colloff et al., 2016; Lavorel et al., 2019; Della Bosca and Gillespie, 2020) and 'green infrastructure' (Lin et al., 2016; Alexandra and Norman, 2020) are increasingly being adopted (Rogers et al., 2020a) (*medium confidence*).

Some businesses have initiated active adaptation (Aldum et al., 2014; Linnenluecke et al., 2015; Bremer and Linnenluecke, 2017; CCATWG, 2017; MfE, 2018) with most focused on identifying climate risks (Aldum et al., 2014; Gasbarro et al., 2016; Cradock-Henry, 2017). Businesses are more likely to engage in anticipatory adaptation when the frequency of climate events is known (McKnight and Linnenluecke, 2019). Effective cooperation and a positive innovation culture can contribute to the collaborative development of climate change adaptation pathways (Bardsley et al., 2018) (*medium confidence*).

Some areas in northern Australia and New Zealand, especially those with higher proportions of Indigenous populations, face severe housing, health, education, employment and services deficits that exacerbate the impacts of climate change (Kotey, 2015) (11.3.5; 11.4; 11.6). Where adaptation relies upon an aging population and an over-stretched volunteer base, vulnerability to climate change impacts is being exacerbated (Astill and Miller, 2018; Davies et al., 2018). Adaptation options that succeed within remote Indigenous communities are founded on connections to traditional lands, alignment with cultural values and contribute to social, cultural and economic goals (Nursey-Bray and Palmer, 2018). Knowledge co-production for Indigenous adaptation pathways can enable transformative change from colonial legacies (Hill et al., 2020). Learning and experimentation across governance boundaries and between agencies and local communities enables adaptation to be better aligned with changing climate risks and community (Fünfgeld, 2015; Howes et al., 2015; Bardsley and Wiseman, 2016; Lawrence et al., 2019b) (*high confidence*).

There is increasing focus on improving adaptive capacity for transitional and transformational responses, but reactive responses dominate (Smith et al., 2015; Schlosberg et al., 2017; Boston and Lawrence, 2018) (*very high confidence*). While extreme events can provide opportunities for positive transitions within communities (Cradock-Henry et al., 2018b) (for example the Queensland Reconstruction Authority Building Back Better scheme), often rebuilding occurs in at-risk places to aid quick recovery (Lawrence and Saunders, 2017). Community-based adaptation innovations (Kench et al., 2018; Forino et al., 2019){Bendall, 2018 #413} include: relationship building; use of new decision tools, pathways planning with communities, visualisation and serious games (Lawrence and Haasnoot, 2017; Schlosberg et al., 2017; Flood et al., 2018; Reiter et al., 2018; Serrao-Neumann and Choy, 2018); communities of practice; and climate information sharing (Astill et al., 2019; Stone et al., 2019).

Table 11.15a: Examples of Australian adaptation strategies, plans and initiatives by government agencies at the (a) national level, (b) sub-national, and (c) regional or local level. These examples have not been assessed for their effectiveness (see Supplementary Material Table SM11.1a).

Jurisdiction	Strategies /Plans /Actions
National Level	
Australia	National Climate Resilience and Adaptation Strategy 2015 (CoA, 2015) National Disaster Risk Reduction Framework (2018) (CoA, 2018b) National Recovery and Resilience Agency and Australian Climate Service (CoA, 2021)
Sub-national	
Australian Capital Territory (ACT)	ACT Climate Change Strategy 2019-2025 (ACT Government, 2019) Canberra's Living Infrastructure Plan: Cooling the City (ACT Government, 2020b); ACT Wellbeing Framework (ACT Government, 2020a)

New South Wales	NSW Climate Change Policy Framework (NSW Government, 2016)
	Coastal Management Framework (OEH, 2018b) including: Coastal Management Act 2016; State Environmental Planning Policy (Coastal Management) 2018; NSW Coastal Management Manual (OEH, 2018c; OEH, 2018a)
Northern Territory	Northern Territory Climate Change Response: Towards 2050 (DENR, 2020b); Three-year action plan (DENR, 2020a)
Queensland	Pathways to climate resilient Queensland: Queensland Climate Adaptation Strategy 2017-2030 (DEHP, 2013) Sector adaptation plans https://www.qld.gov.au/environment/climate/climate-change/adapting/sectors-systems State heatwave risk assessment 2019 (QFES, 2019) Planning Act 2016 (Queensland Government, 2020) and the Coastal Protection and Management Act 1995 (Queensland Government, 1995) plus supporting initiatives: Coastal Management Plan (DEHP, 2013); Shoreline Erosion Management Plans (DES, 2018) Queensland's QCoast2100 program
South Australia	Directions for a Climate Smart South Australia (SA Government, 2019a)
Tasmania	Climate Action 21: Tasmania's Climate Change Action Plan 2017–2021 (State of Tasmania, 2017a) Tasmania's 2016 State Natural Disaster Risk Assessment (White et al., 2016a) Tasmanian Planning Scheme – State Planning Provisions 2017, Coastal Inundation Hazard Code and a Coastal Erosion Hazard Code (Government of Tasmania, 2017).
Victoria	In accordance with the Climate Change Act 2017, Victoria has a Climate Change Adaptation Plan 2017-2020 (Victoria State Government DELWP, 2016) including a Monitoring, Evaluation, Reporting and Improvement (MERI) framework for Climate Change Adaptation in Victoria (DELWP, 2018), Victorian Climate Projections (2019) and multiple resources for regions and local government (Victoria DELWP 2020). Heatwaves in Victoria. A 2018 vulnerability assessment of the state to heatwaves using a Damage and Loss Assessment methodology (Natural Capital Economics, 2018)
Western Australia	Western Australian Government Adapting to our changing climate 2012 (WA Government, 2016) State Planning Policy 2.6 – Coastal Planning (SPP2.6)
Regional and local (examples only)	
104 have declared Climate Emergencies to leverage climate action as of September 2021 covering 36.6% of the Australian population (Climate Emergency Declaration, 2020)	
Tasmania	2017: Tasmanian Planning Scheme – State Planning Provisions. State of Tasmania, 514. (State of Tasmania 2017) (State of Tasmania, 2017b)
South Australia	Regional integrated vulnerability assessments (IVAs) and adaptation plans (SA Government, 2019a)
NSW	Enabling Regional Adaptation (Jacobs et al., 2016)

Victoria	Every region and catchment Management Authority in Victoria has an adaptation plan, as does virtually every local government. There are also three alliances of multiple local governments working on climate change and new initiatives such as the Climate Change Exchange. https://www.parliament.vic.gov.au/967-epc-la/inquiry-into-tackling-climate-change-in-victorian-communities
NSW	Coastal Zone Management Plan for Bilgola Beach (Bilgola) and Basin Beach (Mona Vale) (Haskoning Australia, 2016)
Queensland	Torres Strait Climate Change Strategy (TSRA, 2014); Torres Strait Regional Adaptation and Resilience Plan 2016-2021 (TSRA, 2016) Climate Risk Management Framework for Queensland Local Government (Erhart et al., 2020)
Northern Territory	Climate Change Action Plan (2011-2020) (Darwin City Council, 2011)

Table 11.15b: Examples of New Zealand's adaptation strategies, plans and initiatives by government agencies at the (a) national level, (b) sub-national, and (c) regional or local level. NB These examples have not been assessed for their effectiveness (see Supplementary Material Table SM11.1b)

Jurisdiction	**Strategies/Plans/Actions**
New Zealand central Government	The New Zealand Government's adaptation policy framework is based on the following legislation: Resource Management Act 1991; Local Government Act 2002; National Disaster Resilience Strategy 2019 (CDEM, 2019), and the Climate Change Response (Zero Carbon Amendment) Act 2002 (CCRA 2002). Adaptation preparedness report 2020/21 baseline is the reporting organisation responses from the First Information request under the CCRA 2002 (MfE, 2021) to assist the monitoring of progress and effectiveness of adaptation, by the Climate Change Commission The Department of Conservation's Climate Change Adaptation Action plan sets out a long-term strategy for climate research, monitoring, and action. DOC climate adaptation plan
Local Government	In July 2017, a group of 39 Local Government Mayors and Council Chairs (of 78 in total) endorsed a 2015 local government declaration calling for urgent responsive leadership and a holistic approach on climate change, with the government needing to play a vital enabling leadership role (LGNZ, 2017; Schneider et al., 2017). Seventeen councils have declared Climate Emergencies to leverage climate action plans as of September 2021, covering 75.3% of the New Zealand population. The MFE adaptation preparedness report states that 18% of councils (11 of 61 surveyed in 2021) have some sort of plan or strategy to increase resilience to climate impacts (MfE, 2021). Out of New Zealand's 15 regional and unitary councils, two councils have climate adaptation strategies in place. One council has conducted a climate risk assessment. and four have one in development. Five councils have climate action plans and three are in development.
Regional Councils (examples only)	
Bay of Plenty Regional Council	Climate Action Plan July 2019 (non-statutory) Climate Action Plan
Waikato Regional Council	Long Term Plan 2018-2028 (LTP)

Greater Wellington Regional Council	GWRC's Climate Change Strategy (October 2015) Climate change strategy implementation Hutt River Flood Risk Management Plan
Unitary Authorities (examples only)	
Auckland Council	Auckland Unitary Plan AUP RPS B10 Table B11.9- (bottom of doc) E36. Natural hazards and flooding
Marlborough District Council	Marlborough Environment Plan First to integrate Dynamic Adaptive Pathways Planning (DAPP) into Plan policies.
Gisborne District Council	Tairāwhiti Resource Management Plan (District Plan) March 2020
District Council (example only)	
Waimakariri District Council	Infrastructure Strategy in the Long Term Plan 2017. Long-Term-Plan-Further-Information-Document-WEB.pdf Page 113/31

11.7.2 Barriers and Limits to Adaptation

Major gaps in the adaptation process remain across all sectors and at all levels of decision-making (11.3; Table 11.115a Table 15b) (*very high confidence*). Efforts to build, resource and deploy adaptive capacity are slow compared to escalating impacts and risks (Stephenson et al., 2018; CoA, 2020e). Barriers to effective adaptation include governance inertia at all levels, hindering the development of careful and comprehensive adaptation plans and their implementation (Boston and Lawrence, 2018; MfE and Hawke's Bay Regional Council, 2020; White and Lawrence, 2020). Lack of clarity about mandate, roles and leadership, and inadequate funding for adaptation by national and State governments and sectors, are slowing adaptation (Lukasiewicz et al., 2017; Waters and Barnett, 2018; LGNZ, 2019; MfE, 2020c) (11.3; 11.7.1). Established planning tools and measures were designed for static risk profiles, and practitioners are slow to take up tools better suited to changing climate risks (CoA, 2020e; Schneider et al., 2020) (11.5; Box 11.5). The communication of relevant climate change information remains ad hoc (Stevens and O'Connor, 2015; CCATWG, 2017; Palutikof et al., 2019c; Salmon, 2019). In Australia, the lack of national guidance or adaptation laws create barriers to adaptation, reflected in uneven coastal adaptation based on a "wait and see" approach (Dedekorkut-Howes et al., 2020).

Table 11.16: Examples of barriers to adaptation action in the region

Barrier	Source
Governments Lack of consistent policy direction from higher levels and frequent policy reversals	(Dedekorkut-Howes et al., 2020)
Conflicts between community-based initiatives, City Councils and business interests	(Forino et al., 2019)
Different framings of adaptation between local governments (risk) and community groups (vulnerability, transformation)	(Smith et al., 2015; Schlosberg et al., 2017; McClure and Baker, 2018)
Competing planning objectives	(McClure and Baker, 2018)
Divergent perceptions of risk concepts	(Button and Harvey, 2015; Mills et al., 2016b; Tonmoy et al., 2018)
Focus on climate variability rather than climate change	(Dedekorkut-Howes and Vickers, 2017)

Low prioritization of climate change adaptation among competing institutional objectives	(Glavovic and Smith, 2014; Lawrence et al., 2015; McClure and Baker, 2018)
Constraints in using new knowledge	(Temby et al., 2016)
Lack of institutional and professional capabilities and capacity e.g. to monitor and evaluate adaptation outcomes	(Lawrence et al., 2015; Scott and Moloney, 2021)
Lack of understanding of Indigenous knowledge and practices	(Parsons et al., 2019)
Lack of authority and political legitimacy	(Hayward, 2008; Boston and Lawrence, 2018; CCATWG, 2018; Parsons et al., 2019)
Fear of litigation	(Tombs et al., 2018; Iorns Magallanes and Watts, 2019; O'Donnell et al., 2019)
The upfront costs of adaptation relative to competing demands on government expenditure	(Gawith et al., 2020; Warren-Myers et al., 2020b)
Private sector	
Governance and policy uncertainty, lack of cross sector coordination, lack of capital investment in climate solutions	(CCATWG, 2017; Forino et al., 2017; IGCC, 2021a)
Inconsistent hazard information and incomplete understanding of adaptation	(CCATWG, 2017; Harvey, 2019)
Mismatch in duration of insurance cover (annual) lending (decades) and infrastructure and housing investment (50-100ys)	(Storey and Noy, 2017; O'Donnell, 2020)
Perceived unaffordability of adaptation, lack of client demand and awareness of climate change risks and limited and inconsistent climate risk regulation in the construction industry	(Hurlimann, 2008; Hurlimann et al., 2018)
Translating information into organisations to address disinterest amongst clients in the property industry	(Warren-Myers et al., 2020b; Warren-Myers et al., 2020a)
Erosion of adaptive capacity and challenges of transformational adaptation in agriculture and rural communities	(Jakku et al., 2016)
Communities	
Nature of government engagement with communities	(Public Participation, 2014; MfE, 2017a; Archie et al., 2018; OECD, 2019b)
Lack of clarity regarding roles and responsibilities	(Gorddard et al., 2016; Elrick-Barr et al., 2017; Goode et al., 2017; Waters and Barnett, 2018)
Lack of resourcing of adaptation	(Singh-Peterson et al., 2015; Lukasiewicz et al., 2017; Brookfield and Fitzgerald, 2018)
Lack of deep engagement with climate change	(Kench et al., 2018; Pearce, 2018)
Diverging perceptions, values and goals within communities	(Austin et al., 2018; Fitzgerald et al., 2019; Marshall et al., 2019)
Inequities within and between communities	(Eriksen, 2014; Parkinson, 2019)
Lack of sustained engagement, learning and trust between community, scientists and policy makers	(Serrao-Neumann et al., 2020)

There are many barriers to starting adaptation pre-emptively (CCATWG, 2018) (Table 11.16) (*very high confidence*). Recent institutional changes in New Zealand indicate that this is changing (11.7.1; Table 15b). Many groups are yet to engage deeply with climate change adaptation (Kench et al., 2018) and some adaptation processes are being blocked (Pearce et al., 2018; Garmestani et al., 2019; Alexandra, 2020) or exploited to deflect from mitigation responsibilities (Smith and Lawrence, 2018; Nyberg and Wright, 2020). Some actors are resistant to using climate change information (Tangney and Howes, 2016; Alexandra, 2020). Fear of litigation and demands for compensation can contribute to this reluctance (Tombs et al., 2018; O'Donnell et al., 2019)and is increasingly inviting litigation and other costs (Hodder, 2019; Bell-James and Collins, 2020). Jurisprudence is evolving from cases on projects, to cases about decision making accountability in the public and private sectors (Bell-James and Collins, 2020; Peel et al., 2020) and rights based cases (Peel and Osofsky, 2018). National and sub-national governments may become exposed to unsustainable fiscal risk as insurers of "last resort", which can lead to inequitable outcomes for vulnerable groups and future generations (11.3.8), path dependencies and negative effects on physical, social, economic and cultural systems (Hamin and Gurran, 2015; Boston and Lawrence, 2018). Cross-scale governance tensions can prevent local adaptation initiatives from performing as intended (Tschakert et al., 2016; Piggott-McKellar et al., 2019). Adaptation that draws on Māori cultural understanding in partnership with local government in New Zealand can lead to more effective and equitable adaptation outcomes (MfE, 2020a).

Communities' vulnerabilities are dynamic and uneven (*high confidence*). In Australia, 435,000 people in remote areas face particular challenges (CoA, 2020e). Some groups do not have the time, resources or opportunity to participate in formal adaptation planning as it is currently organised (Victorian Council of Social Service, 2016; Tschakert et al., 2017; Mathew et al., 2018). Linguistically diverse groups can be disadvantaged by social isolation, language barriers, and others' ignorance of the knowledge and skills they can bring to adaptation (Shepherd and van Vuuren, 2014; Dun et al., 2018) (11.1.2). Social, cultural and economic vulnerabilities, biases and injustices, such as those faced by many women (Eriksen, 2014; Parkinson, 2019) and non-heterosexual groups and gender minorities (Dominey-Howes et al., 2016; Gorman-Murray et al., 2017), can deepen impacts and impede adaptation; (Fitzgerald et al., 2019; Marshall et al., 2019) (Cross-Chapter Box GENDER in Chapter 18).

Potential biophysical limits to adaptation for non-human species and ecosystems where impacts are projected to be irreversible, with limited scope for adaptation, are signalled in key risks 1-4 (11.6). In some human systems, fundamental limits to adaptation include thermal thresholds and safe freshwater (Alston et al., 2018) (Table 11.14) and the inability of some low-lying coastal communities to adapt in-place (Box 11.6) (*very high confidence*). Some individuals and communities are already reaching their psycho-social adaptation limits (Evans et al., 2016). A lack of robust and timely adaptation means key risks will increasingly manifest as impacts, and numerous systems, communities and institutions are projected to reach limits (Table 11.14, Figure 11.6), compounding current adaptation deficits and undermining society's capacity to adapt to future impacts (*very high confidence*).

11.7.3 Adaptation enablers

Adaptation enablers include understanding relevant knowledge, diverse values and governance, institutions and resources (Gorddard et al., 2016) (*very high confidence*). Skills and learning, community networks, people-place connections, trust-building, community resources and support and engaged governance build social resilience that support adaptation (Maclean et al., 2014; Eriksen, 2019; Phelps and Kelly, 2019). A multi-faceted focus on the role societal inequalities and environmental degradation play in generating climate change vulnerability can enable fairer adaptation outcomes (McManus et al., 2014; Ambrey et al., 2017; Schlosberg et al., 2017; Graham et al., 2018).

The feasibility and effectiveness of adaptation options will change over time depending on place, values, cultural appropriateness, social acceptability, ongoing cost-effectiveness, leadership and the ability to implement them through the prevailing governance regime (Singh et al., 2020). The capacity and commitment of the political system can drive early action that can reduce risks (Boston, 2017).

Decision makers face the challenge of how to adapt when there are ongoing knowledge gaps, and uncertainties about when some climate change impacts will occur and their scale, e.g. coastal flooding (Box

11.6), or extreme rainfall events and their cascading effects (Box 11.4) (*very high confidence*). No-regrets decisions are *likely* to be insufficient (Hallegatte et al., 2012). A perception exists in some sectors that all climate risks are manageable based on past experience (CCATWG, 2017). Projected impacts, however, are outside the range experienced, meaning that decisions have to be made now for long-lived assets, land uses and communities exposed to the key risks (Paulik et al., 2019a; Paulik et al., 2020) often under contested conditions where adaptation competes with other public expenditure (Kwakkel et al., 2016). New planning approaches being used across the region, can enable more effective adaptation, e.g. continual iterative adaptation (Khan et al., 2015) rapid deployment of decision tools appropriate for addressing uncertainties (Marchau et al., 2019, and transformation of governance and institutional arrangements {Boston, 2018 #444) (Table 11.17). Recognising co-benefits for mitigation and sustainable development can help incentivise adaptation (11.3.5.3, 11.8.2).

Table 11.17: Key enablers for adaptation

Enabler	Example
Governance frameworks	Clear climate change adaptation mandate Measures that inform a shift from reactive to anticipatory decision making, e.g. decision tools that have long timeframes Institutional frameworks integrated across all levels of government for better coordination Revised design standards for buildings, infrastructure, landscape such as common land use planning guidance and codes of practice that integrate consideration of climate risks to address existing and future exposures and vulnerability of people, physical and cultural assets (11.3.1, 11.3.2, 11.3.3, 11.3.4.3, 11.3.5, 1.3.6, 11.4.1, 11.4.2, 11.5.1, 11.5.2, 11.6, 11.7.1, 11.7.2, 11.8.1, 11.8.2, Table 11.7, Table 11.14, Box 11.1, Box 11.3, Box 11.5, Box 11.6)
Building capacity for adaptation	Provision of nationally consistent risk information through agreed methodologies for risk assessment that address non-stationarity Targeted research including understanding the projected scope and scale of cascading and compounding risks Education, training and professional development for adaptation under changing risk conditions Accessible adaptation tools and information (11.1.2, 11.3.4, 11.3.5, 11.4.1, 11.5.1, 11.6, 11.7.1, 11.7.2, Table 11.14, Table 11.16, Table 11.18, Box 11.6)
Community partnership and collaborative engagement	Community engagement based on principles that consider social and cultural and Indigenous Peoples' contexts and an understanding of what people value and wish to protect, e.g. International Association of Public Participation (Public Participation, 2014). Use of collaborative and learning-oriented engagement approaches tailored for the social and informed by the cultural context Community awareness and network building Building on Indigenous Australian and Māori communities' social-cultural networks and conventions that promote collective action and mutual support (11.3.5, 11.4, 11.7.1, 11.7.3.2, Table Box 11.1.1, Table 11.14, Box 11.6)
Dynamic adaptive decision-making	Increased understanding and use of decision-making tools to address uncertainties and changing risks, such as scenario planning and dynamic adaptive pathways planning to enable effective adaptation as climate risk profiles worsen (11.7.3.1, 11.7.3.2, Table 11.14, Table 15b, Table 11.18, Box 11.4, Box 11.6)
Funding mechanisms	Adaptation funding framework to increase investment in adaptation actions New private sector financial instruments to support adaptation (11.7.1, 11.7.2, Table 11.16)
Reducing systemic vulnerabilities	Economic and social policies that reduce income and wealth inequalities Strengthening social capital and cohesion Identifying and redressing rigid or fragmented administrative and service delivery systems Review of land use and spatial planning to reduce exposure to climate risks Restoring degraded ecosystems and avoiding further environmental degradation and loss. (11.1.1,11.1.2,11.3.5, 11.3.11, 11.4.1, 11.5.1.3, 11.7.2, 11.8.1, Table 11.10, Table 11.13)

11.7.3.1 Planning and Tools

Adaptation decision support tools enable a shift from reactive to anticipatory planning for changing climate risks (*high confidence)*. The available tools are diversifying with futures and systems methodologies and dynamic adaptive policy pathways being increasingly used (Bosomworth et al., 2017; Prober et al., 2017; Lawrence et al., 2018a; CoA, 2020e; Rogers et al., 2020a; Schneider et al., 2020) (11.5; Box 11.6) to help shift from static to dynamic adaptation by highlighting path dependencies and potential lock in of decisions, system dependencies and the potential for cascading impacts (Table 11.17) (Wilson et al., 2013; Clarvis et al., 2015; Pearson et al., 2018; Cradock-Henry et al., 2020b; Lawrence et al., 2020b). Modelling and tools to test the robustness and cost-effectiveness of options (Infometrics and PSConsulting, 2015; Qin and Stewart, 2020) can be used alongside adaptation strategies with decision-relevant and usable information (Smith et al., 2016; Tangney, 2019; Serrao-Neumann et al., 2020), particularly when supported by effective governance and national and sub-national guidance (Box 11.6).

More inclusive, collaborative and learning-oriented community engagement processes are fundamental to effective adaptation outcomes (11.7.3.2) (Boston, 2016; Lawrence and Haasnoot, 2017; Sellberg et al., 2018; Serrao-Neumann et al., 2019a; Simon et al., 2020) (*very high confidence*). More participatory vulnerability and risk assessments can better reflect different knowledge systems, values, perspectives, trade-offs, dilemmas, synergies, costs and risks (Jacobs et al., 2019; Ogier et al., 2020; Tonmoy et al., 2020). A shift from hierarchical to more cooperative governance modalities can assist effective adaptation (Vermeulen et al., 2018; Steffen et al., 2019; CoA, 2020e; Lawrence et al., 2020b; MfE, 2020a; Hanna et al., 2021).

Regular monitoring, evaluation, communication and coordination of adaptation are essential for accelerating learning and adjusting to dynamic climate impacts and socio-economic and cultural conditions change (Moloney and McClaren, 2018; Palutikof et al., 2019a; Cradock-Henry et al., 2020a) (*high confidence*). Training to improve decision-makers' 'evaluative capacity' can play a role (Scott and Moloney, 2021). Climate action benchmarking, diagnostic tools and networking can enhance the adaptation process across diverse decision settings e.g. water, coasts, protected areas and Indigenous Peoples (Ayre and Nettle, 2017; Davidson and Gleeson, 2018; Coenen et al., 2019; Gibbs, 2020). Effective adaptation requires cross-jurisdictional and cross-sectoral policy coherence and national coordination (Delany-Crowe et al., 2019; Rychetnik et al., 2019; MfE, 2020c).

Table 11.18: Examples of adaptation decision tools

Tools	Application	Source
Scenario analysis, modelling, futures narratives	For futures planning in coastal, urban, agriculture and health sectors	(Randall et al., 2012; Jones et al., 2013; CSIRO, 2014; Bosomworth et al., 2015; Infometrics and PSConsulting, 2015; Knight-Lenihan, 2016; Maier et al., 2016; Stephens et al., 2017; B. Frame et al., 2018; Stephens et al., 2018; Ausseil et al., 2019a; Coulter et al., 2019; Serrao-Neumann et al., 2019b)
Dynamic Adaptive Pathways Planning (DAPP)	For conditions of deep uncertainty for short-term and long-term options and flexibility, and with communities	(Cradock-Henry et al., 2018b; Cradock-Henry et al., 2020a) (agriculture); (Lawrence et al., 2019b) (flood risk management) (Lawrence and Haasnoot, 2017; Colliar and Blackett, 2018) (coastal communities) (Tasmanian Climate Change Office, 2012; Lin et al., 2017; Ramm et al., 2018) (capacity building) (Moran et al., 2014; Colloff et al., 2016; Dunlop et al., 2016; Bosomworth et al., 2017) (natural resource, management) (Hadwen et al., 2012; Barnett et al., 2014b; Fazey et al., 2015; Lazarow, 2017; Ramm et al., 2018) (coastal) (Siebentritt et al., 2014; Zografos et al., 2016) (regional development)

		(Maru et al., 2014) (disadvantaged communities) (Hertzler et al., 2013; Sanderson et al., 2015) (agriculture) (Ren et al., 2011) (infrastructure and resilient cities) (Cunningham et al., 2017) (social network analysis with communities)
Serious Games	To catalyse learning, raise awareness and explore attitudes and values	(Lawrence and Haasnoot, 2017; Colliar and Blackett, 2018; Flood et al., 2018; Edwards et al., 2019)
Signals and Triggers for monitoring DAPP	For where there is near-term certainty and longer-term deep uncertainty e.g. sea-level rise	(Stephens et al., 2017; Stephens et al., 2018)
Shared Socio-economic Pathways	For where there is deep uncertainty and scenarios are used	(B. Frame et al., 2018)
Hybrid Multi-criteria analysis and DAPP (deep uncertainty)	For conditions of deep uncertainty for short-term and long-term options and flexibility desired	(D. Frame et al., 2018; Lawrence et al., 2019a)
Real Options Analysis (ROA)	For conditions of deep uncertainty	(Infometrics and PSConsulting, 2015; Infometrics, 2017; Lawrence et al., 2019a; Wreford et al., 2020)
Scenario-based cost-benefit analysis	For conditions of deep uncertainty	(Guthrie, 2019)
Portfolio analysis	For uncertainties in the land use sector	(Monge et al., 2016; Awatere et al., 2018)(West et al. 2021)
Cost Benefit Analysis	Where decisions can be easily reversed	(Hadwen et al., 2012; Little and Lin, 2015; Stewart, 2015; Luo et al., 2017; Thamo et al., 2017)
Vulnerability assessment	For assessing and prioritising physical and social place-based risks, using indices, modelling and participatory approaches	(Ramm et al., 2017; Moglia et al., 2018; Pearce et al., 2018; Tonmoy and El-Zein, 2018)
Statutory tools	For planning direction	(DoC NZ, 2010; DoC NZ, 2017a; DoC NZ, 2017b; NSW Government, 2018)
	For planning and design of adaptation	(MfE, 2017a)
Standards	For adaptation best practice	(ISO, 2019)
Jurisprudence	For adaptation implementation and legal interpretation	(O'Donnell and Gates, 2013; McAdam, 2015; Iorns Magallanes and Watts, 2019; Peel et al., 2020)
Guidance	For adaptation and use of uncertainty tools	(CSIRO and BOM, 2015; MfE, 2017a; Lawrence et al., 2018b; Palutikof et al., 2019b)
Information delivery and decision support portal	For adaptation decision making	https://coastadapt.com.au/

Monitoring, evaluation and reporting on adaptation progress (incl. adaptation indices and web-based tools)	For local government, private sector and finance sector to benchmark, track progress	(Goodhue et al., 2012; Little et al., 2015; IGCC, 2017; Lawrence et al., 2020a; LGAQ and DES, 2020; Rogers et al., 2020b; WAGA, 2020) (Moloney and McClaren, 2018)

11.7.3.2 Attitudes, Engagement and Accessible Information as Enablers

Concern for climate change has become widespread (Hopkins, 2015; Borchers Arriagada et al., 2020), giving climate adaptation social legitimacy (*high confidence*). Over three quarters of Australians (77%) agree that climate change is occurring and 61% believe climate change is caused by humans (Merzian et al., 2019). A growing proportion of Australians perceive links between climate change and high temperatures experienced during heatwaves and extremely hot days (2018/2019 Summer) (48%), droughts and flooding (42%), and urban water shortages (30%) (Merzian et al., 2019). Rural populations in NSW perceive climate change impacts as stressing their wellbeing and mental health and requiring leadership and action (Austin et al., 2020). In New Zealand, between 2009 and 2018, the proportion of New Zealanders who agreed or strongly agreed that climate change is real increased from 58% to 78% (a 34.5% increase), while those agreeing or strongly agreeing with human causation increased from 41% to 64% (a 56.1% increase) (Milfont et al., 2021). Nevertheless, New Zealanders have a tendency to overestimate the amount of sea-level rise, especially amongst those most concerned about climate change, and incorrectly associate it with melting sea ice, which has implications for engagement and communication strategies (Priestley et al., 2021).

Use of more systemic, collaborative and future-oriented engagement approaches is facilitating adaptation in local contexts (Rouse et al., 2013; MfE, 2017a; Leitch et al., 2019) (*high confidence*). Local 'adaptation champions' and experimental and tailored engagement processes can enhance learning (McFadgen and Huitema, 2017; Lindsay et al., 2019). Dynamic adaptive pathways planning (Lawrence et al., 2019a) and inclusive community governance (Schneider et al., 2020)can help progress difficult decisions such as the relocation of cultural assets and managed retreat, and contestation about which public goods to prioritise and how adaptation should be implemented (Kwakkel et al., 2016) (Colliar and Blackett, 2018). Participatory climate change scenario planning can test assumptions about the present and the future (Mitchell et al., 2017; Serrao-Neumann and Choy, 2018; Chambers et al., 2019; Serrao-Neumann et al., 2019c) and help envision people-centred, place-based adaptation (Barnett et al., 2014b; Lindsay et al., 2019). Social network analysis can inform engagement and communication of adaptation (Cunningham et al., 2017). Knowledge brokers, information portals and alliances can help communities, governments and sector groups to better access and use climate change information (Shaw et al., 2013; Fünfgeld, 2015; Lawrence and Haasnoot, 2017). Novel approaches to building climate change literacy and adaptation capability go hand in hand with dedicated expert organisational support (Stevens and O'Connor, 2015; CCATWG, 2018; Palutikof et al., 2019c; Salmon, 2019). All of these approaches depend on adequate resourcing (*very high confidence*).

11.7.3.3 Knowledge Gaps and Implementation Enablers

There are two priority areas where new knowledge is critical for accelerating adaptation implementation.

1) *System complexity and uncertainty in observed and projected impacts*
   - Regionally relevant projections of rainfall, runoff, compound and extreme weather (11.2.1; 11.3.3; Box 11.4).
   - Inclusion of cascading and compounding impacts in integrated assessments (11.5.1) including for infrastructure (11.3.5), tourism (11.3.7) and health (11.3.6) and for different groups, including Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori communities (11.4).
   - Impacts on terrestrial and freshwater ecosystems, including in-situ monitoring to detect ongoing changes especially in New Zealand (11.3.1), and marine biodiversity including environmental tolerances of key life stages (11.3.2).
   - Repository of indigenous species distribution data for monitoring responses to climate change and climate advisory services for New Zealand (11.3.1.3).

- National risk assessment for Australia (11.7.1).
- The interactions between adaptation and mitigation, particularly where land carbon mitigation is impacted by climate change (11.3.4.3; Box 11.5).

2) *Supporting adaptation decision making*

- Better understanding of who and what is exposed and where, and their vulnerability to climate hazards (11.3, 11.4).
- National assessments of the costs and benefits of climate change, with and without different levels and timings of adaptation and mitigation (11.5.2.3) (11.7.1).
- Understanding available adaptation strategies and options, their feasibility and effectiveness as the climate changes, including their intended and unintended outcomes (11.7, 11.8).
- Understanding how to embed robust planning approaches into decision making that retain flexibility to change course in the future (11.7.1).
- Mechanisms for sharing knowledge and practice of adaptation (11.7).
- The role of development paradigms, values and political economy in adaptation framing and effective implementation (11.8).
- Understanding social transitions and social licence, for timely, robust and transformational adaptation (11.8.2).

11.8 Climate Resilient Development Pathways

Adaptation to climate risks and global mitigation of greenhouse emissions determine whether development pathways are climate resilient (Chapter 18). In the near-term, progress towards climate resilient development can be monitored by progress on the Sustainable Development Goals (SDGs). According to government reports (OECD, 2019a) (Figure 11.6) current and projected trajectories fall short of meeting all targets (Allen et al., 2019). Key climate risks for the region (11.6, Table 11.14) affect all of the SDGs, and pre-existing societal inequalities exacerbate climate risks (11.3.5). Projected climate risks combined with underlying SDG indicators will increasingly impede the region's capacity to achieve and maintain a number of SDGs, including sustainable agriculture, affordable and clean energy, sustainable cities and communities, life below water and life on land (OECD, 2019a). Reducing these risks would require significant and rapid emission reductions to keep global warming to 1.5-2.0°C, and robust and timely adaptation (IPCC, 2018).

11.8.1 System Adaptations and Transitions

A step-change in adaptation action is needed to address climate risks and to be consistent with climate resilient development *(very high confidence).* Current adaptation falls short on assessment of complex risks, implementation, monitoring, and evaluation. It is largely incremental and temporary given the scale of projected impacts, it has limits and is mainly reactive rather than anticipatory. Furthermore, risks are projected to cascade and compound, with impacts and costs that challenge adaptive capacities (11.5) and call for transformational responses (11.6, Table 11.15a; Table 11.15b; Supplementary Tables SM11.1a; SM11.1b).

Current global emissions reduction policies are projected to lead to a global warming of 2.1-3.9 °C by 2100 (Liu and Raftery, 2021), leaving many of the region's human and natural systems at very high risk and beyond adaptation limits (*high confidence*). With higher levels of warming, adaptation costs increase, loss and damages grow, and governance and institutional responses have reduced adaptive capacity. Underlying social and economic vulnerabilities and injustices further reduce adaptive capacity, exacerbating disadvantage in particular groups in society. Sustainable development across and beyond the region will help reduce shared adaptation challenges (11.5.1.2). Effective adaptation avoids lock-in and path dependency, reduces vulnerabilities, increases flexibility to change, builds adaptive capacity and progresses SDGs, thus improving intra- and inter-generational justice (11.5, 11.6, 11.7). Reducing greenhouse gas emissions and structural inequalities is key to achieving the SDGs and contributing to climate resilient development.

Integrated and inclusive adaptation decision making can contribute to climate resilient development by better mediating competing values, interests and priorities and helping to reconcile short-and long-term objectives, as well as public and private costs and benefits, in the face of rapidly and continuously changing risk profiles

(Gorddard et al., 2016; MfE, 2017a; Schlosberg et al., 2017) (11.5.2) *(very high confidence).* Use of new tools and approaches (Table 11.18) to address system interactions that match the scale and scope of the problem can result in more effective adaptation, including proactive and anticipatory governance and institutional enablers (11.7, Table 11.17) (Schlosberg et al., 2017; Boston and Lawrence, 2018). Building cities and settlements that are resilient to the impacts of climate change requires the simultaneous consideration of infrastructural, ecological, social, economic, institutional, and political dimensions of resilience including political will, leadership, commitment, community support, multilevel governance, and policy continuity (Torabi et al., 2021).

11.8.2 Challenges for Climate Resilient Development Pathways

Implementing enablers can help drive adaptation ambition and action consistent with climate resilient development (11.7.3, Table 11.17) (*very high confidence*). However, the scale and scope of cascading, compounding and aggregate impacts (11.5.1) calls for new and timely adaptation, including more effective ongoing monitoring, evaluation, review and continual adjustment (11.7.3) towards the transformations that can break through the 'path dependencies' that define the way things are done now (Cradock-Henry et al., 2018b; UN et al., 2018; Head, 2020). However, complex interactions between objectives can create social and economic trade-offs (Table 11.1, 11.3.5.3, 11.7.3.1, Box 11.6).

Delay in implementing climate change adaptation and emissions reductions will impede climate resilient development, resulting in more costly climate impacts and greater scale of adjustments in the future (IPCC, 2018) (11.5.1; 11.5.2) (Box 11.6) and legal risks for those with adaptation mandates and for financial institutions (11.5.1) (*very high confidence*). The scale and scope of societal change needed for the region to transition to more climate resilient development pathways requires close attention to governance, ethical questions, the role of civil society, the place of Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori in the co-production of ongoing adaptation at multiple scales (Koehler et al., 2017; Loorbach et al., 2017; Hill et al., 2020).

The region faces an extremely challenging future that will be highly disruptive for many human and natural systems (IPCC, 2018) (UNEP, 2020; AAS, 2021; IPCC, 2021) (11.5.1; 11.6; 11.7) (Box 11.1-11.6) (Table 11.14). The extent to which the limits to adaptation are reached depends on whether global warming peaks this century at 1.5, 2 or 3+°C above pre-industrial levels. Whatever the outcome, adaptation and mitigation are essential and urgent. (*very high confidence*)

[START FAQ11.1 HERE]

FAQ 11.1: How is climate change affecting Australia and New Zealand?

Climate change is affecting Australia and New Zealand significantly. Some natural systems of cultural, environmental, social and economic significance are at risk of irreversible change. The socio-economic costs of climate change are substantial, with impacts that cascade and compound across sectors and regions, as demonstrated by heatwaves, wildfire, cyclone, drought and flood events.

Temperature has increased by 1.4°C in Australia and 1.1°C in New Zealand over the last 110 years, with more extreme hot days. The oceans in the region have warmed significantly, resulting in longer and more frequent marine heatwaves. Sea levels have risen and the oceans have become more acidic. Snow depths have declined and glaciers have receded. North-western Australia and most of southern New Zealand have become wetter, while southern Australia and most of northern New Zealand have become drier. The frequency, severity and duration of extreme wildfire weather conditions has increased in southern and eastern Australia and north-eastern New Zealand.

The impacts of climate change on marine, terrestrial and freshwater ecosystems and species are evident. The mass mortality of corals throughout the Great Barrier Reef during marine heatwaves in 2016–2020 is a striking example. Climate change has contributed to the unprecedented south-eastern Australia wildfires in the spring-summer of 2019–2020, loss of alpine habitats in Australia, extensive loss of kelp forests, shifts further south in the distribution of almost 200 marine species, decline and extinction in some vertebrate species in the Australian wet tropics, expansion of invasive plants, animals and pathogens in New Zealand, erosion and flooding of coastal habitats in New Zealand, river flow decline in southern Australia, increased stress in rural communities, insurance losses for floods in New Zealand, increase in heat wave mortalities in Australian capital cities, and the fish deaths in Murray-Darling River in the summer of 2018–2019.

[END FAQ11.1 HERE]

[START FAQ11.2 HERE]

FAQ 11.2: What systems in Australia and New Zealand are most at risk from ongoing climate change?

The nine key risks to human systems and ecosystems in Australia and New Zealand from ongoing climate change are shown in Figure FAQ 11.2.1. Some risks, especially on ecosystems, are now difficult to avoid. Other risks can be reduced by adaptation, if global mitigation is effective.

Risk is the combination of hazard, exposure and vulnerability. For a given hazard (e.g. fire), the risk will be greater in areas with high exposure (e.g. many houses) and/or high vulnerability (e.g. remote communities with limited escape routes). The severity and type of climate risk varies geographically (Figure FAQ 11.2.1). Everyone will be affected by climate change, with disadvantaged and remote people and communities the most vulnerable.

The risks to natural and human systems are often compounded by impacts across multiple spatial and temporal scales. For example, fires damage property, farms, forests and nature with short- and long-term effects on biodiversity, natural resources, human health, communities and the economy. Major impacts across multiple sectors can disrupt supply chains to industries and communities and constrain delivery of health, energy, water and food services. These impacts create challenges for adaptation and governance of climate risks. When combined, these have far-reaching socio-economic and environmental impacts.

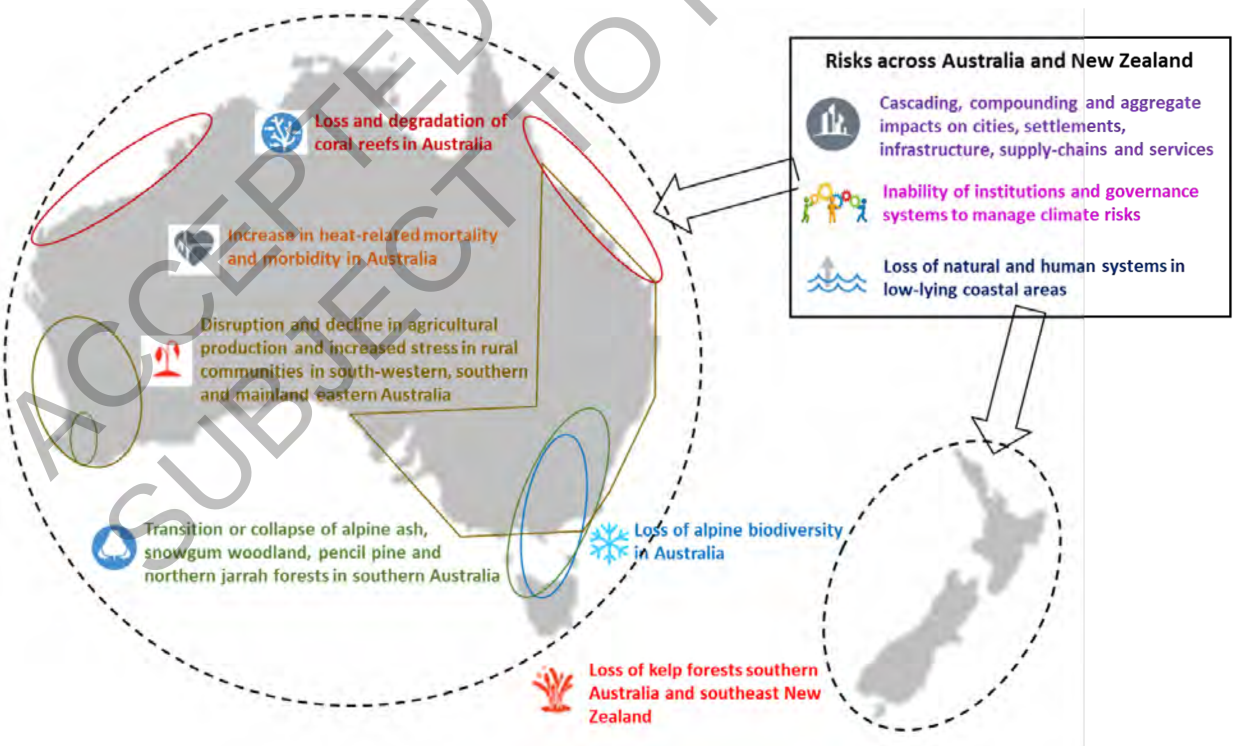

Figure FAQ 11.2.1: Key risks from climate change

[END FAQ11.2 HERE]

[START FAQ11.3 HERE]

FAQ 11.3: How can Indigenous Peoples' knowledge and practice help us understand contemporary climate impacts and inform adaptation in Australia and New Zealand?

In Australia and New Zealand, as with many places around the world, Indigenous Peoples with connections to their traditional country and extensive histories, hold deep knowledge from observing and living in a changing climate. This provides insights that inform adaptation to climate change.

Indigenous Australians - Aboriginal and Torres Strait Islanders - maintain knowledge regarding previous sea-level rise, climate patterns, and shifts in seasonal change associated with flowering of trees and emergence of food sources, developed over thousands of generations of observation of their traditional country. Knowledge of localised contemporary adaptation is also held by many Indigenous Australians with connections to traditional lands. With assured Free and Prior-Informed Consent, this provides a means for Indigenous-guided land management, including for fire management and carbon abatement, fauna studies, medicinal plant products, threatened species recovery, water management, and weed management.

Tangata Whenua Māori in New Zealand are grounded in Mātauranga Māori knowledge which is based on human-nature relationships and ecological integrity and incorporates practices used to detect and anticipate changes taking place in the environment. Social-cultural networks and conventions that promote collective action and mutual support are central features of many Māori communities and these customary approaches are critical to responding to, and recovering from, adverse environmental conditions. Intergenerational approaches to planning for the future are also intrinsic to Māori social-cultural organisation and are expected to become increasingly important, elevating political discussions about conceptions of rationality, diversity and the rights of non-human entities in climate change policy and adaptation.

[END FAQ11.3 HERE]

[START FAQ11.4 HERE]

FAQ 11.4: How can Australia and New Zealand adapt to climate change?

There is already work underway by governments, businesses, communities and Indigenous Peoples to help us adapt to climate change. However, much more adaptation is needed for the ongoing and intensifying climate risks. This includes coordinated laws, plans, guidance and funding that enable society to adapt, and the information, education and training that can support it. Everyone has a role to play, working together.

We currently mainly react to climate events such as wildfires, heatwaves, floods and droughts, and generally rebuild in the same places. However, climate change is making these events more frequent and intense, and ongoing sea-level rise and changes in natural ecosystems are advancing. Better coordination and collaboration between government agencies, communities, Aboriginal and Torres Strait Islanders and Tangata Whenua Indigenous Peoples, not-for-profit organisations and businesses will help prepare for these climate impacts more proactively, in combination with future climate risks integrated into their decisions and planning. This will reduce the impacts we experience now and the risks that will affect future generations.

Some of the risks for natural systems are close to critical thresholds and adaptation may be unable to prevent ecosystem collapse. Other risks will be severe, but we can reduce their impact by acting now, for example coastal flooding from sea-level rise, heat-related mortality and managing water stresses. Many of the risks have potential to cascade across social and economic sectors with widespread societal impacts. In such cases, really significant system-wide changes will be needed to the way we live and govern currently. To facilitate such change, new governance frameworks, nationally consistent and accessible information, collaborative engagement and partnerships with all sectors, communities and Indigenous Peoples and the resources to address the risks, are needed (Figure FAQ 11.4.1).

However, our ability to adapt to climate change impacts also rests on every region in the world playing its part in reducing greenhouse gas emissions. If mitigation is ineffective, global warming will be rapid, adaptation costs will increase, with worsening losses and damages.

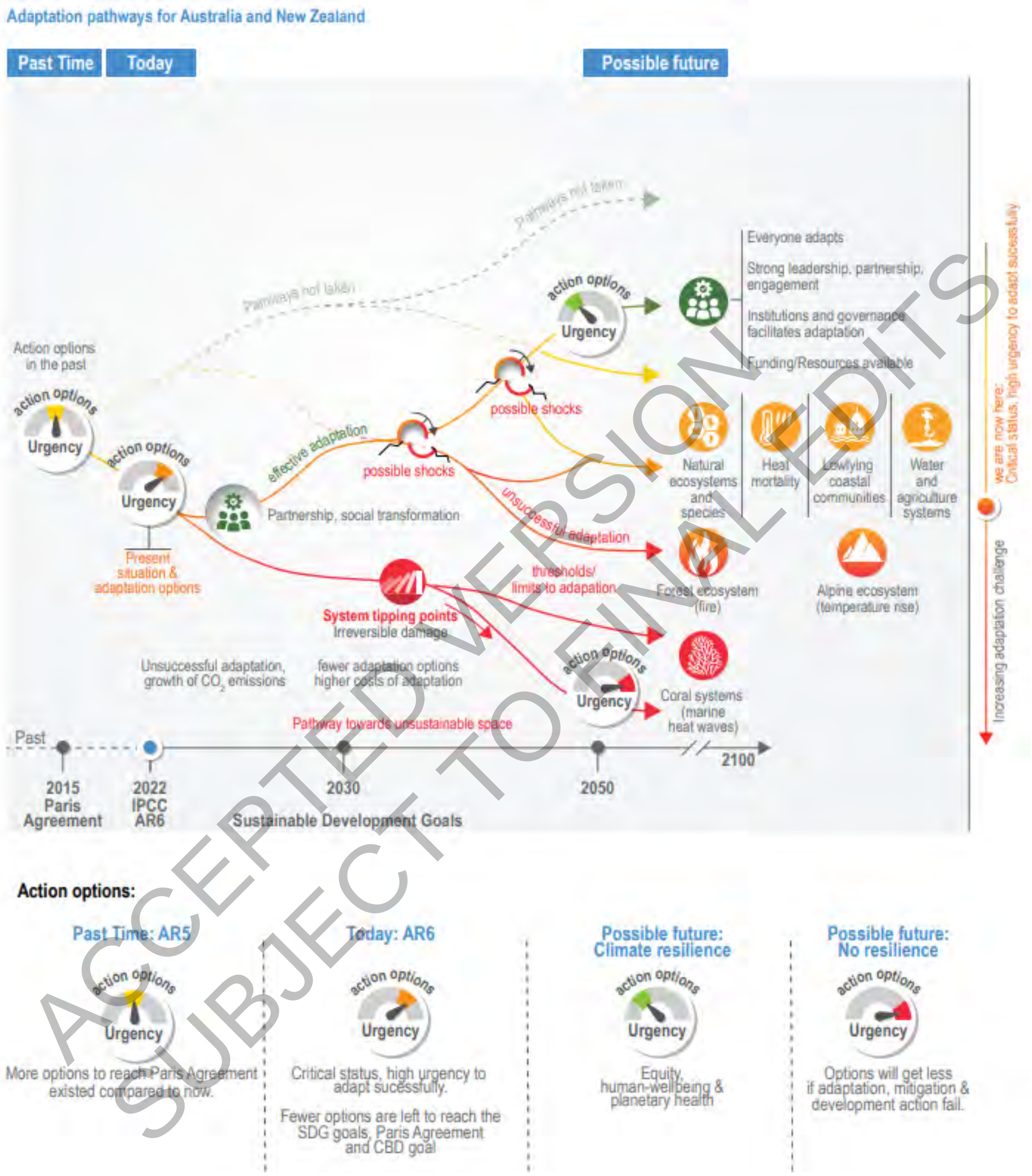

Figure FAQ 11.4.1: Developing adaptation plans in the solutions space showing system tipping points, thresholds and limits to adaptation, unsustainable pathways, critical systems and enablers to climate resilient development

[END FAQ11.4 HERE]

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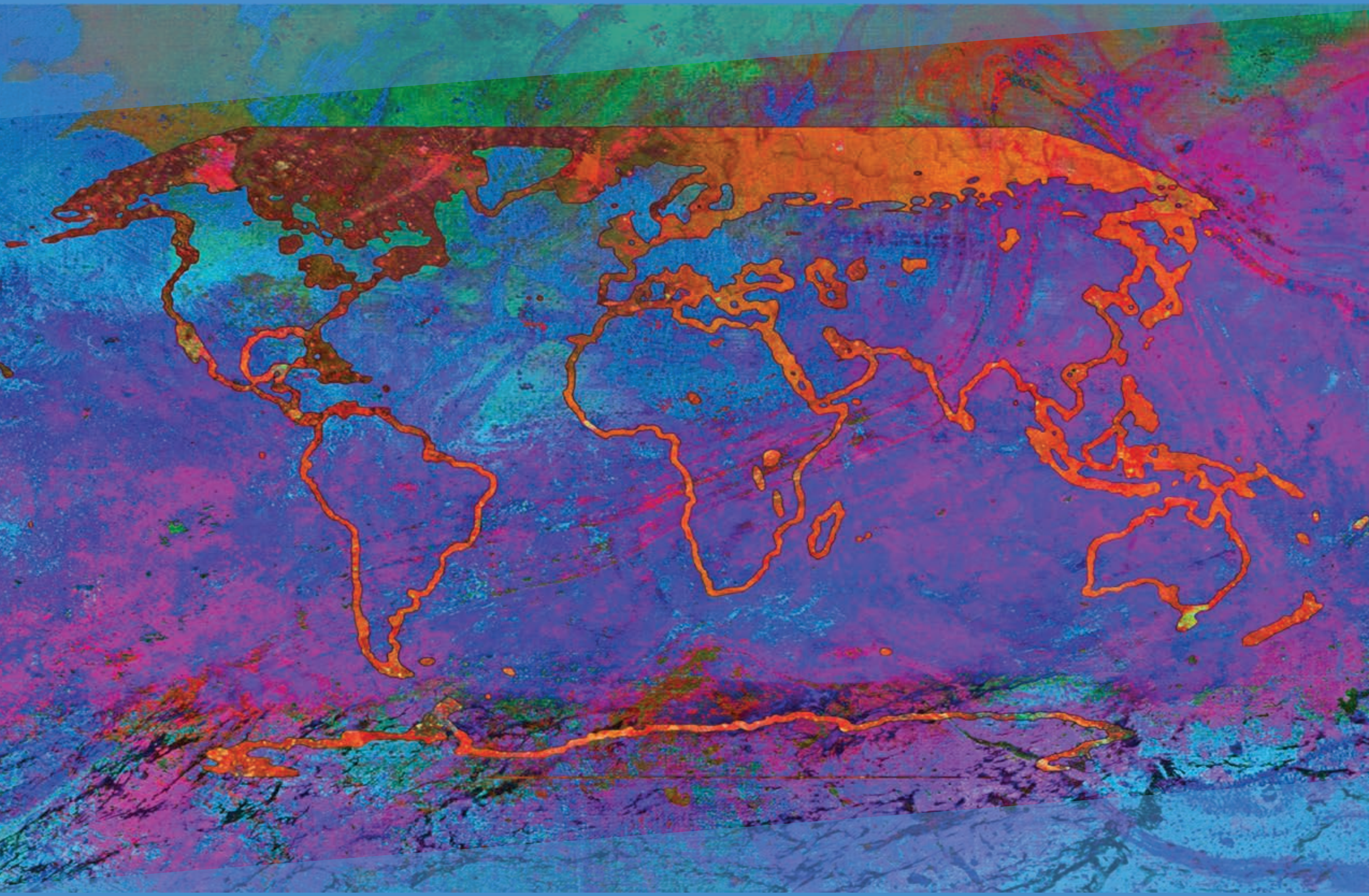
Climate Change 2021

The Physical Science Basis

Summary for Policymakers



WGI

Working Group I Contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Climate Change 2021
The Physical Science Basis

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Edited by

Valérie Masson-Delmotte
Co-Chair Working Group I

Panmao Zhai
Co-Chair Working Group I

Anna Pirani
Head of TSU

Sarah L. Connors
Head of Science Team

Clotilde Péan
Head of Operations

Yang Chen
Senior Science officer

Leah Goldfarb
Senior Science officer

Melissa I. Gomis
Senior Science officer

J.B.Robin Matthews
Senior Science officer

Sophie Berger
Science Officer

Mengtian Huang
Science Officer

Ozge Yelekçi
Science Officer

Rong Yu
Science Officer

Baiquan Zhou
Science Officer

Elisabeth Lonnoy
Project Assistant

Thomas K. Maycock
Science Editor

Tim Waterfield
IT Officer

Katherine Leitzell
Communication Manager

Nada Caud
Outreach Manager

Working Group I Technical Support Unit

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SPM

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Drafting Authors:
Richard P. Allan (United Kingdom), Paola A. Arias (Colombia), Sophie Berger (France/Belgium), Josep G. Canadell (Australia), Christophe Cassou (France), Deliang Chen (Sweden), Annalisa Cherchi (Italy), Sarah L. Connors (France/United Kingdom), Erika Coppola (Italy), Faye Abigail Cruz (Philippines), Aïda Diongue-Niang (Senegal), Francisco J. Doblas-Reyes (Spain), Hervé Douville (France), Fatima Driouech (Morocco), Tamsin L. Edwards (United Kingdom), François Engelbrecht (South Africa), Veronika Eyring (Germany), Erich Fischer (Switzerland), Gregory M. Flato (Canada), Piers Forster (United Kingdom), Baylor Fox-Kemper (United States of America), Jan S. Fuglestvedt (Norway), John C. Fyfe (Canada), Nathan P. Gillett (Canada), Melissa I. Gomis (France/Switzerland), Sergey K. Gulev (Russian Federation), José Manuel Gutiérrez (Spain), Rafiq Hamdi (Belgium), Jordan Harold (United Kingdom), Mathias Hauser (Switzerland), Ed Hawkins (United Kingdom), Helene T. Hewitt (United Kingdom), Tom Gabriel Johansen (Norway), Christopher Jones (United Kingdom), Richard G. Jones (United Kingdom), Darrell S. Kaufman (United States of America), Zbigniew Klimont (Austria/Poland), Robert E. Kopp (United States of America), Charles Koven (United States of America), Gerhard Krinner (France/Germany, France), June-Yi Lee (Republic of Korea), Irene Lorenzoni (United Kingdom/Italy), Jochem Marotzke (Germany), Valérie Masson-Delmotte (France), Thomas K. Maycock (United States of America), Malte Meinshausen (Australia/Germany), Pedro M.S. Monteiro (South Africa), Angela Morelli (Norway/Italy), Vaishali Naik (United States of America), Dirk Notz (Germany), Friederike Otto (United Kingdom/Germany), Matthew D. Palmer (United Kingdom), Izidine Pinto (South Africa/Mozambique), Anna Pirani (Italy), Gian-Kasper Plattner (Switzerland), Krishnan Raghavan (India), Roshanka Ranasinghe (The Netherlands/Sri Lanka, Australia), Joeri Rogelj (United Kingdom/Belgium), Maisa Rojas (Chile), Alex C. Ruane (United States of America), Jean-Baptiste Sallée (France), Bjørn H. Samset (Norway), Sonia I. Seneviratne (Switzerland), Jana Sillmann (Norway/Germany), Anna A. Sörensson (Argentina), Tannecia S. Stephenson (Jamaica), Trude Storelvmo (Norway), Sophie Szopa (France), Peter W. Thorne (Ireland/United Kingdom), Blair Trewin (Australia), Robert Vautard (France), Carolina Vera (Argentina), Noureddine Yassaa (Algeria), Sönke Zaehle (Germany), Panmao Zhai (China), Xuebin Zhang (Canada), Kirsten Zickfeld (Canada/Germany)

Contributing Authors:
Krishna M. AchutaRao (India), Bhupesh Adhikary (Nepal), Edvin Aldrian (Indonesia), Kyle Armour (United States of America), Govindasamy Bala (India/United States of America), Rondrotiana Barimalala (South Africa/Madagascar), Nicolas Bellouin (United Kingdom/France), William Collins (United Kingdom), William D. Collins (United States of America), Susanna Corti (Italy), Peter M. Cox (United Kingdom), Frank J. Dentener (EU/The Netherlands), Claudine Dereczynski (Brazil), Alejandro Di Luca (Australia, Canada/Argentina), Alessandro Dosio (Italy), Leah Goldfarb (France/United States of America), Irina V. Gorodetskaya (Portugal/Belgium, Russian Federation), Pandora Hope (Australia), Mark Howden (Australia), A.K.M Saiful Islam (Bangladesh), Yu Kosaka (Japan), James Kossin (United States of America), Svitlana Krakovska (Ukraine), Chao Li (China), Jian Li (China), Thorsten Mauritsen (Germany/Denmark), Sebastian Milinski (Germany), Seung-Ki Min (Republic of Korea), Thanh Ngo Duc (Vietnam), Andy Reisinger (New Zealand), Lucas Ruiz (Argentina), Shubha Sathyendranath (United Kingdom/Canada, Overseas Citizen of India), Aimée B. A. Slangen (The Netherlands), Chris Smith (United Kingdom), Izuru Takayabu (Japan), Muhammad Irfan Tariq (Pakistan), Anne-Marie Treguier (France), Bart van den Hurk (The Netherlands), Karina von Schuckmann (France/Germany), Cunde Xiao (China)

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Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group I (WGI) contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[1] on the physical science basis of climate change. The report builds upon the 2013 Working Group I contribution to the IPCC's Fifth Assessment Report (AR5) and the 2018–2019 IPCC Special Reports[2] of the AR6 cycle and incorporates subsequent new evidence from climate science.[3]

This SPM provides a high-level summary of the understanding of the current state of the climate, including how it is changing and the role of human influence, the state of knowledge about possible climate futures, climate information relevant to regions and sectors, and limiting human-induced climate change.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence indicated using the IPCC calibrated language.[4]

The scientific basis for each key finding is found in chapter sections of the main Report and in the integrated synthesis presented in the Technical Summary (hereafter TS), and is indicated in curly brackets. The AR6 WGI Interactive Atlas facilitates exploration of these key synthesis findings, and supporting climate change information, across the WGI reference regions.[5]

A. The Current State of the Climate

Since AR5, improvements in observationally based estimates and information from paleoclimate archives provide a comprehensive view of each component of the climate system and its changes to date. New climate model simulations, new analyses, and methods combining multiple lines of evidence lead to improved understanding of human influence on a wider range of climate variables, including weather and climate extremes. The time periods considered throughout this section depend upon the availability of observational products, paleoclimate archives and peer-reviewed studies.

**A.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.
{2.2, 2.3, Cross-Chapter Box 2.3, 3.3, 3.4, 3.5, 3.6, 3.8, 5.2, 5.3, 6.4, 7.3, 8.3, 9.2, 9.3, 9.5, 9.6, Cross-Chapter Box 9.1} (Figure SPM.1, Figure SPM.2)**

A.1.1 Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities. Since 2011 (measurements reported in AR5), concentrations have continued to increase in the atmosphere, reaching annual averages of 410 parts per million (ppm) for carbon dioxide (CO_2), 1866 parts per billion (ppb) for methane (CH_4), and 332 ppb for nitrous oxide (N_2O) in 2019.[6] Land and ocean have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*).[7]
{2.2, 5.2, 7.3, TS.2.2, Box TS.5}

1 Decision IPCC/XLVI-2.

2 The three Special Reports are: Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

3 The assessment covers scientific literature accepted for publication by 31 January 2021.

4 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or result: virtually certain 99–100% probability; very likely 90–100%; likely 66–100%; about as likely as not 33–66%; unlikely 0–33%; very unlikely 0–10%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; more likely than not >50–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

5 The Interactive Atlas is available at https://interactive-atlas.ipcc.ch

6 Other GHG concentrations in 2019 were: perfluorocarbons (PFCs) – 109 parts per trillion (ppt) CF_4 equivalent; sulphur hexafluoride (SF_6) – 10 ppt; nitrogen trifluoride (NF_3) – 2 ppt; hydrofluorocarbons (HFCs) – 237 ppt HFC-134a equivalent; other Montreal Protocol gases (mainly chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)) – 1032 ppt CFC-12 equivalent). Increases from 2011 are 19 ppm for CO_2, 63 ppb for CH_4 and 8 ppb for N_2O.

7 Land and ocean are not substantial sinks for other GHGs.

A.1.2 Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature[8] in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10] °C higher than 1850–1900.[9] Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1°C to the updated estimate of warming in AR6.[10]
{2.3, Cross-Chapter Box 2.3} (Figure SPM.1)

A.1.3 The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979 and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s.
{3.3, 6.4, 7.3, TS.2.3, Cross-Section Box TS.1} (Figure SPM.2)

A.1.4 Globally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). It is *likely* that human influence contributed to the pattern of observed precipitation changes since the mid-20th century and *extremely likely* that human influence contributed to the pattern of observed changes in near-surface ocean salinity. Mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s, with marked seasonality in trends (*medium confidence*). For the Southern Hemisphere, human influence *very likely* contributed to the poleward shift of the closely related extratropical jet in austral summer.
{2.3, 3.3, 8.3, 9.2, TS.2.3, TS.2.4, Box TS.6}

A.1.5 Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (decreases of about 40% in September and about 10% in March). There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability. Human influence *very likely* contributed to the decrease in Northern Hemisphere spring snow cover since 1950. It is *very likely* that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only *limited evidence*, with *medium agreement*, of human influence on the Antarctic Ice Sheet mass loss.
{2.3, 3.4, 8.3, 9.3, 9.5, TS.2.5}

A.1.6 It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century and *medium confidence* that human influence contributed to this drop.
{2.3, 3.5, 3.6, 5.3, 9.2, TS.2.4}

A.1.7 Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971.
{2.3, 3.5, 9.6, Cross-Chapter Box 9.1, Box TS.4}

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8 The term 'global surface temperature' is used in reference to both global mean surface temperature and global surface air temperature throughout this SPM. Changes in these quantities are assessed with *high confidence* to differ by at most 10% from one another, but conflicting lines of evidence lead to *low confidence* in the sign (direction) of any difference in long-term trend. {Cross-Section Box TS.1}

9 The period 1850–1900 represents the earliest period of sufficiently globally complete observations to estimate global surface temperature and, consistent with AR5 and SR1.5, is used as an approximation for pre-industrial conditions.

10 Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

11 The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C.

12 Throughout this SPM, 'main driver' means responsible for more than 50% of the change.

A.1.8 Changes in the land biosphere since 1970 are consistent with global warming: climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics (*high confidence*).
{2.3, TS.2.6}

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Changes in global surface temperature relative to 1850–1900

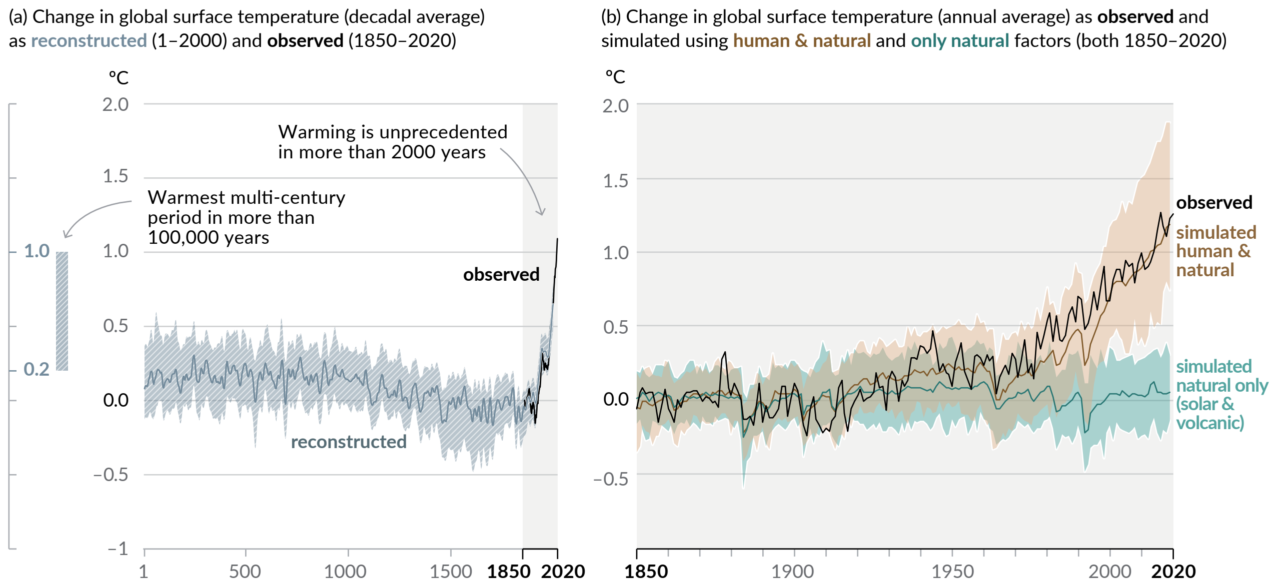

Figure SPM.1 | History of global temperature change and causes of recent warming

Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, years 1–2000) **and from direct observations** (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). The Last Interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.

Panel (b) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model simulations (see Box SPM.1) of the temperature response to both human and natural drivers (brown) and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations. (See Figure SPM.2 for the assessed contributions to warming).

{2.3.1; Cross-Chapter Box 2.3; 3.3; TS.2.2; Cross-Section Box TS.1, Figure 1a}

Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling

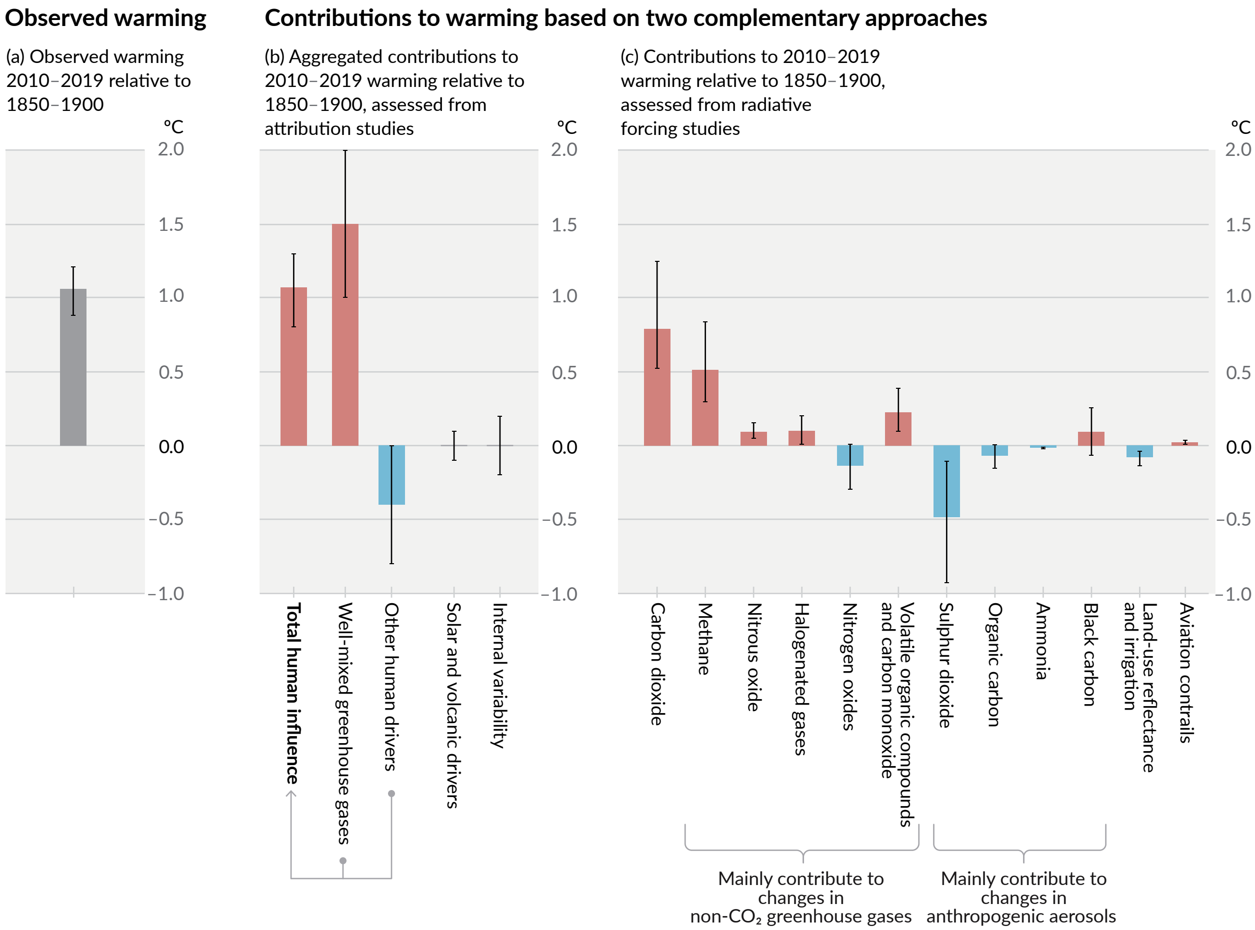

Figure SPM.2 | Assessed contributions to observed warming in 2010–2019 relative to 1850–1900

Panel (a) Observed global warming (increase in global surface temperature). Whiskers show the *very likely* range.

Panel (b) Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to: total human influence; changes in well-mixed greenhouse gas concentrations; other human drivers due to aerosols, ozone and land-use change (land-use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers show *likely* ranges.

Panel (c) Evidence from the assessment of radiative forcing and climate sensitivity. The panel shows temperature changes from individual components of human influence: emissions of greenhouse gases, aerosols and their precursors; land-use changes (land-use reflectance and irrigation); and aviation contrails. Whiskers show *very likely* ranges. Estimates account for both direct emissions into the atmosphere and their effect, if any, on other climate drivers. For aerosols, both direct effects (through radiation) and indirect effects (through interactions with clouds) are considered.

{Cross-Chapter Box 2.3, 3.3.1, 6.4.2, 7.3}

A.2 The scale of recent changes across the climate system as a whole – and the present state of many aspects of the climate system – are unprecedented over many centuries to many thousands of years. {2.2, 2.3, Cross-Chapter Box 2.1, 5.1} (Figure SPM.1)

A.2.1 In 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years (*high confidence*), and concentrations of CH_4 and N_2O were higher than at any time in at least 800,000 years (*very high confidence*). Since 1750, increases in CO_2 (47%) and CH_4 (156%) concentrations far exceed – and increases in N_2O (23%) are similar to – the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (*very high confidence*). {2.2, 5.1, TS.2.2}

A.2.2 Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). Temperatures during the most recent decade (2011–2020) exceed those of the most recent multi-century warm period, around 6500 years ago[13] [0.2°C to 1°C relative to 1850–1900] (*medium confidence*). Prior to that, the next most recent warm period was about 125,000 years ago, when the multi-century temperature [0.5°C to 1.5°C relative to 1850–1900] overlaps the observations of the most recent decade (*medium confidence*). {2.3, Cross-Chapter Box 2.1, Cross-Section Box TS.1} (Figure SPM.1)

A.2.3 In 2011–2020, annual average Arctic sea ice area reached its lowest level since at least 1850 (*high confidence*). Late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years (*medium confidence*). The global nature of glacier retreat since the 1950s, with almost all of the world's glaciers retreating synchronously, is unprecedented in at least the last 2000 years (*medium confidence*). {2.3, TS.2.5}

A.2.4 Global mean sea level has risen faster since 1900 than over any preceding century in at least the last 3000 years (*high confidence*). The global ocean has warmed faster over the past century than since the end of the last deglacial transition (around 11,000 years ago) (*medium confidence*). A long-term increase in surface open ocean pH occurred over the past 50 million years (*high confidence*). However, surface open ocean pH as low as recent decades is unusual in the last 2 million years (*medium confidence*). {2.3, TS.2.4, Box TS.4}

A.3 Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5. {2.3, 3.3, 8.2, 8.3, 8.4, 8.5, 8.6, Box 8.1, Box 8.2, Box 9.2, 10.6, 11.2, 11.3, 11.4, 11.6, 11.7, 11.8, 11.9, 12.3} (Figure SPM.3)

A.3.1 It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006. {Box 9.2, 11.2, 11.3, 11.9, TS.2.4, TS.2.6, Box TS.10} (Figure SPM.3)

A.3.2 The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (*high confidence*), and human-induced climate change is *likely* the main driver. Human-induced climate change has contributed to increases in agricultural and ecological droughts[15] in some regions due to increased land evapotranspiration[16] (*medium confidence*). {8.2, 8.3, 11.4, 11.6, 11.9, TS.2.6, Box TS.10} (Figure SPM.3)

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13 As stated in section B.1, even under the very low emissions scenario SSP1-1.9, temperatures are assessed to remain elevated above those of the most recent decade until at least 2100 and therefore warmer than the century-scale period 6500 years ago.

14 As indicated in footnote 12, throughout this SPM, 'main driver' means responsible for more than 50% of the change.

15 Agricultural and ecological drought (depending on the affected biome): a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general (see Annex VII: Glossary). Observed changes in meteorological droughts (precipitation deficits) and hydrological droughts (streamflow deficits) are distinct from those in agricultural and ecological droughts and are addressed in the underlying AR6 material (Chapter 11).

16 The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soils and vegetation that make up the Earth's surface (Glossary).

A.3.3 Decreases in global land monsoon precipitation[17] from the 1950s to the 1980s are partly attributed to human-caused Northern Hemisphere aerosol emissions, but increases since then have resulted from rising GHG concentrations and decadal to multi-decadal internal variability (*medium confidence*). Over South Asia, East Asia and West Africa, increases in monsoon precipitation due to warming from GHG emissions were counteracted by decreases in monsoon precipitation due to cooling from human-caused aerosol emissions over the 20th century (*high confidence*). Increases in West African monsoon precipitation since the 1980s are partly due to the growing influence of GHGs and reductions in the cooling effect of human-caused aerosol emissions over Europe and North America (*medium confidence*).
{2.3, 3.3, 8.2, 8.3, 8.4, 8.5, 8.6, Box 8.1, Box 8.2, 10.6, Box TS.13}

A.3.4 It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades, and it is *very likely* that the latitude where tropical cyclones in the western North Pacific reach their peak intensity has shifted northward; these changes cannot be explained by internal variability alone (*medium confidence*). There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. Event attribution studies and physical understanding indicate that human-induced climate change increases heavy precipitation associated with tropical cyclones (*high confidence*), but data limitations inhibit clear detection of past trends on the global scale.
{8.2, 11.7, Box TS.10}

A.3.5 Human influence has *likely* increased the chance of compound extreme events[18] since the 1950s. This includes increases in the frequency of concurrent heatwaves and droughts on the global scale (*high confidence*), fire weather in some regions of all inhabited continents (*medium confidence*), and compound flooding in some locations (*medium confidence*).
{11.6, 11.7, 11.8, 12.3, 12.4, TS.2.6, Table TS.5, Box TS.10}

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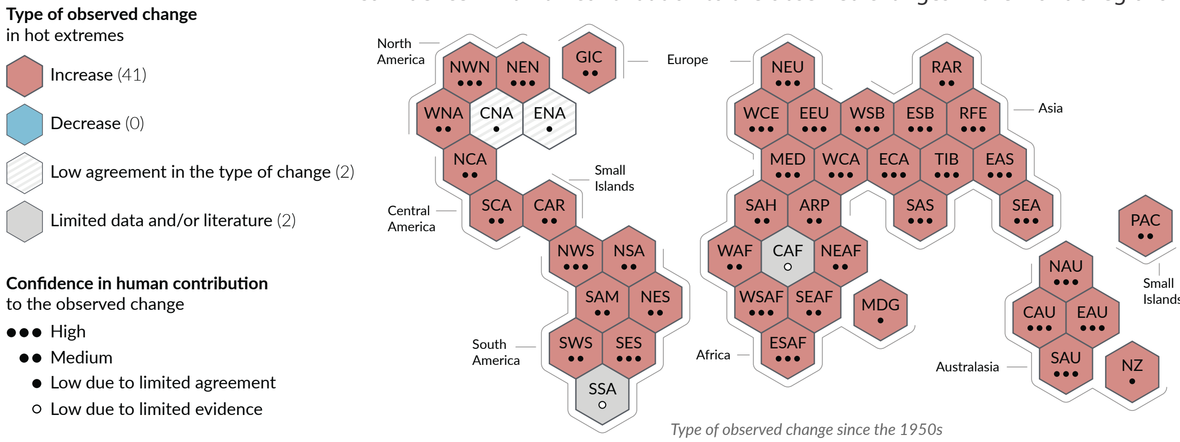
17 The global monsoon is defined as the area in which the annual range (local summer minus local winter) of precipitation is greater than 2.5 mm day^{-1} (Glossary). Global land monsoon precipitation refers to the mean precipitation over land areas within the global monsoon.

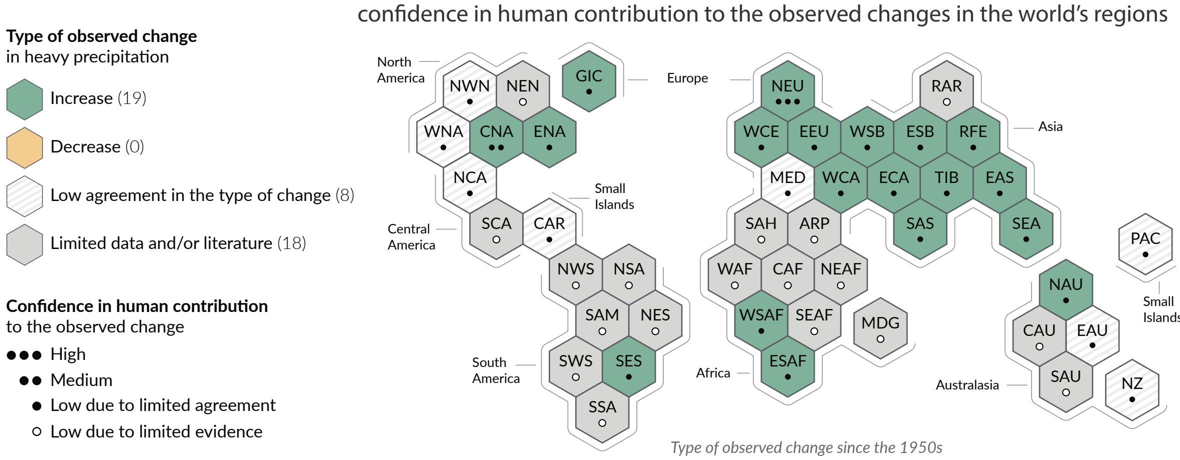
18 Compound extreme events are the combination of multiple drivers and/or hazards that contribute to societal or environmental risk (Glossary). Examples are concurrent heatwaves and droughts, compound flooding (e.g., a storm surge in combination with extreme rainfall and/or river flow), compound fire weather conditions (i.e., a combination of hot, dry and windy conditions), or concurrent extremes at different locations.

Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes

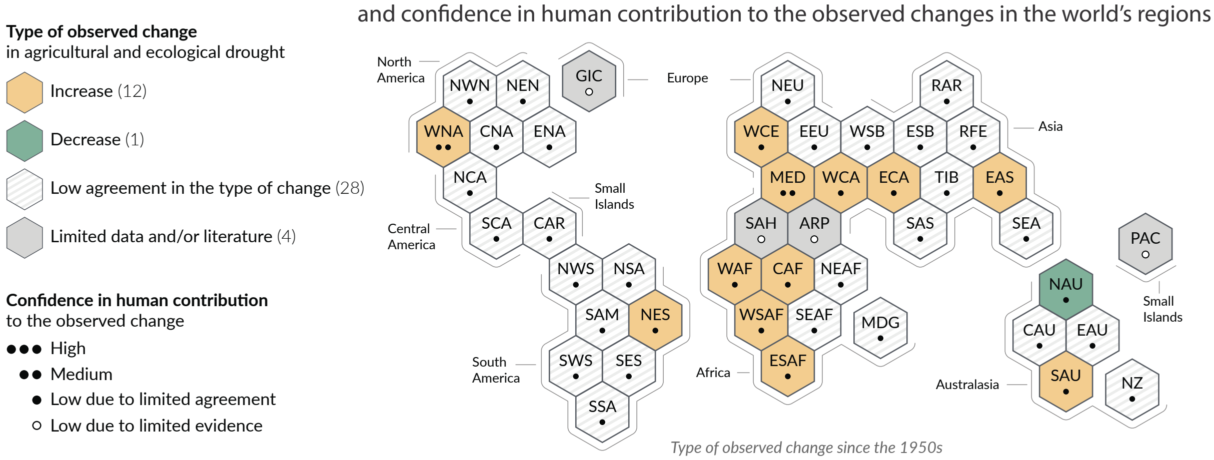
(a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions



(b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions



(c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions



Each hexagon corresponds to one of the IPCC AR6 WGI reference regions

NWN *North-Western North America*

IPCC AR6 WGI reference regions: **North America: NWN** *(North-Western North America,* **NEN** *(North-Eastern North America),* **WNA** *(Western North America),* **CNA** *(Central North America),* **ENA** *(Eastern North America),* **Central America: NCA** *(Northern Central America),* **SCA** *(Southern Central America),* **CAR** *(Caribbean),* **South America: NWS** *(North-Western South America),* **NSA** *(Northern South America),* **NES** *(North-Eastern South America),* **SAM** *(South American Monsoon),* **SWS** *(South-Western South America),* **SES** *(South-Eastern South America),* **SSA** *(Southern South America),* **Europe: GIC** *(Greenland/Iceland),* **NEU** *(Northern Europe),* **WCE** *(Western and Central Europe),* **EEU** *(Eastern Europe),* **MED** *(Mediterranean),* **Africa: MED** *(Mediterranean),* **SAH** *(Sahara),* **WAF** *(Western Africa),* **CAF** *(Central Africa),* **NEAF** *(North Eastern Africa),* **SEAF** *(South Eastern Africa),* **WSAF** *(West Southern Africa),* **ESAF** *(East Southern Africa),* **MDG** *(Madagascar),* **Asia: RAR** *(Russian Arctic),* **WSB** *(West Siberia),* **ESB** *(East Siberia),* **RFE** *(Russian Far East),* **WCA** *(West Central Asia),* **ECA** *(East Central Asia),* **TIB** *(Tibetan Plateau),* **EAS** *(East Asia),* **ARP** *(Arabian Peninsula),* **SAS** *(South Asia),* **SEA** *(South East Asia),* **Australasia: NAU** *(Northern Australia),* **CAU** *(Central Australia),* **EAU** *(Eastern Australia),* **SAU** *(Southern Australia),* **NZ** *(New Zealand),* **Small Islands: CAR** *(Caribbean),* **PAC** *(Pacific Small Islands)*

Figure SPM.3 | Synthesis of assessed observed and attributable regional changes

The IPCC AR6 WGI inhabited regions are displayed as **hexagons** with identical size in their approximate geographical location (see legend for regional acronyms). All assessments are made for each region as a whole and for the 1950s to the present. Assessments made on different time scales or more local spatial scales might differ from what is shown in the figure. The **colours** in each panel represent the four outcomes of the assessment on observed changes. Striped hexagons (white and light-grey) are used where there is *low agreement* in the type of change for the region as a whole, and grey hexagons are used when there is limited data and/or literature that prevents an assessment of the region as a whole. Other colours indicate at least *medium confidence* in the observed change. The **confidence level** for the human influence on these observed changes is based on assessing trend detection and attribution and event attribution literature, and it is indicated by the number of dots: three dots for *high confidence*, two dots for *medium confidence* and one dot for *low confidence* (single, filled dot: limited agreement; single, empty dot: limited evidence).

Panel (a) For hot extremes, the evidence is mostly drawn from changes in metrics based on daily maximum temperatures; regional studies using other indices (heatwave duration, frequency and intensity) are used in addition. Red hexagons indicate regions where there is at least *medium confidence* in an observed increase in hot extremes.

Panel (b) For heavy precipitation, the evidence is mostly drawn from changes in indices based on one-day or five-day precipitation amounts using global and regional studies. Green hexagons indicate regions where there is at least *medium confidence* in an observed increase in heavy precipitation.

Panel (c) Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand. Yellow hexagons indicate regions where there is at least *medium confidence* in an observed increase in this type of drought, and green hexagons indicate regions where there is at least *medium confidence* in an observed decrease in agricultural and ecological drought.

For all regions, Table TS.5 shows a broader range of observed changes besides the ones shown in this figure. Note that Southern South America (SSA) is the only region that does not display observed changes in the metrics shown in this figure, but is affected by observed increases in mean temperature, decreases in frost and increases in marine heatwaves.

{11.9, Atlas 1.3.3, Figure Atlas.2, Table TS.5; Box TS.10, Figure 1}

A.4 Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of equilibrium climate sensitivity of 3°C, with a narrower range compared to AR5. {2.2, 7.3, 7.4, 7.5, Box 7.2, 9.4, 9.5, 9.6, Cross-Chapter Box 9.1}

A.4.1 Human-caused radiative forcing of 2.72 [1.96 to 3.48] W m^{-2} in 2019 relative to 1750 has warmed the climate system. This warming is mainly due to increased GHG concentrations, partly reduced by cooling due to increased aerosol concentrations. The radiative forcing has increased by 0.43 W m^{-2} (19%) relative to AR5, of which 0.34 W m^{-2} is due to the increase in GHG concentrations since 2011. The remainder is due to improved scientific understanding and changes in the assessment of aerosol forcing, which include decreases in concentration and improvement in its calculation (*high confidence*). {2.2, 7.3, TS.2.2, TS.3.1}

A.4.2 Human-caused net positive radiative forcing causes an accumulation of additional energy (heating) in the climate system, partly reduced by increased energy loss to space in response to surface warming. The observed average rate of heating of the climate system increased from 0.50 [0.32 to 0.69] W m^{-2} for the period 1971–2006[19] to 0.79 [0.52 to 1.06] W m^{-2} for the period 2006–2018[20] (*high confidence*). Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*). {7.2, Box 7.2, TS.3.1}

A.4.3 Heating of the climate system has caused global mean sea level rise through ice loss on land and thermal expansion from ocean warming. Thermal expansion explained 50% of sea level rise during 1971–2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land-water storage 8%. The rate of ice-sheet loss increased by a factor of four between 1992–1999 and 2010–2019. Together, ice-sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006–2018 (*high confidence*). {9.4, 9.5, 9.6, Cross-Chapter Box 9.1}

A.4.4 The equilibrium climate sensitivity is an important quantity used to estimate how the climate responds to radiative forcing. Based on multiple lines of evidence,[21] the *very likely* range of equilibrium climate sensitivity is between 2°C (*high confidence*) and 5°C (*medium confidence*). The AR6 assessed best estimate is 3°C with a *likely* range of 2.5°C to 4°C (*high confidence*), compared to 1.5°C to 4.5°C in AR5, which did not provide a best estimate. {7.4, 7.5, TS.3.2}

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19 Cumulative energy increase of 282 [177 to 387] ZJ over 1971–2006 (1 ZJ = 10^{21} joules).

20 Cumulative energy increase of 152 [100 to 205] ZJ over 2006–2018.

21 Understanding of climate processes, the instrumental record, paleoclimates and model-based emergent constraints (Glossary).

SPM

B. Possible Climate Futures

A set of five new illustrative emissions scenarios is considered consistently across this Report to explore the climate response to a broader range of greenhouse gas (GHG), land-use and air pollutant futures than assessed in AR5. This set of scenarios drives climate model projections of changes in the climate system. These projections account for solar activity and background forcing from volcanoes. Results over the 21st century are provided for the near term (2021–2040), mid-term (2041–2060) and long term (2081–2100) relative to 1850–1900, unless otherwise stated.

Box SPM.1 | Scenarios, Climate Models and Projections

Box SPM.1.1: This Report assesses the climate response to five illustrative scenarios that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. They start in 2015, and include scenarios[22] with high and very high GHG emissions (SSP3-7.0 and SSP5-8.5) and CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively, scenarios with intermediate GHG emissions (SSP2-4.5) and CO_2 emissions remaining around current levels until the middle of the century, and scenarios with very low and low GHG emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions[23] (SSP1-1.9 and SSP1-2.6), as illustrated in Figure SPM.4. Emissions vary between scenarios depending on socio-economic assumptions, levels of climate change mitigation and, for aerosols and non-methane ozone precursors, air pollution controls. Alternative assumptions may result in similar emissions and climate responses, but the socio-economic assumptions and the feasibility or likelihood of individual scenarios are not part of the assessment.
{1.6, Cross-Chapter Box 1.4, TS.1.3} (Figure SPM.4)

Box SPM.1.2: This Report assesses results from climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Programme. These models include new and better representations of physical, chemical and biological processes, as well as higher resolution, compared to climate models considered in previous IPCC assessment reports. This has improved the simulation of the recent mean state of most large-scale indicators of climate change and many other aspects across the climate system. Some differences from observations remain, for example in regional precipitation patterns. The CMIP6 historical simulations assessed in this Report have an ensemble mean global surface temperature change within 0.2°C of the observations over most of the historical period, and observed warming is within the *very likely* range of the CMIP6 ensemble. However, some CMIP6 models simulate a warming that is either above or below the assessed *very likely* range of observed warming.
{1.5, Cross-Chapter Box 2.2, 3.3, 3.8, TS.1.2, Cross-Section Box TS.1} (Figure SPM.1b, Figure SPM.2)

Box SPM.1.3: The CMIP6 models considered in this Report have a wider range of climate sensitivity than in CMIP5 models and the AR6 assessed *very likely* range, which is based on multiple lines of evidence. These CMIP6 models also show a higher average climate sensitivity than CMIP5 and the AR6 assessed best estimate. The higher CMIP6 climate sensitivity values compared to CMIP5 can be traced to an amplifying cloud feedback that is larger in CMIP6 by about 20%.
{Box 7.1, 7.3, 7.4, 7.5, TS.3.2}

Box SPM.1.4: For the first time in an IPCC report, assessed future changes in global surface temperature, ocean warming and sea level are constructed by combining multi-model projections with observational constraints based on past simulated warming, as well as the AR6 assessment of climate sensitivity. For other quantities, such robust methods do not yet exist to constrain the projections. Nevertheless, robust projected geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached.
{1.6, 4.3, 4.6, Box 4.1, 7.5, 9.2, 9.6, Cross-Chapter Box 11.1, Cross-Section Box TS.1}

22 Throughout this Report, the five illustrative scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in watts per square metre, or $W\ m^{-2}$) resulting from the scenario in the year 2100. A detailed comparison to scenarios used in earlier IPCC reports is provided in Section TS.1.3, and Sections 1.6 and 4.6. The SSPs that underlie the specific forcing scenarios used to drive climate models are not assessed by WGI. Rather, the SSPx-y labelling ensures traceability to the underlying literature in which specific forcing pathways are used as input to the climate models. IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

23 Net negative CO_2 emissions are reached when anthropogenic removals of CO_2 exceed anthropogenic emissions (Glossary).

Box SPM.1 (continued)

Future emissions cause future additional warming, with total warming dominated by past and future CO_2 emissions

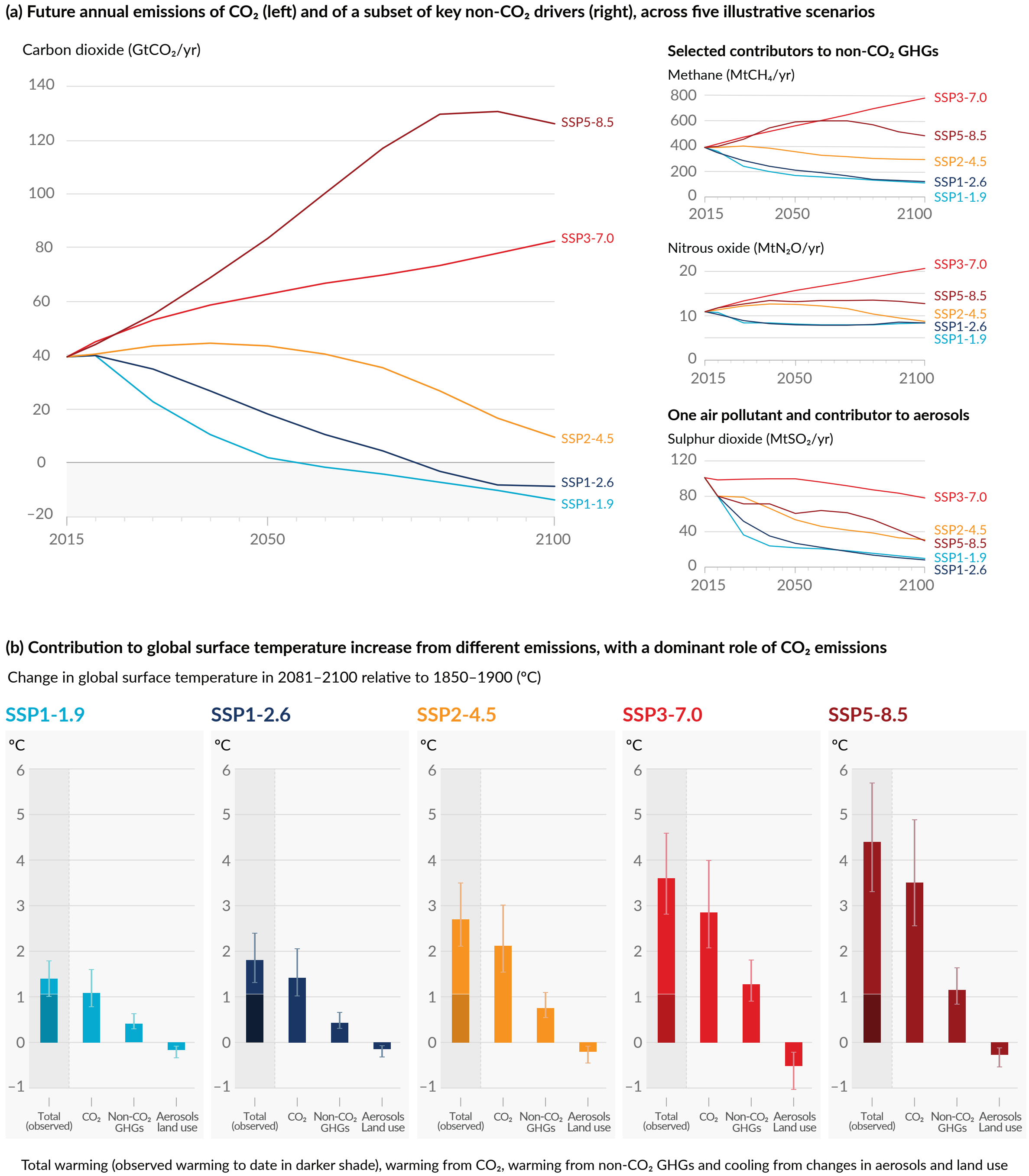

Figure SPM.4 | Future anthropogenic emissions of key drivers of climate change and warming contributions by groups of drivers for the five illustrative scenarios used in this report

The five scenarios are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

Panel (a) Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for carbon dioxide (CO_2) from all sectors ($GtCO_2$/yr) (left graph) and for a subset of three key non-CO_2 drivers considered in the scenarios: methane (CH_4, $MtCH_4$/yr, top-right graph); nitrous oxide (N_2O, MtN_2O/yr, middle-right graph); and sulphur dioxide (SO_2, $MtSO_2$/yr, bottom-right graph, contributing to anthropogenic aerosols in panel (b).

Panel (b) Warming contributions by groups of anthropogenic drivers and by scenario are shown as the change in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date. Bars and whiskers represent median values and the *very likely* range, respectively. Within each scenario bar plot, the bars represent: total global warming (°C; 'total' bar) (see Table SPM.1); warming contributions (°C) from changes in CO_2 ('CO_2' bar) and from non-CO_2 greenhouse gases (GHGs; 'non-CO_2 GHGs' bar: comprising well-mixed greenhouse gases and ozone); and net cooling from other anthropogenic drivers ('aerosols and land use' bar: anthropogenic aerosols, changes in reflectance due to land-use and irrigation changes, and contrails from aviation) (see Figure SPM.2, panel c, for the warming contributions to date for individual drivers). The best estimate for observed warming in 2010–2019 relative to 1850–1900 (see Figure SPM.2, panel a) is indicated in the darker column in the 'total' bar. Warming contributions in panel (b) are calculated as explained in Table SPM.1 for the total bar. For the other bars, the contribution by groups of drivers is calculated with a physical climate emulator of global surface temperature that relies on climate sensitivity and radiative forcing assessments.

{Cross-Chapter Box 1.4; 4.6; Figure 4.35; 6.7; Figures 6.18, 6.22 and 6.24; 7.3; Cross-Chapter Box 7.1; Figure 7.7; Box TS.7; Figures TS.4 and TS.15}

B.1 Global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.
{2.3, Cross-Chapter Box 2.3, Cross-Chapter Box 2.4, 4.3, 4.4, 4.5} (Figure SPM.1, Figure SPM.4, Figure SPM.8, Table SPM.1, Box SPM.1)

B.1.1 Compared to 1850–1900, global surface temperature averaged over 2081–2100 is *very likely* to be higher by 1.0°C to 1.8°C under the very low GHG emissions scenario considered (SSP1-1.9), by 2.1°C to 3.5°C in the intermediate GHG emissions scenario (SSP2-4.5) and by 3.3°C to 5.7°C under the very high GHG emissions scenario (SSP5-8.5).[24] The last time global surface temperature was sustained at or above 2.5°C higher than 1850–1900 was over 3 million years ago (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 4.3, 4.5, Box TS.2, Box TS.4, Cross-Section Box TS.1} (Table SPM.1)

Table SPM.1 | Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. This includes the revised assessment of observed historical warming for the AR5 reference period 1986–2005, which in AR6 is higher by 0.08 [–0.01 to +0.12] °C than in AR5 (see footnote 10). Changes relative to the recent reference period 1995–2014 may be calculated approximately by subtracting 0.85°C, the best estimate of the observed warming from 1850–1900 to 1995–2014.
{Cross-Chapter Box 2.3, 4.3, 4.4, Cross-Section Box TS.1}

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

B.1.2 Based on the assessment of multiple lines of evidence, global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under the high and very high GHG emissions scenarios considered in this report (SSP3-7.0 and SSP5-8.5, respectively). Global warming of 2°C would *extremely likely* be exceeded in the intermediate GHG emissions scenario (SSP2-4.5). Under the very low and low GHG emissions scenarios, global warming of 2°C is *extremely unlikely* to be exceeded (SSP1-1.9) or *unlikely* to be exceeded (SSP1-2.6).[25] Crossing the 2°C global warming level in the mid-term period (2041–2060) is *very likely* to occur under the very high GHG emissions scenario (SSP5-8.5), *likely* to occur under the high GHG emissions scenario (SSP3-7.0), and *more likely than not* to occur in the intermediate GHG emissions scenario (SSP2-4.5).[26]
{4.3, Cross-Section Box TS.1} (Table SPM.1, Figure SPM.4, Box SPM.1)

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24 Changes in global surface temperature are reported as running 20-year averages, unless stated otherwise.

25 SSP1-1.9 and SSP1-2.6 are scenarios that start in 2015 and have very low and low GHG emissions, respectively, and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions.

26 Crossing is defined here as having the assessed global surface temperature change, averaged over a 20-year period, exceed a particular global warming level.

B.1.3 Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high GHG emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9).[27] Furthermore, for the very low GHG emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.
{4.3, Cross-Section Box TS.1} (Table SPM.1, Figure SPM.4)

B.1.4 Global surface temperature in any single year can vary above or below the long-term human-induced trend, due to substantial natural variability.[28] The occurrence of individual years with global surface temperature change above a certain level, for example 1.5°C or 2°C, relative to 1850–1900 does not imply that this global warming level has been reached.[29]
{Cross-Chapter Box 2.3, 4.3, 4.4, Box 4.1, Cross-Section Box TS.1} (Table SPM.1, Figure SPM.1, Figure SPM.8)

B.2 Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost.
{4.3, 4.5, 4.6, 7.4, 8.2, 8.4, Box 8.2, 9.3, 9.5, Box 9.2, 11.1, 11.2, 11.3, 11.4, 11.6, 11.7, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11} (Figure SPM.5, Figure SPM.6, Figure SPM.8)

B.2.1 It is *virtually certain* that the land surface will continue to warm more than the ocean surface (*likely* 1.4 to 1.7 times more). It is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming.
{2.3, 4.3, 4.5, 4.6, 7.4, 11.1, 11.3, 11.9, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Section Box TS.1, TS.2.6} (Figure SPM.5)

B.2.2 With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts[30] in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are larger for rarer events (*high confidence*).
{8.2, 11.2, 11.3, 11.4, 11.6, 11.9, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1, TS.2.6} (Figure SPM.5, Figure SPM.6)

B.2.3 Some mid-latitude and semi-arid regions, and the South American Monsoon region, are projected to see the highest increase in the temperature of the hottest days, at about 1.5 to 2 times the rate of global warming (*high confidence*). The Arctic is projected to experience the highest increase in the temperature of the coldest days, at about three times the rate of global warming (*high confidence*). With additional global warming, the frequency of marine heatwaves will continue to increase (*high confidence*), particularly in the tropical ocean and the Arctic (*medium confidence*).
{Box 9.2, 11.1, 11.3, 11.9, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1, 12.4, TS.2.4, TS.2.6} (Figure SPM.6)

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27 The AR6 assessment of when a given global warming level is first exceeded benefits from the consideration of the illustrative scenarios, the multiple lines of evidence entering the assessment of future global surface temperature response to radiative forcing, and the improved estimate of historical warming. The AR6 assessment is thus not directly comparable to the SR1.5 SPM, which reported *likely* reaching 1.5°C global warming between 2030 and 2052, from a simple linear extrapolation of warming rates of the recent past. When considering scenarios similar to SSP1-1.9 instead of linear extrapolation, the SR1.5 estimate of when 1.5°C global warming is first exceeded is close to the best estimate reported here.

28 Natural variability refers to climatic fluctuations that occur without any human influence, that is, internal variability combined with the response to external natural factors such as volcanic eruptions, changes in solar activity and, on longer time scales, orbital effects and plate tectonics (Glossary).

29 The internal variability in any single year is estimated to be about ±0.25°C (5–95% range, *high confidence*).

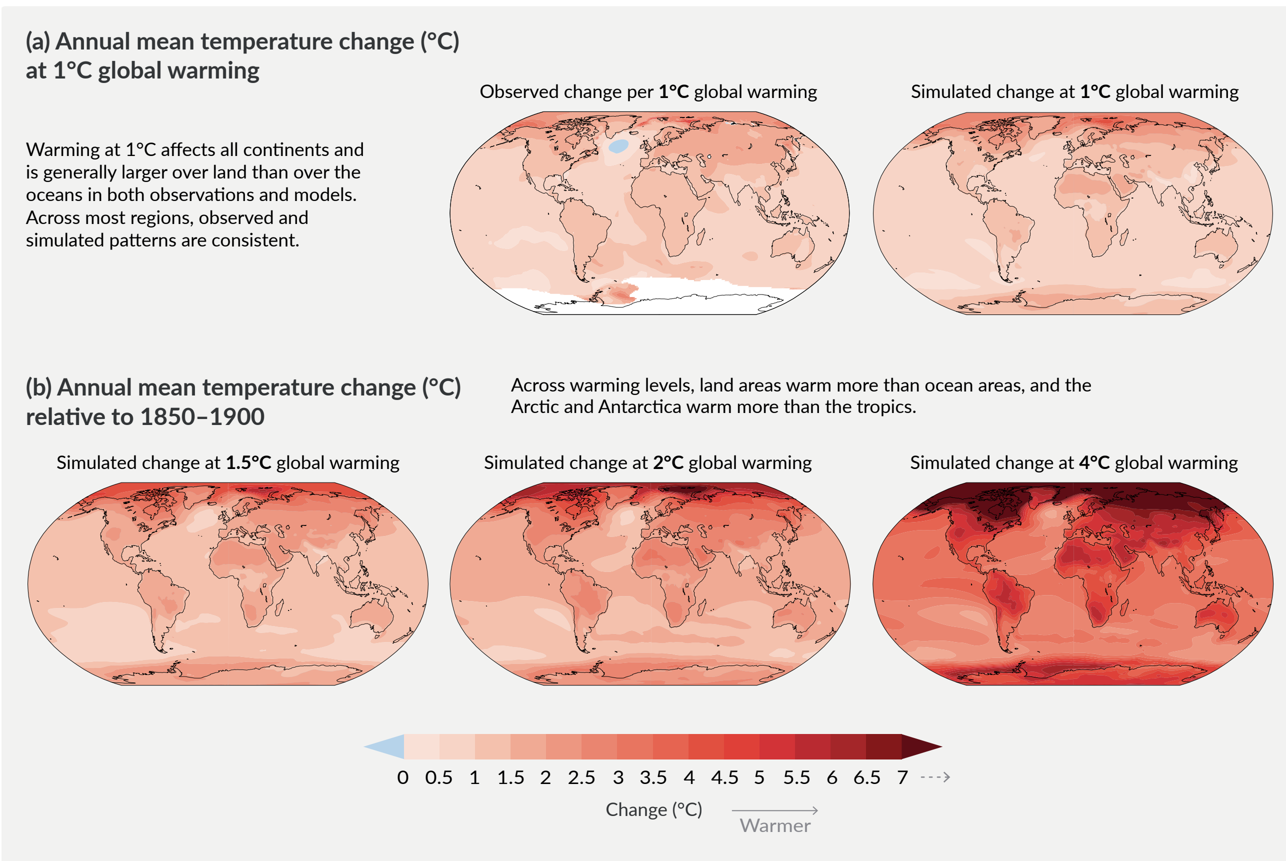
30 Projected changes in agricultural and ecological droughts are primarily assessed based on total column soil moisture. See footnote 15 for definition and relation to precipitation and evapotranspiration.

SPM

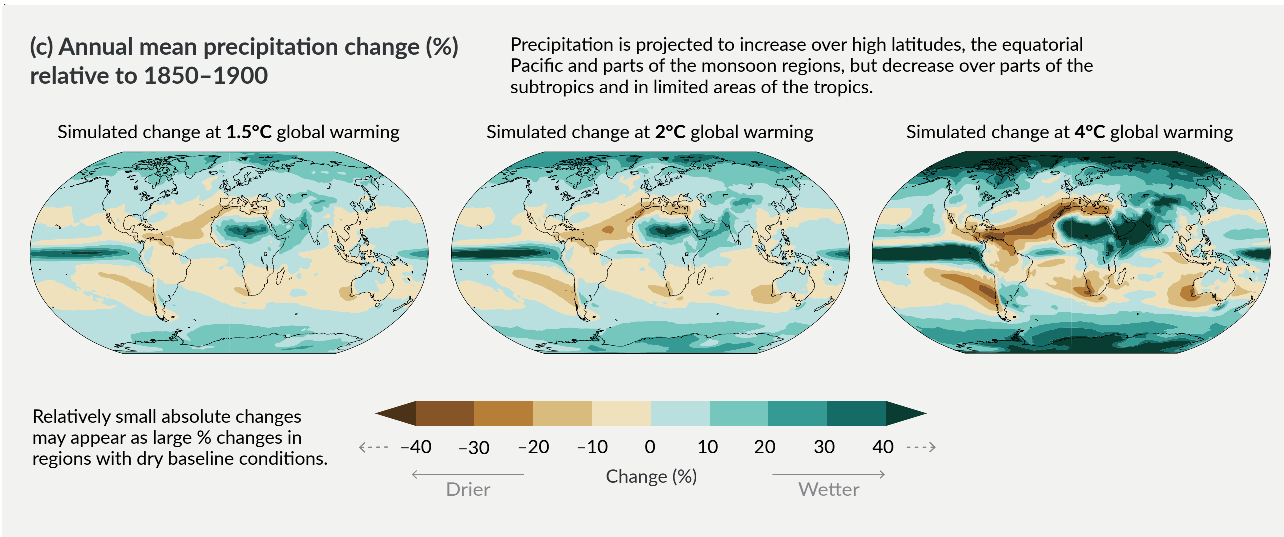
B.2.4 It is *very likely* that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming (*high confidence*). The proportion of intense tropical cyclones (Category 4–5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (*high confidence*). {8.2, 11.4, 11.7, 11.9, Cross-Chapter Box 11.1, Box TS.6, TS.4.3.1} (Figure SPM.5, Figure SPM.6)

B.2.5 Additional warming is projected to further amplify permafrost thawing and loss of seasonal snow cover, of land ice and of Arctic sea ice (*high confidence*). The Arctic is *likely* to be practically sea ice-free in September[31] at least once before 2050 under the five illustrative scenarios considered in this report, with more frequent occurrences for higher warming levels. There is *low confidence* in the projected decrease of Antarctic sea ice.
{4.3, 4.5, 7.4, 8.2, 8.4, Box 8.2, 9.3, 9.5, 12.4, Cross-Chapter Box 12.1, Atlas.5, Atlas.6, Atlas.8, Atlas.9, Atlas.11, TS.2.5} (Figure SPM.8)

With every increment of global warming, changes get larger in regional mean temperature, precipitation and soil moisture



31 Monthly average sea ice area of less than 1 million km^2, which is about 15% of the average September sea ice area observed in 1979–1988.



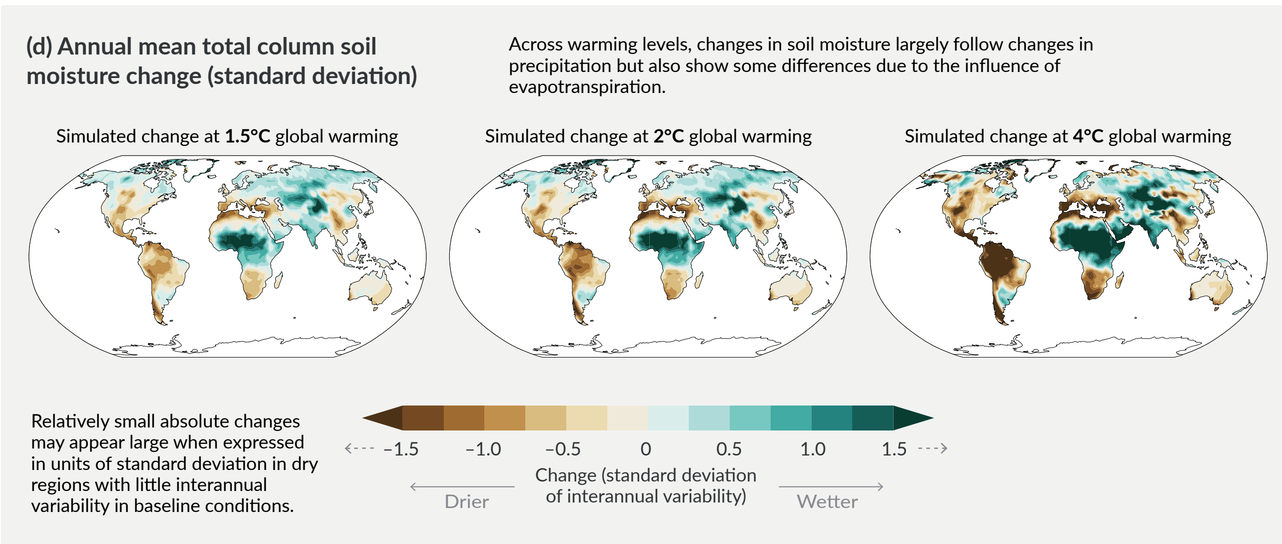


Figure SPM.5 | Changes in annual mean surface temperature, precipitation, and soil moisture

Panel (a) Comparison of observed and simulated annual mean surface temperature change. The **left map** shows the observed changes in annual mean surface temperature in the period 1850–2020 per °C of global warming (°C). The local (i.e., grid point) observed annual mean surface temperature changes are linearly regressed against the global surface temperature in the period 1850–2020. Observed temperature data are from Berkeley Earth, the dataset with the largest coverage and highest horizontal resolution. Linear regression is applied to all years for which data at the corresponding grid point is available. The regression method was used to take into account the complete observational time series and thereby reduce the role of internal variability at the grid point level. White indicates areas where time coverage was 100 years or less and thereby too short to calculate a reliable linear regression. The **right map** is based on model simulations and shows change in annual multi-model mean simulated temperatures at a global warming level of 1°C (20-year mean global surface temperature change relative to 1850–1900). The triangles at each end of the colour bar indicate out-of-bound values, that is, values above or below the given limits.

Panel (b) Simulated annual mean temperature change (°C), panel (c) precipitation change (%), and panel (d) total column soil moisture change (standard deviation of interannual variability) at global warming levels of 1.5°C, 2°C and 4°C (20-year mean global surface temperature change relative to 1850–1900). Simulated changes correspond to Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model mean change (median change for soil moisture) at the corresponding global warming level, that is, the same method as for the right map in panel (a).

In **panel (c)**, high positive percentage changes in dry regions may correspond to small absolute changes. In **panel (d)**, the unit is the standard deviation of interannual variability in soil moisture during 1850–1900. Standard deviation is a widely used metric in characterizing drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850–1900. In panel (d), large changes in dry regions with little interannual variability in the baseline conditions can correspond to small absolute change. The triangles at each end of the colour bars indicate out-of-bound values, that is, values above or below the given limits. Results from all models reaching the corresponding warming level in any of the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are averaged. Maps of annual mean temperature and precipitation changes at a global warming level of 3°C are available in Figure 4.31 and Figure 4.32 in Section 4.6. Corresponding maps of panels (b), (c) and (d), including hatching to indicate the level of model agreement at grid-cell level, are found in Figures 4.31, 4.32 and 11.19, respectively; as highlighted in Cross-Chapter Box Atlas.1, grid-cell level hatching is not informative for larger spatial scales (e.g., over AR6 reference regions) where the aggregated signals are less affected by small-scale variability, leading to an increase in robustness.

{Figure 1.14, 4.6.1, Cross-Chapter Box 11.1, Cross-Chapter Box Atlas.1, TS.1.3.2, Figures TS.3 and TS.5}

Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming

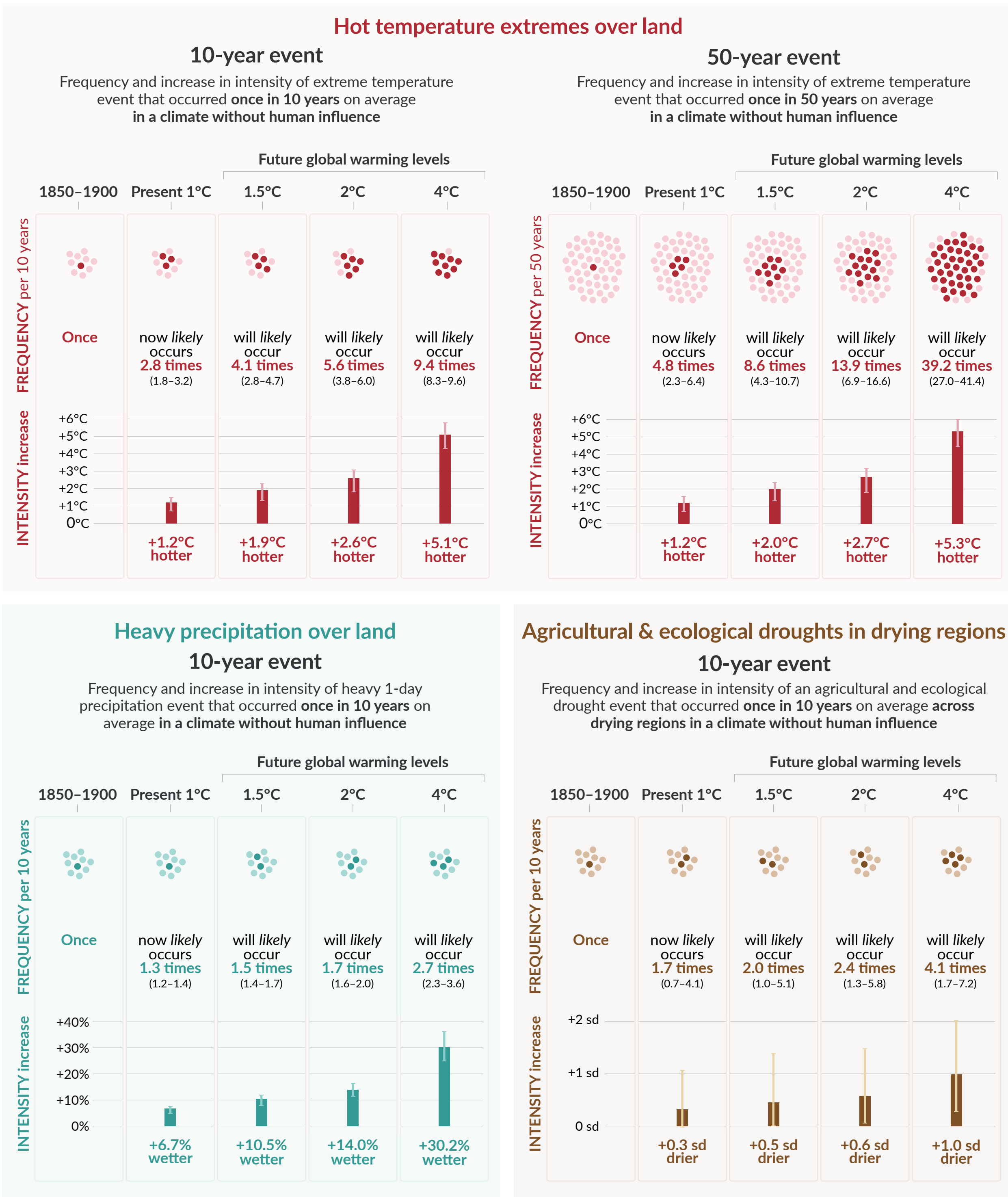


Figure SPM.6 | Projected changes in the intensity and frequency of hot temperature extremes over land, extreme precipitation over land, and agricultural and ecological droughts in drying regions

Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to 1850–1900,[9] representing a climate without human influence. The figure depicts frequencies and increases in intensity of 10- or 50-year extreme events from the base period (1850–1900) under different global warming levels.

Hot temperature extremes are defined as the daily maximum temperatures over land that were exceeded on average once in a decade (10-year event) or once in 50 years (50-year event) during the 1850–1900 reference period. **Extreme precipitation events** are defined as the daily precipitation amount over land that was exceeded on average once in a decade during the 1850–1900 reference period. **Agricultural and ecological drought events** are defined as the annual average of total column soil moisture below the 10th percentile of the 1850–1900 base period. These extremes are defined on model grid box scale. For hot temperature extremes and extreme precipitation, results are shown for the global land. For agricultural and ecological drought, results are shown for drying regions only, which correspond to the AR6 regions in which there is at least *medium confidence* in a projected increase in agricultural and ecological droughts at the 2°C warming level compared to the 1850–1900 base period in the Coupled Model Intercomparison Project Phase 6 (CMIP6). These regions include Western North America, Central North America, Northern Central America, Southern Central America, Caribbean, Northern South America, North-Eastern South America, South American Monsoon, South-Western South America, Southern South America, Western and Central Europe, Mediterranean, West Southern Africa, East Southern Africa, Madagascar, Eastern Australia, and Southern Australia (Caribbean is not included in the calculation of the figure because of the too-small number of full land grid cells). The non-drying regions do not show an overall increase or decrease in drought severity. Projections of changes in agricultural and ecological droughts in the CMIP Phase 5 (CMIP5) multi-model ensemble differ from those in CMIP6 in some regions, including in parts of Africa and Asia. Assessments of projected changes in meteorological and hydrological droughts are provided in Chapter 11.

In the **'frequency' section**, each year is represented by a dot. The dark dots indicate years in which the extreme threshold is exceeded, while light dots are years when the threshold is not exceeded. Values correspond to the medians (in bold) and their respective *likely* ranges based on the 5–95% range of the multi-model ensemble from simulations of CMIP6 under different Shared Socio-economic Pathway scenarios. For consistency, the number of dark dots is based on the rounded-up median. In the **'intensity' section**, medians and their *likely* ranges, also based on the 5–95% range of the multi-model ensemble from simulations of CMIP6, are displayed as dark and light bars, respectively. Changes in the intensity of hot temperature extremes and extreme precipitation are expressed as degree Celsius and percentage. As for agricultural and ecological drought, intensity changes are expressed as fractions of standard deviation of annual soil moisture.

{11.1; 11.3; 11.4; 11.6; 11.9; Figures 11.12, 11.15, 11.6, 11.7, and 11.18}

B.3 Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events.
{4.3, 4.4, 4.5, 4.6, 8.2, 8.3, 8.4, 8.5, Box 8.2, 11.4, 11.6, 11.9, 12.4, Atlas.3} (Figure SPM.5, Figure SPM.6)

B.3.1 There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*). The average annual global land precipitation is projected to increase by 0–5% under the very low GHG emissions scenario (SSP1-1.9), 1.5–8% for the intermediate GHG emissions scenario (SSP2-4.5) and 1–13% under the very high GHG emissions scenario (SSP5-8.5) by 2081–2100 relative to 1995–2014 (*likely* ranges). Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (*very likely*). The portion of the global land experiencing detectable increases or decreases in seasonal mean precipitation is projected to increase (*medium confidence*). There is *high confidence* in an earlier onset of spring snowmelt, with higher peak flows at the expense of summer flows in snow-dominated regions globally.
{4.3, 4.5, 4.6, 8.2, 8.4, Atlas.3, TS.2.6, TS.4.3, Box TS.6} (Figure SPM.5)

B.3.2 A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (*high confidence*), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. It is *very likely* that rainfall variability related to the El Niño–Southern Oscillation is projected to be amplified by the second half of the 21st century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.
{4.3, 4.5, 4.6, 8.2, 8.4, 8.5, 11.4, 11.6, 11.9, 12.4, TS.2.6, TS.4.2, Box TS.6} (Figure SPM.5, Figure SPM.6)

B.3.3 Monsoon precipitation is projected to increase in the mid- to long term at the global scale, particularly over South and South East Asia, East Asia and West Africa apart from the far west Sahel (*high confidence*). The monsoon season is projected to have a delayed onset over North and South America and West Africa (*high confidence*) and a delayed retreat over West Africa (*medium confidence*).
{4.4, 4.5, 8.2, 8.3, 8.4, Box 8.2, Box TS.13}

B.3.4 A projected southward shift and intensification of Southern Hemisphere summer mid-latitude storm tracks and associated precipitation is *likely* in the long term under high GHG emissions scenarios (SSP3-7.0, SSP5-8.5), but in the near term the effect of stratospheric ozone recovery counteracts these changes (*high confidence*). There is *medium confidence* in a continued poleward shift of storms and their precipitation in the North Pacific, while there is *low confidence* in projected changes in the North Atlantic storm tracks.
{4.4, 4.5, 8.4, TS.2.3, TS.4.2}

B.4 Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere.
{4.3, 5.2, 5.4, 5.5, 5.6} (Figure SPM.7)

B.4.1 While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative CO_2 emissions. This is projected to result in a higher proportion of emitted CO_2 remaining in the atmosphere (*high confidence*).
{5.2, 5.4, Box TS.5} (Figure SPM.7)

B.4.2 Based on model projections, under the intermediate GHG emissions scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and ocean are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, the land and ocean begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is *very unlikely* that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions (SSP2-4.5, SSP3-7.0, SSP5-8.5).[32]
{4.3, 5.4, 5.5, 5.6, Box TS.5, TS.3.3}

B.4.3 The magnitude of feedbacks between climate change and the carbon cycle becomes larger but also more uncertain in high CO_2 emissions scenarios (*very high confidence*). However, climate model projections show that the uncertainties in atmospheric CO_2 concentrations by 2100 are dominated by the differences between emissions scenarios (*high confidence*). Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).
{5.4, Box TS.5, TS.3.2}

The proportion of CO_2 emissions taken up by land and ocean carbon sinks is smaller in scenarios with higher cumulative CO_2 emissions

Total cumulative CO_2 emissions **taken up by land and ocean** (colours) and remaining in the atmosphere (grey) under the five illustrative scenarios from 1850 to 2100

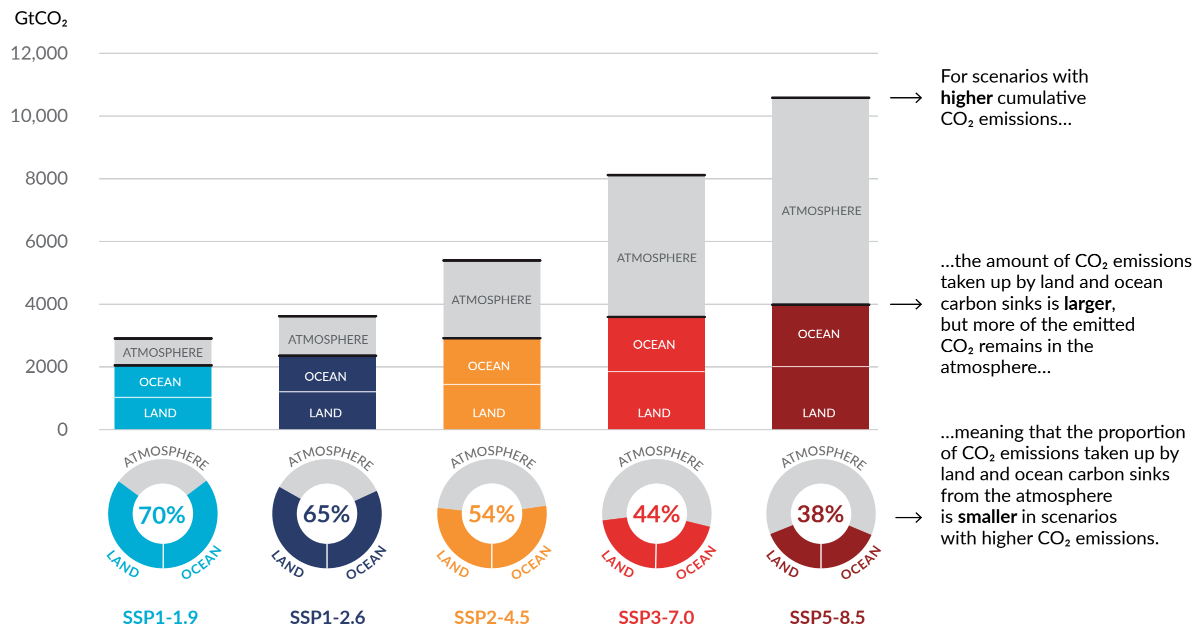


Figure SPM.7 | Cumulative anthropogenic CO_2 emissions taken up by land and ocean sinks by 2100 under the five illustrative scenarios
The cumulative anthropogenic (human-caused) carbon dioxide (CO_2) emissions taken up by the land and ocean sinks under the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are simulated from 1850 to 2100 by Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models in the concentration-driven simulations. Land and ocean carbon sinks respond to past, current and future emissions; therefore, cumulative sinks from 1850 to 2100 are presented here. During the historical period (1850–2019) the observed land and ocean sink took up 1430 $GtCO_2$ (59% of the emissions).

32 These projected adjustments of carbon sinks to stabilization or decline of atmospheric CO_2 are accounted for in calculations of remaining carbon budgets.

The bar chart illustrates the projected amount of cumulative anthropogenic CO_2 emissions ($GtCO_2$) between 1850 and 2100 remaining in the atmosphere (grey part) and taken up by the land and ocean (coloured part) in the year 2100. **The doughnut chart** illustrates the proportion of the cumulative anthropogenic CO_2 emissions taken up by the land and ocean sinks and remaining in the atmosphere in the year 2100. Values in % indicate the proportion of the cumulative anthropogenic CO_2 emissions taken up by the combined land and ocean sinks in the year 2100. The overall anthropogenic carbon emissions are calculated by adding the net global land-use emissions from the CMIP6 scenario database to the other sectoral emissions calculated from climate model runs with prescribed CO_2 concentrations.[33] Land and ocean CO_2 uptake since 1850 is calculated from the net biome productivity on land, corrected for CO_2 losses due to land-use change by adding the land-use change emissions, and net ocean CO_2 flux.

{5.2.1; Table 5.1; 5.4.5; Figure 5.25; Box TS.5; Box TS.5, Figure 1}

B.5 Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.
{2.3, Cross-Chapter Box 2.4, 4.3, 4.5, 4.7, 5.3, 9.2, 9.4, 9.5, 9.6, Box 9.4} (Figure SPM.8)

B.5.1 Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Over the rest of the 21st century, *likely* ocean warming ranges from 2–4 (SSP1-2.6) to 4–8 times (SSP5-8.5) the 1971–2018 change. Based on multiple lines of evidence, upper ocean stratification (*virtually certain*), ocean acidification (*virtually certain*) and ocean deoxygenation (*high confidence*) will continue to increase in the 21st century, at rates dependent on future emissions. Changes are irreversible on centennial to millennial time scales in global ocean temperature (*very high confidence*), deep-ocean acidification (*very high confidence*) and deoxygenation (*medium confidence*).
{4.3, 4.5, 4.7, 5.3, 9.2, TS.2.4} (Figure SPM.8)

B.5.2 Mountain and polar glaciers are committed to continue melting for decades or centuries (*very high confidence*). Loss of permafrost carbon following permafrost thaw is irreversible at centennial time scales (*high confidence*). Continued ice loss over the 21st century is *virtually certain* for the Greenland Ice Sheet and *likely* for the Antarctic Ice Sheet. There is *high confidence* that total ice loss from the Greenland Ice Sheet will increase with cumulative emissions. There is *limited evidence* for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios.[34]
{4.3, 4.7, 5.4, 9.4, 9.5, Box 9.4, Box TS.1, TS.2.5}

B.5.3 It is *virtually certain* that global mean sea level will continue to rise over the 21st century. Relative to 1995–2014, the *likely* global mean sea level rise by 2100 is 0.28–0.55 m under the very low GHG emissions scenario (SSP1-1.9); 0.32–0.62 m under the low GHG emissions scenario (SSP1-2.6); 0.44–0.76 m under the intermediate GHG emissions scenario (SSP2-4.5); and 0.63–1.01 m under the very high GHG emissions scenario (SSP5-8.5); and by 2150 is 0.37–0.86 m under the very low scenario (SSP1-1.9); 0.46–0.99 m under the low scenario (SSP1-2.6); 0.66–1.33 m under the intermediate scenario (SSP2-4.5); and 0.98–1.88 m under the very high scenario (SSP5-8.5) (*medium confidence*).[35] Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice-sheet processes.
{4.3, 9.6, Box 9.4, Box TS.4} (Figure SPM.8)

B.5.4 In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep-ocean warming and ice-sheet melt and will remain elevated for thousands of years (*high confidence*). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C, 2 to 6 m if limited to 2°C and 19 to 22 m with 5°C of warming, and it will continue to rise over subsequent millennia (*low confidence*). Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: *likely* 5–10 m higher than today around 125,000 years ago, when global temperatures were *very likely* 0.5°C–1.5°C higher than 1850–1900; and *very likely* 5–25 m higher roughly 3 million years ago, when global temperatures were 2.5°C–4°C higher (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 9.6, Box TS.2, Box TS.4, Box TS.9}

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33 The other sectoral emissions are calculated as the residual of the net land and ocean CO_2 uptake and the prescribed atmospheric CO_2 concentration changes in the CMIP6 simulations. These calculated emissions are net emissions and do not separate gross anthropogenic emissions from removals, which are included implicitly.

34 Low-likelihood, high-impact outcomes are those whose probability of occurrence is low or not well known (as in the context of deep uncertainty) but whose potential impacts on society and ecosystems could be high. A tipping point is a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. (Glossary) {1.4, Cross-Chapter Box 1.3, 4.7}

35 To compare to the 1986–2005 baseline period used in AR5 and SROCC, add 0.03 m to the global mean sea level rise estimates. To compare to the 1900 baseline period used in Figure SPM.8, add 0.16 m.

Human activities affect all the major climate system components, with some responding over decades and others over centuries

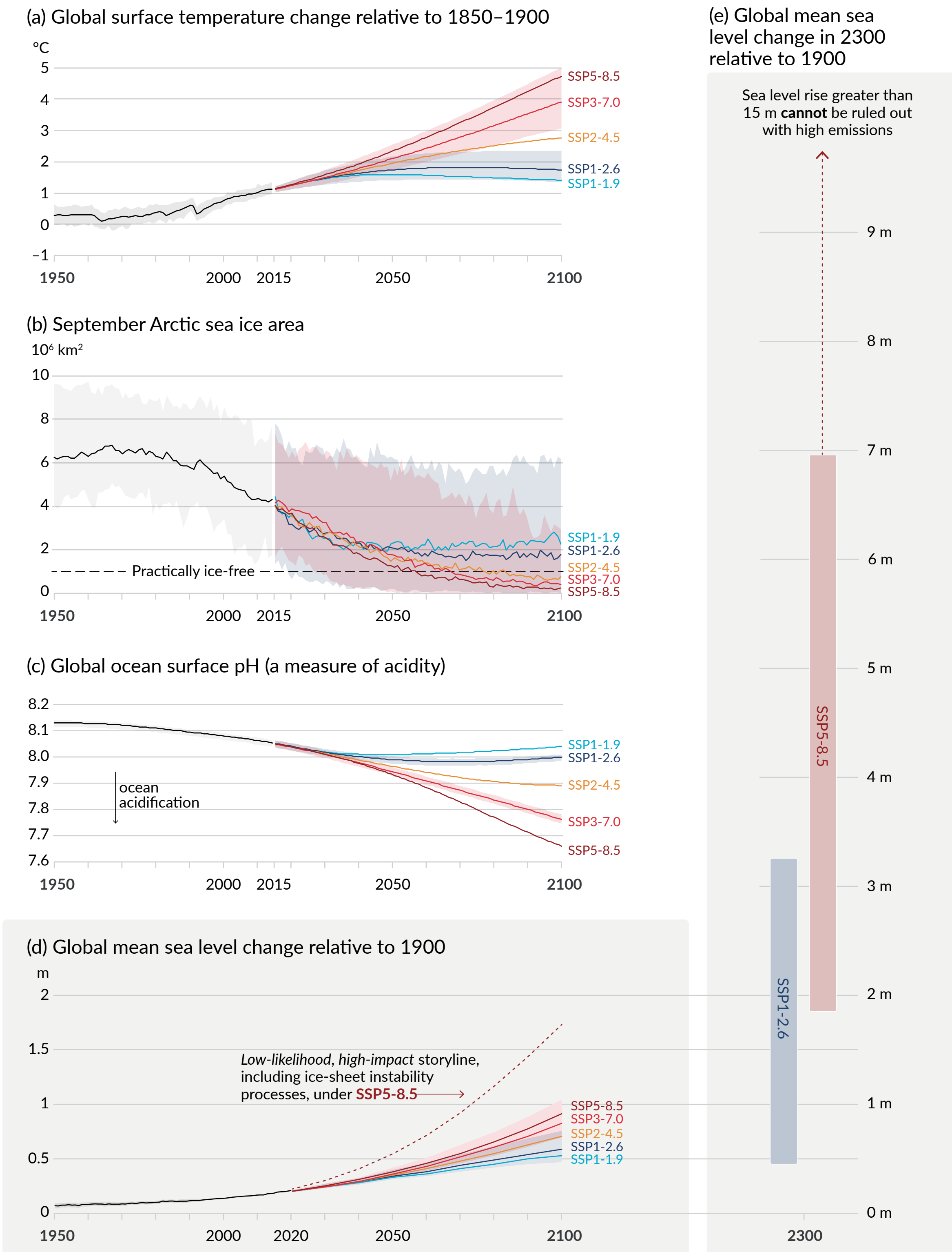


Figure SPM.8 | Selected indicators of global climate change under the five illustrative scenarios used in this Report

The projections for each of the five scenarios are shown in colour. Shades represent uncertainty ranges – more detail is provided for each panel below. The black curves represent the historical simulations (panels a, b, c) or the observations (panel d). Historical values are included in all graphs to provide context for the projected future changes.

Panel (a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining Coupled Model Intercomparison Project Phase 6 (CMIP6) model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (see Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0.

Panel (b) September Arctic sea ice area in 10^6 km^2 based on CMIP6 model simulations. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0. The Arctic is projected to be practically ice-free near mid-century under intermediate and high GHG emissions scenarios.

Panel (c) Global ocean surface pH (a measure of acidity) based on CMIP6 model simulations. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0.

Panel (d) Global mean sea level change in metres, relative to 1900. The historical changes are observed (from tide gauges before 1992 and altimeters afterwards), and the future changes are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models. *Likely* ranges are shown for SSP1-2.6 and SSP3-7.0. Only *likely* ranges are assessed for sea level changes due to difficulties in estimating the distribution of deeply uncertain processes. The dashed curve indicates the potential impact of these deeply uncertain processes. It shows the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice-sheet processes that cannot be ruled out; because of *low confidence* in projections of these processes, this curve does not constitute part of a *likely* range. Changes relative to 1900 are calculated by adding 0.158 m (observed global mean sea level rise from 1900 to 1995–2014) to simulated and observed changes relative to 1995–2014.

Panel (e) Global mean sea level change at 2300 in metres relative to 1900. Only SSP1-2.6 and SSP5-8.5 are projected at 2300, as simulations that extend beyond 2100 for the other scenarios are too few for robust results. The 17th–83rd percentile ranges are shaded. The dashed arrow illustrates the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice-sheet processes that cannot be ruled out.

Panels (b) and (c) are based on single simulations from each model, and so include a component of internal variability. Panels (a), (d) and (e) are based on long-term averages, and hence the contributions from internal variability are small.

{4.3; Figures 4.2, 4.8, and 4.11; 9.6; Figure 9.27; Figures TS.8 and TS.11; Box TS.4, Figure 1}

C. Climate Information for Risk Assessment and Regional Adaptation

Physical climate information addresses how the climate system responds to the interplay between human influence, natural drivers and internal variability. Knowledge of the climate response and the range of possible outcomes, including low-likelihood, high impact outcomes, informs climate services, the assessment of climate-related risks, and adaptation planning. Physical climate information at global, regional and local scales is developed from multiple lines of evidence, including observational products, climate model outputs and tailored diagnostics.

C.1 Natural drivers and internal variability will modulate human-caused changes, especially at regional scales and in the near term, with little effect on centennial global warming. These modulations are important to consider in planning for the full range of possible changes.
{1.4, 2.2, 3.3, Cross-Chapter Box 3.1, 4.4, 4.6, Cross-Chapter Box 4.1, Box 7.2, 8.3, 8.5, 9.2, 10.3, 10.4, 10.6, 11.3, 12.5, Atlas.4, Atlas.5, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Chapter Box Atlas.2}

C.1.1 The historical global surface temperature record highlights that decadal variability has both enhanced and masked underlying human-caused long-term changes, and this variability will continue into the future (*very high confidence*). For example, internal decadal variability and variations in solar and volcanic drivers partially masked human-caused surface global warming during 1998–2012, with pronounced regional and seasonal signatures (*high confidence*). Nonetheless, the heating of the climate system continued during this period, as reflected in both the continued warming of the global ocean (*very high confidence*) and in the continued rise of hot extremes over land (*medium confidence*).
{1.4, 3.3, Cross-Chapter Box 3.1, 4.4, Box 7.2, 9.2, 11.3, Cross-Section Box TS.1} (Figure SPM.1)

C.1.2 Projected human-caused changes in mean climate and climatic impact-drivers (CIDs),[36] including extremes, will be either amplified or attenuated by internal variability (*high confidence*).[37] Near-term cooling at any particular location with respect to present climate could occur and would be consistent with the global surface temperature increase due to human influence (*high confidence*).
{1.4, 4.4, 4.6, 10.4, 11.3, 12.5, Atlas.5, Atlas.10, Atlas.11, TS.4.2}

36 Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions (Glossary). CID types include heat and cold, wet and dry, wind, snow and ice, coastal and open ocean.

37 The main internal variability phenomena include El Niño–Southern Oscillation, Pacific Decadal Variability and Atlantic Multi-decadal Variability through their regional influence.

C.1.3 Internal variability has largely been responsible for the amplification and attenuation of the observed human-caused decadal-to-multi-decadal mean precipitation changes in many land regions (*high confidence*). At global and regional scales, near-term changes in monsoons will be dominated by the effects of internal variability (*medium confidence*). In addition to the influence of internal variability, near-term projected changes in precipitation at global and regional scales are uncertain because of model uncertainty and uncertainty in forcings from natural and anthropogenic aerosols (*medium confidence*).
{1.4, 4.4, 8.3, 8.5, 10.3, 10.4, 10.5, 10.6, Atlas.4, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Chapter Box Atlas.2, TS.4.2, Box TS.6, Box TS.13}

C.1.4 Based on paleoclimate and historical evidence, it is *likely* that at least one large explosive volcanic eruption would occur during the 21st century.[38] Such an eruption would reduce global surface temperature and precipitation, especially over land, for one to three years, alter the global monsoon circulation, modify extreme precipitation and change many CIDs (*medium confidence*). If such an eruption occurs, this would therefore temporarily and partially mask human-caused climate change.
{2.2, 4.4, Cross-Chapter Box 4.1, 8.5, TS.2.1}

C.2 With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels.
{8.2, 9.3, 9.5, 9.6, Box 10.3, 11.3, 11.4, 11.5, 11.6, 11.7, 11.9, Box 11.3, Box 11.4, Cross-Chapter Box 11.1, 12.2, 12.3, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11} (Table SPM.1, Figure SPM.9)

C.2.1 All regions[39] are projected to experience further increases in hot climatic impact-drivers (CIDs) and decreases in cold CIDs (*high confidence*). Further decreases are projected in permafrost; snow, glaciers and ice sheets; and lake and Arctic sea ice (*medium* to *high confidence*).[40] These changes would be larger at 2°C global warming or above than at 1.5°C (*high confidence*). For example, extreme heat thresholds relevant to agriculture and health are projected to be exceeded more frequently at higher global warming levels (*high confidence*).
{9.3, 9.5, 11.3, 11.9, Cross-Chapter Box 11.1, 12.3, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, TS.4.3} (Table SPM.1, Figure SPM.9)

C.2.2 At 1.5°C global warming, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia (*high confidence*), North America (*medium* to *high confidence*)[40] and Europe (*medium confidence*). Also, more frequent and/or severe agricultural and ecological droughts are projected in a few regions in all inhabited continents except Asia compared to 1850–1900 (*medium confidence*); increases in meteorological droughts are also projected in a few regions (*medium confidence*). A small number of regions are projected to experience increases or decreases in mean precipitation (*medium confidence*).
{11.4, 11.5, 11.6, 11.9, Atlas.4, Atlas.5, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, TS.4.3} (Table SPM.1)

C.2.3 At 2°C global warming and above, the level of confidence in and the magnitude of the change in droughts and heavy and mean precipitation increase compared to those at 1.5°C. Heavy precipitation and associated flooding events are projected to become more intense and frequent in the Pacific Islands and across many regions of North America and Europe (*medium* to *high confidence*).[40] These changes are also seen in some regions in Australasia and Central and South America (*medium confidence*). Several regions in Africa, South America and Europe are projected to experience an increase in frequency and/or severity of agricultural and ecological droughts with *medium* to *high confidence*;[40] increases are also projected in Australasia, Central and North America, and the Caribbean with *medium confidence*. A small number of regions in Africa, Australasia, Europe and North America are also projected to be affected by increases in hydrological droughts, and several regions are projected to be affected by increases or decreases in meteorological droughts, with more regions displaying an increase (*medium confidence*). Mean precipitation is projected to increase in all polar, northern European and northern North American regions, most Asian regions and two regions of South America (*high confidence*).
{11.4, 11.6, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.5, Atlas.7, Atlas.8, Atlas.9, Atlas.11, TS.4.3} (Table SPM.1, Figure SPM.5, Figure SPM.6, Figure SPM.9)

38 Based on 2500 year reconstructions, eruptions more negative than $-1\ W\ m^{-2}$ occur on average twice per century.

39 Regions here refer to the AR6 WGI reference regions used in this Report to summarize information in sub-continental and oceanic regions. Changes are compared to averages over the last 20–40 years unless otherwise specified. {1.4, 12.4, Atlas.1}.

40 The specific level of confidence or likelihood depends on the region considered. Details can be found in the Technical Summary and the underlying Report.

C.2.4 More CIDs across more regions are projected to change at 2°C and above compared to 1.5°C global warming (*high confidence*). Region-specific changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), increases in river floods (*medium* to *high confidence*),[40] reductions in mean precipitation and increases in aridity (*medium* to *high confidence*),[40] and increases in fire weather (*medium* to *high confidence*).[40] There is *low confidence* in most regions in potential future changes in other CIDs, such as hail, ice storms, severe storms, dust storms, heavy snowfall and landslides.
{11.7, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.6, Atlas.7, Atlas.8, Atlas.10, TS.4.3.1, TS.4.3.2, TS.5} (Table SPM.1, Figure SPM.9)

C.2.5 It is *very likely* to *virtually certain*[40] that regional mean relative sea level rise will continue throughout the 21st century, except in a few regions with substantial geologic land uplift rates. Approximately two-thirds of the global coastline has a projected regional relative sea level rise within ±20% of the global mean increase (*medium confidence*). Due to relative sea level rise, extreme sea level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100 (*high confidence*). Relative sea level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts (*high confidence*).
{9.6, 12.4, 12.5, Cross-Chapter Box 12.1, Box TS.4, TS.4.3} (Figure SPM.9)

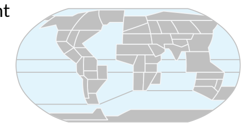
C.2.6 Cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes will increase the severity of heatwaves (*very high confidence*). Urbanization also increases mean and heavy precipitation over and/or downwind of cities (*medium confidence*) and resulting runoff intensity (*high confidence*). In coastal cities, the combination of more frequent extreme sea level events (due to sea level rise and storm surge) and extreme rainfall/riverflow events will make flooding more probable (*high confidence*).
{8.2, Box 10.3, 11.3, 12.4, Box TS.14}

C.2.7 Many regions are projected to experience an increase in the probability of compound events with higher global warming (*high confidence*). In particular, concurrent heatwaves and droughts are *likely* to become more frequent. Concurrent extremes at multiple locations, including in crop-producing areas, become more frequent at 2°C and above compared to 1.5°C global warming (*high confidence*).
{11.8, Box 11.3, Box 11.4, 12.3, 12.4, Cross-Chapter Box 12.1, TS.4.3} (Table SPM.1)

SPM

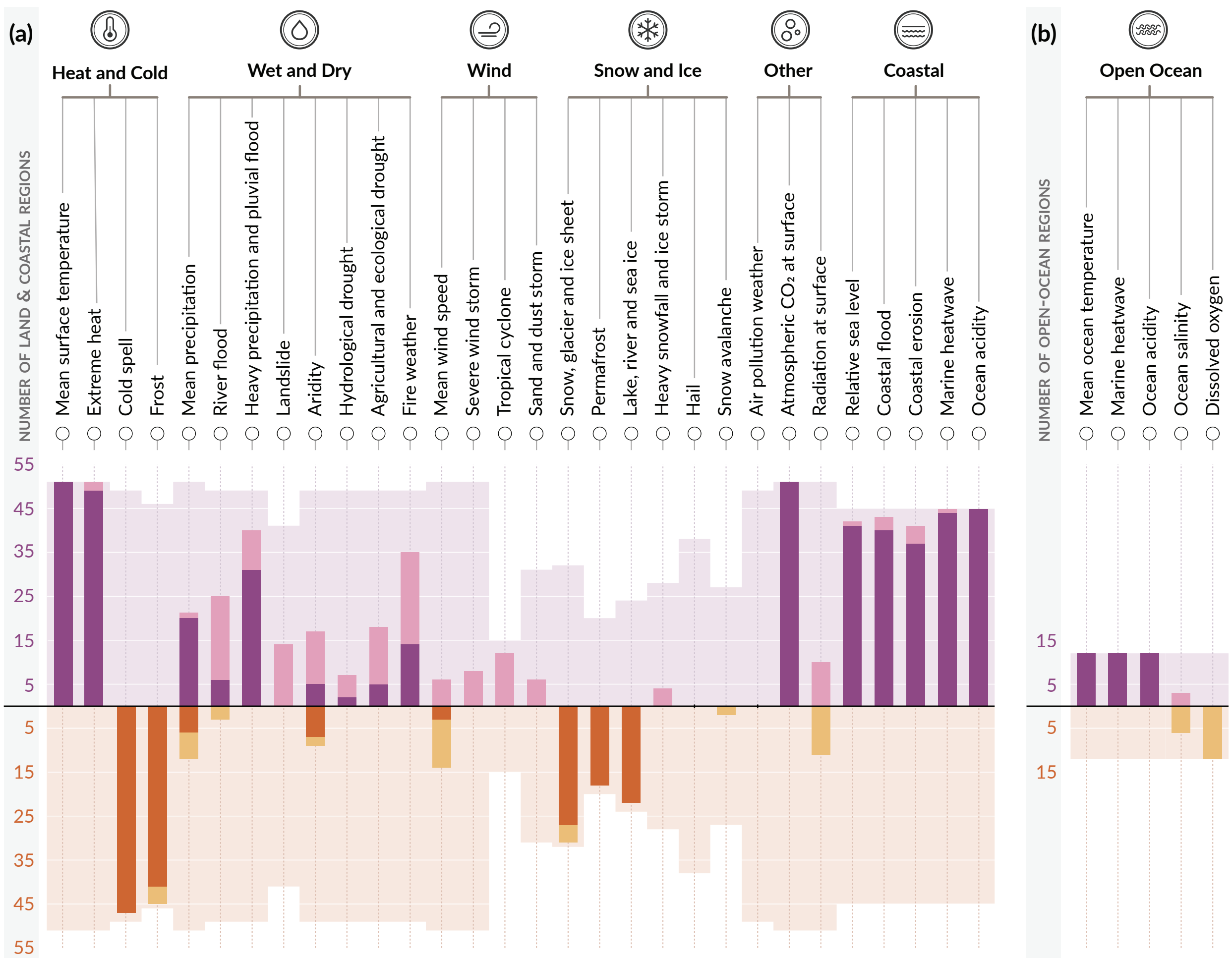
Multiple climatic impact-drivers are projected to change in all regions of the world

Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions. The CIDs are grouped into seven types, which are summarized under the icons in the figure. All regions are projected to experience changes in at least 5 CIDs. Almost all (96%) are projected to experience changes in at least 10 CIDs and half in at least 15 CIDs. For many CID changes, there is wide geographical variation, and so each region is projected to experience a specific set of CID changes. Each bar in the chart represents a specific geographical set of changes that can be explored in the WGI Interactive Atlas.



interactive-atlas.ipcc.ch

Number of land & coastal regions (a) and **open-ocean regions** (b) where each **climatic impact-driver** (CID) is projected to **increase** or **decrease** with ***high** confidence* (dark shade) or ***medium** confidence* (light shade)



BAR CHART LEGEND

- Regions with ***high** confidence* **increase**
- Regions with ***medium** confidence* **increase**
- Regions with ***high** confidence* **decrease**
- Regions with ***medium** confidence* **decrease**

LIGHTER-SHADED 'ENVELOPE' LEGEND

The height of the lighter shaded 'envelope' behind each bar represents the maximum number of regions for which each CID is relevant. The envelope is symmetrical about the x-axis showing the maximum possible number of relevant regions for CID increase (upper part) or decrease (lower part).

ASSESSED FUTURE CHANGES

Changes refer to a 20–30 year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960–2014 or 1850–1900.

Figure SPM.9 | Synthesis of the number of AR6 WGI reference regions where climatic impact-drivers are projected to change

A total of 35 climatic impact-drivers (CIDs) grouped into seven types are shown: heat and cold; wet and dry; wind; snow and ice; coastal; open ocean; and other. For each CID, the bar in the graph below displays the number of AR6 WGI reference regions where it is projected to change. The **colours** represent the direction of change and the level of confidence in the change: purple indicates an increase while brown indicates a decrease; darker and lighter shades refer to *high* and *medium confidence*, respectively. Lighter background colours represent the maximum number of regions for which each CID is broadly relevant.

Panel (a) shows the 30 CIDs relevant to the **land and coastal regions**, while **panel (b)** shows the five CIDs relevant to the **open-ocean regions**. Marine heatwaves and ocean acidity are assessed for coastal ocean regions in panel (a) and for open-ocean regions in panel (b). Changes refer to a 20–30-year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960–2014, except for hydrological drought and agricultural and ecological drought, which is compared to 1850–1900. Definitions of the regions are provided in Sections 12.4 and Atlas.1 and the Interactive Atlas (see https://interactive-atlas.ipcc.ch/).

{11.9, 12.2, 12.4, Atlas.1, Table TS.5, Figures TS.22 and TS.25} (Table SPM.1)

C.3 Low-likelihood outcomes, such as ice-sheet collapse, abrupt ocean circulation changes, some compound extreme events, and warming substantially larger than the assessed *very likely* range of future warming, cannot be ruled out and are part of risk assessment.
{1.4, Cross-Chapter Box 1.3, 4.3, 4.4, 4.8, Cross-Chapter Box 4.1, 8.6, 9.2, Box 9.4, 11.8, Box 11.2, Cross-Chapter Box 12.1} (Table SPM.1)

C.3.1 If global warming exceeds the assessed *very likely* range for a given GHG emissions scenario, including low GHG emissions scenarios, global and regional changes in many aspects of the climate system, such as regional precipitation and other CIDs, would also exceed their assessed *very likely* ranges (*high confidence*). Such low-likelihood, high-warming outcomes are associated with potentially very large impacts, such as through more intense and more frequent heatwaves and heavy precipitation, and high risks for human and ecological systems, particularly for high GHG emissions scenarios.
{Cross-Chapter Box 1.3, 4.3, 4.4, 4.8, Box 9.4, Box 11.2, Cross-Chapter Box 12.1, TS.1.4, Box TS.3, Box TS.4} (Table SPM.1)

C.3.2 Low-likelihood, high-impact outcomes[34] could occur at global and regional scales even for global warming within the *very likely* range for a given GHG emissions scenario. The probability of low-likelihood, high-impact outcomes increases with higher global warming levels (*high confidence*). Abrupt responses and tipping points of the climate system, such as strongly increased Antarctic ice-sheet melt and forest dieback, cannot be ruled out (*high confidence*).
{1.4, 4.3, 4.4, 4.8, 5.4, 8.6, Box 9.4, Cross-Chapter Box 12.1, TS.1.4, TS.2.5, Box TS.3, Box TS.4, Box TS.9} (Table SPM.1)

C.3.3 If global warming increases, some compound extreme events[18] with low likelihood in past and current climate will become more frequent, and there will be a higher likelihood that events with increased intensities, durations and/or spatial extents unprecedented in the observational record will occur (*high confidence*).
{11.8, Box 11.2, Cross-Chapter Box 12.1, Box TS.3, Box TS.9}

C.3.4 The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all emissions scenarios. While there is *high confidence* in the 21st century decline, there is only *low confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. If such a collapse were to occur, it would *very likely* cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons, and drying in Europe.
{4.3, 8.6, 9.2, TS2.4, Box TS.3}

C.3.5 Unpredictable and rare natural events not related to human influence on climate may lead to low-likelihood, high-impact outcomes. For example, a sequence of large explosive volcanic eruptions within decades has occurred in the past, causing substantial global and regional climate perturbations over several decades. Such events cannot be ruled out in the future, but due to their inherent unpredictability they are not included in the illustrative set of scenarios referred to in this Report
{2.2, Cross-Chapter Box 4.1, Box TS.3} (Box SPM.1)

D. Limiting Future Climate Change

Since AR5, estimates of remaining carbon budgets have been improved by a new methodology first presented in SR1.5, updated evidence, and the integration of results from multiple lines of evidence. A comprehensive range of possible future air pollution controls in scenarios is used to consistently assess the effects of various assumptions on projections of climate and air pollution. A novel development is the ability to ascertain when climate responses to emissions reductions would become discernible above natural climate variability, including internal variability and responses to natural drivers.

D.1 From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.
{3.3, 4.6, 5.1, 5.2, 5.4, 5.5, 5.6, Box 5.2, Cross-Chapter Box 5.1, 6.7, 7.6, 9.6} (Figure SPM.10, Table SPM.2)

D.1.1 This Report reaffirms with *high confidence* the AR5 finding that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions and the global warming they cause. Each 1000 $GtCO_2$ of cumulative CO_2 emissions is assessed to *likely* cause a 0.27°C to 0.63°C increase in global surface temperature with a best estimate of 0.45°C.[41] This is a narrower range compared to AR5 and SR1.5. This quantity is referred to as the transient climate response to cumulative CO_2 emissions (TCRE). This relationship implies that reaching net zero anthropogenic CO_2 emissions[42] is a requirement to stabilize human-induced global temperature increase at any level, but that limiting global temperature increase to a specific level would imply limiting cumulative CO_2 emissions to within a carbon budget.[43] {5.4, 5.5, TS.1.3, TS.3.3, Box TS.5} (Figure SPM.10)

Every tonne of CO_2 emissions adds to global warming

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)

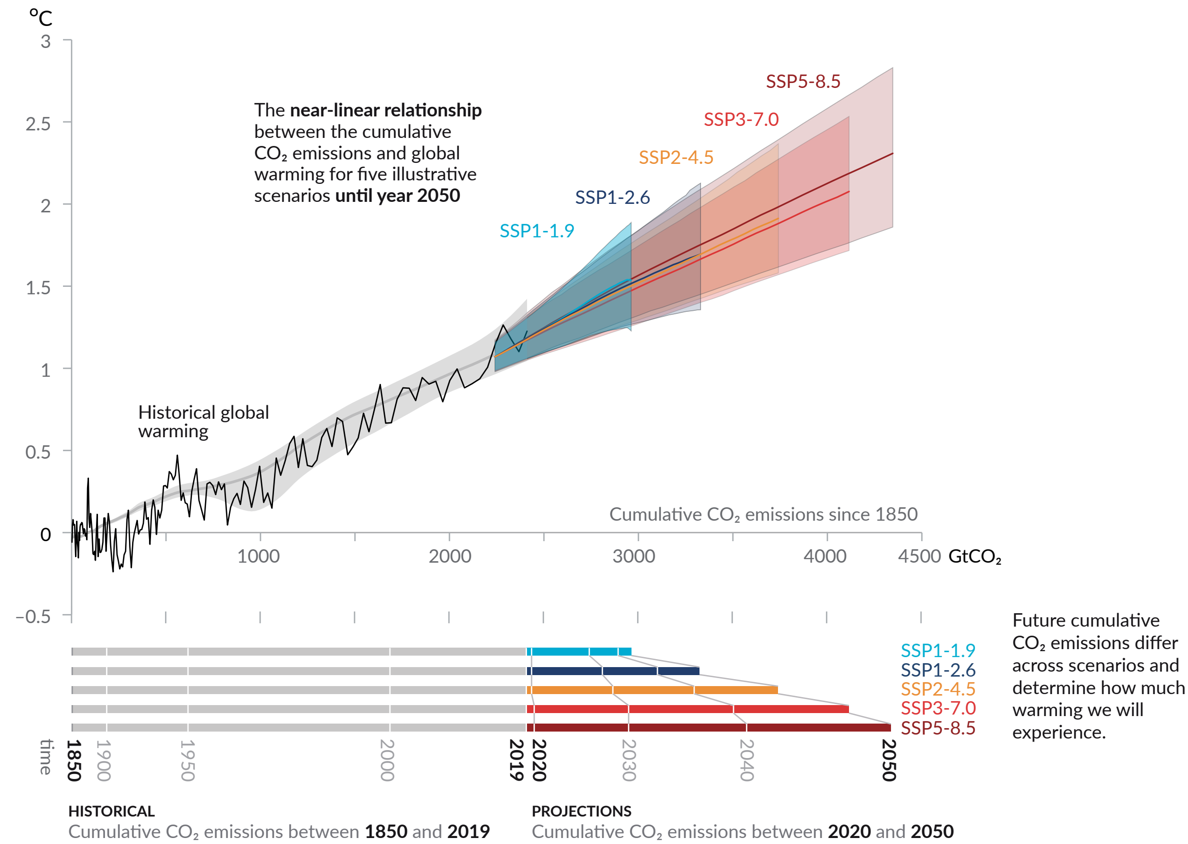


Figure SPM.10 | Near-linear relationship between cumulative CO_2 emissions and the increase in global surface temperature

Top panel: Historical data (thin black line) shows observed global surface temperature increase in °C since 1850–1900 as a function of historical cumulative carbon dioxide (CO_2) emissions in $GtCO_2$ from 1850 to 2019. The grey range with its central line shows a corresponding estimate of the historical human-caused surface warming (see Figure SPM.2). Coloured areas show the assessed *very likely* range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO_2 emissions from 2020 until year 2050 for the set of illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5; see Figure SPM.4). Projections use the cumulative CO_2 emissions of each respective scenario, and the projected global warming includes the contribution from all anthropogenic forcers. The relationship is illustrated over the domain of cumulative CO_2 emissions for which there is *high confidence* that the transient climate response to cumulative CO_2 emissions (TCRE) remains constant, and for the time period from 1850 to 2050 over which global CO_2 emissions remain net positive under all illustrative scenarios, as there is *limited evidence* supporting the quantitative application of TCRE to estimate temperature evolution under net negative CO_2 emissions.

Bottom panel: Historical and projected cumulative CO_2 emissions in $GtCO_2$ for the respective scenarios.

{Section 5.5, Figure 5.31, Figure TS.18}

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41 In the literature, units of °C per 1000 PgC (petagrams of carbon) are used, and the AR6 reports the TCRE ***likely*** range as 1.0°C to 2.3°C per 1000 PgC in the underlying report, with a best estimate of 1.65°C.

42 The condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period (Glossary).

43 The term 'carbon budget' refers to the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic climate forcers. This is referred to as the total carbon budget when expressed starting from the pre-industrial period, and as the remaining carbon budget when expressed from a recent specified date (Glossary). Historical cumulative CO_2 emissions determine to a large degree warming to date, while future emissions cause future additional warming. The remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below a specific temperature level.

D.1.2 Over the period 1850–2019, a total of 2390 ± 240 (*likely* range) $GtCO_2$ of anthropogenic CO_2 was emitted. Remaining carbon budgets have been estimated for several global temperature limits and various levels of probability, based on the estimated value of TCRE and its uncertainty, estimates of historical warming, variations in projected warming from non-CO_2 emissions, climate system feedbacks such as emissions from thawing permafrost, and the global surface temperature change after global anthropogenic CO_2 emissions reach net zero.
{5.1, 5.5, Box 5.2, TS.3.3} (Table SPM.2)

Table SPM.2 | Estimates of historical carbon dioxide (CO_2) emissions and remaining carbon budgets. Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO_2 emissions are reached. They refer to CO_2 emissions, while accounting for the global warming effect of non-CO_2 emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years.
{Table 3.1, 5.5.1, 5.5.2, Box 5.2, Table 5.1, Table 5.7, Table 5.8, Table TS.3}

Global Warming Between 1850–1900 and 2010–2019 (°C)		Historical Cumulative CO_2 Emissions from 1850 to 2019 ($GtCO_2$)					
1.07 (0.8–1.3; likely range)		2390 (± 240; likely range)					
Approximate global warming relative to 1850–1900 until temperature limit (°C)[a]	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$) *Likelihood of limiting global warming to temperature limit*[b]					Variations in reductions in non-CO_2 emissions[c]
		17%	*33%*	*50%*	*67%*	*83%*	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

[a] Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.

[b] This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 $GtCO_2$) and non-CO_2 forcing and response (±220 $GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 $GtCO_2$) and the climate response after net zero CO_2 emissions are reached (±420 $GtCO_2$) are separate.

[c] Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO_2 emissions.

D.1.3 Several factors that determine estimates of the remaining carbon budget have been re-assessed, and updates to these factors since SR1.5 are small. When adjusted for emissions since previous reports, estimates of remaining carbon budgets are therefore of similar magnitude compared to SR1.5 but larger compared to AR5 due to methodological improvements.[44]
{5.5, Box 5.2, TS.3.3} (Table SPM.2)

D.1.4 Anthropogenic CO_2 removal (CDR) has the potential to remove CO_2 from the atmosphere and durably store it in reservoirs (*high confidence*). CDR aims to compensate for residual emissions to reach net zero CO_2 or net zero GHG emissions or, if implemented at a scale where anthropogenic removals exceed anthropogenic emissions, to lower surface temperature. CDR methods can have potentially wide-ranging effects on biogeochemical cycles and climate, which can either weaken or strengthen the potential of these methods to remove CO_2 and reduce warming, and can also influence water availability and quality, food production and biodiversity[45] (*high confidence*).
{5.6, Cross-Chapter Box 5.1, TS.3.3}

D.1.5 Anthropogenic CO_2 removal (CDR) leading to global net negative emissions would lower the atmospheric CO_2 concentration and reverse surface ocean acidification (*high confidence*). Anthropogenic CO_2 removals and emissions are partially

44 Compared to AR5, and when taking into account emissions since AR5, estimates in AR6 are about 300–350 $GtCO_2$ larger for the remaining carbon budget consistent with limiting warming to 1.5°C; for 2°C, the difference is about 400–500 $GtCO_2$.

45 Potential negative and positive effects of CDR for biodiversity, water and food production are methods-specific and are often highly dependent on local context, management, prior land use, and scale. IPCC Working Groups II and III assess the CDR potential and ecological and socio-economic effects of CDR methods in their AR6 contributions.

compensated by CO_2 release and uptake respectively, from or to land and ocean carbon pools (*very high confidence*). CDR would lower atmospheric CO_2 by an amount approximately equal to the increase from an anthropogenic emission of the same magnitude (*high confidence*). The atmospheric CO_2 decrease from anthropogenic CO_2 removals could be up to 10% less than the atmospheric CO_2 increase from an equal amount of CO_2 emissions, depending on the total amount of CDR (*medium confidence*).
{5.3, 5.6, TS.3.3}

D.1.6 If global net negative CO_2 emissions were to be achieved and be sustained, the global CO_2-induced surface temperature increase would be gradually reversed but other climate changes would continue in their current direction for decades to millennia (*high confidence*). For instance, it would take several centuries to millennia for global mean sea level to reverse course even under large net negative CO_2 emissions (*high confidence*).
{4.6, 9.6, TS.3.3}

D.1.7 In the five illustrative scenarios, simultaneous changes in CH_4, aerosol and ozone precursor emissions, which also contribute to air pollution, lead to a net global surface warming in the near and long term (*high confidence*). In the long term, this net warming is lower in scenarios assuming air pollution controls combined with strong and sustained CH_4 emissions reductions (*high confidence*). In the low and very low GHG emissions scenarios, assumed reductions in anthropogenic aerosol emissions lead to a net warming, while reductions in CH_4 and other ozone precursor emissions lead to a net cooling. Because of the short lifetime of both CH_4 and aerosols, these climate effects partially counterbalance each other, and reductions in CH_4 emissions also contribute to improved air quality by reducing global surface ozone (*high confidence*).
{6.7, Box TS.7} (Figure SPM.2, Box SPM.1)

D.1.8 Achieving global net zero CO_2 emissions, with anthropogenic CO_2 emissions balanced by anthropogenic removals of CO_2, is a requirement for stabilizing CO_2-induced global surface temperature increase. This is different from achieving net zero GHG emissions, where metric-weighted anthropogenic GHG emissions equal metric-weighted anthropogenic GHG removals. For a given GHG emissions pathway, the pathways of individual GHGs determine the resulting climate response,[46] whereas the choice of emissions metric[47] used to calculate aggregated emissions and removals of different GHGs affects what point in time the aggregated GHGs are calculated to be net zero. Emissions pathways that reach and sustain net zero GHG emissions defined by the 100-year global warming potential are projected to result in a decline in surface temperature after an earlier peak (*high confidence*).
{4.6, 7.6, Box 7.3, TS.3.3}

D.2 Scenarios with very low or low GHG emissions (SSP1-1.9 and SSP1-2.6) lead within years to discernible effects on greenhouse gas and aerosol concentrations and air quality, relative to high and very high GHG emissions scenarios (SSP3-7.0 or SSP5-8.5). Under these contrasting scenarios, discernible differences in trends of global surface temperature would begin to emerge from natural variability within around 20 years, and over longer time periods for many other climatic impact-drivers (*high confidence*).
{4.6, 6.6, 6.7, Cross-Chapter Box 6.1, 9.6, 11.2, 11.4, 11.5, 11.6, Cross-Chapter Box 11.1, 12.4, 12.5} (Figure SPM.8, Figure SPM.10)

D.2.1 Emissions reductions in 2020 associated with measures to reduce the spread of COVID-19 led to temporary but detectable effects on air pollution (*high confidence*) and an associated small, temporary increase in total radiative forcing, primarily due to reductions in cooling caused by aerosols arising from human activities (*medium confidence*). Global and regional climate responses to this temporary forcing are, however, undetectable above natural variability (*high confidence*). Atmospheric CO_2 concentrations continued to rise in 2020, with no detectable decrease in the observed CO_2 growth rate (*medium confidence*).[48]
{Cross-Chapter Box 6.1, TS.3.3}

D.2.2 Reductions in GHG emissions also lead to air quality improvements. However, in the near term,[49] even in scenarios with strong reduction of GHGs, as in the low and very low GHG emissions scenarios (SSP1-2.6 and SSP1-1.9), these improvements

46 A general term for how the climate system responds to a radiative forcing (Glossary).

47 The choice of emissions metric depends on the purposes for which gases or forcing agents are being compared. This Report contains updated emissions metric values and assesses new approaches to aggregating gases.

48 For other GHGs, there was insufficient literature available at the time of the assessment to assess detectable changes in their atmospheric growth rate during 2020.

49 Near term: 2021–2040.

are not sufficient in many polluted regions to achieve air quality guidelines specified by the World Health Organization (*high confidence*). Scenarios with targeted reductions of air pollutant emissions lead to more rapid improvements in air quality within years compared to reductions in GHG emissions only, but from 2040, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions, with the magnitude of the benefit varying between regions (*high confidence*).
{6.6, 6.7, Box TS.7}.

D.2.3 Scenarios with very low or low GHG emissions (SSP1-1.9 and SSP1-2.6) would have rapid and sustained effects to limit human-caused climate change, compared with scenarios with high or very high GHG emissions (SSP3-7.0 or SSP5-8.5), but early responses of the climate system can be masked by natural variability. For global surface temperature, differences in 20-year trends would *likely* emerge during the near term under a very low GHG emissions scenario (SSP1-1.9), relative to a high or very high GHG emissions scenario (SSP3-7.0 or SSP5-8.5). The response of many other climate variables would emerge from natural variability at different times later in the 21st century (*high confidence*).
{4.6, Cross-Section Box TS.1} (Figure SPM.8, Figure SPM.10)

D.2.4 Scenarios with very low and low GHG emissions (SSP1-1.9 and SSP1-2.6) would lead to substantially smaller changes in a range of CIDs[36] beyond 2040 than under high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5). By the end of the century, scenarios with very low and low GHG emissions would strongly limit the change of several CIDs, such as the increases in the frequency of extreme sea level events, heavy precipitation and pluvial flooding, and exceedance of dangerous heat thresholds, while limiting the number of regions where such exceedances occur, relative to higher GHG emissions scenarios (*high confidence*). Changes would also be smaller in very low compared to low GHG emissions scenarios, as well as for intermediate (SSP2-4.5) compared to high or very high GHG emissions scenarios (*high confidence*).
{9.6, 11.2, 11.3, 11.4, 11.5, 11.6, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, TS.4.3}

DOCUMENT 5

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Global Carbon Budget 2021

Pierre Friedlingstein[1,2], Matthew W. Jones[3], Michael O'Sullivan[1], Robbie M. Andrew[4], Dorothee, C. E. Bakker[5], Judith Hauck[6], Corinne Le Quéré[3], Glen P. Peters[4], Wouter Peters[7,8], Julia Pongratz[9,10], Stephen Sitch[11], Josep G. Canadell[12], Philippe Ciais[13], Rob B. Jackson[14], Simone R. Alin[15], Peter Anthoni[16], Nicholas R. Bates[17], Meike Becker[18,19], Nicolas Bellouin[20], Laurent Bopp[2], Thi Tuyet Trang Chau[13], Frédéric Chevallier[13], Louise P. Chini[21], Margot Cronin[22], Kim I. Currie[23], Bertrand Decharme[24], Laique M. Djeutchouang[25,26], Xinyu Dou[27], Wiley Evans[28], Richard A. Feely[15], Liang Feng[29], Thomas Gasser[30], Dennis Gilfillan[31], Thanos Gkritzalis[32], Giacomo Grassi[33], Luke Gregor[34], Nicolas Gruber[34], Özgür Gürses[6], Ian Harris[35], Richard A. Houghton[36], George C. Hurtt[21], Yosuke Iida[37], Tatiana Ilyina[10], Ingrid T. Luijkx[7], Atul Jain[38], Steve D. Jones[18,19], Etsushi Kato[39], Daniel Kennedy[40], Kees Klein Goldewijk[41], Jürgen Knauer[12,42], Jan Ivar Korsbakken[4], Arne Körtzinger[43], Peter Landschützer[10], Siv K. Lauvset[19, 44], Nathalie Lefèvre[45], Sebastian Lienert[46], Junjie Liu[47], Gregg Marland[48,49], Patrick C. McGuire[50], Joe R. Melton[51], David R. Munro[52,53], Julia E.M.S. Nabel[10,54], Shin-Ichiro Nakaoka[55], Yosuke Niwa[55,56], Tsuneo Ono[57], Denis Pierrot[58], Benjamin Poulter[59], Gregor Rehder[60], Laure Resplandy[61], Eddy Robertson[62], Christian Rödenbeck[54], Thais M. Rosan[11], Jörg Schwinger[19, 44], Clemens Schwingshackl[9], Roland Séférian[24], Adrienne J. Sutton[15], Colm Sweeney[53], Toste Tanhua[43], Pieter P. Tans[63], Hanqin Tian[64], Bronte Tilbrook[65,66], Francesco Tubiello[67], Guido van der Werf[68], Nicolas Vuichard[13], Chisato Wada[55], Rik Wanninkhof[58], Andrew J. Watson[11], David Willis[3], Andrew J. Wiltshire[62], Wenping Yuan[69], Chao Yue[13], Xu Yue[70], Sönke Zaehle[54], Jiye Zeng[55]

[1] College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter EX4 4QF, UK
[2] Laboratoire de Météorologie Dynamique / Institut Pierre-Simon Laplace, CNRS, Ecole Normale Supérieure / Université PSL, Sorbonne Université, Ecole Polytechnique, Paris, France
[3] Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK
[4] CICERO Center for International Climate Research, Oslo 0349, Norway
[5] School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK
[6] Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Am Handelshafen 12, 27570 Bremerhaven
[7] Wageningen University, Environmental Sciences Group, P.O. Box 47, 6700AA, Wageningen, The Netherlands
[8] University of Groningen, Centre for Isotope Research, Groningen, The Netherlands
[9] Ludwig-Maximilians-Universität München, Luisenstr. 37, 80333 München, Germany
[10] Max Planck Institute for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany
[11] College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK
[12] CSIRO Oceans and Atmosphere, Canberra, ACT 2101, Australia
[13] Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, F-91198 Gif-sur-Yvette, France
[14] Department of Earth System Science, Woods Institute for the Environment, and Precourt Institute for Energy, Stanford University, Stanford, CA 94305–2210, United States of America
[15] National Oceanic & Atmospheric Administration, Pacific Marine Environmental Laboratory (NOAA/PMEL), 7600 Sand Point Way NE, Seattle, WA 98115, USA

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[16] Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research/Atmospheric Environmental Research, 82467 Garmisch-Partenkirchen, Germany
[17] Bermuda Institute of Ocean Sciences (BIOS), 17 Biological Lane, Ferry Reach, St. Georges, GEO1, Bermuda
[18] Geophysical Institute, University of Bergen, Bergen, Norway
[19] Bjerknes Centre for Climate Research, Bergen, Norway
[20] Department of Meteorology, University of Reading, Reading, UK
[21] Department of Geographical Sciences, University of Maryland, College Park, Maryland 20742, USA
[22] Marine Institute Ireland, Galway, Rinville, Ireland
[23] NIWA, Union Place West, Dunedin, New Zealand
[24] CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France
[25] Department of Oceanography, University of Cape Town, Cape Town, 7701, South Africa
[26] SOCCO, Council for Scientific and Industrial Research, Cape Town, 7700, South Africa
[27] Department of Earth System Science, Tsinghua University, Beijing, China
[28] Hakai Institute, Heriot Bay, BC, Canada
[29] National Centre for Earth Observation, University of Edinburgh, UK
[30] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1 A-2361 Laxenburg, Austria
[31] North Carolina School for Science and Mathematics, Durham, North Carolina, USA
[32] Flanders Marine Institute (VLIZ), InnovOceanSite, Wandelaarkaai 7, 8400 Ostend, Belgium
[33] European Commission, Joint Research Centre, 21027 Ispra (VA), Italy
[34] Environmental Physics Group, ETH Zürich, Institute of Biogeochemistry and Pollutant Dynamics and Center for Climate Systems Modeling (C2SM), 8092 Zurich, Switzerland
[35] NCAS-Climate, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK
[36] Woodwell Climate Research Center, Falmouth, MA 02540, USA
[37] Atmosphere and Ocean Department, Japan Meteorological Agency, Minato-Ku, Tokyo 105-8431, Japan
[38] Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61821, USA
[39] Institute of Applied Energy (IAE), Minato-ku, Tokyo 105-0003, Japan
[40] National Center for Atmospheric Research, Climate and Global Dynamics, Terrestrial Sciences Section, Boulder, CO 80305, USA
[41] Utrecht University, Faculty of Geosciences, Department IMEW, Copernicus Institute of Sustainable Development, Heidelberglaan 2, P.O. Box 80115, 3508 TC, Utrecht, the Netherlands
[42] Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia
[43] GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany
[44] NORCE Norwegian Research Centre, Jahnebakken 5, 5007 Bergen, Norway
[45] LOCEAN/IPSL laboratory, Sorbonne Université, CNRS/IRD/MNHN, Paris, France
[46] Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[47] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.
[48] Research Institute for Environment, Energy, and Economics, Appalachian State University, Boone, North Carolina, USA
[49] Department of Geological and Environmental Sciences, Appalachian State University, Boone, North Carolina, USA

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[50] Department of Meteorology, Department of Geography & Environmental Science, National Centre for Atmospheric Science, University of Reading, Reading, UK
[51] Climate Research Division, Environment and Climate Change Canada, Victoria, BC, Canada
[52] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, 80305, USA
[53] National Oceanic & Atmospheric Administration/Global Monitoring Laboratory (NOAA/GML), Boulder, CO, 80305, USA
[54] Max Planck Institute for Biogeochemistry, Jena, Germany
[55] Earth System Division, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506 Japan
[56] Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki, 305-0052 Japan
[57] Japan Fisheries Research and Education Agency, 2-12-4 Fukuura, Kanazawa-Ku, Yokohama 236-8648, Japan
[58] National Oceanic & Atmospheric Administration/Atlantic Oceanographic & Meteorological Laboratory (NOAA/AOML), Miami, FL 33149, USA
[59] NASA Goddard Space Flight Center, Biospheric Sciences Laboratory, Greenbelt, Maryland 20771, USA
[60] Leibniz Institute for Baltic Sea Research Warnemuende (IOW), Seestrasse 15; 18119 Rostock, Germany
[61] Princeton University, Department of Geosciences and Princeton Environmental Institute, Princeton, NJ, USA
[62] Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK
[63] National Oceanic and Atmospheric Administration, Earth System Research Laboratory (NOAA ESRL),Boulder, CO 80305, USA
[64] School of Forestry and Wildlife Sciences, Auburn University, 602 Ducan Drive, Auburn, AL 36849, USA
[65] CSIRO Oceans and Atmosphere, PO Box 1538, Hobart Tasmania 7001, Australia
[66] Australian Antarctic Partnership Program, University of Tasmania, Hobart, Australia
[67] Statistics Division, Food and Agriculture Organization of the United Nations, Via Terme di Caracalla, Rome 00153, Italy
[68] Faculty of Earth and Life Sciences, VU University, Amsterdam, The Netherlands
[69] School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, Guangdong 510245, China
[70] School of Environmental Science and Engineering, Nanjing University of Information Science and Technology (NUIST)

Correspondence: Pierre Friedlingstein (p.friedlingstein@exeter.ac.uk)

Abstract

Accurate assessment of anthropogenic carbon dioxide (CO_2) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere in a changing climate is critical to better understand the global carbon cycle, support the development of climate policies, and project future climate change. Here we describe and synthesize data sets and methodology to quantify the five major components of the global carbon budget and their uncertainties. Fossil CO_2 emissions (E_{FOS}) are based on energy statistics and

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cement production data, while emissions from land-use change (E_{LUC}), mainly deforestation, are based on land-use and land-use change data and bookkeeping models. Atmospheric CO_2 concentration is measured directly, and its growth rate (G_{ATM}) is computed from the annual changes in concentration. The ocean CO_2 sink (S_{OCEAN}) is estimated with global ocean biogeochemistry models and observation-based data-products. The terrestrial CO_2 sink (S_{LAND}) is estimated with dynamic global vegetation models. The resulting carbon budget imbalance (B_{IM}), the difference between the estimated total emissions and the estimated changes in the atmosphere, ocean, and terrestrial biosphere, is a measure of imperfect data and understanding of the contemporary carbon cycle. All uncertainties are reported as ±1σ. For the first time, an approach is shown to reconcile the difference in our E_{LUC} estimate with the one from national greenhouse gases inventories, supporting the assessment of collective countries' climate progress.

For the year 2020, E_{FOS} declined by 5.4% relative to 2019, with fossil emissions at 9.5 ± 0.5 GtC yr^{-1} (9.3 ± 0.5 GtC yr^{-1} when the cement carbonation sink is included), E_{LUC} was 0.9 ± 0.7 GtC yr^{-1}, for a total anthropogenic CO_2 emission of 10.2 ± 0.8 GtC yr^{-1} (37.4 ± 2.9 $GtCO_2$). Also, for 2020, G_{ATM} was 5.0 ± 0.2 GtC yr^{-1} (2.4 ± 0.1 ppm yr^{-1}), S_{OCEAN} was 3.0 ± 0.4 GtC yr^{-1} and S_{LAND} was 2.9 ± 1 GtC yr^{-1}, with a B_{IM} of -0.8 GtC yr^{-1}. The global atmospheric CO_2 concentration averaged over 2020 reached 412.45 ± 0.1 ppm. Preliminary data for 2021, suggest a rebound in E_{FOS} relative to 2020 of +4.9% (4.1% to 5.7%) globally.

Overall, the mean and trend in the components of the global carbon budget are consistently estimated over the period 1959-2020, but discrepancies of up to 1 GtC yr^{-1} persist for the representation of annual to semi-decadal variability in CO_2 fluxes. Comparison of estimates from multiple approaches and observations shows: (1) a persistent large uncertainty in the estimate of land-use changes emissions, (2) a low agreement between the different methods on the magnitude of the land CO_2 flux in the northern extra-tropics, and (3) a discrepancy between the different methods on the strength of the ocean sink over the last decade. This living data update documents changes in the methods and data sets used in this new global carbon budget and the progress in understanding of the global carbon cycle compared with previous publications of this data set (Friedlingstein et al., 2020; Friedlingstein et al., 2019; Le Quéré et al., 2018b, 2018a, 2016, 2015b, 2015a, 2014, 2013).

The data presented in this work are available at https://doi.org/10.18160/gcp-2021 (Friedlingstein et al., 2021).

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Executive Summary

Global fossil CO_2 emissions (excluding cement carbonation) in 2021 are returning towards their 2019 levels after decreasing [5.4%] in 2020. The 2020 decrease was 0.52 GtC yr^{-1} (1.9 $GtCO_2$ yr^{-1}), bringing 2020 emissions to 9.5 ± 0.5 GtC yr^{-1} (34.8 ± 1.8 $GtCO_2$ yr^{-1}), comparable to the emissions level of 2012. Preliminary estimates based on data available in October 2021 and a projection for the rest of the year suggest fossil CO_2 emissions will rebound 4.9% in 2021 (4.1% to 5.7%), bringing emissions at 9.9 GtC yr^{-1} (36.4 $GtCO_2$ yr^{-1}), back to about the same level as in 2019 (10.0 ± 0.5 GtC yr^{-1}, 36.7 ± 1.8 $GtCO_2$ yr^{-1}). Emissions from coal and gas in 2021 are expected to rebound above 2019 levels, while emissions from oil are still below their 2019 level. Emissions in China are expected to be 5.5% higher in 2021 than in 2019, reaching 3.0 GtC (11.1 $GtCO_2$) and also higher in India with a 4.4% increase in 2021 relative to 2019, reaching 0.75 GtC (2.7 $GtCO_2$). In contrast, projected 2021 emissions in the United States (1.4 GtC, 5.1 $GtCO_2$), European Union (0.8 GtC, 2.8 $GtCO_2$), and the rest of the world (4.0 GtC, 14.8 $GtCO_2$, in aggregate) remain respectively 3.7%, 4.2%, and 4.2% below their 2019 levels. These patterns reflect the stringency of the COVID-19 confinement levels and the background trends in emissions in these countries.

Fossil CO_2 emissions significantly decreased in 23 countries during the decade 2010-2019. Altogether, these 23 countries contribute to about 2.5 GtC yr^{-1} fossil fuel CO_2 emissions over the last decade, only about one quarter of world CO_2 fossil emissions.

Global CO_2 emissions from land-use, land-use change, and forestry (LUC) converge based on revised data of land-use change and show a small decrease over the past two decades. Near constant gross emissions estimated at 3.8 ± 0.6 GtC yr^{-1} in the 2011-2020 decade are only partly offset by growing carbon removals on managed land of 2.7 ± 0.4 GtC yr^{-1}, resulting in the net emissions in managed land of 1.1 ± 0.7 GtC yr^{-1} (4.1 ± 2.6 GtCO2 yr^{-1}). These net emissions decreased by 0.2 GtC in 2020 compared to 2019 levels, with large uncertainty. Preliminary estimates for emissions in 2021 suggest a 0.1 GtC decrease for 2021, giving net emissions of 0.8 GtC yr^{-1} (2.9 GtCO2 yr^{-1}). The convergence of different emission estimates does not reflect the high uncertainty in land-use change datasets, which likely underestimate interannual variability and the (rising) importance of degradation, highlighting the need for accurate land-use data. For the first time, we link the global carbon

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

budget models' estimates to the official country reporting of national greenhouse gases inventories. While the global carbon budget distinguishes anthropogenic from natural drivers of land carbon fluxes, country reporting is area based and attributes part of the natural terrestrial sink on managed land to the land-use sector. Accounting for this redistribution, the two approaches are shown to be consistent with each other.

The remaining carbon budget for a 50% likelihood to limit global warming to 1.5°C, 1.7°C and 2°C has shrunk to 120 GtC (420 $GtCO_2$), 210 GtC (770 $GtCO_2$) and 350 GtC (1270 $GtCO_2$) respectively, equivalent to 11, 20 and 32 years from the beginning of 2022, assuming 2021 emissions levels. Total anthropogenic emissions were 10.4 GtC yr^{-1} (38.0 $GtCO_2$ yr-1) in 2020, with a preliminary estimate of 10.7 GtC yr^{-1} (39.4 GtCO2 yr^{-1}) for 2021. The remaining carbon budget to keep global temperatures below the climate targets of the Paris Agreement has shrunk by 21 GtC (77 $GtCO_2$) relative to the remaining carbon budget estimate assessed in the IPCC AR6 Working Group 1 assessment. Reaching net zero CO_2 emissions by 2050 entails cutting total anthropogenic CO_2 emissions by about 0.4 GtC (1.4 $GtCO_2$) each year on average, comparable to the decrease during 2020, highlighting the scale of the action needed.

The concentration of CO_2 in the atmosphere is set to reach 414.7 ppm in 2021, 49% above pre-industrial levels. The atmospheric CO_2 growth was 5.1 ± 0.02 GtC yr^{-1} during the decade 2011-2020 (47% of total CO_2 emissions) with a preliminary 2021 growth rate estimate of around 4.2 GtC yr^{-1}. The 2020 decrease in total CO_2 emissions of about 0.7 GtC propagated to a reduction of the atmospheric CO_2 growth rate of 0.38GtC (0.18 ppm).

The ocean CO_2 sink resumed a more rapid growth in the past decade after low or no growth during the 1991-2002 period. However, the growth of the ocean CO_2 sink in the past decade has an uncertainty of a factor of three, with estimates based on data products and estimates based on models showing an ocean sink increase of 0.9 GtC yr^{-1} and 0.3 GtC yr^{-1} since 2010, respectively. The discrepancy in the trend originates from all latitudes but is largest in the Southern Ocean. The ocean CO_2 sink was 2.8 ± 0.4 GtC yr^{-1} during the decade 2011-2020 (26% of total CO_2 emissions), with a preliminary 2021 estimate of around 2.9 GtC yr^{-1}.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

The land CO_2 sink continued to increase during the 2011-2020 period primarily in response to increased atmospheric CO_2, albeit with large interannual variability. The land CO_2 sink was 3.1 ± 0.6 GtC yr^{-1} during the 2011-2020 decade (29% of total CO_2 emissions), 0.5 GtC yr^{-1} larger than during the previous decade (2000-2009), with a preliminary 2021 estimate of around 3.3 GtC yr^{-1}. Year to year variability in the land sink is about 1 GtC yr^{-1}, making small annual changes in anthropogenic emissions hard to detect in global atmospheric CO_2 concentration.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

1 Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere has increased from approximately 277 parts per million (ppm) in 1750 (Joos and Spahni, 2008), the beginning of the Industrial Era, to 412.4 ± 0.1 ppm in 2020 (Dlugokencky and Tans, 2021); Fig. 1). The atmospheric CO_2 increase above pre-industrial levels was, initially, primarily caused by the release of carbon to the atmosphere from deforestation and other land-use change activities (Canadell et al., 2021). While emissions from fossil fuels started before the Industrial Era, they became the dominant source of anthropogenic emissions to the atmosphere from around 1950 and their relative share has continued to increase until present. Anthropogenic emissions occur on top of an active natural carbon cycle that circulates carbon between the reservoirs of the atmosphere, ocean, and terrestrial biosphere on time scales from sub-daily to millennia, while exchanges with geologic reservoirs occur at longer timescales (Archer et al., 2009).

The global carbon budget (GCB) presented here refers to the mean, variations, and trends in the perturbation of CO_2 in the environment, referenced to the beginning of the Industrial Era (defined here as 1750). This paper describes the components of the global carbon cycle over the historical period with a stronger focus on the recent period (since 1958, onset of atmospheric CO_2 measurements), the last decade (2011-2020), the last year (2020) and the current year (2021). We quantify the input of CO_2 to the atmosphere by emissions from human activities, the growth rate of atmospheric CO_2 concentration, and the resulting changes in the storage of carbon in the land and ocean reservoirs in response to increasing atmospheric CO_2 levels, climate change and variability, and other anthropogenic and natural changes (Fig. 2). An understanding of this perturbation budget over time and the underlying variability and trends of the natural carbon cycle is necessary to understand the response of natural sinks to changes in climate, CO_2 and land-use change drivers, and to quantify the permissible emissions for a given climate stabilization target.

The components of the CO_2 budget that are reported annually in this paper include separate and independent estimates for the CO_2 emissions from (1) fossil fuel combustion and oxidation from all energy and industrial processes; also including cement production and carbonation (E_{FOS}; GtC yr^{-1}) and (2) the emissions resulting from deliberate human activities on land, including those leading to land-use change (E_{LUC}; GtC yr^{-1}); and their partitioning

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

among (3) the growth rate of atmospheric CO_2 concentration (G_{ATM}; GtC yr^{-1}), and the uptake of CO_2 (the 'CO_2 sinks') in (4) the ocean (S_{OCEAN}; GtC yr^{-1}) and (5) on land (S_{LAND}; GtC yr^{-1}). The CO_2 sinks as defined here conceptually include the response of the land (including inland waters and estuaries) and ocean (including coasts and territorial seas) to elevated CO_2 and changes in climate and other environmental conditions, although in practice not all processes are fully accounted for (see Section 2.7). Global emissions and their partitioning among the atmosphere, ocean and land are in reality in balance. Due to the combination of imperfect spatial and/or temporal data coverage, errors in each estimate, and smaller terms not included in our budget estimate (discussed in Section 2.7), the independent estimates (1) to (5) above do not necessarily add up to zero. We therefore (a) additionally assess a set of global atmospheric inverse model results that by design close the global carbon balance (see Section 2.6), and (b) estimate a budget imbalance (B_{IM}), which is a measure of the mismatch between the estimated emissions and the estimated changes in the atmosphere, land and ocean, as follows:

$$B_{IM} = E_{FOS} + E_{LUC} - (G_{ATM} + S_{OCEAN} + S_{LAND}) \quad (1)$$

G_{ATM} is usually reported in ppm yr^{-1}, which we convert to units of carbon mass per year, GtC yr^{-1}, using 1 ppm = 2.124 GtC (Ballantyne et al., 2012; Table 1). All quantities are presented in units of gigatonnes of carbon (GtC, 10^{15} gC), which is the same as petagrams of carbon (PgC; Table 1). Units of gigatonnes of CO_2 (or billion tonnes of CO_2) used in policy are equal to 3.664 multiplied by the value in units of GtC.

We also include a quantification of E_{FOS} by country, computed with both territorial and consumption-based accounting (see Section 2), and discuss missing terms from sources other than the combustion of fossil fuels (see Section 2.7).

The global CO_2 budget has been assessed by the Intergovernmental Panel on Climate Change (IPCC) in all assessment reports (Prentice et al., 2001; Schimel et al., 1995; Watson et al., 1990; Denman et al., 2007; Ciais et al., 2013; Canadell et al., 2021), and by others (e.g. Ballantyne et al., 2012). The Global Carbon Project (GCP, www.globalcarbonproject.org, last access: 15 October 2021) has coordinated this cooperative community effort for the annual publication of global carbon budgets for the year 2005 (Raupach et al., 2007; including fossil emissions only), year 2006 (Canadell et al., 2007), year 2007 (GCP, 2008), year 2008 (Le Quéré et al., 2009), year 2009 (Friedlingstein et al., 2010), year 2010 (Peters et al., 2012b), year 2012 (Le Quéré et al., 2013; Peters et al., 2013), year 2013 (Le Quéré et al., 2014), year 2014 (Le Quéré et al., 2015a; Friedlingstein et al., 2014), year 2015 (Jackson et al., 2016; Le Quéré et al., 2015b), year 2016 (Le Quéré et al., 2016), year 2017 (Le Quéré et al., 2018a; Peters et al., 2017), year 2018 (Le Quéré et al., 2018b; Jackson et al., 2018) year 2019 (Friedlingstein et al., 2019; Jackson et al., 2019; Peters et al., 2020) and more recently the year 2020 (Friedlingstein et al., 2020; Le Quéré et al., 2021) . Each of these papers updated previous estimates with the latest available information for the entire time series.

We adopt a range of ±1 standard deviation (σ) to report the uncertainties in our estimates, representing a likelihood of 68% that the true value will be within the provided range if the errors have a Gaussian distribution, and no bias is assumed. This choice reflects the difficulty of characterising the uncertainty in the CO_2 fluxes between the atmosphere and the ocean and land reservoirs individually, particularly on an annual basis, as well as the difficulty of updating the CO_2 emissions from land-use change. A likelihood of 68% provides an indication of our current capability to quantify each term and its uncertainty given the available information. The uncertainties reported here combine statistical analysis of the underlying data, assessments of uncertainties in the generation of the data sets, and expert judgement of the likelihood of results lying outside this range. The limitations of current information are discussed in the paper and have been examined in detail elsewhere (Ballantyne et al., 2015; Zscheischler et al., 2017). We also use a qualitative assessment of confidence level to characterise the annual estimates from each term based on the type, amount, quality, and consistency of the evidence as defined by the IPCC (Stocker et al., 2013).

This paper provides a detailed description of the data sets and methodology used to compute the global carbon budget estimates for the industrial period, from 1750 to 2020, and in more detail for the period since 1959. It also provides decadal averages starting in 1960 including the most recent decade (2011-2020), results for the year 2020, and a projection for the year 2021. Finally, it provides cumulative emissions from fossil fuels and land-use change since the year 1750, the pre-industrial period; and since the year 1850, the reference year for historical simulations in IPCC AR6 (Eyring et al., 2016). This paper is updated every year using the format of 'living data' to keep a record of budget versions and the changes in new data, revision of data, and changes in methodology that lead to changes

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

in estimates of the carbon budget. Additional materials associated with the release of each new version will be posted at the Global Carbon Project (GCP) website (http://www.globalcarbonproject.org/carbonbudget, last access: 15 October 2021), with fossil fuel emissions also available through the Global Carbon Atlas (http://www.globalcarbonatlas.org, last access: 15 October 2021). With this approach, we aim to provide the highest transparency and traceability in the reporting of CO_2, the key driver of climate change.

2 Methods

Multiple organizations and research groups around the world generated the original measurements and data used to complete the global carbon budget. The effort presented here is thus mainly one of synthesis, where results from individual groups are collated, analysed, and evaluated for consistency. We facilitate access to original data with the understanding that primary data sets will be referenced in future work (see Table 2 for how to cite the data sets). Descriptions of the measurements, models, and methodologies follow below, and detailed descriptions of each component are provided elsewhere.

This is the 16th version of the global carbon budget and the tenth revised version in the format of a living data update in Earth System Science Data. It builds on the latest published global carbon budget of Friedlingstein et al. (2020). The main changes are: the inclusion of (1) data to year 2020 and a projection for the global carbon budget for year 2021; (2) a Kaya analysis to identify the driving factors behind the recent trends in fossil fuel emissions (changes in population, GDP per person, energy use per GDP, and CO_2 emissions per unit energy), (3) an estimate of the ocean sink from models and data-products combined, (4) an assessment of the relative contributions of increased atmospheric CO_2 and climate change in driving the land and ocean sinks, and (5) an assessment of the current trends in anthropogenic emissions and implications for the remaining carbon budget for specific climate targets. The main methodological differences between recent annual carbon budgets (2016-2020) are summarised in Table 3 and previous changes since 2006 are provided in Table A7.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

2.1 Fossil CO_2 emissions (E_{FOS})

2.1.1 Historical period 1850-2020

The estimates of global and national fossil CO_2 emissions (E_{FOS}) include the oxidation of fossil fuels through both combustion (e.g., transport, heating) and chemical oxidation (e.g. carbon anode decomposition in aluminium refining) activities, and the decomposition of carbonates in industrial processes (e.g. the production of cement). We also include CO_2 uptake from the cement carbonation process. Several emissions sources are not estimated or not fully covered: coverage of emissions from lime production are not global, and decomposition of carbonates in glass and ceramic production are included only for UNFCCC Annex 1 countries for lack of activity data. These omissions are considered to be minor. Short-cycle carbon emissions - for example from combustion of biomass - are not included.

Our estimates of fossil CO_2 emissions are derived using the standard approach of activity data and emission factors, relying on data collection by many other parties. Our goal is to produce the best estimate of this flux, and we therefore use a prioritisation framework to combine data from different sources that have used different methods, while being careful to avoid double counting and undercounting of emissions sources. The CDIAC-FF emissions dataset, derived largely from UN energy data, forms the foundation, and we extend emissions to year Y-1 using energy growth rates reported by BP. We then proceed to replace estimates using data from what we consider to be superior sources, for example Annex 1 countries' official submissions to the UNFCCC. All data points are potentially subject to revision, not just the latest year. For full details see Andrew and Peters (2021).

Other estimates of global fossil CO_2 emissions exist, and these are compared by Andrew (2020a). The most common reason for differences in estimates of global fossil CO_2 emissions is a difference in which emissions sources are included in the datasets. Datasets such as those published by BP, the US Energy Information Administration, and the International Energy Agency's 'CO_2 emissions from fuel combustion' are all generally limited to emissions from combustion of fossil fuels. In contrast, datasets such as PRIMAP-hist, CEDS, EDGAR, and GCP's dataset aim to include all sources of fossil CO_2 emissions. See Andrew (2020a) for detailed comparisons and discussion.

Cement absorbs CO_2 from the atmosphere over its lifetime, a process known as 'cement carbonation'. We estimate this CO_2 sink as the average of two studies in the literature (Cao

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

et al., 2020; Guo et al., 2021). Both studies use the same model, developed by Xi et al. (2016), with different parameterisations and input data. Since carbonation is a function of both current and previous cement production, we extend these estimates by one year to 2020 by using the growth rate derived from the smoothed cement emissions (10-year smoothing) fitted to the carbonation data.

We use the Kaya Identity for a simple decomposition of CO_2 emissions into the key drivers (Raupach et al., 2007). While there are variations (Peters et al 2017), we focus here on a decomposition of CO_2 emissions into population, GDP per person, energy use per GDP, and CO_2 emissions per energy. Multiplying these individual components together returns the CO_2 emissions. Using the decomposition, it is possible to attribute the change in CO_2 emissions to the change in each of the drivers. This method gives a first order understanding of what causes CO_2 emissions to change each year.

2.1.2 2021 projection

We provide a projection of global CO_2 emissions in 2021 by combining separate projections for China, USA, EU, India, and all other countries combined. The methods are different for each of these. For China we combine monthly fossil fuel production data from the National Bureau of Statistics, import/export data from the Customs Administration, and monthly coal consumption estimates from SX Coal (2021), giving us partial data for the growth rates to date of natural gas, petroleum, and cement, and of the consumption itself for raw coal. We then use a regression model to project full-year emissions based on historical observations. For the USA our projection is taken directly from the Energy Information Administration's (EIA) Short-Term Energy Outlook (EIA, 2021), combined with the year-to-date growth rate of cement production. For the EU we use monthly energy data from Eurostat to derive estimates of monthly CO_2 emissions through July, with coal emissions extended first through September using a statistical relationship with reported electricity generation from coal and other factors, then through December assuming normal seasonal patterns. EU emissions from natural gas - a strongly seasonal cycle - are extended through December using bias-adjusted Holt-Winters exponential smoothing (Chatfield, 1978). EU emissions from oil are derived using the EIA's projection of oil consumption for Europe. EU cement emissions are based on available year-to-date data from two of the largest producers, Germany and Poland. India's projected emissions are derived from estimates through August (September

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

for coal) using the methods of Andrew (2020b) and extrapolated assuming normal seasonal patterns. Emissions for the rest of the world are derived using projected growth in economic production from the IMF (2021) combined with extrapolated changes in emissions intensity of economic production. More details on the E_{FOS} methodology and its 2021 projection can be found in Appendix C.1.

2.2 CO_2 emissions from land-use, land-use change and forestry (E_{LUC})

The net CO_2 flux from land-use, land-use change and forestry (E_{LUC}, called land-use change emissions in the rest of the text) includes CO_2 fluxes from deforestation, afforestation, logging and forest degradation (including harvest activity), shifting cultivation (cycle of cutting forest for agriculture, then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture. Emissions from peat burning and drainage are added from external datasets.

Three bookkeeping approaches (updated estimates each of BLUE (Hansis et al., 2015), OSCAR (Gasser et al., 2020), and H&N2017 (Houghton and Nassikas, 2017)) were used to quantify gross sources and sinks and the resulting net E_{LUC}. Uncertainty estimates were derived from the DGVMs ensemble for the time period prior to 1960, using for the recent decades an uncertainty range of ±0.7 GtC yr-1, which is a semi-quantitative measure for annual and decadal emissions and reflects our best value judgment that there is at least 68% chance (±1σ) that the true land-use change emission lies within the given range, for the range of processes considered here. This uncertainty range had been increased from 0.5 GtC yr-1 after new bookkeeping models were included that indicated a larger spread than assumed before (Le Quéré et al., 2018). Projections for 2021 are based on fire activity from tropical deforestation and degradation as well as emissions from peat fires and drainage.

Our E_{LUC} estimates follow the definition of global carbon cycle models of CO_2 fluxes related to land-use and land management and differ from IPCC definitions adopted in national GHG inventories (NGHGI) for reporting under the UNFCCC, which additionally generally include, through adoption of the IPCC so-called managed land proxy approach, the terrestrial fluxes occurring on land defined by countries as managed. This partly includes fluxes due to environmental change (e.g. atmospheric CO_2 increase), which are part of S_{LAND} in our definition. This causes the global emission estimates to be smaller for NGHGI than for the

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

global carbon budget definition (Grassi et al., 2018). The same is the case for FAO estimates of carbon fluxes on forest land, which include, compared to S_{LAND}, both anthropogenic and natural sources on managed land (Tubiello et al., 2021). Using the approach outlined in Grassi et al. (2021), here we map as additional information the two definitions to each other, to provide a comparison of the anthropogenic carbon budget to the official country reporting to the climate convention. More details on the E_{LUC} methodology can be found in Appendix C.2.

2.3 Growth rate in atmospheric CO_2 concentration (G_{ATM})

2.3.1 Historical period

The rate of growth of the atmospheric CO_2 concentration is provided for years 1959-2020 by the US National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL; Dlugokencky and Tans, 2021), which is updated from Ballantyne et al. (2012) and includes recent revisions to the calibration scale of atmospheric CO_2 measurements (Hall et al., 2021). For the 1959-1979 period, the global growth rate is based on measurements of atmospheric CO_2 concentration averaged from the Mauna Loa and South Pole stations, as observed by the CO_2 Program at Scripps Institution of Oceanography (Keeling et al., 1976). For the 1980-2020 time period, the global growth rate is based on the average of multiple stations selected from the marine boundary layer sites with well-mixed background air (Ballantyne et al., 2012), after fitting each station with a smoothed curve as a function of time, and averaging by latitude band (Masarie and Tans, 1995). The annual growth rate is estimated by Dlugokencky and Tans (2021) from atmospheric CO_2 concentration by taking the average of the most recent December-January months corrected for the average seasonal cycle and subtracting this same average one year earlier. The growth rate in units of ppm yr^{-1} is converted to units of GtC yr^{-1} by multiplying by a factor of 2.124 GtC per ppm, assuming instantaneous mixing of CO_2 throughout the atmosphere (Ballantyne et al., 2012).

Starting in 2020, NOAA/ESRL now provides estimates of atmospheric CO_2 concentrations with respect to a new calibration scale, referred to as WMO-CO2-X2019, in line with the recommendation of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) community (Hall et al., 2021). The WMO-CO2-X2019 scale improves upon the

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

earlier WMO-CO2-X2007 scale by including a broader set of standards, which contain CO_2 in a wider range of concentrations that span the range 250-800 ppm (versus 250–520 ppm for WMO-CO2-X2007). In addition, NOAA/ESRL made two minor corrections to the analytical procedure used to quantify CO_2 concentrations, fixing an error in the second virial coefficient of CO_2 and accounting for loss of a small amount of CO_2 to materials in the manometer during the measurement process. The difference in concentrations measured using WMO-CO2-X2019 versus WMO-CO2-X2007 is ~+0.18 ppm at 400 ppm and the observational record of atmospheric CO_2 concentrations have been revised accordingly. The revisions have been applied retrospectively in all cases where the calibrations were performed by NOAA/ESRL, thus affecting measurements made by members of the WMO-GAW programme and other regionally coordinated programmes (e.g., Integrated Carbon Observing System, ICOS). Changes to the CO_2 concentrations measured across these networks propagate to the global mean CO_2 concentrations. Comparing the estimates of G_{ATM} made by Dlugokencky and Tans (2020), used in the Global Carbon Budget 2020 (Friedlingstein et al., 2020), with updated estimates from Dlugokencky and Tans (2021), used here, we find that G_{ATM} reduced on average by -0.06 GtC yr^{-1} during 2010-2019 and by -0.01 GtC yr^{-1} during 1959-2019 (well within the uncertainty ranges reported below). Hence the change in analytical procedures made by NOAA/ESRL has a negligible impact on the atmospheric growth rate G_{ATM}.

The uncertainty around the atmospheric growth rate is due to four main factors. First, the long-term reproducibility of reference gas standards (around 0.03 ppm for 1σ from the 1980s; Dlugokencky and Tans, 2021). Second, small unexplained systematic analytical errors that may have a duration of several months to two years come and go. They have been simulated by randomizing both the duration and the magnitude (determined from the existing evidence) in a Monte Carlo procedure. Third, the network composition of the marine boundary layer with some sites coming or going, gaps in the time series at each site, etc (Dlugokencky and Tans, 2021). The latter uncertainty was estimated by NOAA/ESRL with a Monte Carlo method by constructing 100 "alternative" networks (Masarie and Tans, 1995; NOAA/ESRL, 2019). The second and third uncertainties, summed in quadrature, add up to 0.085 ppm on average (Dlugokencky and Tans, 2021). Fourth, the uncertainty associated with using the average CO_2 concentration from a surface network to approximate the true atmospheric average CO_2 concentration (mass-weighted, in 3 dimensions) as needed to assess the total atmospheric CO_2 burden. In reality, CO_2 variations measured at the stations will not exactly track changes in total atmospheric burden, with offsets in magnitude and phasing due to vertical and horizontal mixing. This effect must be very small on decadal and longer time scales, when the atmosphere can be considered well mixed. Preliminary estimates suggest this effect would increase the annual uncertainty, but a full analysis is not yet available. We therefore maintain an uncertainty around the annual growth rate based on the multiple stations data set ranges between 0.11 and 0.72 GtC yr^{-1}, with a mean of 0.61 GtC yr^{-1} for 1959-1979 and 0.17 GtC yr^{-1} for 1980-2020, when a larger set of stations were available as provided by Dlugokencky and Tans (2021) but recognise further exploration of this uncertainty is required. At this time, we estimate the uncertainty of the decadal averaged growth rate after 1980 at 0.02 GtC yr^{-1} based on the calibration and the annual growth rate uncertainty but stretched over a 10-year interval. For years prior to 1980, we estimate the decadal averaged uncertainty to be 0.07 GtC yr^{-1} based on a factor proportional to the annual uncertainty prior and after 1980 (0.02 * [0.61/0.17] GtC yr^{-1}).

We assign a high confidence to the annual estimates of G_{ATM} because they are based on direct measurements from multiple and consistent instruments and stations distributed around the world (Ballantyne et al., 2012; Hall et al., 2021).

To estimate the total carbon accumulated in the atmosphere since 1750 or 1850, we use an atmospheric CO_2 concentration of 277 ± 3 ppm or 286 ± 3 ppm, respectively, based on a cubic spline fit to ice core data (Joos and Spahni, 2008). For the construction of the cumulative budget shown in Figure 3, we use the fitted estimates of CO_2 concentration from Joos and Spahni (2008) to estimate the annual atmospheric growth rate using the conversion factors shown in Table 1. The uncertainty of ±3 ppm (converted to ±1σ) is taken directly from the IPCC's AR5 assessment (Ciais et al., 2013). Typical uncertainties in the growth rate in atmospheric CO_2 concentration from ice core data are equivalent to ±0.1-0.15 GtC yr^{-1} as evaluated from the Law Dome data (Etheridge et al., 1996) for individual 20-year intervals over the period from 1850 to 1960 (Bruno and Joos, 1997).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Earth System Science Data Discussions
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2.3.2 2021 projection

We provide an assessment of G_{ATM} for 2021 based on the monthly calculated global atmospheric CO_2 concentration (GLO) through August (Dlugokencky and Tans, 2021), and bias-adjusted Holt–Winters exponential smoothing with additive seasonality (Chatfield, 1978) to project to January 2022. Additional analysis suggests that the first half of the year (the boreal winter-spring-summer transition) shows more interannual variability than the second half of the year (the boreal summer-autumn-winter transition), so that the exact projection method applied to the second half of the year has a relatively smaller impact on the projection of the full year. Uncertainty is estimated from past variability using the standard deviation of the last 5 years' monthly growth rates.

2.4 Ocean CO_2 sink

The reported estimate of the global ocean anthropogenic CO_2 sink S_{OCEAN} is derived as the average of two estimates. The first estimate is derived as the mean over an ensemble of eight global ocean biogeochemistry models (GOBMs, Table 4 and Table A2). The second estimate is obtained as the mean over an ensemble of seven observation-based data-products (Table 4 and Table A3). The GOBMs simulate both the natural and anthropogenic CO_2 cycles in the ocean. They constrain the anthropogenic air-sea CO_2 flux (the dominant component of S_{OCEAN}) by the transport of carbon into the ocean interior, which is also the controlling factor of present-day ocean carbon uptake in the real world. They cover the full globe and all seasons and were recently evaluated against surface ocean carbon observations, suggesting they are suitable to estimate the annual ocean carbon sink (Hauck et al., 2020). The data-products are tightly linked to observations of fCO_2 (fugacity of CO_2, which equals pCO_2 corrected for the non-ideal behaviour of the gas; Pfeil et al., 2013), which carry imprints of temporal and spatial variability, but are also sensitive to uncertainties in gas-exchange parameterizations and data-sparsity. Their asset is the assessment of interannual and spatial variability (Hauck et al., 2020). We further use two diagnostic ocean models to estimate S_{OCEAN} over the industrial era (1781-1958).

The global fCO_2-based flux estimates were adjusted to remove the pre-industrial ocean source of CO_2 to the atmosphere of 0.61 GtC yr^{-1} from river input to the ocean (the average of 0.45 ± 0.18 GtC yr^{-1} by Jacobson et al. (2007) and 0.78 ± 0.41 GtC yr^{-1} by Resplandy et al.,

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

2018), to satisfy our definition of S_{OCEAN} (Hauck et al., 2020). The river flux adjustment was distributed over the latitudinal bands using the regional distribution of Aumont et al. (2001; North: 0.16 GtC yr^{-1}, Tropics: 0.15 GtC yr^{-1}, South: 0.30 GtC yr^{-1}), acknowledging that the boundaries of Aumont et al (2001; namely 20°S and 20°N) are not consistent with the boundaries otherwise used in the GCB (30°S and 30°N). A recent modelling study (Lacroix et al., 2020) suggests that more of the riverine outgassing is located in the tropics than in the Southern Ocean; and hence this regional distribution is associated with a major uncertainty. Anthropogenic perturbations of river carbon and nutrient transport to the ocean are not considered (see section 2.7).

We derive S_{OCEAN} from GOBMs by using a simulation (sim A) with historical forcing of climate and atmospheric CO_2, accounting for model biases and drift from a control simulation (sim B) with constant atmospheric CO_2 and normal year climate forcing. A third simulation (sim C) with historical atmospheric CO_2 increase and normal year climate forcing is used to attribute the ocean sink to CO_2 (sim C minus sim B) and climate (sim A minus sim C) effects. Data-products are adjusted to represent the full ocean area by a simple scaling approach when coverage is below 98%. GOBMs and data-products fall within the observational constraints over the 1990s (2.2 ± 0.7 GtC yr^{-1} , Ciais et al., 2013) after applying adjustments . We assign an uncertainty of ± 0.4 GtC yr^{-1} to the ocean sink based on a combination of random (ensemble standard deviation) and systematic uncertainties (GOBMs bias in anthropogenic carbon accumulation, previously reported uncertainties in fCO_2-based data-products; see section C.3.3). We assess a medium confidence level to the annual ocean CO_2 sink and its uncertainty because it is based on multiple lines of evidence, it is consistent with ocean interior carbon estimates (Gruber et al., 2019, see section 3.5.5) and the results are consistent in that the interannual variability in the GOBMs and data-based estimates are all generally small compared to the variability in the growth rate of atmospheric CO_2 concentration. We refrain from assigning a high confidence because of the systematic deviation between the GOBM and data-product trends since around 2002. More details on the S_{OCEAN} methodology can be found in Appendix C.3.

The ocean CO_2 sink forecast for the year 2021 is based on the annual historical and estimated 2021 atmospheric CO_2 concentration (Dlugokencky and Tans 2021), historical and estimated 2021 annual global fossil fuel emissions from this year's carbon budget, and the spring (March, April, May) Oceanic Niño Index (ONI) index (NCEP, 2021). Using a non-linear

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

regression approach, i.e., a feed-forward neural network, atmospheric CO_2, the ONI index and the fossil fuel emissions are used as training data to best match the annual ocean CO_2 sink (i.e. combined S_{OCEAN} estimate from GOBMs and data products) from 1959 through 2020 from this year's carbon budget. Using this relationship, the 2021 S_{OCEAN} can then be estimated from the projected 2021 input data using the non-linear relationship established during the network training. To avoid overfitting, the neural network was trained with a variable number of hidden neurons (varying between 2-5) and 20% of the randomly selected training data were withheld for independent internal testing. Based on the best output performance (tested using the 20% withheld input data), the best performing number of neurons was selected. In a second step, we trained the network 10 times using the best number of neurons identified in step 1 and different sets of randomly selected training data. The mean of the 10 trainings is considered our best forecast, whereas the standard deviation of the 10 ensembles provides a first order estimate of the forecast uncertainty. This uncertainty is then combined with the S_{OCEAN} uncertainty (0.4 GtC yr^{-1}) to estimate the overall uncertainty of the 2021 prediction.

2.5 Terrestrial CO_2 sink

The terrestrial land sink (S_{LAND}) is thought to be due to the combined effects of fertilisation by rising atmospheric CO_2 and N inputs on plant growth, as well as the effects of climate change such as the lengthening of the growing season in northern temperate and boreal areas. S_{LAND} does not include land sinks directly resulting from land-use and land-use change (e.g., regrowth of vegetation) as these are part of the land-use flux (E_{LUC}), although system boundaries make it difficult to attribute exactly CO_2 fluxes on land between S_{LAND} and E_{LUC} (Erb et al., 2013).

S_{LAND} is estimated from the multi-model mean of 17 DGVMs (Table A1). As described in Appendix C.4**,** DGVMs simulations include all climate variability and CO_2 effects over land, with 12 DGVMs also including the effect of N inputs. The DGVMs estimate of S_{LAND} does not include the export of carbon to aquatic systems or its historical perturbation, which is discussed in Appendix D3. See Appendix C.4 for DGVMs evaluation and uncertainty assessment for S_{LAND}, using the International Land Model Benchmarking system (ILAMB; Collier et al., 2018). More details on the S_{LAND} methodology can be found in Appendix C.4.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Like the ocean forecast, the land CO_2 sink (S_{LAND}) forecast is based on the annual historical and estimated 2021 atmospheric CO_2 concentration (Dlugokencky and Tans 2021), historical and estimated 2021 annual global fossil fuel emissions from this year's carbon budget, and the summer (June, July, August) ONI index (NCEP, 2021). All training data are again used to best match S_{LAND} from 1959 through 2020 from this year's carbon budget using a feed-forward neural network. To avoid overfitting, the neural network was trained with a variable number of hidden neurons (varying between 2-15), larger than for S_{OCEAN} prediction due to the stronger land carbon interannual variability. As done for S_{OCEAN}, a pre-training selects the optimal number of hidden neurons based on 20% withheld input data, and in a second step, an ensemble of 10 forecasts is produced to provide the mean forecast plus uncertainty. This uncertainty is then combined with the S_{LAND} uncertainty for 2020 (1.0 GtC yr^{-1}) to estimate the overall uncertainty of the 2021 prediction.

2.6 The atmospheric perspective

The world-wide network of in-situ atmospheric measurements and satellite derived atmospheric CO_2 column (xCO_2) observations put a strong constraint on changes in the atmospheric abundance of CO_2. This is true globally (hence our large confidence in G_{ATM}), but also regionally in regions with sufficient observational density found mostly in the extra-tropics. This allows atmospheric inversion methods to constrain the magnitude and location of the combined total surface CO_2 fluxes from all sources, including fossil and land-use change emissions and land and ocean CO_2 fluxes. The inversions assume E_{FOS} to be well known, and they solve for the spatial and temporal distribution of land and ocean fluxes from the residual gradients of CO_2 between stations that are not explained by fossil fuel emissions. By design, such systems thus close the carbon balance (B_{IM} = 0) and thus provide an additional perspective on the independent estimates of the ocean and land fluxes.

This year's release includes six inversion systems that are described in Table A4. Each system is rooted in Bayesian inversion principles but uses slightly different methodologies. These differences concern the selection of atmospheric CO_2 data and the choice of a-priori fluxes to refine with these datas. They also differ in spatial and temporal resolution, assumed correlation structures, and mathematical approach of the models (see references in Table A4 for details). Importantly, the systems use a variety of transport models, which was demonstrated to be a driving factor behind differences in atmospheric inversion-based flux

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

estimates, and specifically their distribution across latitudinal bands (Gaubert et al., 2019; Schuh et al., 2019). Multiple inversion systems (UoE, CTE, and CAMS) were previously tested with satellite xCO_2 retrievals from GOSAT or OCO-2 measurements, but their results at the larger scales (as discussed in this work) did not deviate substantially from their in-situ counterparts and are therefore not separately included. One inversion this year (CMS-Flux) used ACOS-GOSAT v9 retrievals between July 2009 and Dec 2014 and OCO-2 b10 retrievals between Jan 2015 to Dec 2015, in addition to the in-situ observational CO_2 mole fraction records.

The original products delivered by the inverse modelers were modified to facilitate the comparison to the other elements of the budget, specifically on 3 accounts: (1) global total fossil fuel emissions, (2) riverine CO_2 transport, and (3) cement carbonation CO_2 uptake. Details are given below. We note that with these adjustments the inverse results no longer represent the net atmosphere-surface exchange over land/ocean areas as sensed by atmospheric observations. Instead for land they become the net loss/uptake of CO_2 by vegetation and soils that is not exported by fluvial systems, similar to the DGVMs estimates. For oceans, they become the net uptake of anthropogenic CO_2, similar to the GOBMs estimates.

The inversion systems prescribe global fossil fuel emissions based on the GCP's Gridded Fossil Emissions Dataset version 2021.2 (GCP-GridFEDv2021.2; Jones et al., 2021b), which is an update to 2019 of the first version of GCP-GridFED presented by Jones et al. (2021a). GCP-GridFEDv2021.2 scales gridded estimates of CO_2 emissions from EDGARv4.3.2 (Janssens-Maenhout et al., 2019) within national territories to match national emissions estimates provided by the GCB for the years 1959-2020, which were compiled following the methodology described in Section 2.1 with all datasets available on August 14th 2021 (R. Andrew, *pers. comm.*). Small differences between the systems due to for instance regridding to the transport model resolution are corrected for in the latitudinal partitioning we present, to ensure agreement with the estimate of E_{FOS} in this budget. We also note that the ocean fluxes used as prior by 5 out of 6 inversions are part of the suite of the ocean process model or fCO2 data products suite listed in Section 2.4. Although these fluxes are further adjusted by the atmospheric inversions, it makes the inversion estimates of the ocean fluxes not completely independent of S_{OCEAN} assessed here.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

To facilitate comparisons to the independent S_{OCEAN} and S_{LAND}, we used the same corrections for transport and outgassing of carbon transported from land to ocean, as done for the observation-based estimates of S_{OCEAN} (see Appendix C.3). Furthermore, the inversions did not include a cement carbonation sink (see section 2.1) and therefore this GCB component is implicitly part of their total land sink estimate. In the numbers presented in this budget, each year's global carbonation sink from cement was subtracted from each year's estimated land sink in each inversion, distributed proportional to fossil fuel emissions per region (North-Tropics-South).

The atmospheric inversions are evaluated using vertical profiles of atmospheric CO_2 concentrations (Fig. B4). More than 30 aircraft programs over the globe, either regular programs or repeated surveys over at least 9 months, have been used to assess model performance (with space-time observational coverage sparse in the SH and tropics, and denser in NH mid-latitudes; Table A6). The six models are compared to the independent aircraft CO_2 measurements between 2 and 7 km above sea level between 2001 and 2020. Results are shown in Fig. B4 and discussed in Section 3.7.

With a relatively small ensemble (N=6) of systems that moreover share some a-priori fluxes used with one another, or with the process-based models, it is difficult to justify using their mean and standard deviation as a metric for uncertainty across the ensemble. We therefore report their full range (min-max) without their mean. More details on the atmospheric inversions methodology can be found in Appendix C.5.

2.7 Processes not included in the global carbon budget

The contribution of anthropogenic CO and CH4 to the global carbon budget is not fully accounted for in Eq. (1) and is described in Appendix D1. The contributions of other carbonates to CO_2 emissions is described in Appendix D2. The contribution of anthropogenic changes in river fluxes is conceptually included in Eq. (1) in S_{OCEAN} and in S_{LAND}, but it is not represented in the process models used to quantify these fluxes. This effect is discussed in Appendix D3. Similarly, the loss of additional sink capacity from reduced forest cover is missing in the combination of approaches used here to estimate both land fluxes (E_{LUC} and S_{LAND}) and its potential effect is discussed and quantified in Appendix D4.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

3 Results

For each component of the global carbon budget, we present results for three different time periods: the full historical period, from 1850 to 2020, the six decades in which we have atmospheric concentration records from Mauna Loa (1960-2020), a specific focus on last year (2020), and the projection for the current year (2021). Subsequently, we assess the combined constraints from the budget components (often referred to as a bottom-up budget) against the top-down constraints from inverse modeling of atmospheric observations. We do this for the global balance of the last decade, as well as for a regional breakdown of land and ocean sinks by broad latitude bands.

3.1 Fossil CO_2 Emissions

3.1.1 Historical period 1850-2020

Cumulative fossil CO_2 emissions for 1850-2020 were 455 ± 25 GtC, including the cement carbonation sink (Fig. 3, Table 8) .

In this period, 46% of fossil CO_2 emissions came from coal, 35% from oil, 14% from natural gas, 3% from decomposition of carbonates, and 1% from flaring.

In 1850, the UK stood for 62% of global fossil CO_2 emissions. In 1891 the combined cumulative emissions of the current members of the European Union reached and subsequently surpassed the level of the UK. Since 1917 US cumulative emissions have been the largest. Over the entire period 1850-2020, US cumulative emissions amount to 110GtC (25% of world total) , the EU's to 80 GtC (18%), and China's to 60 GtC (14%).

There are three additional global datasets that include all sources of fossil CO_2 emissions: CDIAC-FF (Gilfillan and Marland, 2021), CEDS version v_2021_04_21 (Hoesly et al., 2018); O'Rourke et al., 2021) and PRIMAP-hist version 2.3.1 (Gütschow et al., 2016, 2021), although these datasets are not independent. CDIAC-FF has the lowest cumulative emissions over 1750-2018 at 437 GtC, GCP has 443 GtC, CEDS 445 GtC, PRIMAP-hist TP 453 GtC, and PRIMAP-hist CR 455 GtC. CDIAC-FF excludes emissions from lime production, while both CDIAC-FF and GCP exclude emissions from international bunker fuels prior to 1950. CEDS has higher emissions from international shipping in recent years, while PRIMAP-hist has higher fugitive emissions than the other datasets. However, in general these four datasets are in relative agreement as to total historical global emissions of fossil CO_2.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

3.1.2 Recent period 1960-2020

Global fossil CO_2 emissions, E_{FOS} (including the cement carbonation sink), have increased every decade from an average of 3.0 ± 0.2 GtC yr^{-1} for the decade of the 1960s to an average of 9.5 ± 0.5 GtC yr^{-1} during 2011-2020 (Table 6, Fig. 2 and Fig. 5). The growth rate in these emissions decreased between the 1960s and the 1990s, from 4.3% yr^{-1} in the 1960s (1960-1969), 3.2% yr^{-1} in the 1970s (1970-1979), 1.6% yr^{-1} in the 1980s (1980-1989), to 0.9% yr^{-1} in the 1990s (1990-1999). After this period, the growth rate began increasing again in the 2000s at an average growth rate of 3.0% yr^{-1}, decreasing to 0.6% yr^{-1} for the last decade (2011-2020). China's emissions increased by +1.0% yr^{-1} on average over the last 10 years dominating the global trend, followed by India's emissions increase by +3.9% yr^{-1}, while emissions decreased in EU27 by –1.9% yr^{-1}, and in the USA by –1.1% yr^{-1}. Fig.6 illustrates the spatial distribution of fossil fuel emissions for the 2011-2020 period.

E_{FOS} includes the uptake of CO_2 by cement via carbonation which has increased with increasing stocks of cement products, from an average of 20 MtC yr^{-1} (0.02 GtC yr^{-1}) in the 1960s to an average of 200 MtC yr^{-1} (0.2 GtC yr^{-1}) during 2011-2020 (Fig. 5).

3.1.3 Final year 2020

The estimate of global fossil CO_2 emissions for 2020 is 5.4% lower than in 2019, declining 0.5 GtC to reach 9.5 ± 0.5 GtC (9.3 ± 0.5 GtC when including the cement carbonation sink) in 2020 (Fig. 5), distributed among coal (40%), oil (32%), natural gas (21%), cement (5%) and others (2%). Compared to the previous year, 2020 emissions from coal, oil and gas declined by 4.4%, 9.7% and 2.3% respectively, while emissions from cement increased by 0.8%. All growth rates presented are adjusted for the leap year, unless stated otherwise.

In 2020, the largest absolute contributions to global fossil CO_2 emissions were from China (31%), the USA (14%), the EU27 (7%), and India (7%). These four regions account for 59% of global CO_2 emissions, while the rest of the world contributed 41%, including international aviation and marine bunker fuels (2.9% of the total). Growth rates for these countries from 2019 to 2020 were +1.4% (China), -10.6% (USA), –10.9% (EU27), and -7.3% (India), with -7.0% for the rest of the world. The per-capita fossil CO_2 emissions in 2020 were 1.2 tC $person^{-1}$ yr^{-1} for the globe, and were 3.9 (USA), 2.0 (China), 1.6 (EU27) and 0.5 (India) tC $person^{-1}$ yr^{-1} for the four highest emitting countries (Fig. 5).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

The decline in emissions of -5.4% in 2020 is close to the projected decline of -6.7%, which was the median of four approaches, published in Friedlingstein et al. (2020). Of the four approaches, the 'GCP' method was closest at -5.8%. That method was based on national emissions projections for China, the USA, the EU27, and India using reported monthly activity data when available and projections of gross domestic product corrected for trends in fossil fuel intensity (I_{FOS}) for the rest of the world. Of the regions, the projection for the EU27 was least accurate, and the reasons for this are discussed by Andrew (2021).

3.1.4 Year 2021 Projection

Globally, we estimate that global fossil CO_2 emissions will rebound 4.9% in 2021 (4.1% to 5.7%) to 9.9 GtC (36.4 $GtCO_2$), returning near their 2019 emission levels of 10.0 GtC (36.7 $GtCO_2$). Global increase in 2021 emissions per fuel types are +5.7% (range 4.5% to 6.8%) for coal, +4.4% (range 3.0% to 5.8%) for oil, +4.3% (range 3.2% to 5.4%) for natural gas, and +6.5% (range 4.8% to 8.3%) for cement.

For China, projected fossil emissions in 2021 are expected to increase by 4.0% (range 2.1% to 5.8%) compared with 2020 emissions, bringing 2021 emissions for China around 3.0 GtC yr^{-1} (11.1 $GtCO_2$ yr^{-1}). Chinese emissions appear to have risen in both 2020 and 2021 despite the economic disruptions of COVID-19. Increases in fuel specific projections for China are +2.5% for coal, +6.0% for oil, +15.3% natural gas, and +6.4% for cement.

For the USA, the Energy Information Administration (EIA) emissions projection for 2021 combined with cement clinker data from USGS gives an increase of 7.6% (range 5.3% to 10.0%) compared to 2020, bringing USA 2021 emissions around 1.4 GtC yr^{-1} (5.1 $GtCO_2$ yr^{-1}). This is based on separate projections for coal +20.4%, oil +9.1%, natural gas -0.4%, and cement +0.7%.

For the European Union, our projection for 2021 is for an increase of 7.6% (range 5.6% to 9.5%) over 2020, with 2021 emissions around 0.8 GtC yr^{-1} (2.8 $GtCO_2$ yr^{-1}). This is based on separate projections for coal of +15.4%, oil +4.3%, natural gas +7.6%, and cement -0.2%.

For India, our projection for 2021 is an increase of 12.6% (range of 10.7% to 13.6%) over 2020, with 2021 emissions around 0.7 GtC yr^{-1} (2.7 $GtCO_2$ yr^{-1}). This is based on separate projections for coal of +14.8%, oil +6.7%, natural gas +4.7%, and cement +21.4%.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

For the rest of the world, the expected growth rate for 2021 is 2.9% (range 1.8% to 4.1%). This is computed using the GDP projection for the world (excluding China, the USA, the EU, and India) of 4.4% made by the IMF (2021) and a decrease in I_{FOS} of -1.7%yr^{-1}, which is the average over 2011-2020. The uncertainty range is based on the standard deviation of the interannual variability in I_{FOS} during 2011–2020 of 0.6%yr^{-1} and our estimates of uncertainty in the IMF's GDP forecast of 0.6%. The methodology allows independent projections for coal, oil, natural gas, cement, and other components, which add to the total emissions in the rest of the world. The fuel specific projected 2021 growth rates for the rest of the world are: +3.0% (range 0.5% to 5.6%) for coal, +2.1% (-0.5% to +4.7%) for oil, +3.9% (2.4% to 5.5%) for natural gas, +4.6% (+2.5% to +6.7%) for cement.

Independently, the IEA has published two forecasts of global fossil energy CO_2 emissions (i.e., a subset of fossil CO_2 emissions), first in April (4.8%; IEA, 2021a) and so revised in October at 4% (IEA, 2021b). Carbon Monitor produces estimates of global emissions with low temporal lag, and their estimates suggest that emissions in the first eight months of 2021 were 7.0% higher than in the same period in 2020 (Carbon Monitor, 2021).

3.2 Emissions from Land Use Changes

3.2.1 Historical period 1850-2020

Cumulative CO_2 emissions from land-use changes (E_{LUC}) for 1850-2020 were 200 ± 65 GtC (Table 8; Fig. 3; Fig. 13). The cumulative emissions from E_{LUC} are particularly uncertain, with large spread among individual estimates of 140 GtC (updated H&N2017), 270 GtC (BLUE), and 195 GtC (OSCAR) for the three bookkeeping models and a similar wide estimate of 190 ± 60 GtC for the DGVMs (all cumulative numbers are rounded to the nearest 5GtC). These estimates are broadly consistent with indirect constraints from vegetation biomass observations, giving a cumulative source of 155 ± 50 GtC over the 1901-2012 period (Li et al., 2017). However, given the large spread a best estimate is difficult to ascertain.

3.2.2 Recent period 1960-2020

In contrast to growing fossil emissions, CO_2 emissions from land-use, land-use change and forestry have remained relatively constant, at around 1.3 ± 0.7 GtC yr^{-1} over the 1970-1999 period, and even show a slight decrease over the last 20 years (Table 6) but with large spread across estimates (Table 5, Fig. 7). Emissions are relatively constant in the DGVMs

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

ensemble of models since the 1970s, with similar mean values until the 1990s as the bookkeeping mean and large model spread (Table 5, Fig. 7). The DGVMs average grows larger than the bookkeeping average in the recent decades and shows no sign of decreasing emissions, which is, however, expected as DGVM-based estimates include the loss of additional sink capacity, which grows with time, while the bookkeeping estimates do not (Appendix D4).

E_{LUC} is a net term of various gross fluxes, which comprise emissions and removals. Gross emissions are on average 2-4 times larger than the net E_{LUC} emissions, and remained largely constant over the last 60 years, with a moderate increase from an average of 3.4 ± 0.9 GtC yr^{-1} for the decade of the 1960s to an average of 3.8 ± 0.6 GtC yr^{-1} during 2011-2020 (Fig.7, Table 5), showing the relevance of land management such as harvesting or rotational agriculture. Increases in gross removals, from 1.9 ± 0.4 GtC yr^{-1} for the 1960s to 2.7 ± 0.4 GtC yr^{-1} for 2011-2020, were larger than the increase in gross emissions. Since the processes behind gross removals, foremost forest regrowth and soil recovery, are all slow, while gross emissions include a large instantaneous component, short-term changes in land-use dynamics, such as a temporary decrease in deforestation, influences gross emissions dynamics more than gross removals dynamics. It is these relative changes to each other that explain the decrease in net E_{LUC} emissions over the last two decades and the last few years. Gross fluxes differ more across the three bookkeeping estimates than net fluxes, which is expected due to different process representation; in particular, treatment of shifting cultivation, which increases both gross emissions and removals, differs across models.

There is a decrease in net CO_2 emissions from land-use change over the last decade (Fig. 7, Table 6), in contrast to earlier estimates of no clear trend across E_{LUC} estimates (Friedlingstein et al., 2020, Hong et al., 2021). The trend in the last decade is now about -4% per year, compared to the +1.8% per year reported by Friedlingstein et al. (2020). This decrease is principally attributable to changes in E_{LUC} estimates from BLUE and OSCAR, which relate to changes in the underlying land-use forcing, LUH2 (Chini et al. 2021, Hurtt et al. 2020) based on HYDE3.3 (Klein Goldewijk et al., 2017a, b). HYDE3.3 now incorporates updated estimates of agricultural areas by the FAO (see Appendix C.2.2) and uses multi-annual land cover maps from satellite remote sensing (ESA CCI Land Cover) to constrain contemporary land cover patterns. These changes lead to lower global E_{LUC} estimates in the

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

last two decades compared to earlier versions of the global carbon budget due most notably to lower emissions from cropland expansion, particularly in the tropical regions. Rosan et al. (2021) showed that for Brazil, the new HYDE3.3 version is closer to independent, regional estimates of land-use and land cover change (MapBiomas, 2021) with respect to spatial patterns, but it shows less land-use and land cover changes than these independent estimates, while HYDE3.2-based estimates had shown higher changes. The update in land-use forcing leads to a decrease in estimated emissions in Brazil across several models after the documented deforestation peak of 2003-2004 that preceded policies and monitoring systems decreasing deforestation rates. However, estimated emissions based on the new land-use forcing do not reflect the rise in Brazilian deforestation in the recent few years (Silva Junior, 2021), and associated increasing emissions from deforestation would have been missed here. The update in FAO agricultural areas in Brazil also implied that substantial interannual variability reported to earlier FAO assessment and captured by the HYDE3.2 version since 2000 was removed. Due to the asymmetry of (fast) decay (like clearing by fire) and (slower) regrowth, such reduced variability is expected to decrease annual emissions. Also, the approach by Houghton and Nassikas (2017) smooths land use area changes before calculating carbon fluxes by a 5-year running mean, hence the three emission estimates are in better agreement than in previous GCB estimates. However, differences still exist, which highlight the need for accurate knowledge of land-use transitions and their spatial and temporal variability. A further caveat is that global land-use change data for model input does not capture forest degradation, which often occurs on small scale or without forest cover changes easily detectable from remote sensing and poses a growing threat to forest area and carbon stocks that may surpass deforestation effects (e.g., Matricardi et al., 2020, Qin et al., 2021).

Highest land-use emissions occur in the tropical regions of all three continents, including the Arc of Deforestation in the Amazon basin (Fig. 6b). This is related to massive expansion of cropland, particularly in the last few decades in Latin America, Southeast Asia, and sub-Saharan Africa Emissions (Hong et al., 2021), to a substantial part for export (Pendrill et al., 2019). Emission intensity is high in many tropical countries, particularly of Southeast Asia, due to high rates of land conversion in regions of carbon-dense and often still pristine, undegraded natural forests (Hong et al., 2021). Emissions are further increased by peat fires

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

in equatorial Asia (GFED4s, van der Werf et al., 2017). Uptake due to land-use change occurs, particularly in Europe, partly related to expanding forest area as a consequence of the forest transition in the 19th and 20th century and subsequent regrowth of forest (Fig. 6b) (Mather 2001; McGrath et al., 2015).

National GHG inventory data (NGHGI) under the LULUCF sector or data submitted by countries to FAOSTAT differ from the global models' definition of E_{LUC} we adopt here in that in the NGHGI reporting, the natural fluxes (S_{LAND}) are counted towards E_{LUC} when they occur on managed land (Grassi et al., 2018). In order to compare our results to the NGHGI approach, we perform a re-mapping of our E_{LUC} estimate by including the S_{LAND} over managed forest from the DGVMs simulations (following Grassi et al., 2021) to the bookkeeping E_{LUC} estimate (see Appendix C.2.3). For the 2010-2019 period, we estimate that 1.5 GtC yr^{-1} of S_{LAND} occurred on managed forests and is then reallocated to E_{LUC} here, as done in the NGHGI method. Doing so, our mean estimate of E_{LUC} is reduced from a source of 1.2 GtC to a sink of -0.4 GtC, very similar to the NGHGI estimate of -0.3 GtC (Table A.8).

Though estimates between GHGI, FAOSTAT, individual process-based models and the mapped budget estimates still differ in value and need further analysis, the approach taken here provides a possibility to relate the global models' and NGHGI approach to each other routinely and thus link the anthropogenic carbon budget estimates of land CO_2 fluxes directly to the Global Stocktake, as part of UNFCCC Paris Agreement.

3.2.3 Final year 2020

The global CO_2 emissions from land-use change are estimated as 0.9 ± 0.7 GtC in 2020, 0.2 GtC lower than 2019, which had featured particularly large peat and tropical deforestation/degradation fires. The surge in deforestation fires in the Amazon, causing about 30% higher emissions from deforestation and degradation fires in 2019 over the previous decade, continued into 2020 (GFED4.1s, van der Werf et al., 2017). However, the unusually dry conditions for a non-El Niño year that occurred in Indonesia in 2019 and led to fire emissions from peat burning, deforestation and degradation in equatorial Asia to be about twice as large as the average over the previous decade (GFED4.1s, van der Werf et al., 2017) ceased in 2020. However, confidence in the annual change remains low.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Land-use change and related emissions may have been affected by the COVID-19 pandemic (e.g. Poulter et al., 2021). Although emissions from tropical deforestation and degradation fires have been decreasing from 2019 to 2020 on the global scale, they increased in Latin America (GFED4s; van der Werf et al., 2017). During the period of the pandemic, environmental protection policies and their implementation may have been weakened in Brazil (Vale et al., 2021). In other countries, too, monitoring capacities and legal enforcement of measures to reduce tropical deforestation have been reduced due to budget restrictions of environmental agencies or impairments to ground-based monitoring that prevents land grabs and tenure conflicts (Brancalion et al., 2020, Amador-Jiménez et al., 2020). Effects of the pandemic on trends in fire activity or forest cover changes are hard to separate from those of general political developments and environmental changes and the long-term consequences of disruptions in agricultural and forestry economic activities (e.g., Gruère and Brooks, 2020; Golar et al., 2020; Beckman and Countryman, 2021) remain to be seen.

3.2.4 Year 2021 Projection

With wet conditions in Indonesia and a below-average fire season in South America our preliminary estimate of E_{LUC} for 2021 is substantially lower than the 2011-2020 average. By the end of September 2021 emissions from tropical deforestation and degradation fires were estimated to be 192 TgC, down from 347 TgC in 2019 and 288 in 2020 (315 TgC 1997-2020 average). Peat fire emissions in Equatorial Asia were estimated to be 1 TgC, down from 117 TgC in 2019 and 2 TgC in 2020 (74 TgC 1997-2020 average) (GFED4.1s, van der Werf et al., 2017). Based on the fire emissions until the end of September, we expect E_{LUC} emissions of around 0.8 GtC in 2021. Note that although our extrapolation is based on tropical deforestation and degradation fires, degradation attributable to selective logging, edge-effects or fragmentation will not be captured.

3.3 Total anthropogenic emissions

Cumulative anthropogenic CO_2 emissions for 1850-2020 totalled 660 ± 65 GtC (2420 ± 240 $GtCO_2$), of which almost 70% (455 GtC) occurred since 1960 and more than 30% (205 GtC) since 2000 (Table 6 and 8). Total anthropogenic emissions more than doubled over the last

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Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

60 years, from 4.6 ± 0.7 GtC yr^{-1} for the decade of the 1960s to an average of 10.6 ± 0.8 GtC yr^{-1} during 2011-2020.

The total anthropogenic CO_2 emissions from fossil plus land-use change amounted to 10.2 ± 0.8 GtC (37.2 ± 2.9 $GtCO_2$) in 2020, while for 2021, we project global total anthropogenic CO_2 emissions from fossil and land use changes to be around 10.5 GtC (38.5 $GtCO_2$).

During the historical period 1850-2020, 30% of historical emissions were from land use change and 70% from fossil emissions. However, fossil emissions have grown significantly since 1960 while land use changes have not, and consequently the contributions of land use change to total anthropogenic emissions were smaller during recent periods (17% during the period 1960-2020 and 10% during 2011-2020).

3.4 Atmospheric CO_2

3.4.1 Historical period 1850-2020

Atmospheric CO_2 concentration was approximately 277 parts per million (ppm) in 1750 (Joos and Spahni, 2008), reaching 300ppm in the 1910s, 350ppm in the late 1980s, and reaching 412.44 ± 0.1 ppm in 2020 (Dlugokencky and Tans, 2021); Fig. 1). The mass of carbon in the atmosphere increased by 48% from 590 GtC in 1750 to 876 GtC in 2020. Current CO_2 concentrations in the atmosphere are unprecedented in the last 2 million years and the current rate of atmospheric CO_2 increase is at least 10 times faster than at any other time during the last 800,000 years (Canadell et al., 2021).

3.4.2 Recent period 1960-2020

The growth rate in atmospheric CO_2 level increased from 1.7 ± 0.07 GtC yr^{-1} in the 1960s to 5.1 ± 0.02 GtC yr^{-1} during 2011-2020 with important decadal variations (Table 6, Fig. 3 and Fig 4).

During the last decade (2011-2020), the growth rate in atmospheric CO_2 concentration continued to increase, albeit with large interannual variability (Fig. 4).

The airborne fraction (AF), defined as the ratio of atmospheric CO_2 growth rate to total anthropogenic emissions:

$$AF = G_{ATM} / (E_{FOS} + E_{LUC}) \quad (2)$$

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

provides a diagnostic of the relative strength of the land and ocean carbon sinks in removing part of the anthropogenic CO_2 perturbation. The evolution of AF over the last 60 years shows no significant trend, remaining nearly at around 45%, albeit showing a large interannual variability driven by the year-to-year variability in G_{ATM} (Fig. 8). The observed stability of the airborne fraction over the 1960-2020 period indicates that the ocean and land CO_2 sinks have been removing on average about 55% of the anthropogenic emissions (see sections 3.5 and 3.6).

3.4.3 Final year 2020

The growth rate in atmospheric CO_2 concentration was 5.0 ± 0.2 GtC (2.37 ± 0.08 ppm) in 2020 (Fig. 4; Dlugokencky and Tans, 2021), very close to the 2011-2020 average. The 2020 decrease in E_{FOS} and E_{LUC} of about 0.7 GtC propagated to an atmospheric CO_2 growth rate reduction of 0.38 GtC (0.18 ppm), given the significant interannual variability of the land carbon sink.

3.4.4 Year 2021 Projection

The 2021 growth in atmospheric CO_2 concentration (G_{ATM}) is projected to be about 4.2 GtC (1.98 ppm) based on GLO observations until the end of July 2021, bringing the atmospheric CO_2 concentration to an expected level of 414.7 ppm averaged over the year, 49% over the pre-industrial level.

3.5 Ocean Sink

3.5.1 Historical period 1850-2020

Cumulated since 1850, the ocean sink adds up to 170 ± 35 GtC, with two thirds of this amount being taken up by the global ocean since 1960. Over the historical period, the ocean sink increased in pace with the anthropogenic emissions exponential increase (Fig. 3b). Since 1850, the ocean has removed 26% of total anthropogenic emissions.

3.5.2 Recent period 1960-2020

The ocean CO_2 sink increased from 1.1 ± 0.4 GtC yr^{-1} in the 1960s to 2.8 ± 0.4 GtC yr^{-1} during 2011-2020 (Table 6), with interannual variations of the order of a few tenths of GtC yr^{-1} (Fig. 9). The ocean-borne fraction ($S_{OCEAN}/(E_{FOS}+E_{LUC})$ has been remarkably constant around 25%

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

on average (Fig. 8). Variations around this mean illustrate decadal variability of the ocean carbon sink. So far, there is no indication of a decrease in the ocean-borne fraction from 1960 to 2020. The increase of the ocean sink is primarily driven by the increased atmospheric CO_2 concentration, with the strongest CO_2 induced signal in the North Atlantic and the Southern Ocean (Fig. 10a). The effect of climate change is much weaker, reducing the ocean sink globally by 0.12 ± 0.07 GtC yr^{-1} or 5% (2011-2020, range -0.8 to -7.4%), and does not show clear spatial patterns across the GOBMs ensemble (Fig. 10b). This is the combined effect of change and variability in all atmospheric forcing fields, previously attributed to wind and temperature changes in one model (LeQuéré et al., 2010).

The global net air-sea CO_2 flux is a residual of large natural and anthropogenic CO_2 fluxes into and out of the ocean with distinct regional and seasonal variations (Fig. 6 and B1). Natural fluxes dominate on regional scales, but largely cancel out when integrated globally (Gruber et al., 2009). Mid-latitudes in all basins and the high-latitude North Atlantic dominate the ocean CO_2 uptake where low temperatures and high wind speeds facilitate CO_2 uptake at the surface (Takahashi et al., 2009). In these regions, formation of mode, intermediate and deep-water masses transport anthropogenic carbon into the ocean interior, thus allowing for continued CO_2 uptake at the surface. Outgassing of natural CO_2 occurs mostly in the tropics, especially in the equatorial upwelling region, and to a lesser extent in the North Pacific and polar Southern Ocean, mirroring a well-established understanding of regional patterns of air-sea CO_2 exchange (e.g., Takahashi et al., 2009, Gruber et al., 2009). These patterns are also noticeable in the Surface Ocean CO_2 Atlas (SOCAT) dataset, where an ocean fCO_2 value above the atmospheric level indicates outgassing (Fig. B1). This map further illustrates the data-sparsity in the Indian Ocean and the southern hemisphere in general.

Interannual variability of the ocean carbon sink is driven by climate variability with a first-order effect from a stronger ocean sink during large El Niño events (e.g., 1997-1998) (Fig. 9; Rödenbeck et al., 2014, Hauck et al., 2020). The GOBMs show the same patterns of decadal variability as the mean of the fCO_2-based data products, with a stagnation of the ocean sink in the 1990s and a strengthening since the early 2000s (Fig. 9, Le Quéré et al., 2007; Landschützer et al., 2015, 2016; DeVries et al., 2017; Hauck et al., 2020; McKinley et al., 2020). Different explanations have been proposed for this decadal variability, ranging from the ocean's response to changes in atmospheric wind and pressure systems (e.g., Le Quéré et al., 2007, Keppler and Landschützer, 2019), including variations in upper ocean overturning circulation (DeVries et al., 2017) to the eruption of Mount Pinatubo and its effects on sea surface temperature and slowed atmospheric CO_2 growth rate in the 1990s (McKinley et al., 2020). The main origin of the decadal variability is a matter of debate with a number of studies initially pointing to the Southern Ocean (see review in Canadell et al., 2021), but also contributions from the North Atlantic and North Pacific (Landschützer et al., 2016, DeVries et al., 2019), or a global signal (McKinley et al., 2020) were proposed.

Although all individual GOBMs and data-products fall within the observational constraint, the ensemble means of GOBMs, and data-products adjusted for the riverine flux diverge over time with a mean offset increasing from 0.24 GtC yr^{-1} in the 1990s to 0.66 GtC yr^{-1} in the decade 2011-2020 and reaching 1.1 GtC yr^{-1} in 2020. The S_{OCEAN} trend diverges with a factor two difference since 2002 (GOBMs: 0.3 ± 0.1 GtC yr^{-1} per decade, data-products: 0.7 ± 0.2 GtC yr^{-1} per decade, best estimate: 0.5 GtC yr^{-1} per decade) and with a factor of three since 2010 (GOBMs: 0.3 ± 0.1 GtC yr^{-1} per decade, data-products: 0.9 ± 0.3 GtC yr^{-1} per decade , best estimate: 0.6 GtC yr^{-1} per decade). The GOBMs estimate is lower than in the previous global carbon budget (Friedlingstein et al., 2020), because one high-sink model was not available. The effect of two models (CNRM, MOM6-COBALT) revising their estimates downwards was largely balanced by two models revising their estimate upwards (FESOM-REcoM, PlankTOM).

The discrepancy between the two types of estimates stems mostly from a larger Southern Ocean sink in the data-products prior to 2001, and from a larger S_{OCEAN} trend in the northern and southern extra-tropics since then (Fig. 12). Possible explanations for the discrepancy in the Southern Ocean could be missing winter observations and data sparsity in general (Bushinsky et al., 2019, Gloege et al., 2021), model biases (as indicated by the large model spread in the South, Figure 12, and the larger model-data mismatch, Figure B2), or uncertainties in the regional river flux adjustment (Hauck et al., 2020, Lacroix et al., 2020).

During 2010-2016, the ocean CO_2 sink appears to have intensified in line with the expected increase from atmospheric CO_2 (McKinley et al., 2020). This effect is stronger in the fCO_2-based data products (Fig. 9, GOBMs: +0.43 GtC yr^{-1}, data-products: +0.56 GtC yr^{-1}). The reduction of -0.09 GtC yr^{-1} (range: -0.30 to +0.12 GtC yr^{-1}) in the ocean CO_2 sink in 2017 is

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

consistent with the return to normal conditions after the El Niño in 2015/16, which caused an enhanced sink in previous years. After 2017, the GOBMs ensemble mean suggests the ocean sink levelling off at about 2.5 GtC yr^{-1}, whereas the data-products' estimate increases by 0.3 GtC yr^{-1} over the same period.

3.5.3 Final year 2020

The estimated ocean CO_2 sink was 3.0 ± 0.4 GtC in 2020. This is the average of GOBMs and data-products, and is a small increase of 0.02 GtC compared to 2019, in line with the competing effects from an expected sink strengthening from atmospheric CO_2 growth and expected sink weakening from La Nina conditions. There is, however, a substantial difference between GOBMs and fCO_2-based data-products in their mean 2020 S_{OCEAN} estimate (GOBMs: 2.5 GtC, data-products: 3.5 GtC). While the GOBMs simulate a stagnation of the sink from 2019 to 2020 (-0.02 ±0.11 GtCGtC), the data-products suggest an increase by 0.06 GtC, although not significant at the 1σ level (±0.13 GtC). Four models and four data products show an increase of S_{OCEAN} (GOBMs up to +0.18 GtC, data-product up to +0.21 GtC), while four models and three data products show no change or a decrease of S_{OCEAN} (GOBMs down to -0.12 GtC, data-products down to -0.13 GtC; Fig. 9). The data-products have a larger uncertainty at the tails of the reconstructed time series (e.g., Watson et al., 2020). Specifically, the data-products' estimate of the last year is regularly adjusted in the following release owing to the tail effect and an incrementally increasing data availability with 1-5 years lag (Figure 9 bottom).

3.5.4 Year 2021 Projection

Using a feed-forward neural network method (see section 2.4) we project an ocean sink of 2.9 GtC for 2021. This is a reduction of the sink by 0.1 GtC relative to the 2020 value which we attribute to La Niña conditions in January to May 2021 and projections of a re-emergence of La Niña later in the year.

3.5.5 Model Evaluation

The evaluation of the ocean estimates (Fig. B2) shows an RMSE from annually detrended data of 1.3 to 2.8 µatm for the seven fCO_2-based data products over the globe, relative to the fCO_2 observations from the SOCAT v2021 dataset for the period 1990-2020. The GOBMs

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

RMSEs are larger and range from 3.3 to 5.9 µatm. The RMSEs are generally larger at high latitudes compared to the tropics, for both the data products and the GOBMs. The data products have RMSEs of 1.3 to 3.6 µatm in the tropics, 1.3 to 2.7 µatm in the north, and 2.2 to 6.1 µatm in the south. Note that the data products are based on the SOCAT v2021 database, hence the latter are not independent dataset for the evaluation of the data products. The GOBMs RMSEs are more spread across regions, ranging from 2.7 to 4.3 µatm in the tropics, 2.9 to 6.9 µatm in the North, and 6.4 to 9.8 µatm in the South. The higher RMSEs occur in regions with stronger climate variability, such as the northern and southern high latitudes (poleward of the subtropical gyres). The upper-range of the model RMSEs have decreased somewhat relative to Friedlingstein et al. (2020), owing to one model with upper-end RMSE not being represented this year, and the reduction of RMSE in one model (MPIOM-HAMOCC6), presumably related to the inclusion of riverine carbon fluxes.

The additional simulation C allows to separate the steady-state anthropogenic carbon component (sim C - sim B) and to compare the model flux and DIC inventory change directly to the interior ocean estimate of Gruber et al (2019) without further assumptions. The GOBMs ensemble average of steady-state anthropogenic carbon inventory change 1994-2007 amounts to 2.1 GtC yr^{-1}, and is significantly lower than the 2.6 ± 0.3 GtC yr^{-1} estimated by Gruber et al (2019). Only the three models with the highest sink estimate fall within the range reported by Gruber et al. (2019). This suggests that most of the models underestimates anthropogenic carbon uptake by the ocean likely due to biases in ocean carbon transport and mixing from the surface mixed layer to the ocean interior.

The reported S_{OCEAN} estimate from GOBMs and data-products is 2.1 ± 0.4 GtC yr^{-1} over the period 1994 to 2007, which is in agreement with the ocean interior estimate of 2.2 ± 0.4 GtC yr^{-1} when accounting for the climate effect on the natural CO_2 flux of −0.4 ± 0.24 GtC yr^{-1} (Gruber et al., 2019) to match the definition of S_{OCEAN} used here (Hauck et al., 2020). This comparison depends critically on the estimate of the climate effect on the natural CO_2 flux, which is smaller from the GOBMs (section 3.5.2) than in Gruber et al. (2019).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

3.6 Land Sink

3.6.1 Historical period 1850-2020

Cumulated since 1850, the terrestrial CO_2 sink amounts to 195 ± 45 GtC, 30% of total anthropogenic emissions. Over the historical period, the sink increased in pace with the anthropogenic emissions exponential increase (Fig. 3b).

3.6.2 Recent period 1960-2020

The terrestrial CO_2 sink increased from 1.2 ± 0.5 GtC yr^{-1} in the 1960s to 3.1 ± 0.6 GtC yr^{-1} during 2010-2019, with important interannual variations of up to 2 GtC yr^{-1} generally showing a decreased land sink during El Niño events (Fig. 7), responsible for the corresponding enhanced growth rate in atmospheric CO_2 concentration. The larger land CO_2 sink during 2010-2019 compared to the 1960s is reproduced by all the DGVMs in response to the combined atmospheric CO_2 increase and the changes in climate, and consistent with constraints from the other budget terms (Table 5).

Over the period 1960 to present the increase in the global terrestrial CO_2 sink is largely attributed to the CO_2 fertilization effect in the models (Prentice et al., 2001, Piao et al., 2009), directly stimulating plant photosynthesis and increased plant water use in water limited systems, with a small negative contribution of climate change (Fig. 10). There is a range of evidence to support a positive terrestrial carbon sink in response to increasing atmospheric CO_2, albeit with uncertain magnitude (Walker et al., 2021). As expected from theory the greatest CO_2 effect is simulated in the tropical forest regions, associated with warm temperatures and long growing seasons (Hickler et al., 2008) (Fig. 10a). However, evidence from tropical intact forest plots indicate an overall decline in the land sink across Amazonia (1985-2011), attributed to enhanced mortality offsetting productivity gains (Brienen et al., 2005, Hubau et al., 2020). During 2011-2020 the land sink is positive in all regions (Fig. 6) with the exception of central and eastern Brazil, Southwest USA and northern Mexico, Southeast Europe and Central Asia, South Africa, and eastern Australia, where the negative effects of climate variability and change (i.e. reduced rainfall) counterbalance CO_2 effects. This is clearly visible on Figure 10 where the effects of CO_2 (Fig. 10a) and climate (Fig. 10b) as simulated by the DGVMs are isolated. The negative effect of climate is the strongest in most of South America, Central America, Southwest US and

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Central Europe (Fig. 10b). Globally, climate change reduces the land sink by 0.45 ± 0.39 GtC yr^{-1} (2011-2020).

In the past years several regions experienced record-setting fire events. While global burned area has declined over the past decades mostly due to declining fire activity in savannas (Andela et al., 2017), forest fire emissions are rising and have the potential to counter the negative fire trend in savannas (Zheng et al., 2021). Noteworthy events include the 2019-2020 Black Summer event in Australia (emissions of roughly 0.2 GtC; van der Velde et al., 2021) and Siberia in 2021 where emissions approached 0.4 GtC or three times the 1997-2020 average according to GFED4s. While other regions, including Western US and Mediterranean Europe, also experienced intense fire seasons in 2021 their emissions are substantially lower.

Despite these regional negative effects of climate change on S_{LAND}, the efficiency of land to remove anthropogenic CO_2 emissions has remained broadly constant over the last six decades, with a land-borne fraction ($S_{LAND}/(E_{FOS}+E_{LUC})$ of ~30% (Fig 8).

3.6.3 Final year 2020

The terrestrial CO_2 sink from the DGVMs ensemble was 2.9 ± 1.0 GtC in 2020, slightly below the decadal average of 3.1 GtC yr^{-1} (Fig. 4, Table 6). We note that the DGVMs estimate for 2020 is significantly larger than the 2.1 ± 0.9 GtC yr^{-1} estimate from the residual sink from the global budget ($E_{FOS}+E_{LUC}-G_{ATM}-S_{OCEAN}$) (Table 5).

3.6.4 Year 2021 Projection

Using a feed-forward neural network method (see section 2.5) we project a land sink of 3.3 GtC for 2021. This is an increase of the land sink by 0.3 GtC relative to the 2020 value which we attribute to La Niña conditions in 2021.

3.6.5 Model Evaluation

The evaluation of the DGVMs (Fig. B3) shows generally high skill scores across models for runoff, and to a lesser extent for vegetation biomass, GPP, and ecosystem respiration (Fig. B3, left panel). Skill score was lowest for leaf area index and net ecosystem exchange, with a widest disparity among models for soil carbon. Further analysis of the results will be provided separately, focusing on the strengths and weaknesses in the DGVMs ensemble and its validity for use in the global carbon budget.

3.7 Partitioning the carbon sinks

3.7.1 Global sinks and spread of estimates

In the period 2011-2020, the bottom-up view of total global carbon sinks provided by the GCB (S_{OCEAN} + S_{LAND}– E_{LUC}) agrees closely with the top-down budget delivered by the atmospheric inversions. Figure 11 shows both total sink estimates of the last decade split by land and ocean, which match the difference between G_{ATM} and E_{FOS} to within 0.06–0.17 GtC yr^{-1} for inverse models, and to 0.3 GtC yr^{-1} for the GCB mean. The latter represents the B_{IM} discussed in Section 3.8, which by design is minimal for the inverse models.
The distributions based on the individual models and data products reveal substantial spread but converge near the decadal means quoted in Tables 5 and 6. Sink estimates for S_{OCEAN} and from inverse models are mostly non-Gaussian, while the ensemble of DGVMs appears more normally distributed justifying the use of a multi-model mean and standard deviation for their errors in the budget. Noteworthy is that the tails of the distributions provided by the land and ocean bottom-up estimates would not agree with the global constraint provided by the fossil fuel emissions and the observed atmospheric CO_2 growth rate (E_{FOS} – G_{ATM}). This illustrates the power of the atmospheric joint constraint from G_{ATM} and the global CO_2 observation network it derives from.

3.7.2 Total atmosphere-to-land fluxes

The total atmosphere-to-land fluxes (S_{LAND} – E_{LUC}), calculated here as the difference between S_{LAND} from the DGVMs and E_{LUC} from the bookkeeping models, amounts to a 1.9 ± 0.9 GtC yr^{-1} sink during 2011-2020 (Table 5). Estimates of total atmosphere-to-land fluxes (S_{LAND} – E_{LUC}) from the DGVMs alone (1.6 ± 0.6 GtC yr^{-1}) are consistent with this estimate and also with the global carbon budget constraint (E_{FOS} – G_{ATM} – S_{OCEAN}, 1.7 ± 0.8 GtC yr^{-1} Table 5). Consistent with the bookkeeping models estimates, the DGVM-based E_{LUC} is substantially lower than in Friedlingstein et al., (2020) due to the improved land cover forcing (see section 3.2.2), increasing their total atmosphere-to-land fluxes and hence the consistency with the budget constraint. For the last decade (2011-2020), the inversions estimate the net

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

atmosphere-to-land uptake to lie within a range of 1.3 to 2.0 GtC yr^{-1}, consistent with the GCB and DGVMs estimates of $S_{LAND} - E_{LUC}$ (Figure 11, Figure 12 top row).

3.7.3 Total atmosphere-to-ocean fluxes

For the 2011-2020 period, the GOBMs (2.5 ± 0.6 GtC yr^{-1}) produce a lower estimate for the ocean sink than the fCO_2-based data products (3.1 ± 0.5 GtC yr^{-1}), which shows up in Figure 11 as a separate peak in the distribution from the GOBMs (triangle symbols pointing right) and from the fCO_2-based products (triangle symbols pointing left). Atmospheric inversions (2.6 to 3.1 GtC yr^{-1}) also suggest higher ocean uptake in the recent decade (Figure 11, Figure 12 top row). In interpreting these differences, we caution that the riverine transport of carbon taken up on land and outgassing from the ocean is a substantial (0.6 GtC yr^{-1}) and uncertain term that separates the various methods. A recent estimate of decadal ocean uptake from observed O_2/N_2 ratios (Tohjima et al., 2019) also points towards a larger ocean sink, albeit with large uncertainty (2012-2016: 3.1 ± 1.5 GtC yr^{-1}).

3.7.4 Regional breakdown and interannual variability

Figure 12 also shows the latitudinal partitioning of the total atmosphere-to-surface fluxes excluding fossil CO_2 emissions ($S_{OCEAN} + S_{LAND} - E_{LUC}$) according to the multi-model average estimates from GOBMs and ocean fCO_2-based products (S_{OCEAN}) and DGVMs ($S_{LAND} - E_{LUC}$), and from atmospheric inversions (S_{OCEAN} and $S_{LAND} - E_{LUC}$).

3.7.4.1 North

Despite being one of the most densely observed and studied regions of our globe, annual mean carbon sink estimates in the northern extra-tropics (north of 30°N) continue to differ by about 0.5 GtC yr^{-1}. The atmospheric inversions suggest an atmosphere-to-surface sink ($S_{OCEAN}+ S_{LAND} - E_{LUC}$) for 2011-2020 of 2.0 to 3.4 GtC yr^{-1}, which is higher than the process models' estimate of 2.1 ± 0.5 GtC yr^{-1} (Fig. 12). The GOBMs (1.1 ± 0.2 GtC yr^{-1}), fCO_2-based data products (1.3 ± 0.1 GtC yr^{-1}), and inversion models (0.9 to 1.5 GtC yr^{-1}) produce consistent estimates of the ocean sink. Thus, the difference mainly arises from the total land flux ($S_{LAND} - E_{LUC}$) estimate, which is 1.0 ± 0.4 GtC yr^{-1} in the DGVMs compared to 0.7 to 2.4 GtC yr^{-1} in the atmospheric inversions (Figure 12, second row).

Discrepancies in the northern land fluxes conforms with persistent issues surrounding the quantification of the drivers of the global net land CO_2 flux (Arneth et al., 2017; Huntzinger

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

et al., 2017) and the distribution of atmosphere-to-land fluxes between the tropics and high northern latitudes (Baccini et al., 2017; Schimel et al., 2015; Stephens et al., 2007; Ciais et al. 2019; Gaubert et al,. 2019).

In the northern extratropics, the process models, inversions, and fCO_2-based data products consistently suggest that most of the variability stems from the land (Fig. 12). Inversions generally estimate similar interannual variations (IAV) over land to DGVMs (0.28 – 0.47 vs 0.20 – 0.73 GtC yr^{-1}, averaged over 1990-2020), and they have higher IAV in ocean fluxes (0.03 – 0.19 GtC yr^{-1}) relative to GOBMs (0.03 – 0.05 GtC yr^{-1}, Fig. B2), and fCO_2-based data products (0.03 – 0.09 GtC yr^{-1}).

3.7.4.2 Tropics

In the tropics (30°S-30°N), both the atmospheric inversions and process models estimate a total carbon balance (S_{OCEAN}+S_{LAND}-E_{LUC}) that is close to neutral over the past decade. The GOBMs (0.0 ± 0.3 GtC yr^{-1}), fCO_2-based data products (0.03 ± 0.2 GtC yr^{-1}), and inversion models (-0.2 to 0.2 GtC yr^{-1}) all indicate an approximately neutral tropical ocean flux (see Fig. B1 for spatial patterns). DGVMs indicate a net land sink (S_{LAND}-E_{LUC}) of 0.6 ± 0.3 GtC yr^{-1}, whereas the inversion models indicate a net land flux between -0.7 and 0.9 GtC yr^{-1}, though with high uncertainty (Figure 12, third row).

The tropical lands are the origin of most of the atmospheric CO_2 interannual variability (Ahlström et al., 2015), consistently among the process models and inversions (Fig. 12). The interannual variability in the tropics is similar among the ocean data products (0.07 – 0.15 GtC yr−1) and the models (0.07 – 0.15 GtC yr^{-1}, Fig. B2), which is the highest ocean sink variability of all regions. The DGVMs and inversions indicate that atmosphere-to-land CO_2 fluxes are more variable than atmosphere-to-ocean CO_2 fluxes in the tropics, with interannual variability of 0.4 to 1.2 and 0.6 to 1.1 GtC yr^{-1} respectively.

3.7.4.3 South

In the southern extra-tropics (south of 30°S), the atmospheric inversions suggest a total atmosphere-to-surface sink (S_{OCEAN}+S_{LAND}-E_{LUC}) for 2011-2020 of 1.6 to 1.9 GtC yr^{-1}, slightly higher than the process models' estimate of 1.4 ± 0.3 GtC yr^{-1} (Fig. 12). An approximately neutral total land flux (S_{LAND}-E_{LUC}) for the southern extra-tropics is estimated by both the DGVMs (0.02 ± 0.05 GtC yr^{-1}) and the inversion models (sink of -0.1 to 0.2 GtC yr^{-1}). This means nearly all carbon uptake is due to oceanic sinks south of 30°S. The southern ocean flux in the fCO_2-based data products (1.7 ± 0.1 GtC yr^{-1}) and inversion estimates (1.4 to 1.8 GtCyr-1) is higher than in the GOBMs (1.4 ± 0.3 GtC yr^{-1}) (Figure 12, bottom row). This might be explained by the data-products potentially underestimating the winter CO_2 outgassing south of the Polar Front (Bushinsky et al., 2019), by model biases, or by the uncertainty in the regional distribution of the river flux adjustment (Aumont et al., 2001, Lacroix et al., 2020) applied to fCO_2-based data products and inverse models to isolate the anthropogenic S_{OCEAN} flux. CO_2 fluxes from this region are more sparsely sampled by all methods, especially in wintertime (Fig. B1).

The interannual variability in the southern extra-tropics is low because of the dominance of ocean area with low variability compared to land areas. The split between land (S_{LAND}-E_{LUC}) and ocean (S_{OCEAN}) shows a substantial contribution to variability in the south coming from the land, with no consistency between the DGVMs and the inversions or among inversions. This is expected due to the difficulty of separating exactly the land and oceanic fluxes when viewed from atmospheric observations alone. The S_{OCEAN} interannual variability was found to be higher in the fCO_2-based data products (0.09 to 0.14 GtC yr−1) compared to GOBMs (0.04 to 0.06 GtC yr−1) in 1990-2020 (Fig. B2). Model subsampling experiments recently illustrated that observation-based products may overestimate decadal variability in the Southern Ocean carbon sink by 30% due to data sparsity, based on one data product with the highest decadal variability (Gloege et al., 2021).

3.7.4.4 Tropical vs northern land uptake

A continuing conundrum is the partitioning of the global atmosphere-land flux between the northern hemisphere land, and the tropical land (Stephens et al., 2017; Pan et al., 2011; Gaubert et al., 2019). It is of importance because each region has its own history of land-use change, climate drivers, and impact of increasing atmospheric CO_2 and nitrogen deposition. Quantifying the magnitude of each sink is a prerequisite to understanding how each individual driver impacts the tropical and mid/high-latitude carbon balance.

We define the North-South (N-S) difference as net atmosphere-land flux north of 30N minus the net atmosphere-land flux south of 30°N. For the inversions, the N-S difference ranges from -0.1 GtC yr^{-1} to 2.9 GtC yr^{-1} across this year's inversion ensemble with an equal

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

preference across models for either a small Northern land sink and a tropical land sink (small N-S difference), a medium Northern land sink and a neutral tropical land flux (medium N-S difference), or a large Northern land sink and a tropical land source (large N-S difference).

In the ensemble of DGVMs the N-S difference is 0.5 ± 0.5 GtC $yr^{-1,}$ a much narrower range than the one from inversions. Only three DGVMs have a N-S difference larger than 1.0 GtC yr^{-1}. The larger agreement across DGVMs than across inversions is to be expected as there is no correlation between Northern and Tropical land sinks in the DGVMs as opposed to the inversions where the sum of the two regions being well-constrained leads to an anti-correlation between these two regions. The much smaller spread in the N-S difference between the DGVMs could help to scrutinize the inverse models further. For example, a large northern land sink and a tropical land source in an inversion would suggest a large sensitivity to CO_2 fertilization (the dominant factor driving the land sinks) for Northern ecosystems, which would be not mirrored by tropical ecosystems. Such a combination could be hard to reconcile with the process understanding gained from the DGVMs ensembles and independent measurements (e.g., FACE experiments). Such investigations will be further pursued in the upcoming assessment from REgional Carbon Cycle Assessment and Processes (RECCAP2; Ciais et al., 2020).

3.8 Closing the Global Carbon Cycle

3.8.1 Partitioning of Cumulative Emissions and Sink Fluxes

The global carbon budget over the historical period (1850-2020) is shown in Fig. 3.

Emissions during the period 1850-2020 amounted to 660 ± 65 GtC and were partitioned among the atmosphere (270 ± 5 GtC; 41%), ocean (170 ± 35 GtC; 26%), and the land (195 ± 45 GtC; 30%). The cumulative land sink is almost equal to the cumulative land-use emissions (200 ± 65 GtC), making the global land nearly neutral over the whole 1850-2020 period.

The use of nearly independent estimates for the individual terms shows a cumulative budget imbalance of 25 GtC (4%) during 1850-2020 (Fig. 3, Table 8), which, if correct, suggests that emissions are slightly too high by the same proportion (4%) or that the combined land and ocean sinks are slightly underestimated (by about 7%). The bulk of the imbalance could originate from the estimation of large E_{LUC} between the mid 1920s and the

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

mid 1960s which is unmatched by a growth in atmospheric CO_2 concentration as recorded in ice cores (Fig. 3). However, the known loss of additional sink capacity of 30-40 GtC (over the 1850-2020 period) due to reduced forest cover has not been accounted for in our method and would further exacerbate the budget imbalance (Section 2.7.4).

For the more recent 1960-2020 period where direct atmospheric CO_2 measurements are available, 375 ± 20 GtC (82%) of the total emissions ($E_{FOS} + E_{LUC}$) were caused by fossil CO_2 emissions, and 80 ± 45 GtC (18%) by land-use change (Table 8). The total emissions were partitioned among the atmosphere (205 ± 5 GtC; 47%), ocean (115 ± 25 GtC; 25%), and the land (135 ± 25 GtC; 30%), with a near zero unattributed budget imbalance. All components except land-use change emissions have significantly grown since 1960, with important interannual variability in the growth rate in atmospheric CO_2 concentration and in the land CO_2 sink (Fig. 4), and some decadal variability in all terms (Table 6). Differences with previous budget releases are documented in Fig. B5.

The global carbon budget averaged over the last decade (2011-2020) is shown in Fig. 2, Fig. 13 (right panel) and Table 6. For this time period, 90% of the total emissions ($E_{FOS} + E_{LUC}$) were from fossil CO_2 emissions (E_{FOS}), and 10% from land-use change (E_{LUC}). The total emissions were partitioned among the atmosphere (47%), ocean (26%) and land (29%), with a near-zero unattributed budget imbalance (~3%). For single years, the budget imbalance can be larger (Figure 4). For 2020, the combination of our sources and sinks estimates leads to a B_{IM} of -0.8 GtC, suggesting an underestimation of the anthropogenic sources (potentially E_{LUC}), and/or an overestimation of the combined land and ocean sinks

3.8.2 Carbon Budget Imbalance

The carbon budget imbalance (B_{IM}; Eq. 1, Fig.4) quantifies the mismatch between the estimated total emissions and the estimated changes in the atmosphere, land, and ocean reservoirs. The mean budget imbalance from 1960 to 2020 is very small (average of 0.03 GtC $yr^{-1)}$ and shows no trend over the full time series. The process models (GOBMs and DGVMs) and data-products have been selected to match observational constraints in the 1990s, but no further constraints have been applied to their representation of trend and variability. Therefore, the near-zero mean and trend in the budget imbalance is seen as evidence of a coherent community understanding of the emissions and their partitioning on those time

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

scales (Fig. 4). However, the budget imbalance shows substantial variability of the order of ±1 GtC yr^{-1}, particularly over semi-decadal time scales, although most of the variability is within the uncertainty of the estimates. The positive carbon imbalance during the 1960s, and early 1990s, indicates that either the emissions were overestimated, or the sinks were underestimated during these periods. The reverse is true for the 1970s, 1980s, and for the 2011-2020 period (Fig. 4, Table 6).

We cannot attribute the cause of the variability in the budget imbalance with our analysis, we only note that the budget imbalance is unlikely to be explained by errors or biases in the emissions alone because of its large semi-decadal variability component, a variability that is untypical of emissions and has not changed in the past 60 years despite a near tripling in emissions (Fig. 4). Errors in S_{LAND} and S_{OCEAN} are more likely to be the main cause for the budget imbalance. For example, underestimation of the S_{LAND} by DGVMs has been reported following the eruption of Mount Pinatubo in 1991 possibly due to missing responses to changes in diffuse radiation (Mercado et al., 2009). Although in GCB2021 we have for the first time accounted for aerosol effects on solar radiation quantity and quality (diffuse vs direct), most DGVMs only used the former as input (i.e., total solar radiation). Thus, the ensemble mean may not capture the full effects of volcanic eruptions, i.e. associated with high light scattering sulphate aerosols, on the land carbon sink (O'Sullivan et al., 2021). DGVMs are suspected to overestimate the land sink in response to the wet decade of the 1970s (Sitch et al., 2008). Quasi-decadal variability in the ocean sink has also been reported, with all methods agreeing on a smaller than expected ocean CO_2 sink in the 1990s and a larger than expected sink in the 2000s (Fig. 9; Landschützer et al., 2016, DeVries et al., 2019, Hauck et al., 2020, McKinley et al., 2020). Errors in sink estimates could also be driven by errors in the climatic forcing data, particularly precipitation for S_{LAND} and wind for S_{OCEAN}. The budget imbalance (B_{IM}) was negative (-0.3 GtC yr^{-1}) on average over 2011-2020, although the B_{IM} uncertainty is large (1.1 GtC yr^{-1} over the decade). Also, the B_{IM} shows substantial departure from zero on yearly time scales (Fig. 4), highlighting unresolved variability of the carbon cycle, likely in the land sink (S_{LAND}), given its large year to year variability (Fig. 4e and 7).

Both the budget imbalance (B_{IM}, Table 6) and the residual land sink from the global budget (E_{FOS}+E_{LUC}-G_{ATM}-S_{OCEAN}, Table 5) include an error term due to the inconsistencies that arises

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

from using E_{LUC} from bookkeeping models, and S_{LAND} from DGVMs, most notably the loss of additional sink capacity (see section 2.7). Other differences include a better accounting of land use changes practices and processes in bookkeeping models than in DGVMs, or the bookkeeping models error of having present-day observed carbon densities fixed in the past. That the budget imbalance shows no clear trend towards larger values over time is an indication that these inconsistencies probably play a minor role compared to other errors in S_{LAND} or S_{OCEAN}.

Although the budget imbalance is near zero for the recent decades, it could be due to compensation of errors. We cannot exclude an overestimation of CO_2 emissions, particularly from land-use change, given their large uncertainty, as has been suggested elsewhere (Piao et al., 2018), combined with an underestimate of the sinks. A larger S_{LAND} would reconcile model results with inversion estimates for fluxes in the total land during the past decade (Fig. 12; Table 5). Likewise, a larger S_{OCEAN} is also possible given the higher estimates from the data-products (see section 3.1.2, Fig. 9 and Fig. 12) and the recently suggested upward correction of the ocean carbon sink (Watson et al., 2020, Fig. 9). If S_{OCEAN} were to be based on data-products alone, with all data-products including the Watson et al. (2020) adjustment, this would result in a 2011-2020 S_{OCEAN} of nearly 4 GtC yr^{-1}, outside of the range supported by the atmospheric inversions, with a negative B_{IM} of more than 1 GtC yr^{-1} indicating that a closure of the budget could only be achieved with either anthropogenic emissions being larger and/or the net land sink being substantially smaller than estimated here. More integrated use of observations in the Global Carbon Budget, either on their own or for further constraining model results, should help resolve some of the budget imbalance (Peters et al., 2017).

4 Tracking progress towards mitigation targets

Fossil CO_2 emissions growth peaked at 3% per year during the 2000s, driven by the rapid growth in Chinese emissions. In the last decade, however, the growth rate for the preceding 10 years has slowly declined, reaching a low 0.4% per year from 2012-2021 (including the 2020 global decline and the expected 2021 emissions rebound). While this slowdown in global fossil CO_2 emissions growth is welcome, it is far from what is needed to be consistent with the temperature goals of the Paris Agreement.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Since the 1990s, the average growth rate of fossil CO_2 emissions has continuously declined across the group of developed countries of the Organisation for Economic Co-operation and Development (OECD), with emissions peaking in around 2005 and now declining at around 1% yr^{-1} (Le Quéré et al., 2021). In the decade 2010-2019, territorial fossil CO_2 emissions decreased significantly (at the 95% confidence level) in 23 countries whose economies grew significantly (also at the 95% confidence level): Barbados, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Israel, Japan, Luxembourg, North Macedonia, Malta, Mexico, Netherlands, Slovakia, Slovenia, Solomon Islands, Sweden, Switzerland, Tuvalu, United Kingdom and the USA (updated from Le Quéré et al., 2019). Altogether, these 23 countries contribute to 2.5 GtC yr^{-1} over the last decade, about one quarter of world CO_2 fossil emissions. Consumption-based emissions are also falling significantly in 15 of these countries (Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Israel, Japan, Mexico, Netherlands, Slovenia, Sweden, United Kingdom, and the USA). Figure 14 shows that the emission declines in the USA and the EU27 are primarily driven by increased decarbonisation (CO_2 emissions per unit energy) in the last decade compared to the previous, with smaller contributions in the EU27 from slightly weaker economic growth and slightly larger declines in energy per GDP. These countries have stable or declining energy use and so decarbonisation policies replace existing fossil fuel infrastructure (Le Quéré et al. 2019).

In contrast, fossil CO_2 emissions continue to grow in non-OECD countries, although the growth rate has slowed from over 5% yr^{-1} during the 2000s to around 2% yr^{-1} in the last decade. A large part of this slowdown in non-OECD countries is due to China, which has seen emissions growth declining from nearly 10% yr^{-1} in the 2000s to 2% yr^{-1} in the last decade. Excluding China, non-OECD emissions grew at 3% yr^{-1} in the 2000s compared to 2% yr^{-1} in the last decade. Figure 14 shows that compared to the previous decade, China has had weaker economic growth in the last decade and a larger decarbonisation rate, with more rapid declines in energy per GDP which are now back to levels during the 1990s. India and the rest of the world have strong economic growth that is not compensated by decarbonisation or declines in energy per GDP, implying fossil CO_2 emissions continue to grow. Despite the high deployment of renewables in some countries (e.g., India), fossil energy sources continue to grow to meet growing energy demand (Le Quéré et al. 2019).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Globally, fossil CO_2 emissions growth is slowing, and this is primarily due to the emergence of climate policy and emission declines in OECD countries (Eskander and Fankhauser 2020). At the aggregated global level, decarbonisation shows a strong and growing signal in the last decade, with smaller contributions from lower economic growth and declines in energy per GDP. Despite the slowing growth in global fossil CO_2 emissions, emissions are still growing, far from the reductions needed to meet the ambitious climate goals of the UNFCCC Paris agreement.

We update the remaining carbon budget assessed by the IPCC AR6 (Canadell et al., 2021), accounting for the 2020 and estimated 2021 emissions from fossil fuel combustion (E_{FOS}) and land use changes (E_{LUC}). From January 2022, the remaining carbon (50% likelihood) for limiting global warming to 1.5°C, 1.7°C and 2°C is estimated to amount to 120, 210, and 350 GtC (420, 770, 1270 $GtCO_2$). These numbers include an uncertainty based on model spread (as in IPCC AR6), which is reflected through the percent likelihood of exceeding the given temperature threshold. These remaining abouts correspond to respectively about 11, 20 and 32 years from beginning of 2020, at the 2021 level of total CO_2 emissions. Reaching net zero CO_2 emissions by 2050 entails cutting total anthropogenic CO_2 emissions by about 0.4 GtC (1.4 $GtCO_2$) each year on average, comparable to the decrease during 2020.

5 Discussion

Each year when the global carbon budget is published, each flux component is updated for all previous years to consider corrections that are the result of further scrutiny and verification of the underlying data in the primary input data sets. Annual estimates may be updated with improvements in data quality and timeliness (e.g., to eliminate the need for extrapolation of forcing data such as land-use). Of all terms in the global budget, only the fossil CO_2 emissions and the growth rate in atmospheric CO_2 concentration are based primarily on empirical inputs supporting annual estimates in this carbon budget. The carbon budget imbalance, yet an imperfect measure, provides a strong indication of the limitations in observations in understanding and representing processes in models, and/or in the integration of the carbon budget components.

The persistent unexplained variability in the carbon budget imbalance limits our ability to verify reported emissions (Peters et al., 2017) and suggests we do not yet have a complete

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Earth System Science Data
Open Access Discussions

understanding of the underlying carbon cycle dynamics on annual to decadal timescales. Resolving most of this unexplained variability should be possible through different and complementary approaches. First, as intended with our annual updates, the imbalance as an error term is reduced by improvements of individual components of the global carbon budget that follow from improving the underlying data and statistics and by improving the models through the resolution of some of the key uncertainties detailed in Table 9. Second, additional clues to the origin and processes responsible for the variability in the budget imbalance could be obtained through a closer scrutiny of carbon variability in light of other Earth system data (e.g., heat balance, water balance), and the use of a wider range of biogeochemical observations to better understand the land-ocean partitioning of the carbon imbalance (e.g. oxygen, carbon isotopes). Finally, additional information could also be obtained through higher resolution and process knowledge at the regional level, and through the introduction of inferred fluxes such as those based on satellite CO_2 retrievals. The limit of the resolution of the carbon budget imbalance is yet unclear, but most certainly not yet reached given the possibilities for improvements that lie ahead.

Estimates of global fossil CO_2 emissions from different datasets are in relatively good agreement when the different system boundaries of these datasets are considered (Andrew, 2020a). But while estimates of E_{FOS} are derived from reported activity data requiring much fewer complex transformations than some other components of the budget, uncertainties remain, and one reason for the apparently low variation between datasets is precisely the reliance on the same underlying reported energy data. The budget excludes some sources of fossil CO_2 emissions, which available evidence suggests are relatively small (<1%). We have added emissions from lime production in China and the US, but these are still absent in most other non-Annex I countries, and before 1990 in other Annex I countries. Further changes to E_{FOS} this year are documented by Andrew and Peters (2021).

Estimates of E_{LUC} suffer from a range of intertwined issues, including the poor quality of historical land-cover and land-use change maps, the rudimentary representation of management processes in most models, and the confusion in methodologies and boundary conditions used across methods (e.g., Arneth et al., 2017; Pongratz et al., 2014, see also Section 2.7.4 on the loss of sink capacity; Bastos et al., 2021). Uncertainties in current and historical carbon stocks in soils and vegetation also add uncertainty in the E_{LUC} estimates.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Unless a major effort to resolve these issues is made, little progress is expected in the resolution of E_{LUC}. This is particularly concerning given the growing importance of E_{LUC} for climate mitigation strategies, and the large issues in the quantification of the cumulative emissions over the historical period that arise from large uncertainties in E_{LUC}.

By adding the DGVMs estimates of CO_2 fluxes due to environmental change from countries' managed forest areas (part of S_{LAND} in this budget) to the budget E_{LUC} estimate, we successfully reconciled the large gap between our E_{LUC} estimate and the land use flux from NGHGIs using the approach described in Grassi et al. (2021). This latter estimate has been used in the recent UNFCCC's Synthesis Report on Nationally Determined Contribution (UNFCCC, 2021b) to enable the total national emission estimates to be comparable with those of the IPCC. However, while Grassi et al. (2021) used only one DGVM, here 17 DGVMs are used, thus providing a more robust value to be used as potential adjustment in the policy context, e.g., to help assessing the collective countries' progress towards the goal of the Paris Agreement and avoiding double-accounting for the sink in managed forests. In the absence of this adjustment, collective progress would hence appear better than it is (Grassi et al. 2021).

The comparison of GOBMs, data products and inversions highlights substantial discrepancy in the Southern Ocean (Fig. 12, Hauck et al., 2020). The long-standing sparse data coverage of fCO_2 observations in the Southern compared to the Northern Hemisphere (e.g., Takahashi et al., 2009) continues to exist (Bakker et al., 2016, 2021, Fig. B1) and to lead to substantially higher uncertainty in the S_{OCEAN} estimate for the Southern Hemisphere (Watson et al., 2020, Gloege et al., 2021). This discrepancy, which also hampers model improvement, points to the need for increased high-quality fCO_2 observations especially in the Southern Ocean. At the same time, model uncertainty is illustrated by the large spread of individual GOBM estimates (indicated by shading in Fig. 12) and highlights the need for model improvement. Further uncertainty stems from the regional distribution of the river flux adjustment term being based on one model study yielding the largest riverine outgassing flux south of 20°S (Aumont et al., 2001), with a recent study questioning this distribution (Lacroix et al., 2020). The diverging trends in S_{OCEAN} from different methods is a matter of concern, which is unresolved. The assessment of the net land-atmosphere exchange from DGVMs and atmospheric inversions also shows substantial discrepancy, particularly for the estimate of

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

the total land flux over the northern extra-tropic. This discrepancy highlights the difficulty to quantify complex processes (CO_2 fertilisation, nitrogen deposition and fertilisers, climate change and variability, land management, etc.) that collectively determine the net land CO_2 flux. Resolving the differences in the Northern Hemisphere land sink will require the consideration and inclusion of larger volumes of observations.

We provide metrics for the evaluation of the ocean and land models and the atmospheric inversions (Figs. B2 to B4). These metrics expand the use of observations in the global carbon budget, helping 1) to support improvements in the ocean and land carbon models that produce the sink estimates, and 2) to constrain the representation of key underlying processes in the models and to allocate the regional partitioning of the CO_2 fluxes. However, GOBMs skills have changed little since the introduction of the ocean model evaluation. An additional simulation this year allows for direct comparison with interior ocean anthropogenic carbon estimates and suggests that the models underestimate anthropogenic carbon uptake and storage. This is an initial step towards the introduction of a broader range of observations that we hope will support continued improvements in the annual estimates of the global carbon budget.

We assessed before that a sustained decrease of –1% in global emissions could be detected at the 66% likelihood level after a decade only (Peters et al., 2017). Similarly, a change in behaviour of the land and/or ocean carbon sink would take as long to detect, and much longer if it emerges more slowly. To continue reducing the carbon imbalance on annual to decadal time scales, regionalising the carbon budget, and integrating multiple variables are powerful ways to shorten the detection limit and ensure the research community can rapidly identify issues of concern in the evolution of the global carbon cycle under the current rapid and unprecedented changing environmental conditions.

6 Conclusions

The estimation of global CO_2 emissions and sinks is a major effort by the carbon cycle research community that requires a careful compilation and synthesis of measurements, statistical estimates, and model results. The delivery of an annual carbon budget serves two purposes. First, there is a large demand for up-to-date information on the state of the anthropogenic perturbation of the climate system and its underpinning causes. A broad

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

stakeholder community relies on the data sets associated with the annual carbon budget including scientists, policy makers, businesses, journalists, and non-governmental organizations engaged in adapting to and mitigating human-driven climate change. Second, over the last decades we have seen unprecedented changes in the human and biophysical environments (e.g., changes in the growth of fossil fuel emissions, impact of COVID-19 pandemic, Earth's warming, and strength of the carbon sinks), which call for frequent assessments of the state of the planet, a better quantification of the causes of changes in the contemporary global carbon cycle, and an improved capacity to anticipate its evolution in the future. Building this scientific understanding to meet the extraordinary climate mitigation challenge requires frequent, robust, transparent, and traceable data sets and methods that can be scrutinized and replicated. This paper via 'living data' helps to keep track of new budget updates.

7 Data availability

The data presented here are made available in the belief that their wide dissemination will lead to greater understanding and new scientific insights of how the carbon cycle works, how humans are altering it, and how we can mitigate the resulting human-driven climate change. The free availability of these data does not constitute permission for publication of the data. For research projects, if the data are essential to the work, or if an important result or conclusion depends on the data, co-authorship may need to be considered for the relevant data providers. Full contact details and information on how to cite the data shown here are given at the top of each page in the accompanying database and summarised in Table 2.

The accompanying database includes two Excel files organised in the following spreadsheets:

File Global_Carbon_Budget_2021v1.0.xlsx includes the following:

1. Summary
2. The global carbon budget (1959-2020);
3. The historical global carbon budget (1750-2020);
4. Global CO_2 emissions from fossil fuels and cement production by fuel type, and the per-capita emissions (1959-2020);

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

5. CO_2 emissions from land-use change from the individual methods and models (1959-2020);
6. Ocean CO_2 sink from the individual ocean models and fCO_2-based products (1959-2020);
7. Terrestrial CO_2 sink from the DGVMs (1959-2020).

File National_Carbon_Emissions_2021v1.0.xlsx includes the following:

1. Summary
2. Territorial country CO_2 emissions from fossil CO_2 emissions (1959-2020);
3. Consumption country CO_2 emissions from fossil CO_2 emissions and emissions transfer from the international trade of goods and services (1990-2019) using CDIAC/UNFCCC data as reference;
4. Emissions transfers (Consumption minus territorial emissions; 1990-2019);
5. Country definitions;
6. Details of disaggregated countries;
7. Details of aggregated countries.

Both spreadsheets are published by the Integrated Carbon Observation System (ICOS) Carbon Portal and are available at https://doi.org/10.18160/gcp-2021 (Friedlingstein et al., 2021). National emissions data are also available from the Global Carbon Atlas (http://www.globalcarbonatlas.org/, last access: 21 October 2021) and from Our World in Data (https://ourworldindata.org/co2-emissions, last access: 21 October 2021).

Author contributions

PF, MWJ, MOS, CLQ, RMA, DCEB, JH, GPP, WP, JP and SS designed the study, conducted the analysis, and wrote the paper with input from JGC, PC and RBJ. RMA, GPP and JIK produced the fossil fuel emissions and their uncertainties and analysed the emissions data. DG and GM provided fossil fuel emission data. JP, TG, CS and RAH provided the bookkeeping land-use change emissions. JH, LB, OG, NG, TI, LR, JS, RS and DW provided an update of the global ocean biogeochemical models. SRA, TTTC, LD, LG, YI, PL, CR, AJW and JZ provided an update of the ocean fCO_2 data products, with synthesis by JH. MB, NRB, KIC, MC, WE, RAF, SRA, TG, AK, NL, SKL, DRM, ClS, CoS, SN, CW, TO, DP, GR, AJS, BT, TT, CW, and RW provided ocean fCO_2 measurements for the year 2020, with synthesis by DCEB and SDJ. PA, BD, AKJ, DK, EK, JK, SL, PCM, JRM, JEMSN, BP, HT, NV, AJW, WY, XY and SZ provided an update of the Dynamic Global Vegetation Models, with synthesis by SS. WP, FC, LF, ITL, JL, YN and CR provided an updated atmospheric inversion, developed the protocol and produced the evaluation, with synthesis by WP. RMA provided predictions of the 2021 emissions and atmospheric CO_2 growth rate. PL provided the predictions of the 2021 ocean and land sinks. LPC, GCH, KKG, TMS and GRvdW provided forcing data for land-use change. GG, FT, and CY provided data for the land-use change NGHGI mapping. PPT provided key atmospheric CO_2 data. MWJ produced the historical record of atmospheric CO_2 concentration and growth rate, including the atmospheric CO_2 forcing. MOS and NB produced the aerosol diffuse radiative forcing for the DGVMs. IH provided the climate forcing data for the DGVMs. ER provided the evaluation of the DGVMs. MWJ provided the emissions prior for use in the inversion models. XD provided seasonal emissions data for years 2019-2020 for the emission prior. MWJ and MOS developed a new data management pipeline which automates many aspects of the data collation, analysis, plotting and synthesis. PF, MWJ, and MOS revised all figures, tables, text and/or numbers to ensure the update is clear from the 2020 edition and in phase with the globalcarbonatlas.org.

Competing interests. The authors declare that they have no conflict of interest.

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Preprint. Discussion started: 4 November 2021

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Preprint. Discussion started: 4 November 2021

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https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

1 **Tables**

Table 1. Factors used to convert carbon in various units (by convention, Unit 1 = Unit 2 × conversion).

Unit 1	Unit 2	Conversion	Source
GtC (gigatonnes of carbon)	ppm (parts per million) (a)	2.124 (b)	Ballantyne et al. (2012)
GtC (gigatonnes of carbon)	PgC (petagrams of carbon)	1	SI unit conversion
GtCO2 (gigatonnes of carbon dioxide)	GtC (gigatonnes of carbon)	3.664	44.01/12.011 in mass equivalent
GtC (gigatonnes of carbon)	MtC (megatonnes of carbon)	1000	SI unit conversion

(a) Measurements of atmospheric CO2 concentration have units of dry-air mole fraction. 'ppm' is an abbreviation for micromole/mol, dry air.

(b) The use of a factor of 2.124 assumes that all the atmosphere is well mixed within one year. In reality, only the troposphere is well mixed and the growth rate of CO2 concentration in the less well-mixed stratosphere is not measured by sites from the NOAA network. Using a factor of 2.124 makes the approximation that the growth rate of CO2 concentration in the stratosphere equals that of the troposphere on a yearly basis.

2

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table 2. How to cite the individual components of the global carbon budget presented here.

Component	Primary reference
Global fossil CO2 emissions (EFOS), total and by fuel type	Andrew and Peters (2021)
National territorial fossil CO2 emissions (EFOS)	Gilfillan and Marland (2021), UNFCCC (2021a)
National consumption-based fossil CO2 emissions (EFOS) by country (consumption)	Peters et al. (2011b) updated as described in this paper
Net land-use change flux (ELUC)	This paper (see Table 4 for individual model references).
Growth rate in atmospheric CO2 concentration (GATM)	Dlugokencky and Tans (2021)
Ocean and land CO2 sinks (SOCEAN and SLAND)	This paper (see Table 4 for individual model references).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table 3. Main methodological changes in the global carbon budget since 2017. Methodological changes introduced in one year are kept for the following years unless noted. Empty cells mean there were no methodological changes introduced that year. Table A7 lists methodological changes from the first global carbon budget publication up to 2016.

Publication year	Fossil fuel emissions		LUC emissions	Reservoirs			Uncertainty & other changes
	Global	Country (territorial)		Atmosphere	Ocean	Land	
2017 Le Quéré et al. (2018a) GCB2017	Projection includes India-specific data		Average of two bookkeeping models; use of 12 DGVMs		Based on eight models that match the observed sink for the 1990s; no longer normalised	Based on 15 models that meet observation-based criteria (see Sect. 2.5)	Land multi-model average now used in main carbon budget, with the carbon imbalance presented separately; new table of key uncertainties
2018 Le Quéré et al. (2018b) GCB2018	Revision in cement emissions; Projection includes EU-specific data	Aggregation of overseas territories into governing nations for total of 213 countries a	Average of two bookkeeping models; use of 16 DGVMs	Use of four atmospheric inversions	Based on seven models	Based on 16 models; revised atmospheric forcing from CRUNCEP to CRU-JRA-55	Introduction of metrics for evaluation of individual models using observations
2019 Friedlingstein et al. (2019) GCB2019	Global emissions calculated as sum of all countries plus bunkers, rather than taken directly from CDIAC.		Average of two bookkeeping models; use of 15 DGVMs	Use of three atmospheric inversions	Based on nine models	Based on 16 models	
2020 Friedlingstein et al. (2020) GCB2020	Cement carbonation now included in the EFOS estimate, reducing EFOS by about 0.2GtC yr-1 for the last decade	India's emissions from Andrew (2020: India); Corrections to Netherland Antilles and Aruba and Soviet emissions before 1950 as per Andrew (2020: CO2);	Average of three bookkeeping models; use of 17 DGVMs. Estimate of gross land use sources and sinks provided	Use of six atmospheric inversions	Based on nine models. River flux revised and partitioned NH, Tropics, SH	Based on 17 models	

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

		China's coal emissions in 2019 derived from official statistics, emissions now shown for EU27 instead of EU28.Projection for 2020 based on assessment of four approaches.					
2021 Friedlingstein et al. (2021) GCB2021 (This study)	Projections are no longer an assessment of four approaches.	Official data included for a number of additional countries, new estimates for South Korea, added emissions from lime production in China.	ELUC estimate compared to the estimates adopted in national GHG inventories (NGHGI)		Average of means of eight models and means of seven data-products. Current year prediction of SOCEAN using a feed-forward neural network method	Current year prediction of SLAND using a feed-forward neural network method	

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

1

Table 4. References for the process models, fCO2-based ocean data products, and atmospheric inversions. All models and products are updated with new data to end of year 2020, and the atmospheric forcing for the DGVMs has been updated as described in Section 2.2.2.

Model/data name	Reference	Change from Global Carbon Budget 2020 (Friedlingstein et al., 2020)
Bookkeeping models for land-use change emissions		
BLUE	Hansis et al. (2015)	No change to model, but simulations performed with updated LUH2 forcing.
updated H&N2017	Houghton and Nassikas (2017)	Adjustment to treatment of harvested wood products. Update to FRA2020 and 2021 FAOSTAT for forest cover and land-use areas. Forest loss in excess of increases in cropland and pastures represented an increase in shifting cultivation. Extratropical peatland drainage emissions added (based on Qiu et al., 2021).
OSCAR	Gasser et al. (2020)	Update to OSCAR3.1.2, which provides finer resolution (96 countries/regions). LUH2-TRENDYv8 input data replaced by LUH2-TRENDYv10. FRA2015 (Houghton & Nassikas, 2017) still used as a second driving dataset, with emissions from FRA2015 extended to 2020. Constraining based on this year's budget data.
Dynamic global vegetation models		
CABLE-POP	Haverd et al. (2018)	changes in parameterisation, minor bug fixes
CLASSIC	Melton et al. (2020) (a)	Non-structural carbohydrates are now explicitly simulated.
CLM5.0	Lawrence et al. (2019)	No Change.
DLEM	Tian et al. (2015) (b)	Updated algorithms for land use change processes.
IBIS	Yuan et al. (2014) (c)	Several changes in parameterisation; Dynamic carbon allocation scheme.
ISAM	Meiyappan et al. (2015) (d)	ISAM now accounting for vertically-resolved soil biogeochemistry (carbon and nitrogen) module (Shu et al., 2020)
ISBA-CTRIP	Delire et al. (2020) (e)	Updated spinup protocol + model name updated (SURFEXv8 in GCB2017) + inclusion of crop harvesting module
JSBACH	Reick et al. (2021) (f)	Wood product pools per plant functional type.
JULES-ES	Wiltshire et al. (2021) (g)	Version 1.1 Inclusion of interactive fire Burton et al., (2019)
LPJ-GUESS	Smith et al. (2014) (h)	No code change. Using updated LUH2 and climate forcings.
LPJ	Poulter et al. (2011) (i)	Updated soil data from FAO to HWSD v2.0

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

LPX-Bern	Lienert and Joos (2018)	No Change.
OCN	Zaehle and Friend (2010) (j)	No change (uses r294).
ORCHIDEEv3	Vuichard et al. (2019) (k)	Updated growth respiration scheme (revision 7267)
SDGVM	Walker et al. (2017) (l)	No changes from version used in Friedlingstein et al. (2019), except for properly switching from grasslands to pasture in the blending of the ESA data with LUH2; this change affects mostly the semi-arid lands.
VISIT	Kato et al. (2013) (m)	Minor bug fix on CH4 emissions of recent few years.
YIBs	Yue and Unger (2015)	Inclusion of nutrient limit with down regulation approach of Arora et al. (2009)
Global ocean biogeochemistry models		
NEMO-PlankTOM12	Wright et al. (2021) (n)	Updated biochemical model to include 12 functional types. Change to spin-up, now using a looped 1990.
MICOM-HAMOCC (NorESM-OCv1.2)	Schwinger et al. (2016)	No change
MPIOM-HAMOCC6	Lacroix et al. (2021)	Added riverine fluxes; cmip6 model version including modifications and bug-fixes in HAMOCC and MPIOM
NEMO3.6-PISCESv2-gas (CNRM)	Berthet et al. (2019) (o)	small bug fixes; updated model-spin-up (new forcings); atm forcing is now JRA55-Do including 2020 year and varying riverine freshwater inputs
FESOM-2.1-REcoM2	Hauck et al. (2020) (p)	Updated physical model version FESOM2.1, and including 2nd zooplankton and 2nd detritus group. Used new atmospheric CO2 time series provided by GCB
MOM6-COBALT (Princeton)	Liao et al. (2020)	Adjustment of the piston velocity prefactor (0.337 cph/m2/s2 to 0.251 cph/m2/s2). MOM6 update from GitHub version b748b1b (2018-10-03) to version 69a096b (2021-02-24). Updated model spin-up and simulation using JRA55-do v1.5. Used new atmospheric CO2 time series provided by GCB.
CESM-ETHZ	Doney et al. (2009)	No change in the model. Used new atmospheric CO2 time series provided by GCB
NEMO-PISCES (IPSL)	Aumont et al. (2015)	No change
ocean fCO2-based data products		
Landschützer (MPI-SOMFFN)	Landschützer et al. (2016)	update to SOCATv2021 measurements and time period 1982-2020; The estimate now covers the full open ocean and coastal domain as well as the Arctic Ocean extension described in Landschützer et al. (2020)
Rödenbeck (Jena-MLS)	Rödenbeck et al. (2014)	update to SOCATv2021 measurements, time period extended to 1957-2020, involvement of a multi-linear regression for extrapolation (combined with an explicitly interannual correction), use of OCIM (deVries, 2014) as decadal prior, carbonate chemistry parameterization now time-dependent, grid resolution increased to 2.5*2 degrees, adjustable degrees

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

		of freedom now also covering shallow areas and Arctic, some numerical revisions
CMEMS-LSCE-FFNNv2	Chau et al. (2021)	Update to SOCATv2021 measurements and time period 1985-2020. The CMEMS-LSCE-FFNNv2 product now covers both the open ocean and coastal regions (see in Chau et al. 2021 for model description and evaluation).
CSIR-ML6	Gregor et al. (2019)	Updated to SOCATv2021. Reconstruction now spans the period 1985 - 2020 and includes updates using the SeaFlux protocols (Fay et al., 2021b)
Watson et al	Watson et al. (2020)	Updated to SOCAT v2021. A monthly climatology of the skin temperature deviation as calculated for years 2003-2011 is now used in place of a single global average figure. SOM calculation updated to treat the Arctic as a separate biome.
NIES-NN	Zeng et al. (2014)	New this year
JMA-MLR	Iida et al. (2021)	New this year
OS-ETHZ-GRaCER	Gregor and Gruber (2021)	New this year
Atmospheric inversions		
CAMS	Chevallier et al. (2005) (q)	No change.
CarbonTracker Europe (CTE)	van der Laan-Luijkx et al. (2017)	No change.
Jena CarboScope	Rödenbeck et al. (2018) (r)	No change.
UoE in-situ	Feng et al., (2016) (s)	Fossil fuels now from GCP-GridFEDv2021.2
NISMON-CO2	Niwa et al., (2017) (t)	Some inversion parameters were changed.
CMS-Flux	Liu et al., (2021)	New this year
(a) see also Asaadi et al. (2018).		
(b) see also Tian et al. (2011)		
(c) the dynamic carbon allocation scheme was presented by Xia et al. (2015)		
(d) see also Jain et al. (2013). Soil biogeochemistry is updated based on Shu et al. (2020)		
(e) see also Decharme et al. (2019) and Seferian et al. (2019)		
(f) Mauritsen et al. (2019)		
(g) see also Sellar et al. (2019) and Burton et al., (2019). JULES-ES is the Earth System configuration of the Joint UK Land Environment Simulator as used in the UK Earth System Model (UKESM).		
(h) to account for the differences between the derivation of shortwave radiation from CRU cloudiness and DSWRF from CRUJRA, the photosynthesis scaling parameter αa was modified (-15%) to yield similar results.		

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

(i) compared to published version, decreased LPJ wood harvest efficiency so that 50 % of biomass was removed off-site compared to 85 % used in the 2012 budget. Residue management of managed grasslands increased so that 100 % of harvested grass enters the litter pool.
(j) see also Zaehle et al. (2011).
(k) see also Zaehle and Friend (2010) and Krinner et al. (2005)
(l) see also Woodward and Lomas (2004)
(m) see also Ito and Inatomi (2012).
(n) see also Buitenhuis et al. (2013)
(o) see also Séférian et al. (2019)
(p) see also Schourup-Kristensen et al (2014)
(q) see also Remaud (2018)
(r) see also Rödenbeck et al. (2003)
(s) see also Feng et al. (2009) and Palmer et al. (2019)
(t) see also Niwa et al. (2020)

1

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Table 5. Comparison of results from the bookkeeping method and budget residuals with results from the DGVMs and inverse estimates for different periods, the last decade, and the last year available. All values are in GtCyr^{-1}. The DGVM uncertainties represent ±1σ of the decadal or annual (for 2020 only) estimates from the individual DGVMs: for the inverse models the range of available results is given. All values are rounded to the nearest 0.1 GtC and therefore columns do not necessarily add to zero.

	Mean (GtC/yr)						
	1960s	1970s	1980s	1990s	2000s	2011-2020	2020
Land-use change emissions (ELUC)							
Bookkeeping methods - net flux (1a)	1.6±0.7	1.3±0.7	1.2±0.7	1.3±0.7	1.2±0.7	1.1±0.7	0.9±0.7
Bookkeeping methods - source	3.4±0.9	3.3±0.8	3.4±0.8	3.6±0.6	3.7±0.6	3.8±0.6	3.6±0.6
Bookkeeping methods - sink	-1.9±0.4	-2±0.4	-2.1±0.3	-2.3±0.4	-2.5±0.4	-2.7±0.4	-2.8±0.4
DGVMs-net flux (1b)	1.6±0.5	1.3±0.4	1.4±0.5	1.4±0.5	1.4±0.5	1.5±0.5	1.4±0.7
Terrestrial sink (SLAND)							
Residual sink from global budget (EFOS+ELUC-GATM-SOCEAN) (2a)	1.8±0.8	1.9±0.8	1.6±0.9	2.5±0.9	2.7±0.9	2.8±0.9	2.1±0.9
DGVMs (2b)	1.2±0.5	2±0.5	1.8±0.5	2.3±0.4	2.6±0.5	3.1±0.6	2.9±1
Total land fluxes (SLAND-ELUC)							
GCB2021 Budget (2b-1a)	-0.4±0.8	0.8±0.8	0.5±0.9	1±0.8	1.4±0.9	1.9±0.9	2±1.2
Budget constraint (2a-1a)	0.2±0.4	0.6±0.5	0.3±0.5	1.2±0.5	1.5±0.6	1.7±0.6	1.3±0.6
DGVMs-net (2b-1b)	-0.4±0.6	0.7±0.4	0.3±0.4	0.9±0.4	1.2±0.4	1.6±0.6	1.5±0.8
Inversions*	—	—	0.5-0.6 (2)	0.9-1.2 (3)	1.3-1.8 (3)	1.3-2 (6)	-0.1-1.3 (6)

* Estimates are adjusted for the pre-industrial influence of river fluxes, for the cement carbonation sink, and adjusted to common EFOS (Sect. 2.6). The ranges given include varying numbers (in parentheses) of inversions in each decade (Table A4)

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Table 6. Decadal mean in the five components of the anthropogenic CO2 budget for different periods, and last year available. All values are in GtC yr-1, and uncertainties are reported as ±1σ. Fossil CO_2 emissions include cement carbonation. The table also shows the budget imbalance (B_{IM}), which provides a measure of the discrepancies among the nearly independent estimates and has an uncertainty exceeding ± 1 GtC yr^{-1}. A positive imbalance means the emissions are overestimated and/or the sinks are too small. All values are rounded to the nearest 0.1 GtC and therefore columns do not necessarily add to zero.

	Mean (GtC/yr)							
	1960s	1970s	1980s	1990s	2000s	2011-2020	2020	2021 (Projection)
Total emissions (EFOS + ELUC)								
Fossil CO2 emissions (EFOS)*	3±0.2	4.7±0.2	5.5±0.3	6.3±0.3	7.7±0.4	9.5±0.5	9.3±0.5	9.7±0.5
Land-use change emissions (ELUC)	1.6±0.7	1.3±0.7	1.2±0.7	1.3±0.7	1.2±0.7	1.1±0.7	0.9±0.7	0.8±0.7
Total emissions	4.6±0.7	5.9±0.7	6.7±0.8	7.7±0.8	9±0.8	10.6±0.8	10.2±0.8	10.5±0.9
Partitioning								
Growth rate in atmos CO2 (GATM)	1.7±0.07	2.8±0.07	3.4±0.02	3.1±0.02	4±0.02	5.1±0.02	5±0.2	4.2±0.4
Ocean sink (SOCEAN)	1.1±0.4	1.3±0.4	1.8±0.4	2±0.4	2.2±0.4	2.8±0.4	3±0.4	2.9±0.4
Terrestrial sink (SLAND)	1.2±0.5	2±0.5	1.8±0.5	2.3±0.4	2.6±0.5	3.1±0.6	2.9±1	3.3±1
Budget Imbalance								
BIM=EFOS+ELUC-(GATM+SOCEAN+SLAND)	0.6	-0.2	-0.2	0.2	0.1	-0.3	-0.8	0.1

- Fossil emissions excluding the cement carbonation sink amount to 3.1±0.2 GtC/yr, 4.7±0.2 GtC/yr, 5.5±0.3 GtC/yr, 6.4±0.3 GtC/yr, 7.9±0.4 GtC/yr, and 9.7±0.5 GtC/yr for the decades 1960s to 2010s respectively and to 9.5±0.5 GtC/yr for 2020.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table 7. Comparison of the projection with realised fossil CO2 emissions (EFOS). The 'Actual' values are first the estimate available using actual data, and the 'Projected' values refers to estimates made before the end of the year for each publication. Projections based on a different method from that described here during 2008-2014 are available in Le Quéré et al., (2016). All values are adjusted for leap years.

	World		China		USA		EU28 (h)		India		Rest of World	
	Projected	Actual	Projected	Actual	Projected	Actual	Projected	Actual	Projected	Actual	Projected	Actual
2015 (a)	−0.6% (−1.6 to 0.5)	0.06%	−3.9% (−4.6 to −1.1)	−0.7%	−1.5% (−5.5 to 0.3)	−2.5%	–	–	–	–	1.2% (−0.2 to 2.6)	1.2%
2016 (b)	−0.2% (−1.0 to +1.8)	0.20%	−0.5% (−3.8 to +1.3)	−0.3%	−1.7% (−4.0 to +0.6)	−2.1%	–	–	–	–	1.0% (−0.4 to +2.5)	1.3%
2017 (c)	2.0% (+0.8 to +3.0)	1.6%	3.5% (+0.7 to +5.4)	1.5%	−0.4% (−2.7 to +1.0)	−0.5%	–	–	2.00% (+0.2 to +3.8)	3.9%	1.6% (0.0 to +3.2)	1.9%
2018 (d)	2.7% (+1.8 to +3.7)	2.1%	4.7% (+2.0 to +7.4)	2.3%	2.5% (+0.5 to +4.5)	2.8%	-0.7% (-2.6 to +1.3)	-2.1%	6.3% (+4.3 to +8.3)	8.0%	1.8% (+0.5 to +3.0)	1.7%
2019 (e)	0.5% (-0.3 to +1.4)	0.1%	2.6% (+0.7 to +4.4)	2.2%	-2.4% (-4.7 to -0.1)	-2.6%	-1.7% (-5.1% to +1.8%)	-4.3%	1.8% (-0.7 to +3.7)	1.0%	0.5% (-0.8 to +1.8)	0.5%
2020 (f)	-6.7%	-5.4%	-1.7%	1.4%	-12.2%	-10.6%	-11.3% (EU27)	-10.9%	-9.1%	-7.3%	-7.4%	-7.0%
2021 (g)	4.9% (4.1% to 5.7%)		4.0% (2.1% to 5.8%)		7.6% (5.3% to 10.0%)		7.6% (5.6% to 9.5%)		12.6% (10.7% to 13.6%)		2.9% (1.8% to 4.1%)	

(a) Jackson et al. (2016) and Le Quéré et al. (2015a). (b) Le Quéré et al. (2016). (c) Le Quéré et al. (2018a). (d) Le Quéré et al. (2018b). (e) Friedlingstein et al., (2019), (f) Friedlingstein et al., (2020), (g) This study (median of four reported estimates, Section 3.4.1.2)

(h) EU28 until 2019, EU27 from 2020

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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Table 8. Cumulative CO_2 for different time periods in gigatonnes of carbon (GtC). All uncertainties are reported as ±1σ. Fossil CO_2 emissions include cement carbonation. The budget imbalance (B_{IM}) provides a measure of the discrepancies among the nearly independent estimates. All values are rounded to the nearest 5 GtC and therefore columns do not necessarily add to zero.

	1750-2020	1850-2014	1850-2020	1960-2020	1850-2021
Emissions					
Fossil CO2 emissions (EFOS)	460±25	400±20	455±25	375±20	465±25
Land-use change emissions (ELUC)	235±75	195±60	200±65	80±45	205±65
Total emissions	690±80	595±65	660±65	455±45	670±65
Partitioning					
Growth rate in atmos CO2 (GATM)	290±5	235±5	270±5	205±5	270±5
Ocean sink (SOCEAN)	180±35	150±30	170±35	115±25	170±35
Terrestrial sink (SLAND)	215±50	180±40	195±45	135±25	200±45
Budget imbalance					
BIM=EFOS+ELUC-(GATM+SOCEAN+SLAND)	10	30	25	0	25

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

1

Table 9. Major known sources of uncertainties in each component of the Global Carbon Budget, defined as input data or processes that have a demonstrated effect of at least ±0.3 GtC yr-1.

Source of uncertainty	Time scale (years)	Location	Status	Evidence
Fossil CO2 emissions (EFOS; Section 2.1)				
energy statistics	annual to decadal	global, but mainly China & major developing countries	see Sect. 2.1	(Korsbakken et al., 2016, Guan et al., 2012)
carbon content of coal	annual to decadal	global, but mainly China & major developing countries	see Sect. 2.1	(Liu et al., 2015)
system boundary	annual to decadal	all countries	see Sect. 2.1	(Andrew, 2020)
Net land-use change flux (ELUC; section 2.2)				
land-cover and land-use change statistics	continuous	global; in particular tropics	see Sect. 2.2	(Houghton et al., 2012; Gasser et al., 2020)
sub-grid-scale transitions	annual to decadal	global	see Table A1	(Wilkenskjeld et al., 2014)
vegetation biomass	annual to decadal	global; in particular tropics	see Table A1	(Houghton et al., 2012)
forest degradation (fire, selective logging)	annual to decadal	tropics		(Aragão et al., 2018; Qin et al., 2020)
wood and crop harvest	annual to decadal	global; SE Asia	see Table A1	(Arneth et al., 2017, Erb et al., 2018)
peat burning (a)	multi-decadal trend	global	see Table A1	(van der Werf et al., 2010, 2017)
loss of additional sink capacity	multi-decadal trend	global	not included; see Appendix D1.4	(Pongratz et al, 2014, Gasser et al, 2020; Obermeier et al., 2021)
Atmospheric growth rate (GATM; section 2.3) no demonstrated uncertainties larger than ±0.3 GtC yr-1 (b)				
Ocean sink (SOCEAN; section 2.4)				

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

sparsity in surface fCO2 observations	mean, decadal variability and trend	global, in particular southern hemisphere	see Sect 3.5.2	(Gloege et al., 2021, Denvil-Sommer et al., 2021, Bushinsky et al., 2019)
riverine carbon outgassing and its anthropogenic perturbation	annual to decadal	global, in particular partitioning between Tropics and South	see Sect. 2.4 (anthropogenic perturbations not included)	(Aumont et al., 2001, Resplandy et al., 2018, Lacroix et al., 2020)
interior ocean anthropogenic carbon storage	annual to decadal	global	see Sect 3.5.5	(Gruber et al., 2019)
near-surface temperature and salinity gradients	mean on all time-scales	global	see Sect. 3.8.2	(Watson et al., 2020)
Land sink (SLAND; section 2.5)				
strength of CO2 fertilisation	multi-decadal trend	global	see Sect. 2.5	(Wenzel et al., 2016; Walker et al., 2021)
response to variability in temperature and rainfall	annual to decadal	global; in particular tropics	see Sect. 2.5	(Cox et al., 2013; Jung et al., 2017; Humphrey et al., 2018; 2021)
nutrient limitation and supply				
tree mortality	annual	global in particular tropics	see Sect. 2.5	(Hubau et al., 2021; Brienen et al., 2020)
response to diffuse radiation	annual	global	see Sect. 2.5	(Mercado et al., 2009; O'Sullivan et al., 2021)
a As result of interactions between land-use and climate				
b The uncertainties in GATM have been estimated as ±0.2 GtC yr-1, although the conversion of the growth rate into a global annual flux assuming instantaneous mixing throughout the atmosphere introduces additional errors that have not yet been quantified.				

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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Figures and Captions

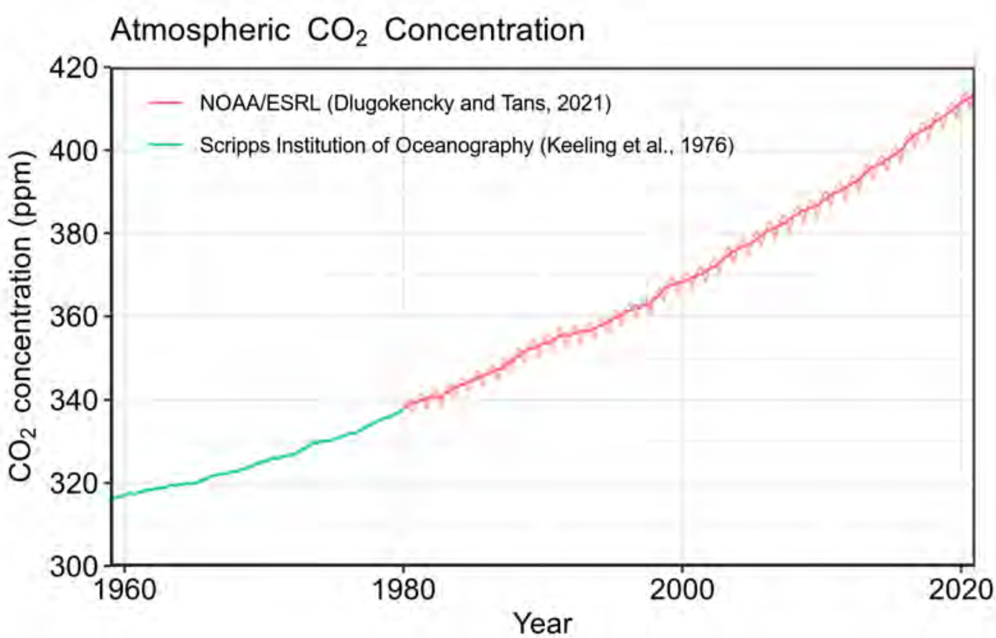

Figure 1. Surface average atmospheric CO_2 concentration (ppm). Since 1980, monthly data are from NOAA/ESRL (Dlugokencky and Tans, 2021) and are based on an average of direct atmospheric CO_2 measurements from multiple stations in the marine boundary layer (Masarie and Tans, 1995). The 1958-1979 monthly data are from the Scripps Institution of Oceanography, based on an average of direct atmospheric CO_2 measurements from the Mauna Loa and South Pole stations (Keeling et al., 1976). To account for the difference of mean CO_2 and seasonality between the NOAA/ESRL and the Scripps station networks used here, the Scripps surface average (from two stations) was de-seasonalised and adjusted to match the NOAA/ESRL surface average (from multiple stations) by adding the mean difference of 0.667 ppm, calculated here from overlapping data during 1980-2012.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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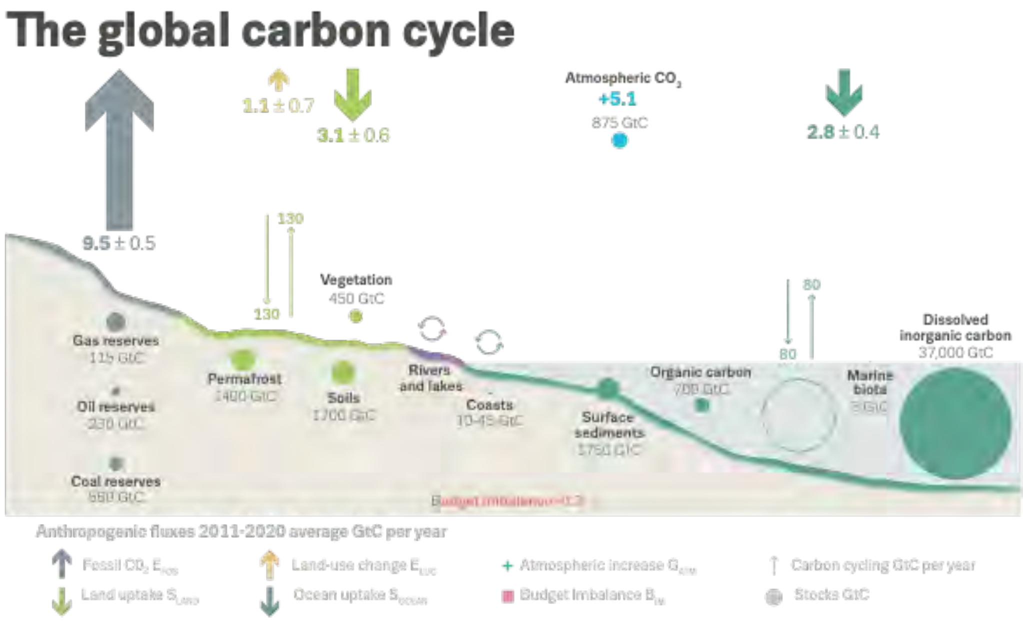

Figure 2. Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2011-2020. See legends for the corresponding arrows and units. The uncertainty in the atmospheric CO_2 growth rate is very small (±0.02 GtC yr^{-1}) and is neglected for the figure. The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Canadell et al. (2021) for all numbers, except for the carbon stocks in coasts which is from a literature review of coastal marine sediments (Price and Warren, 2016).

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https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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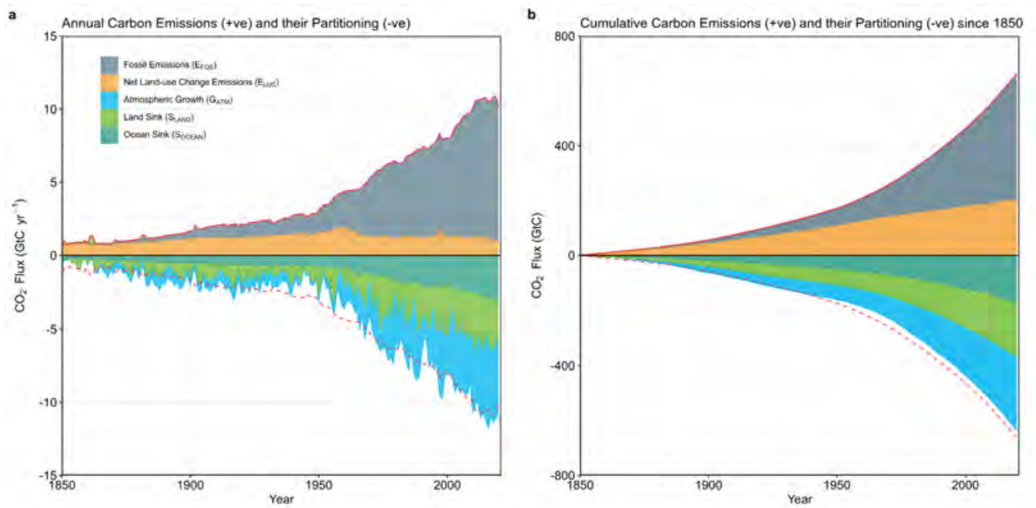

Figure 3. Combined components of the global carbon budget illustrated in Fig. 2 as a function of time, for fossil CO_2 emissions (E_{FOS}, including a small sink from cement carbonation; grey) and emissions from land-use change (E_{LUC}; brown), as well as their partitioning among the atmosphere (G_{ATM}; cyan), ocean (S_{OCEAN}; blue), and land (S_{LAND}; green). Panel (a) shows annual estimates of each flux and panel (b) the cumulative flux (the sum of all prior annual fluxes) since the year 1850. The partitioning is based on nearly independent estimates from observations (for G_{ATM}) and from process model ensembles constrained by data (for S_{OCEAN} and S_{LAND}) and does not exactly add up to the sum of the emissions, resulting in a budget imbalance (BI_M) which is represented by the difference between the bottom red line (mirroring total emissions) and the sum of carbon fluxes in the ocean, land, and atmosphere reservoirs. All data are in GtC yr^{-1} (panel a) and GtC (panel b). The E_{FOS} estimates are primarily from (Gilfillan and Marland, 2021), with uncertainty of about ±5% (±1σ). The E_{LUC} estimates are from three bookkeeping models (Table 4) with uncertainties of about ±0.7 GtC yr^{-1}. The G_{ATM} estimates prior to 1959 are from Joos and Spahni (2008) with uncertainties equivalent to about ±0.1-0.15 GtC yr^{-1} and from Dlugokencky and Tans (2021) since 1959 with uncertainties of about +-0.07 GtC yr^{-1} during 1959-1979 and ±0.02 GtC yr^{-1} since 1980. The S_{OCEAN} estimate is the average from Khatiwala et al. (2013) and DeVries (2014) with uncertainty of about ±30% prior to 1959, and the average of an ensemble of models and an ensemble of fCO_2 data products (Table 4) with uncertainties of about ±0.4 GtC yr^{-1} since 1959. The S_{LAND} estimate is the average of an ensemble of models (Table 4) with uncertainties of about ±1 GtC yr^{-1}. See the text for more details of each component and their uncertainties.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

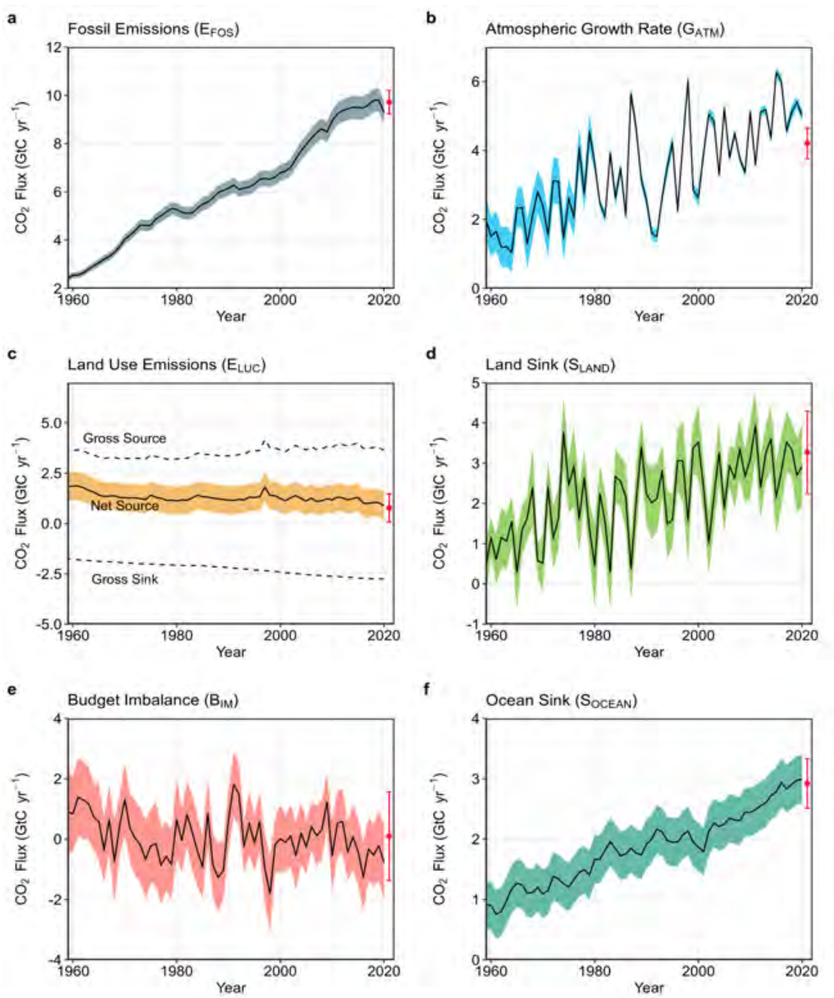

Figure 4. Components of the global carbon budget and their uncertainties as a function of time, presented individually for (a) fossil CO_2 emissions (E_{FOS}), (b) growth rate in atmospheric CO_2 concentration (G_{ATM}), (c) emissions from land-use change (E_{LUC}), (d) the land CO_2 sink (S_{LAND}), (e) the ocean CO_2 sink (S_{OCEAN}), (f) the budget imbalance that is not accounted for by the other terms. Positive values of S_{LAND} and S_{OCEAN} represent a flux from the atmosphere to land or the ocean. All data are in GtC yr^{-1} with the uncertainty bounds representing ±1 standard deviation in shaded colour. Data sources are as in Fig. 3. The red dots indicate our projections for the year 2021 and the red error bars the uncertainty in the projections (see methods).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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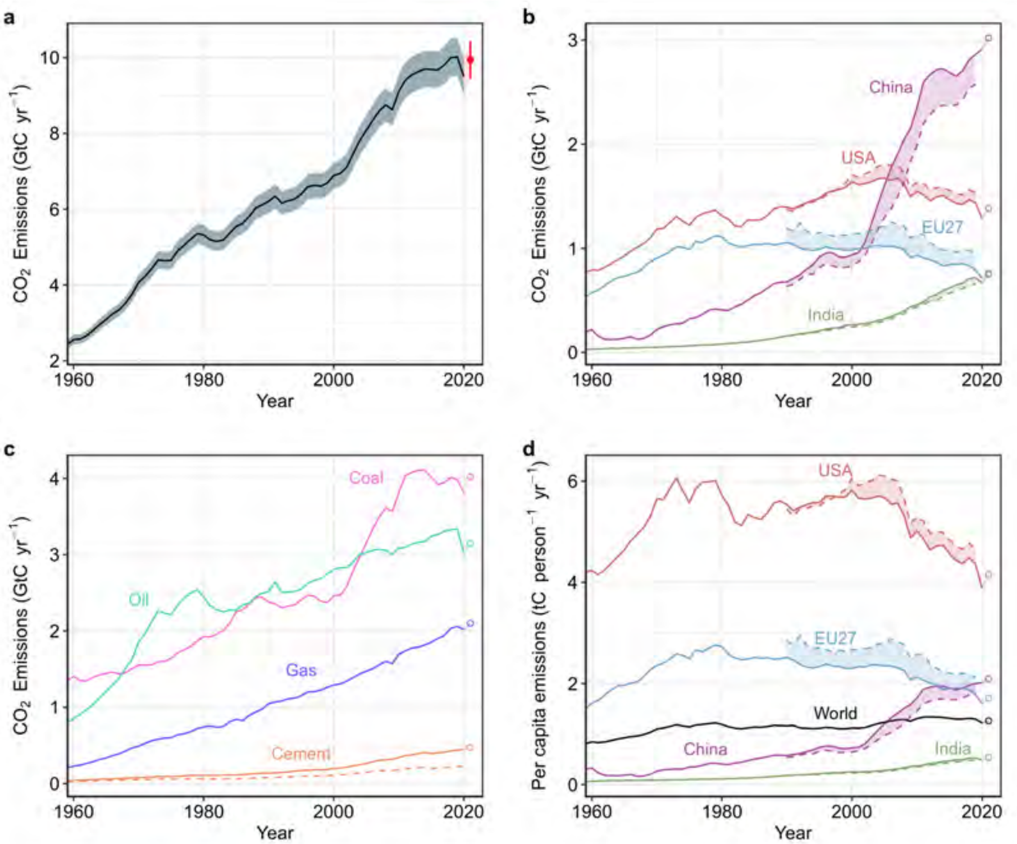

Figure 5. Fossil CO_2 emissions for (a) the globe, including an uncertainty of ± 5% (grey shading) and a projection through the year 2021 (red dot and uncertainty range), (b) territorial (solid lines) and consumption (dashed lines) emissions for the top three country emitters (USA, China, India) and for the European Union (EU27), (c) global emissions by fuel type, including coal, oil, gas, and cement, and cement minus cement carbonation (dashed), and (d) per-capita emissions the world and for the large emitters as in panel (b). Territorial emissions are primarily from Gilfillan and Marland (2021) except national data for the USA and EU27 for 1990-2018, which are reported by the countries to the UNFCCC as detailed in the text; consumption-based emissions are updated from Peters et al. (2011b). See Section 2.1 and Appendix C.1 for details of the calculations and data sources.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

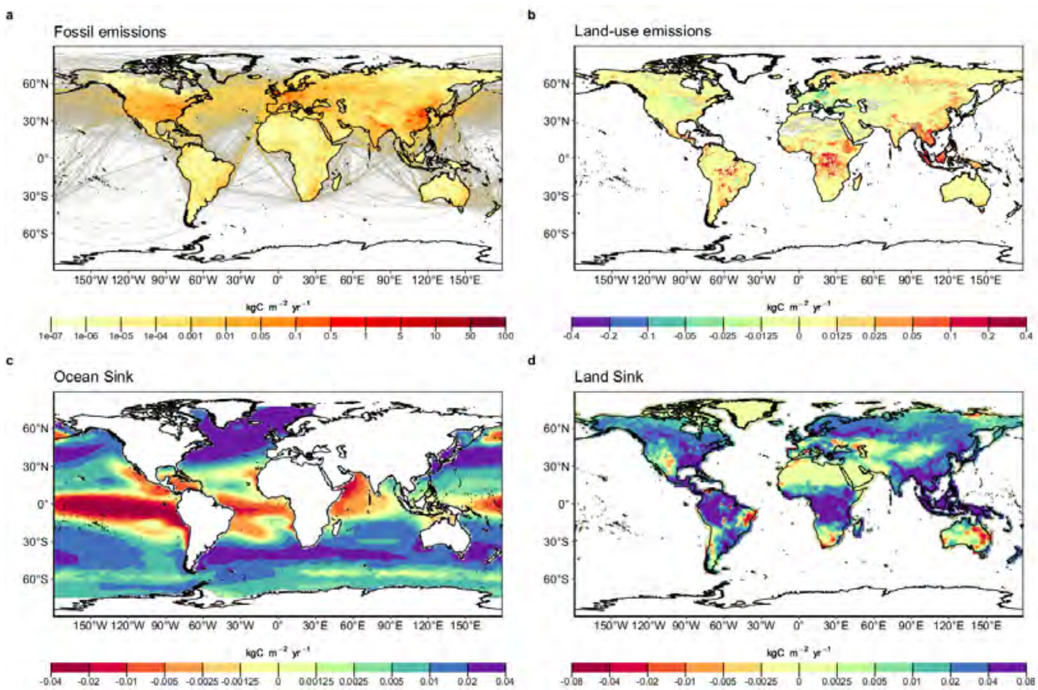

Figure 6. The 2011-2020 decadal mean components of the global carbon budget, presented for (a) fossil CO_2 emissions (E_{FOS}), (b) land-use change emissions (E_{LUC}), (c) the ocean CO_2 sink (S_{OCEAN}), and (d) the land CO_2 sink (S_{LAND}). Positive values for E_{FOS} and E_{LUC} represent a flux to the atmosphere, whereas positive values of S_{OCEAN} and S_{LAND} represent a flux from the atmosphere to the ocean or the land. In all panels, yellow/red (green/blue) colours represent a flux from (into) the land/ocean to (from) the atmosphere. All units are in kgC m^{-2} yr^{-1}. Note the different scales in each panel. E_{FOS} data shown is from GCP-GridFEDv2021.2. E_{LUC} data shown is only from BLUE as the updated H&N2017 and OSCAR do not resolve gridded fluxes. S_{OCEAN} data shown is the average of GOBMs and data-products means, using GOBMs simulation A, no adjustment for bias and drift applied to the gridded fields (see Sections 2.4). S_{LAND} data shown is the average of DGVMs for simulation S2 (see Sections 2.5).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

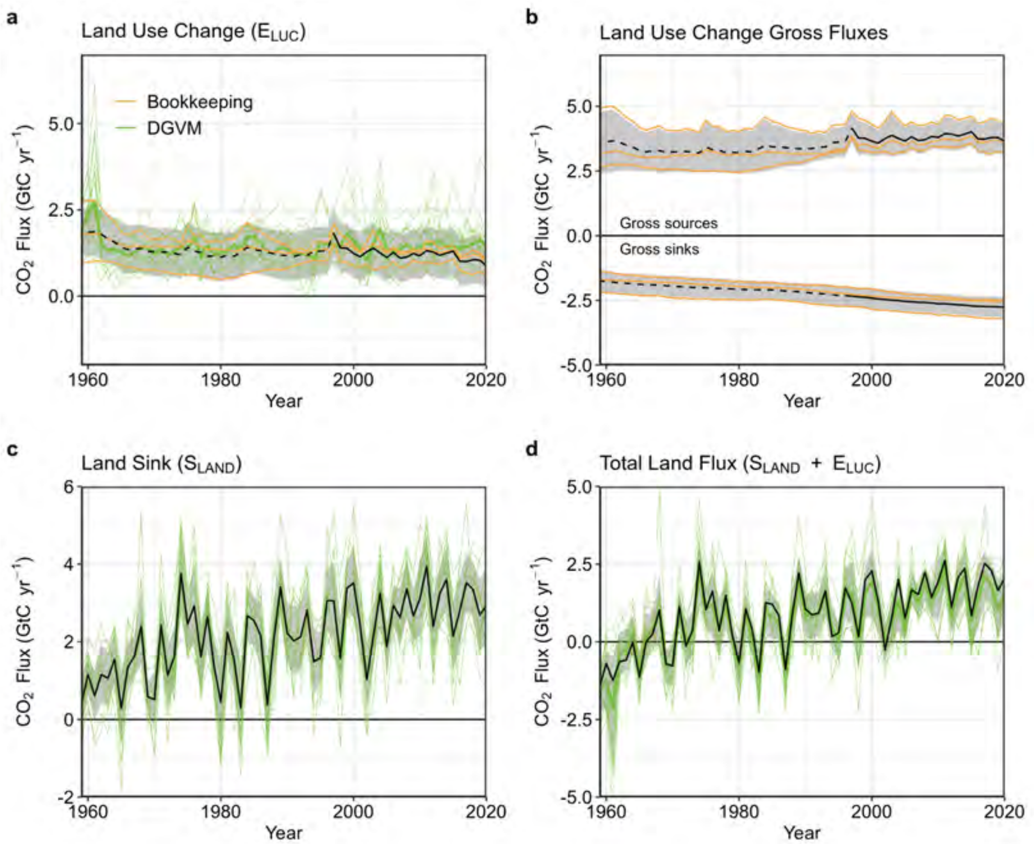

Figure 7. CO_2 exchanges between the atmosphere and the terrestrial biosphere as used in the global carbon budget (black with ±1σ uncertainty in grey shading in all panels). (a) CO_2 emissions from land-use change (E_{LUC}) with estimates from the three bookkeeping models (yellow lines) and DGVMs models (green) shown individually, with DGVMs ensemble means (dark green). The dashed line identifies the pre-satellite period before the inclusion of peatland burning. (b) CO_2 gross sinks (positive, from regrowth after agricultural abandonment and wood harvesting) and gross sources (negative, from decaying material left dead on site, products after clearing of natural vegetation for agricultural purposes, wood harvesting, and for BLUE, degradation from primary to secondary land through usage of natural vegetation as rangeland, and also from emissions from peat drainage and peat burning) from the three bookkeeping models (yellow lines). The sum of the gross sinks and sources is E_{LUC} shown in panel(a). (c) Land CO_2 sink (S_{LAND}) with individual DGVMs estimates (green). (d) Total atmosphere-land CO_2 fluxes (S_{LAND} – E_{LUC}), with individual DGVMs (green) and their multi-model mean (dark green).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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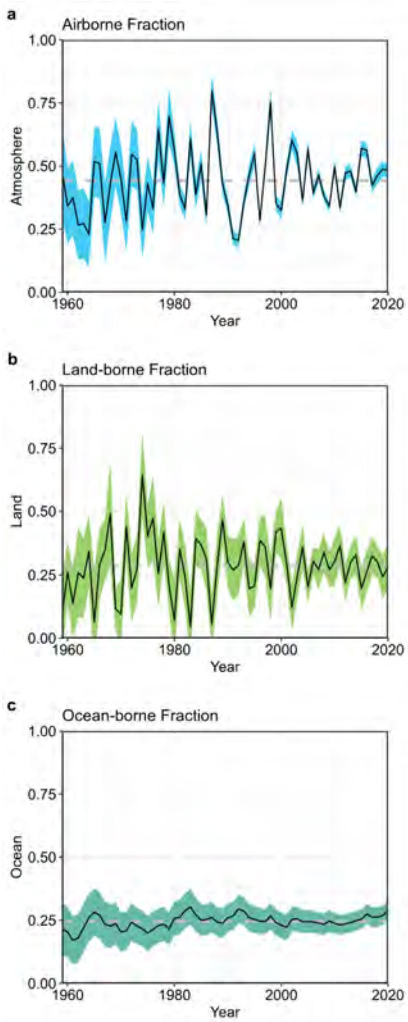

Figure 8. The partitioning of total anthropogenic CO_2 emissions (E_{FOS} + E_{LUC}) across (a) the atmosphere (airborne fraction), (b) land (land-borne fraction), and (c) ocean (ocean-borne fraction). Black lines represent the central estimate, and the coloured shading represents the uncertainty. The grey dashed lines represent the long-term average of the airborne (44%), land-borne (28%) and ocean-borne (24%) fractions during 1959-2020.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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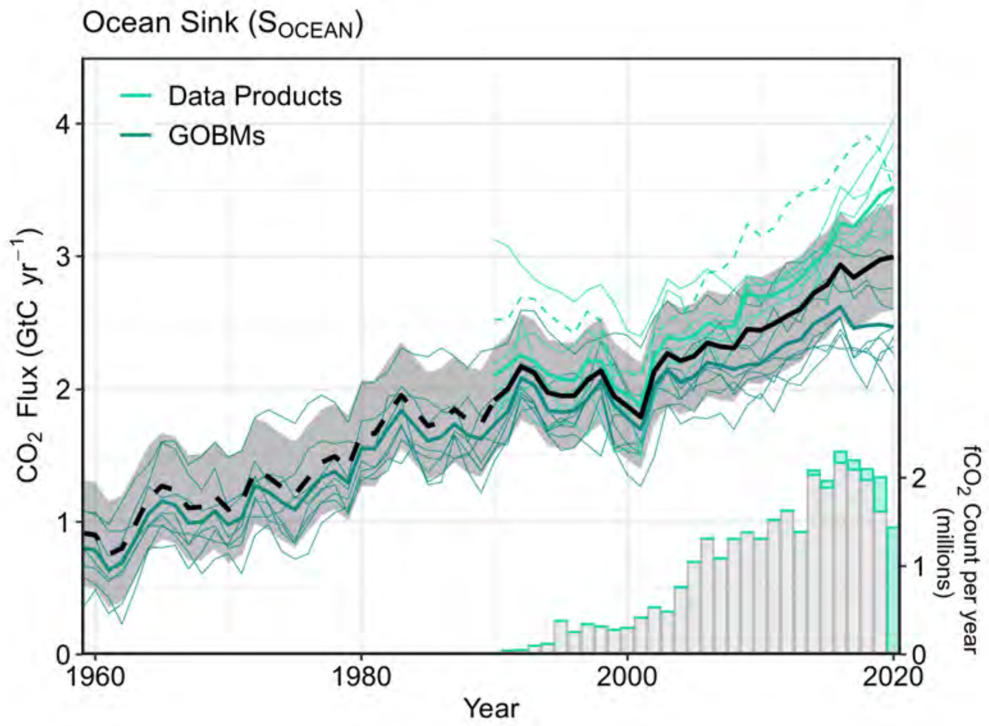

Figure 9. Comparison of the anthropogenic atmosphere-ocean CO_2 flux showing the budget values of S_{OCEAN} (black; with the uncertainty in grey shading), individual ocean models (teal), and the ocean fCO_2-based data products (cyan; with Watson et al. (2020) in dashed line as not used for ensemble mean). The fCO_2-based data products were adjusted for the pre-industrial ocean source of CO_2 from river input to the ocean, by subtracting a source of 0.61 GtC yr^{-1} to make them comparable to S_{OCEAN} (see Section 2.4). Bar-plot in the lower right illustrates the number of fCO_2 observations in the SOCAT v2021 database (Bakker et al., 2021). Grey bars indicate the number of data points in SOCAT v2020, and coloured bars the newly added observations in v2021.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

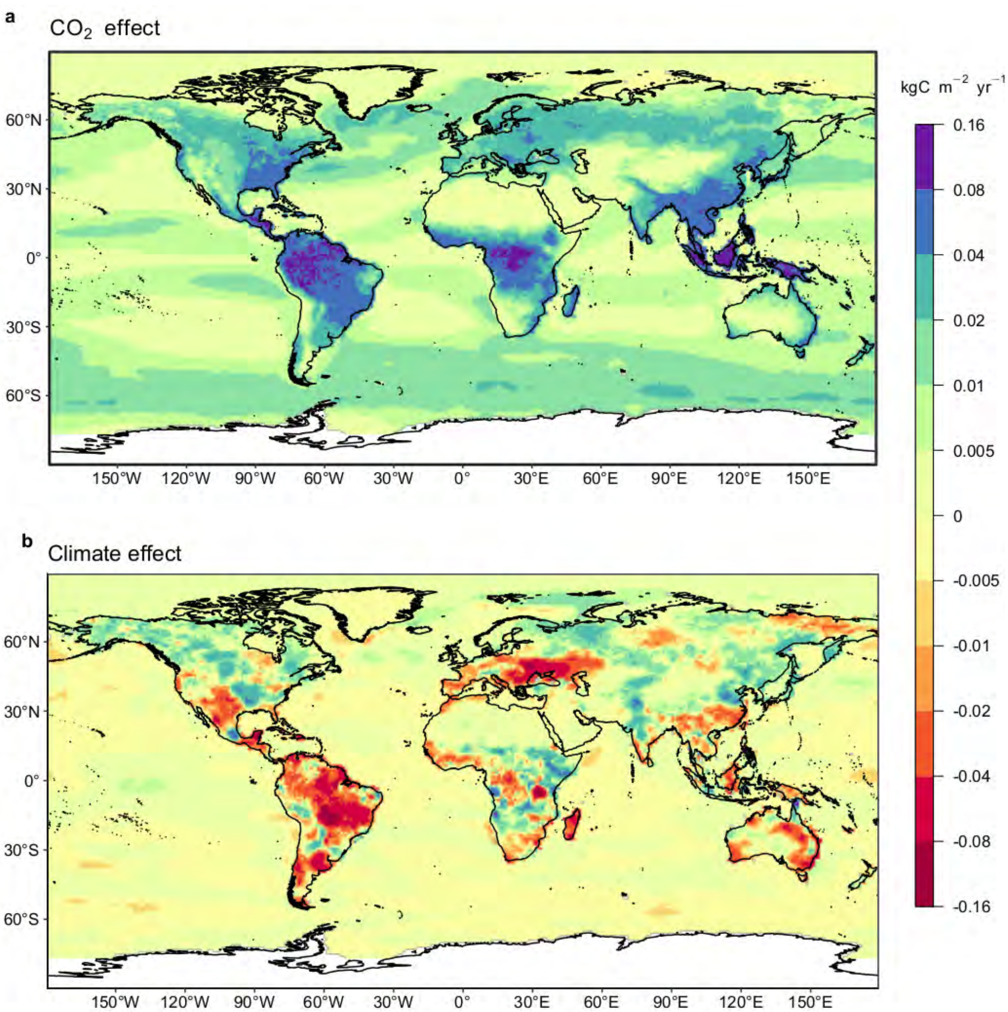

Figure 10. Attribution of the atmosphere-ocean (S_{OCEAN}) and atmosphere-land (S_{LAND}) CO_2 fluxes to (**a**) increasing atmospheric CO_2 concentrations and (**b**) changes in climate, averaged over the previous decade 2011-2020. All data shown is from the processed-based GOBMs and DGVMs. The sum of ocean CO_2 and climate effects will not equal the ocean sink shown in Figure 6 which includes the fCO_2-based data products. See Appendix C.3.2 and C.4.1 for attribution methodology. Units are in kgC m^{-2} yr^{-1} (note the non-linear colour scale).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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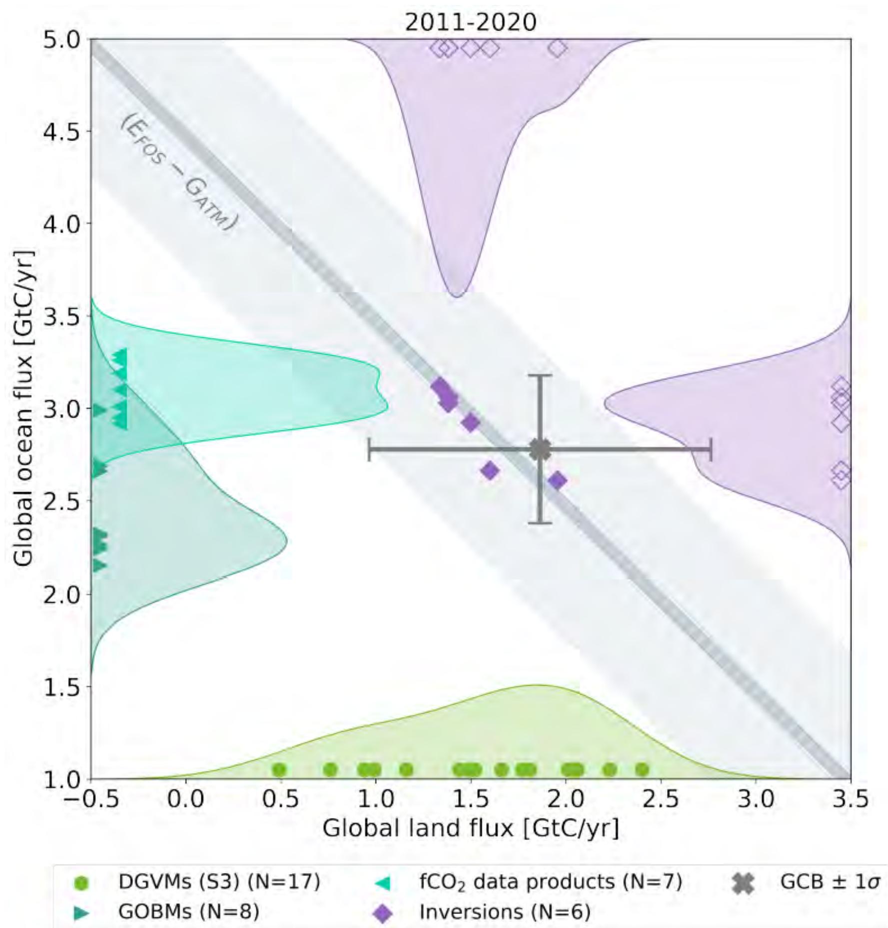

Figure 11. The 2011-2020 decadal mean net atmosphere-ocean and atmosphere-land fluxes derived from the ocean models and fCO_2 products (y-axis, right and left pointing blue triangles respectively), and from the DGVMs (x-axis, green symbols), and the same fluxes estimated from the six inversions (purple symbols on secondary x- and y-axis). The grey central point is the mean (±1σ) of S_{OCEAN} and (S_{LAND} – E_{LUC}) as assessed in this budget. The shaded distributions show the density of the ensemble of individual estimates. The grey diagonal band represents the fossil fuel emissions minus the atmospheric growth rate from this budget (E_{FOS} – G_{ATM}). Note that positive values are CO_2 sinks.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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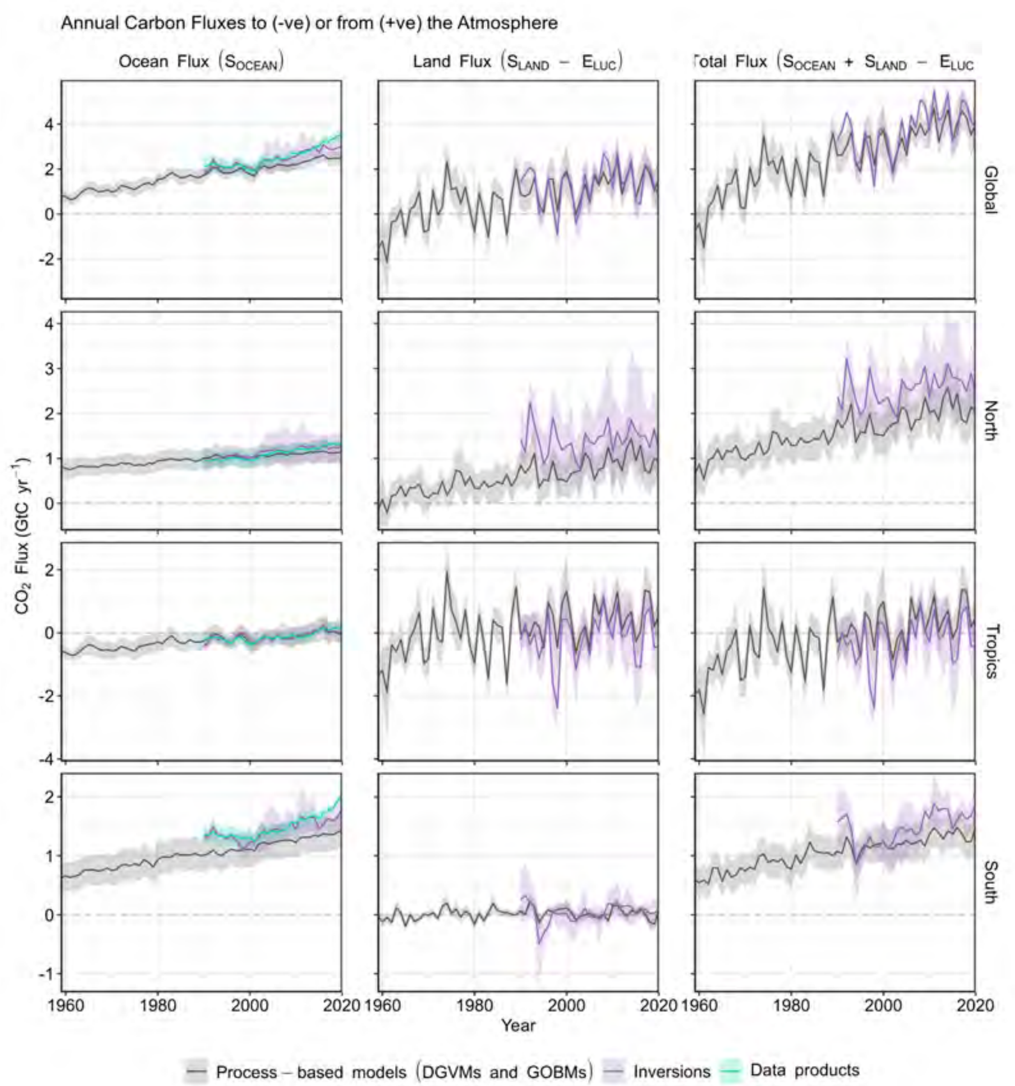

Figure 12. CO_2 fluxes between the atmosphere and the Earth's surface separated between land and oceans, globally and in three latitude bands. The ocean flux is S_{OCEAN} and the land flux is the net atmosphere-land fluxes from the DGVMs. The latitude bands are (top row) global, (2nd row) north (>30°N), (3rd row) tropics (30°S-30°N), and (bottom row) south (<30°S), and over ocean (left column), land (middle column), and total (right column). Estimates are shown for: process-based models (DGVMs for land, GOBMs for oceans); inversion models (land and ocean); and fCO_2-based data products (ocean only). Positive values indicate a flux from the atmosphere to the land or the ocean. Mean estimates from the combination of the process models for the land and oceans are

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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shown (black line) with ±1 standard deviation (1σ) of the model ensemble (grey shading). For the total uncertainty in the process-based estimate of the total sink, uncertainties are summed in quadrature. Mean estimates from the atmospheric inversions are shown (purple lines) with their full spread (purple shading). Mean estimates from the fCO_2-based data products are shown for the ocean domain (light blue lines) with their ±1σ spread (light blue shading). The global S_{OCEAN} (upper left) and the sum of S_{OCEAN} in all three regions represents the anthropogenic atmosphere-to-ocean flux based on the assumption that the preindustrial ocean sink was 0 GtC yr^{-1} when riverine fluxes are not considered. This assumption does not hold at the regional level, where preindustrial fluxes can be significantly different from zero. Hence, the regional panels for S_{OCEAN} represent a combination of natural and anthropogenic fluxes. Bias-correction and area-weighting were only applied to global S_{OCEAN}; hence the sum of the regions is slightly different from the global estimate (<0.06 GtC yr^{-1}).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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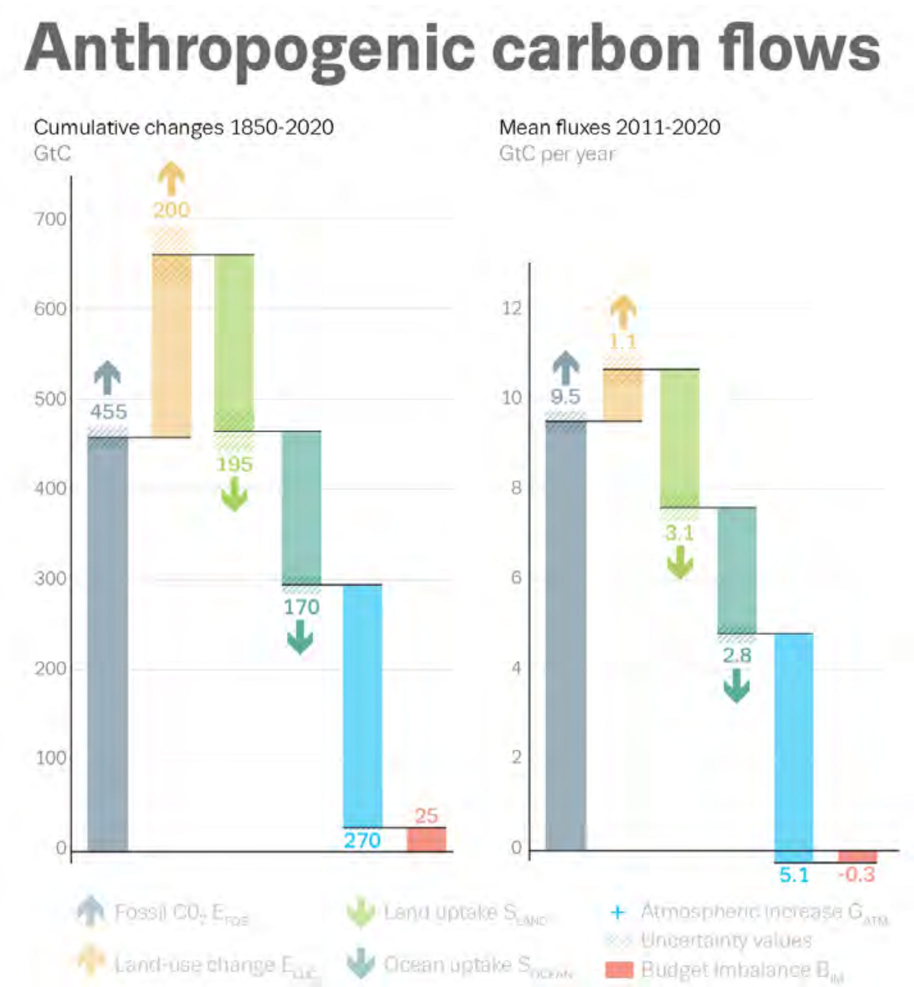

Figure 13. Cumulative changes over the 1850-2020 period (left) and average fluxes over the 2011-2020 period (right) for the anthropogenic perturbation of the global carbon cycle. See the caption of Figure 3 for key information and the methods in text for full details.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Figure 14. Kaya decomposition of the main drivers of fossil CO_2 emissions, considering population, GDP per person, Energy per GDP, and CO_2 emissions per energy, for China (top left), USA (top right), EU27 (middle left), India (middle right), Rest of the World (bottom left), and World (bottom right). Black dots are the annual fossil CO_2 emissions growth rate, coloured bars are the contributions from the different drivers. A general trend is that population and GDP growth put upward pressure on emissions, while energy per GDP and more recently CO_2 emissions per energy put downward pressure on emissions. The changes during 2020 led to a stark contrast to previous years, with different drivers in each region.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

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1 **Appendix A. Supplementary Tables**

Table A1. Comparison of the processes included in the bookkeeping method and DGVMs in their estimates of ELUC and SLAND. See Table 4 for model references. All models include deforestation and forest regrowth after abandonment of agriculture (or from afforestation activities on agricultural land). Processes relevant for ELUC are only described for the DGVMs used with land-cover change in this study.

	Bookkeeping Models			**DGVMs**																
	H&N	BLUE	OSCAR	CABLE-POP	CLASSIC	CLM5.0	DLEM	IBIS	ISAM	ISBA-CTRIP(h)	JSBACH	JULES-ES	LPJ-GUESS	LPJ	LPX-Bern	OCNv2	ORCHIDEEv3	SDGVM	VISIT	YIBs
Processes relevant for ELUC																				
Wood harvest and forest degradation (a)	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes	no	yes	yes	no (d)	yes	yes	no	yes	no
Shifting cultivation / Subgrid scale transitions	no (b)	yes	yes	yes	no	yes	no	no	no	no	yes	no	yes	yes	no (d)	no	no	no	yes	no
Cropland harvest (removed, R, or added to litter, L)	yes (R) (p)	yes (R) (p)	yes (R)	yes (R)	yes (L)	yes (R)	yes	yes (R)	yes	yes (R+L)	yes (R+L)	yes (R)	yes (R)	yes (L)	yes (R)	yes (R+L)	yes (R)	yes (R)	yse (R)	yes (L)
Peat fires	yes	yes	yes	no	no	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no
fire as a management tool	yes (p)	yes (p)	yes (j)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
N fertilization	yes (p)	yes (p)	yes (j)	no	no	yes	yes	no	yes	no	no	yes(k)	yes	no	yes	yes	yes	no	no	no
tillage	yes (p)	yes (p)	yes (j)	no	yes (g)	no	no	no	no	no	no	no	yes	no	no	no	yes (g)	no	no	no
irrigation	yes (p)	yes (p)	yes (j)	no	no	yes	yes	no	yes	no	no	no	yes	no	no	no	no	no	no	no
wetland drainage	yes (p)	yes (p)	yes (j)	no	no	no	no	no	yes	no	no	no	no	no	no	no	no	no	no	no
erosion	yes (p)	yes (p)	yes (j)	no	no	no	yes	no	no	no	no	no	no	no	no	no	no	no	yes	no
peat drainage	yes	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Grazing and mowing Harvest (removed, r, or added to litter, l)	yes (r) (p)	yes (r) (p)	yes (r)	yes (r)	no	no	no	no	yes (l)	no	yes (l)	no	yes (r)	yes (l)	no	yes (r+l)	no	no	no	no
Processes also relevant for SLAND (in addition to CO2 fertilization and climate)																				
Fire simulation and/or suppression	N.A.	N.A.	N.A.	no	yes	yes	no	yes	no	yes	yes	yes	yes	yes	yes	no	no	yes	yes	no
Carbon-nitrogen interactions, including N deposition	N.A.	N.A.	N.A.	yes	no (f)	yes	yes	no	yes	no (e)	yes	yes	yes	no	yes	yes	yes	yes (c)	no	no (f)
Separate treatment of direct and diffuse solar radiation	N.A.	N.A	N.A	no	no	yes	no	no	no	no	no	yes	no	no	no	no	no	no	no	no

(a) Refers to the routine harvest of established managed forests rather than pools of harvested products.
(b) No back- and forth-transitions between vegetation types at the country-level, but if forest loss based on FRA exceeded agricultural expansion based on FAO, then this amount of area was cleared for cropland and the same amount of area of old croplands abandoned.
(c) Limited. Nitrogen uptake is simulated as a function of soil C, and Vcmax is an empirical function of canopy N. Does not consider N deposition.
(d) Available but not active.
(e) Simple parameterization of nitrogen limitation based on Yin (2002; assessed on FACE experiments)
(f) Although C-N cycle interactions are not represented, the model includes a parameterization of down-regulation of photosynthesis as CO2 increases to emulate nutrient constraints (Arora et al., 2009)

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

(g) Tillage is represented over croplands by increased soil carbon decomposition rate and reduced humification of litter to soil carbon.
(h) ISBA-CTRIP corresponds to SURFEXv8 in GCB2018
(i) Bookkeeping models include the effect of CO2-fertilization as captured by present-day carbon densities, but not as an effect transient in time.
(j) as far as the DGVMs that OSCAR is calibrated to include it
(k) perfect fertilisation assumed, i.e. crops are not nitrogen limited and the implied fertiliser diagnosed
(m) fire intensity responds to climate and CO2, but no fire suppression
(z) Process captured implicitly by use of observed carbon densities.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table A2. Comparison of the processes and model set up for the Global Ocean Biogeochemistry Models for their estimates of SOCEAN. See Table 4 for model references.

	NEMO-PlankTOM12	**NEMO-PISCES (IPSL)**	**MICOM-HAMOCC (NorESM1-OCv1.2)**	**MPIOM-HAMOCC6**	**FESOM-2.1-REcoM2**	**NEMO3.6-PISCESv2-gas (CNRM)**	**MOM6-COBALT (Princeton)**	**CESM-ETHZ**
SPIN-UP procedure								
Initialisation of carbon chemistry	GLODAPv1 corrected for anthropogenic carbon from Sabine et al. (2004)	GLODAPv2	GLODAP v1 (preindustrial DIC)	initialization from previous model simulations	GLODAPv2 alkalinity and preindustrial DIC	GLODAPv2	GLODAPv2 for Alkalinity and DIC. DIC is corrected to 1959 level for simulation A and C and corrected to pre-industrial level for simulation B using Khatiwala et al. (2009, 2013)	GLODAPv2 preindustrial
Preindustrial spin-up prior to 1850? If yes, how long?	spin-up 1750-1947	spin-up starting in 1836 with 3 loops of JRA55	1000 year spin up	yes, ~2000 years	50 years	long spin-up (> 1000 years)	Other biogeochemical tracers are initialized from a GFDL-ESM2M spin-up (> 1000 years)	spinup 1655-1849
atmospheric forcing for pre-industrial spin-up	looping NCEP year 1990	JRA55	CORE-I (normal year) forcing	spinup with omip climatology to reach steady state with the rivers	JRA55-do v.1.5.0 repeated year 1961	JRA55-do	GFDL-ESM2M internal forcing	COREv2 forcing until 1835, three cycles of conditions from 1949-2009. from 1835-1850: JRA forcing
atmospheric forcing for historical spin-up 1850-1958 for simulation A	1750-1947: looping NCEP year 1990; 1948-2020: NCEP	1836-1958 : looping full JRA55 reanalysis	CORE-I (normal year) forcing; from 1948 onwards NCEP-R1 with CORE-II corrections	NCEP 6 hourly cyclic forcing (10 years starting from 1948) with co2 at 278 ppm and rivers	JRA55-do-v1.5.0 repeated year 1961	JRA55-do cycling year 1958	JRA55-do-v1.5 repeat year 1959 (71 years)	JRA55 version 1.3, repeat cycle between 1958-2018.
atmospheric CO2 for historical spin-up 1850-1958 for simulation A	provided by the GCP; converted to pCO2 temperature formulation (Sarmiento et al., 1992), monthly	xCO2 as provided by the GCB, global mean, annual resolution, converted to pCO2 with sea-level	xCO2 as provided by the GCB, converted to pCO2 with sea level pressure and water vapor correction	provided by the GCB	xCO2 as provided by the GCB, converted to pCO2 with sea-level pressure and water vapour pressure,	xCO2 as provided by the GCB, converted to pCO2 with constant sea-level pressure and water vapour	xCO2 at year 1959 level (315 ppm), converted to pCO2 with sea-level pressure and water vapour pressure,	xCO2 as provided by the GCB (new version 2021), converted to pCO2 with atmospheric pressure,

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

	resolution	pressure and water vapour pressure			global mean, monthly resolution	pressure, global mean, yearly resolution	global mean, yearly resolution	and locally determined water vapour pressure from SST and SSS (100% saturation)
atmospheric forcing for control spin-up 1850-1958 for simulation B	1750-2020: looping NCEP 1990	1836-1958 : looping full JRA55 reanalysis	CORE-I (normal year) forcing	NCEP 1957 fixed forcing, co2=278 and rivers	JRA55-do-v1.5.0 repeat year 1961	JRA55-do cycling year 1958	JRA55-do-v1.5 repeat year 1959 (71 years)	normal year forcing created from JRA-55 version 1.3, NYF = climatology with anomalies from the year 2001
atmospheric CO_2 for control spin-up 1850-1958 for simulation B	constant 278ppm; converted to pCO_2 temperature formulation (Sarmiento et al., 1992), monthly resolution	xCO_2 of 286.46ppm, converted to pCO_2 with constant sea-level pressure and water vapour pressure	xCO_2 of 278 ppm, converted to pCO_2 with seal level pressure and water vapor correction	278, no conversion, assuming constant standard sea level pressure	xCO_2 of 278ppm, converted to pCO_2 with sea-level pressure and water vapour pressure	xCO_2 of 286.46ppm, converted to pCO_2 with constant sea-level pressure and water vapour pressure	xCO_2 of 278ppm, converted to pCO_2 with sea-level pressure and water vapour pressure	xCO_2 as provided by the GCB for 1850, converted to pCO_2 with atmospheric pressure, and locally determined water vapour pressure from SST and SSS (100% saturation)
simulation A								
Atmospheric forcing for simulation A	NCEP	JRA55-v1.4 then 1.5 for 2020.	NCEP-R1 with CORE-II corrections	till1948: continue from A_spinup with cyclic NCEP forcing (1948+10) and increasing CO_2 => GCBA-1777-1948 -1948-2020 : with transient NCEP forcing and transient monthly CO_2	JRA55-do-v1.5.0	JRA55-do	JRA55-do-v1.5.0 1959-2019 and JRA55-do-v1.5.0.1b for 2020	JRA-55 version 1.3
atmospheric CO_2 for simulation A	provided by the GCP; converted to pCO_2 temperature formulation (Sarmiento et al., 1992), monthly resolution	xCO_2 as provided by the GCB, global mean, annual resolution, converted to pCO_2 with sea-level pressure and	xCO_2 as provided by the GCB, converted to pCO_2 with sea level pressure and water vapor correction		xCO_2 as provided by the GCB, converted to pCO_2 with sea-level pressure and water vapour pressure, global mean,	xCO_2 as provided by the GCB, converted to pCO_2 with constant sea-level pressure and water vapour pressure,	xCO_2 as provided by the GCB, converted to pCO_2 with sea-level pressure and water vapour pressure, global mean,	xCO_2 as provided by the GCB (new version 2021), converted to pCO_2 with atmospheric pressure, and locally

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

		water vapour pressure			monthly resolution	global mean, yearly resolution	yearly resolution	determined water vapour pressure from SST and SSS (100% saturation)
simulation B								
Atmospheric forcing for simulation B	NCEP 1990	N/A	CORE-I (normal year) forcing	1948-2020: continue with B_spinup with fixed NCEP forcing 1957, co2=278 and rivers	JRA55-do-v1.5.0 repeat year 1961	JRA55-do cycling year 1958	JRA55-do-v1.5.0 repeat year 1959	normal year forcing created from JRA-55 version 1.3, NYF = climatology with anomalies from the year 2001
atmospheric CO2 for simulation B	constant 278ppm; converted to pCO2 temperature formulation (Sarmiento et al., 1992), monthly resolution	N/A	xCO2 of 278 ppm, converted to pCO2 with sea level pressure and water vapor correction		xCO2 of 278ppm, converted to pCO2with sea-level pressure and water vapour pressure	xCO2 of 286.46ppm, converted to pCO2 with constant sea-level pressure and water vapour pressure	xCO2 of 278ppm, converted to pCO2 with sea-level pressure and water vapour pressure	xCO2 as provided by the GCB for 1850, converted to pCO2 with atmospheric pressure, and locally determined water vapour pressure from SST and SSS (100% saturation)
model specifics								
Physical ocean model	NEMOv3.6-ORCA2	NEMOv3.6-eORCA1L75	MICOM (NorESM1-OCv1.2)	MPIOM	FESOM-2.1	NEMOv3.6-GELATOv6-eORCA1L75	MOM6-SIS2	CESMv1.3 (ocean model based on POP2)
Biogeochemistry model	PlankTOM12	PISCESv2	HAMOCC (NorESM1-OCv1.2)	HAMOCC6	REcoM-2-M	PISCESv2-gas	COBALTv2	BEC (modified & extended)
Horizontal resolution	2o lon, 0.3 to 1.5o lat	1° lon, 0.3 to 1° lat	1° lon, 0.17 to 0.25 lat (nominally 1°)	1.5◦	unstructured multi-resolution mesh. CORE-mesh, with 20-120 km resolution. Highest resolution north of 50N, intermediate in the equatorial belt and Southern Ocean, lowest in the subtropical gyres	1° lon, 0.3 to 1° lat	0.5° lon, 0.25 to 0.5° lat	Lon: 1.125°, Lat varying from 0.53° in the extratropics to 0.27° near the equator

Vertical resolution	31 levels	75 levels, 1m at the surface	51 isopycnic layers + 2 layers representing a bulk mixed layer	40 levels, layer thickness increase with depth	46 levels, 10 m spacing in the top 100 m	75 levels, 1m at surface	75 levels hybrid coordinates, 2 m at surface	60 levels (z-coordinates)
Total ocean area on native grid (km2)	3.6080E+08	3.6270E+08	3.6006E+08	3.6598E+08	3.6475E+08	3.6270E+14	3.6110E+08	3.5926E+08
Ocean area on native grid (km2) - NORTH	6.2646E+07		6.2049E+07	6.4440E+07		6.3971E+13		
Ocean area on native grid (km2) - TROPICS	1.1051E+08		1.9037E+08	1.9248E+08		1.9025E+14		
Ocean area on native grid (km2) - SOUTH	1.8766E+08		1.0765E+08	1.0986E+08		1.0848E+14		
gas-exchange parameterization	Quadratic exchange formulation (function of T + 0.3*U^2)* (Sc/660)^-0.5) ; Wanninkhof (1992, Equation 8); Sweeney et al. (2007)	see Orr et al. (2017): kw parameterized from Wanninkhof (1992), with kw = a* (Sc/660)^-0.5) *u2*(1-f_ice) with a from Wanninkhof (2014)	see Orr et al. (2017): kw parameterized from Wanninkhof (1992), with kw = a* (Sc/660)^-0.5) *u2*(1-f_ice) with a=0.337 following the OCMIP2 protocols	Gas transfer velocity formulation and parameter setup of Wanninkhof (2014), including updated Schmidt number parameterizations for CO2 to comply with OMIP protocol (Orr et al., 2017)	see Orr et al. (2017): kw parameterized from Wanninkhof (1992), with kw = a* (Sc/660)^-0.5) *u2*(1-f_ice) with a from Wanninkhof (2014)	see Orr et al. (2017): kw parameterized from Wanninkhof (1992), with kw = a* (Sc/660)^-0.5) *u2*(1-f_ice) with a from Wanninkhof (2014)	see Orr et al. (2017): kw parameterized from Wanninkhof (1992), with kw = a* (Sc/660)^-0.5) *u2*(1-f_ice) with a from Wanninkhof (2014)	Gas exchange is parameterized using the Wanninkhof (1992) quadratic windspeed dependency formulation, but with the coefficient scaled down to reflect the recent 14C inventories. Concretely, we used a coefficent a of 0:31 cm hr-1 s2 m-2 to read kw = 0:31 ws^2 (1-fice) (Sc=660)^{-1/2}
time-step	96 mins	45 min	3200 sec	60 mins	45 min	15min	30 min	3757 sec
output frequency	Monthly	monthly	monthly/daily	monthly	monthly	monthly	monthly	monthly
CO2 chemistry routines	Following Broecker et al. (1982)	mocsy	Following Dickson et al. (2007)	as in Ilyina et al. (2013) adapted to comply with OMIP protocol (Orr et al., 2017).	mocsy	mocsy	mocsy	OCMIP2 (Orr et al., 2017)
river carbon input (PgC/yr)	60.24 Tmol/yr; 0.723 PgC/yr	0.61 PgC y-1	0	0.77 PgC/yr	0	~0.611 PgC y-1	~0.15 PgC y-1	0.33 Pg C yr-1
burial/net flux into the sediment (PgC/yr)	0.723 PgC/yr	0.59 GtC y-1	around 0.54	around 0.44 PgC/yr	0	~0.656 GtC y-1	~0.18 PgC y-1	0.21 Pg C yr-1

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Table A3: Description of ocean data-products used for assessment of SOCEAN. See Table 4 for references.

	Jena-MLS	MPI-SOMFFN	CMEMS-LSCE-FFNN	CSIR-ML6	Watson et al	NIES-NN	JMA-MLR	OS-ETHZ-GRaCER
Method	Spatio-temporal interpolation (update of Rödenbeck et al., 2013, version oc_v2021). Specifically, the sea-air CO_2 fluxes and the pCO_2 field are numerically linked to each other and to the spatio-temporal field of ocean-internal carbon sources/sinks through process parametrizations, and the ocean-internal sources/sink field is then fit to the SOCATv2021 pCO_2 data (Bakker et al., 2021). The fit includes a multi-linear regression against environmental drivers to bridge data gaps, and interannually explicit corrections to represent the data signals more completely.	2-step neural network method where in a first step the global ocean is clustered into 16 biogeochemical provinces (one stand alone province for the Arctic Ocean - see Landschützer et al 2020) using a self-organizing map (SOM). In a second step, the non-linear relationship between available pCO_2 measurements from the SOCAT database (Bakker et al 2016) and environmental predictor data (SST, SSS, MLD, CHL-a, atmospheric CO_2 - references see Landschützer et al 2016) are established using a feed-forward neural network (FFN) for each province separately. The established relationship is then used to fill the existing data gaps (see Landschützer et al. 2013, 2016).	An ensemble of neural network models trained on 100 subsampled datasets from the Surface Ocean CO_2 Atlas v2021 (SOCATv2021, Bakker et al. 2021) . Like the original data, subsamples are distributed after interpolation on 1x1 grid cells along ship tracks. Sea surface salinity, temperature, sea surface height, mixed layer depth, atmospheric CO_2 mole fraction, chlorophyll-a, pCO_2 climatology, latitude and longitude are used as predictors. The models are used to reconstruct sea surface pCO_2 and convert to air-sea CO_2 fluxes (see the proposed ensemble-based approach and analysis in Chau et al. 2020, 2021).	An ensemble average of six machine learning estimates of surface ocean pCO_2 using the approach described in Gregor et al. (2019) with the updated product using SOCAT v2021 (Bakker et al., 2016). All ensemble members use a cluster-regression approach. Two different cluster configurations are used: (1) based on K-means clustering; (2) Fay and McKinley (2014) 's CO_2 biomes. Three regression algorithms are used: (1) gradient boosted decision trees; (2) feed-forward neural network; (3) support vector regression. The product of the cluster configurations and the regression algorithms results in an ensemble with six members., hence the CSIR-ML6.	Derived from the SOCAT(v2021) pCO_2 database, but corrected to the subskin temperature of the ocean as measured by satellite, using the methodology described by Goddijn-Murphy et al. (2015). A correction to the flux calculation is also applied for the cool and salty surface skin. In other respects the product uses interpolation of the data using the two step neural network based on MPI-SOMFFN :in the first step the ocean is divided into a monthly climatology of 16 biogeochemical provinces using a SOM, In the second step a feed-forward neural network establishes non-linear relationships between pCO_2 and SST, SSS, mixed layer depth(MLD) and atmospheric xCO_2 in each	A feed forward neural network model was used to reconstruct monthly global surface ocean CO_2 concentrations 1x1 degree meshes and estimate air-sea CO_2 fluxes. The target variable is the per cruise weighted fCO_2 mean of SOCAT 2021. Feature variables include sea surface temperature (SST), salinity, chlorophyll-a, mixed layer depth, and the monthly nomaly of SST. See Zeng et al. (2014)	Fields of total alkalinity (TA) were estimated by using a multiple linear regressions (MLR) method based on GLODAPv2.2021 and satellite observation data. TA = f(SSDH, SSS) SOCATv2021 fCO_2 data were converted to total dissolved inorganic carbon (DIC) concentrations in combination with the TA, and then fields of DIC were estimated by using a MLR method based on the DIC and satellite observation data. DIC = f(SSDH, SST, SSS, log(Chl), log(MLD), time)	OceanSODA-ETHZ's Geospatial Random Cluster Ensemble Regression is a two-step cluster-regression approach, where multiple clustering instances with slight variations are run to create an ensemble of estimates (n_membersd=16). We use K-means clustering (n_clusters=21) for the clustering step and a combination of Gradient boosted trees (n_members=8) and Feed-forward neural-networks (n_members=8) to estimate SOCAT v2021 fCO_2. Clustering is performed on the following variables: SOCOM_pCO2_climatology, SST_clim, MLD_clim, CHL_clim. Regression is performed on the following variables: xCO2atm, SST, SST_anomaly, SSS, CHL, MLD, u10_wind, v10_wind, sea-

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

					of the 16 provinces. Further description in Watson et al. (2020).			ice changes, SSH (note that the latter two variables are an update from Gregor and Gruber, 2021).
Gas-exchange parameterization	Quadratic exchange formulation (k*U^2*(Sc/660)^-0.5) (Wanninkhof, 1992) with the transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr by Naegler (2009)	Quadratic exchange formulation (k*U^2*(Sc/660)^-0.5) (Wanninkhof, 1992) with the transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr (calculated myself over the full period 1982-2020)	Quadratic exchange formulation (k*U^2*(Sc/660)^-0.5) (Wanninkhof., 2014) with the transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr (Naegler, 2009).	Quadratic formulation kw = a *U10^2 * (Sc/660)^0.5 (). We use scaled kw for ERA5 reanalysis wind data, which is scaled globally to 16.5 cm/hr (after Naegler 2009) like in Fay and Gregor et al. (2021) https://doi.org/10.5194/essd-2021-16	Nightingale et al. (2000) formulation : K=((Sc/600)^-0.5)*(0.333*U+0.222*U^2)	Kw=0.251*Wnd*Wnd/sqrt(Sc/660.0) (Wanninkhof, 2014)	Quadratic exchange formulation (k*U^2*(Sc/660)^-0.5) (Wanninkhof., 2014) with the transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr (Naegler, 2009) under fitted to the JRA55 wind field.	Quadratic formulation of bulk air-sea CO2 flux: kw = a * U10^2 * (Sc/660)^0.5 We use individually scaled kw's for JRA55, ERA5, and NCEP-R1, which are all scaled globally to 16.5 cm/hr (after Naegler, 2009). See Fay and Gregor et al. (2021)
Wind product	JMA55-do reanalysis	ERA 5	ERA5	ERA5	CCMP wind product, 0.25 x 0.25 degrees x 6-hourly, from which we calculate mean and mean square winds over 1 x 1 degree and 1 month intervals. CCMP product does not cover years 1985-1987, for which we use a monthly climatology calculated as the means of 1988-1991.	ERA5	JRA55	JRA55, ERA5, NCEP1
Spatial resolution	2.5 degrees longitude * 2 degrees latitude	1x1 degree	1x1 degree	1 x 1	1 x 1 degree	1x1 degree	1x1 degree	1x1 degree

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Temporal resolution	daily	monthly	monthly	monthly	monthly	monthly	monthly	monthly
Atmospheric CO2	Spatially and temporally varying field based on atmospheric CO2 data from 169 stations (Jena CarboScope atmospheric inversion sEXTALL_v2021)	atmospheric pCO2_wet calculated from the NOAA ESRL marine boundary layer xCO2 and the NCEP sea level pressure with the moisture correction by Dickson et al 2007 (details and references can be obtained from Appendix A3 in Landschützer et al 2013)	Spatially and monthly varying fields of atmospheric pCO2 computed from CO2 mole fraction (Chevallier, 2013; CO2 atmospheric inversion from the Copernicus Atmosphere Monitoring Service), and atmospheric dry-air pressure which is derived from monthly surface pressure (ERA5) and water vapour pressure fitted by Weiss and Price (1980)	The NOAA's marine boundary layer product for the mole fraction of carbon dioxide (xCO2) is linearly interpolated onto a 1°x1° grid and resampled from weekly to monthly. Basically, xCO2 is multiplied by ERA5 mean sea level pressure (MSLP), and a water vapour pressure correction is applied to MSLP using the equation from Dickson et al. (2007). This results in monthly 1°x 1° atmospheric pCO2.	Atmospheric pCO2 (wet) calculated from NOAA marine boundary layer XCO2 and NCEP sea level pressure, with pH2O calculated from Cooper et al. (1998). (2019 XCO2 marine boundary values were not available at submission so we used preliminary values, estimated from 2018 values and increase at Mauna Loa.)	NOAA Greenhouse Gas Marine Boundary Layer Reference. https://gml.noaa.gov/ccgg/mbl/mbl.html	Atmospheric xCO2 fields of JMA-GSAM inversion model (Maki et al. 2010; Nakamura et al. 2015) were used. They were converted to pCO2 by using JRA55 sea level pressure. xCO2 fields in 2020 were not available at this stage, and we use observation data of obspack_co2_1_NRT_v6.1.1_2021-05-17 (Di Sarra et al. 2021) to estimate the increase from 2019 to 2020.	NOAA's marine boundary layer product for xCO2 is linearly interpolated onto a 1x1 degree grid and resampled from weekly to monthly. xCO2 is multiplied by ERA5 mean sea level pressure, where the latter corrected for water vapour pressure using Dickson et al. (2007). This results in monthly 1x1 degree pCO2atm.
Total ocean area on native grid (km2)	3.63E+08	3.63E+08	3.46E+08	3.48E+08	3.51E+08	3.28E+08 (3.23E+08 to 3.35E+08, depending on ice cover)	3.05E+08 (2.98E+08 to 3.15E+08, depending on ice cover)	3.55E+08
method to extend product to full global ocean coverage		Arctic and marginal seas added following Landschützer et al. (2020). previously applied coastal cut (1degree off coast) was dropped					We used the same method as Fay et al. (2021a)	Method has near full coverage
Ocean area on native grid (km2) - NORTH			5.4545E+07	5.0528E+07	5.0700E+07		3.90E+07 (3.75E+07 to 4.09E+07, depending on ice cover)	5.9771E+07
Ocean area on native grid (km2) - TROPICS			1.8875E+08	1.8933E+08	1.9230E+08		1.74E+08	1.8779E+08

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Ocean area on native grid (km2) - SOUTH			1.0241E+08	1.0767E+08	1.0868E+08		9.20E+07 (8.47E+07 to 1.02E+08, depending on ice cover)	1.0705E+08

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table A4. Comparison of the inversion set up and input fields for the atmospheric inversions. Atmospheric inversions see the full CO2 fluxes, including the anthropogenic and pre-industrial fluxes. Hence they need to be adjusted for the pre-industrial flux of CO2 from the land to the ocean that is part of the natural carbon cycle before they can be compared with SOCEAN and SLAND from process models. See Table 4 for references.

	CarbonTracker Europe (CTE)	Jena CarboScope	Copernicus Atmosphere Monitoring Service (CAMS)	UoE	CMS-Flux	NISMON-CO2
Version number	CTE2021	sEXTocNEET_v2021	v20r2	in-situ		v2021.1
Observations						
Atmospheric observations	Hourly resolution (well-mixed conditions) obspack GLOBALVIEWplus v6.1 and NRT_v6.1.1 (a)	Flasks and hourly from various institutions (outliers removed by 2-sigma criterion)	Hourly resolution (well-mixed conditions) obspack GLOBALVIEWplus v6.1 and NRT_v6.1.1 (a), WDCGG, RAMCES and ICOS ATC	Hourly resolution (well-mixed conditions) obspack GLOBALVIEWplus v6.1 and NRT_v6.1.1 (a)	ACOS-GOSAT v9 (6) retrievals between July 2009 and Dec 2014 and OCO-2 b10 (7) retrievals between Jan 2015 to Dec 2015. In addition, surface flask observations from remote sites were also assimilated from GLOBALVIEWplus v6.1 and NRT_v6.1.1 .	Hourly resolution (well-mixed conditions) obspack GLOBALVIEWplus v6.1 and NRT_v6.1.1 (a)
Period covered	2001-2020	1957-2020	1979-2021	2001-2020	2010-2020	1990-2020
Prior fluxes						
Biosphere and fires	SIBCASA biosphere (b) with 2019-2020 climatological, GFAS fires	No prior	ORCHIDEE (climatological), GFEDv4.1s	CASA v1.0, climatology after 2016 & GFED4.0	yearly repeating CARDAMOM biosphere+fires	VISIT & GFEDv4.1s
Ocean	oc_v2020 (Rodenbeck et al., 2014), with updates, For 2020: climatology based on years 2015-2019	oc_v2021 (Rödenbeck et al., 2014) with updates	CMEMS Copernicus ocean fluxes (Denvil-Sommer et al., 2019), with updates	Takahashi climatology	MOM6	JMA global ocean mapping (Iida et al., 2015)
Fossil fuels	GCP-GridFEDv2021.1 (Jones et al., 2021b) for 2000-2018, GCP-GridFEDv2021.2 for 2019+2020 (c)	GCP-GridFEDv2021.2 (Jones et al., 2021b) (c)	GCP-GridFEDv2021.2 (Jones et al., 2021b) (c)	GCP-GridFEDv2021.2 (Jones et al., 2021b) (c)	GCP-GridFEDv2021.2 (Jones et al., 2021b) (c)	GCP-GridFEDv2021.2 (Jones et al., 2021b) (c)
Transport and optimization						
Transport model	TM5	TM3	LMDZ v6	GEOS-CHEM	GEOS-CHEM	NICAM-TM
Weather forcing	ECMWF	NCEP	ECMWF	MERRA2	MERRA-2	JRA55

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Horizontal Resolution	Global: 3° x 2°, Europe: 1° x 1°, North America: 1° x 1°	Global: 4° x 5°	Global: 3.75° x 1.875°	Global: 4° x 5°	Global: 4° x 5°	isocahedral grid: ~225km
Optimization	Ensemble Kalman filter	Conjugate gradient (re-ortho-normalization) (d)	Variational	Ensemble Kalman filter	Variational	Variational
(a) (Cox et al., 2021; Di Sarra et al., 2021)						
(b) (van der Velde et al., 2014)						
(c) GCP-GridFEDv2021.2 (Jones et al., 2021b) is an update through the year 2020 of the GCP-GridFED dataset presented by Jones et al. (2021a).						
(d) ocean prior not optimised						

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

1

Table A5 Attribution of fCO2 measurements for the year 2020 included in SOCATv2021 (Bakker et al., 2016, 2021) to inform ocean fCO2-based data products.

Platform name	Regions	No. of measurements	Principal Investigators	No. of data sets	Platform type
1 degree	North Atlantic, Coastal	8,652	Gutekunst, S.	2	Ship
Allure of the Seas	North Atlantic, Tropical Atlantic, Coastal	19,321	Wanninkhof, R.; Pierrot, D.	8	Ship
Atlantic Explorer	North Atlantic	15,665	Bates, N.	11	Ship
Atlantic Sail	North Atlantic, Coastal	25,082	Steinhoff, T.; Körtzinger, A.	6	Ship
Aurora Australis	Southern Ocean	14,316	Tilbrook, B.	1	Ship
Bjarni Saemundsson	Coastal	3,269	Benoit-Cattin A.; Ólafsdóttir, S. R.	1	Ship
BlueFin	North Pacific, Tropical Pacific, Coastal	76,505	Alin, S. R.; Feely, R. A.	12	Ship
Cap San Lorenzo	Tropical Atlantic, Coastal	12,417	Lefèvre, N.	2	Ship
Celtic Explorer	North Atlantic, Coastal	18,617	Cronin, M.	6	Ship
Colibri	North Atlantic, Tropical Atlantic, Coastal	13,402	Lefèvre, N.	2	Ship
Equinox	North Atlantic, Coastal	25,052	Wanninkhof, R.; Pierrot, D.	11	Ship
F. G. Walton Smith	Coastal	10,460	Rodriguez, C.; Millero, F. J.; Pierrot, D.; Wanninkhof, R.	6	Ship
Finnmaid	Coastal	253,894	Rehder, G.; Glockzin, M.	11	Ship
Flora	Tropical Pacific	4,099	Wanninkhof, R.; Pierrot, D.	2	Ship
G.O. Sars	Arctic, North Atlantic, Coastal	75,833	Skjelvan, I.	7	Ship
GAKOA_149W_60N	Coastal	68	Cross, J. N.; Monacci, N. M.	3	Mooring
Gulf Challenger	Coastal	2,717	Salisbury, J.; Vandemark, D.; Hunt, C.	3	Ship
Healy	Arctic, North Pacific, Coastal	16,943	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	4	Ship
Henry B. Bigelow	North Atlantic, Coastal	14,436	Wanninkhof, R.; Pierrot, D.	4	Ship
Heron Island	Coastal	768	Tilbrook B.	1	Mooring
James Clark Ross	Southern Ocean	2,000	Kitidis, V.	1	Ship
James Cook	North Atlantic, Tropical Atlantic, Coastal	46,710	Theetaert, H.	1	Ship
KC_BUOY	Coastal	1,983	Evans, W.	1	Mooring
Laurence M. Gould	Southern Ocean	25,414	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	4	Ship
Maria. S. Merian	Tropical Atlantic, Coastal	35,806	Ritschel, M.	1	Ship
Marion Dufresne	Southern Ocean, Indian	4,709	Lo Monaco, C.; Metzl, N.	1	Ship
Nathaniel B. Palmer	Southern Ocean, Tropical Pacific	34,357	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	3	Ship
New Century 2	North Pacific, Tropical Pacific, Tropical Atlantic, North Atlantic, Coastal	27,793	Nakaoka, S.-I.	14	Ship
Nuka Arctica	North Atlantic, Coastal	26,576	Becker, M.; Olsen, A.	6	Ship
Oscar Dyson	Arctic, North Pacific, Coastal	28,196	Alin, S. R.; Feely, R. A.	6	Ship
Quadra Island Field Station	Coastal	78,098	Evans, W.	1	Mooring
Ronald H. Brown	Southern Ocean, Tropical Atlantic, North Atlantic, Coastal	51,611	Wanninkhof, R.; Pierrot, D.	6	Ship

Earth System Science Data
Open Access Discussions

Saildrone1030	North Atlantic, Tropical Atlantic, Coastal	4,080	Skjelvan, I.; Fiedler, B.; Pfeil, B.; Jones, S. D.	1	Saildrone
Sea Explorer	Southern Ocean, Tropical Atlantic, North Atlantic, Coastal	89,896	Landschützer, P.; Tanhua, T.	6	Ship
Sikuliaq	Arctic, North Pacific, Coastal	36,278	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	10	Ship
Simon Stevin	Coastal	16,448	Gkritzalis, T.	4	Ship
Soyo Maru	Coastal	46,280	Ono, T.	2	Ship
Tangaroa	Southern Ocean, Tropical Pacific	121,135	Currie, K. I.	13	Ship
TAO110W_0N	Tropical Pacific	1,518	Sutton, A. J.	3	Mooring
Tavastland	Coastal	4,214	Willstrand Wranne, A., Steinhoff, T.	5	Ship
Thomas G. Thompson	Southern Ocean, Tropical Atlantic	1,317	Alin, S. R.; Feely, R. A.	1	Ship
Trans Carrier	Coastal	24,135	Omar, A. M.	13	Ship
Trans Future 5	Southern Ocean, Coastal	16,404	Nakaoka, S.-I.; Nojiri, Y.	15	Ship
Wakataka Maru	North Pacific, Coastal	101,327	Tadokoro, K.; Ono, T.	7	Ship

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Table A6. Aircraft measurement programs archived by Cooperative Global Atmospheric Data Integration Project (CGADIP; Cox et al., 2021) that contribute to the evaluation of the atmospheric inversions (Figure B4).

Site code	Measurement program name in Obspack	Specific doi	Data providers	used in 2021
AAO	Airborne Aerosol Observatory, Bondville, Illinois		Sweeney, C.; Dlugokencky, E.J.	yes
ACG	Alaska Coast Guard		Sweeney, C.; McKain, K.; Karion, A.; Dlugokencky, E.J.	yes
ACT	Atmospheric Carbon and Transport - America		Sweeney, C.; Dlugokencky, E.J.; Baier, B; Montzka, S.; Davis, K.	yes
ALF	Alta Floresta		Gatti, L.V.; Gloor, E.; Miller, J.B.;	yes
AOA	Aircraft Observation of Atmospheric trace gases by JMA		ghg_obs@met.kishou.go.jp	yes
BGI	Bradgate, Iowa		Sweeney, C.; Dlugokencky, E.J.	yes
BNE	Beaver Crossing, Nebraska		Sweeney, C.; Dlugokencky, E.J.	yes
BRZ	Berezorechka, Russia		Sasakama, N.; Machida, T.	yes
CAR	Briggsdale, Colorado		Sweeney, C.; Dlugokencky, E.J.	yes
CMA	Cape May, New Jersey		Sweeney, C.; Dlugokencky, E.J.	yes
CON	CONTRAIL (Comprehensive Observation Network for TRace gases by AIrLiner)	http://dx.doi.org/10.17595/20180208.001	Machida, T.; Matsueda, H.; Sawa, Y. Niwa, Y.	yes
CRV	Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)		Sweeney, C.; Karion, A.; Miller, J.B.; Miller, C.E.; Dlugokencky, E.J.	yes
DND	Dahlen, North Dakota		Sweeney, C.; Dlugokencky, E.J.	yes
ESP	Estevan Point, British Columbia		Sweeney, C.; Dlugokencky, E.J.	yes
ETL	East Trout Lake, Saskatchewan		Sweeney, C.; Dlugokencky, E.J.	yes
FWI	Fairchild, Wisconsin		Sweeney, C.; Dlugokencky, E.J.	yes
GSFC	NASA Goddard Space Flight Center Aircraft Campaign		Kawa, S.R.; Abshire, J.B.; Riris, H.	yes
HAA	Molokai Island, Hawaii		Sweeney, C.; Dlugokencky, E.J.	yes
HFM	Harvard University Aircraft Campaign		Wofsy, S.C.	yes
HIL	Homer, Illinois		Sweeney, C.; Dlugokencky, E.J.	yes
HIP	HIPPO (HIAPER Pole-to-Pole Observations)	https://doi.org/10.3334/CDIAC/HIPPO_010	Wofsy, S.C.; Stephens, B.B.; Elkins, J.W.; Hintsa, E.J.; Moore, F.	yes
IAGOS - CARIBIC	In-service Aircraft for a Global Observing System		Obersteiner, F.; Boenisch., H; Gehrlein, T.; Zahn, A.; Schuck, T.	yes
INX	INFLUX (Indianapolis Flux Experiment)		Sweeney, C.; Dlugokencky, E.J.; Shepson, P.B.; Turnbull, J.	yes
LEF	Park Falls, Wisconsin		Sweeney, C.; Dlugokencky, E.J.	yes
NHA	Offshore Portsmouth, New Hampshire (Isles		Sweeney, C.; Dlugokencky, E.J.	yes

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

	of Shoals)			
OIL	Oglesby, Illinois		Sweeney, C.; Dlugokencky, E.J.	yes
PFA	Poker Flat, Alaska		Sweeney, C.; Dlugokencky, E.J.	yes
RBA-B	Rio Branco		Gatti, L.V.; Gloor, E.; Miller, J.B.	yes
RTA	Rarotonga		Sweeney, C.; Dlugokencky, E.J.	yes
SCA	Charleston, South Carolina		Sweeney, C.; Dlugokencky, E.J.	yes
SGP	Southern Great Plains, Oklahoma		Sweeney, C.; Dlugokencky, E.J.; Biraud, S.	yes
TAB	Tabatinga		Gatti, L.V.; Gloor, E.; Miller, J.B.	yes
TGC	Offshore Corpus Christi, Texas		Sweeney, C.; Dlugokencky, E.J.	yes
THD	Trinidad Head, California		Sweeney, C.; Dlugokencky, E.J.	yes
WBI	West Branch, Iowa		Sweeney, C.; Dlugokencky, E.J.	yes

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table A7. Main methodological changes in the global carbon budget since first publication. Methodological changes introduced in one year are kept for the following years unless noted. Empty cells mean there were no methodological changes introduced that year.

Publication year	Fossil fuel emissions			LUC emissions	Reservoirs			Uncertainty & other changes
	Global	Country (territorial)	Country (consumption)		Atmosphere	Ocean	Land	
2006 (a)		Split in regions						
2007 (b)				ELUC based on FAO-FRA 2005; constant ELUC for 2006	1959-1979 data from Mauna Loa; data after 1980 from global average	Based on one ocean model tuned to reproduced observed 1990s sink		±1σ provided for all components
2008 (c)				Constant ELUC for 2007				
2009 (d)		Split between Annex B and non-Annex B	Results from an independent study discussed	Fire-based emission anomalies used for 2006-2008		Based on four ocean models normalised to observations with constant delta	First use of five DGVMs to compare with budget residual	
2010 (e)	Projection for current year based on GDP	Emissions for top emitters		ELUC updated with FAO-FRA 2010				
2011 (f)			Split between Annex B and non-Annex B					
2012 (g)		129 countries from 1959	129 countries and regions from 1990-2010 based on GTAP8.0	ELUC for 1997-2011 includes interannual anomalies from fire-based emissions	All years from global average	Based on 5 ocean models normalised to observations with ratio	Ten DGVMs available for SLAND; First use of four models to compare with ELUC	
2013 (h)		250 countriesb	134 countries and regions 1990-2011 based on GTAP8.1, with detailed estimates for years 1997, 2001, 2004, and 2007	ELUC for 2012 estimated from 2001-2010 average		Based on six models compared with two data-products to year 2011	Coordinated DGVM experiments for SLAND and ELUC	Confidence levels; cumulative emissions; budget from 1750
2014 (i)	Three years of BP data	Three years of BP data	Extended to 2012 with updated GDP data	ELUC for 1997-2013 includes interannual anomalies from fire-based emissions		Based on seven models	Based on ten models	Inclusion of breakdown of the sinks in three latitude bands and comparison with three atmospheric inversions

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

2015 (j)	Projection for current year based Jan-Aug data	National emissions from UNFCCC extended to 2014 also provided	Detailed estimates introduced for 2011 based on GTAP9			Based on eight models	Based on ten models with assessment of minimum realism	The decadal uncertainty for the DGVM ensemble mean now uses ±1σ of the decadal spread across models
2016 (k)	Two years of BP data	Added three small countries; China's emissions from 1990 from BP data (this release only)		Preliminary ELUC using FRA-2015 shown for comparison; use of five DGVMs		Based on seven models	Based on fourteen models	Discussion of projection for full budget for current year
a Raupach et al. (2007)								
b Canadell et al. (2007)								
c GCP (2008)								
d Le Quéré et al. (2009)								
e Friedlingstein et al. (2010)								
f Peters et al. (2012b)								
g Le Quéré et al. (2013), Peters et al. (2013)								
h Le Quéré et al. (2014)								
i Le Quéré et al. (2015a)								
j Le Quéré et al. (2015b)								
k Le Quéré et al. (2016)								

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Table A8: Mapping of scientific land flux definitions to the definition of the LULUCF net flux used in national reporting Note that estimates are based on the global carbon budget estimates from Friedlingstein et al (2020), which estimated higher emissions from the net land-use change flux (ELUC) and a larger natural terrestrial sink Non-intact lands are a proxy for "managed lands" in the country reporting

			2000-2009	2010-2019
ELUC from bookkeeping estimates (from Tab. 5)			1.44	1.61
SLAND	Total	from DGVMs	-2.90	-3.40
	on non-forest lands	from DGVMs	-1.05	-1.38
	on non-intact forest	from DGVMs	-1.39	-1.54
	on intact land (intact forest only for DGVMs)	from DGVMs	-0.46	-0.49
		from cohort-based ORCHIDEE	-1.29	-1.47
SLAND on non-intact lands plus ELUC		from DGVMs and bookkeeping ELUC	0.05	0.08
		from cohort-based ORCHIDEE	1.00	0.61
National greenhouse gas inventories (LULUCF)			0.00	-0.31
FAOSTAT (LULUCF)			0.39	0.20

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

1

Table A9. Funding supporting the production of the various components of the global carbon budget in addition to the authors' supporting institutions (see also acknowledgements).

Funder and grant number (where relevant)	Author Initials
Australia, Integrated Marine Observing System (IMOS)	BT
Australian National Environment Science Program (NESP)	JGC
Belgium, FWO (Flanders Research Foundation, contract IRI I001019N)	TG
BNP Paribas Foundation through Climate & Biodiversity initiative, philanthropic grant for developments of the Global Carbon Atlas	PC
Canada, Tula Foundation	WE
China, National Natural Science Foundation (grant no. 41975155)	XY
Commonwealth Scientific and Industrial Organization (CSIRO) - Climate Science Centre	JGC, JK
EC Copernicus Atmosphere Monitoring Service implemented by ECMWF on behalf of the European Commission	FC
EC Copernicus Marine Environment Monitoring Service implemented by Mercator Ocean	TTTC
EC H2020 (4C; grant no 821003)	PF, RMA, SS, GPP, PC, JIK, TI, LB, PL, LG, SL, NG
EC H2020 (CHE; grant no 776186)	MWJ
EC H2020 (CoCO2: grant no. 958927)	RMA, GPP
EC H2020 (COMFORT: grant no. 820989)	DCEB, LG
EC H2020 (CONSTRAIN: grant no 820829)	RS, PMF, TG
EC H2020 (CRESCENDO: grant no. 641816)	RS, EJ AJPS, TI
EC H2020 (ESM2025 – Earth System Models for the Future; grant agreement No 101003536).	RS, TG, TI, LB, BD
EC H2020 (EuroSea: grant no. 862626)	SDJ
EC H2020 (JERICO-S3: grant no. 871153)	GR
EC H2020 (QUINCY; grant no 647204)	SZ
EC H2020 (RINGO: grant no. 730944)	DCEB
EC H2020 (VERIFY: grant no. 776810)	MWJ, RMA, GPP, PC, JIK, NV, GG
Efg International	TT
EFG International	TT
European Space Agency Climate Change Initiative ESA-CCI RECCAP2 project 655 (ESRIN/4000123002/18/I-NB)	PF, SS, PC
European Space Agency OceanSODA project (grant no. 4000112091/14/I-LG)	LG
France, ICOS (Integrated Carbon Observation System) France	NL
France, Institut de Recherche pour le Développement (IRD)	NL
Germany, Blue Ocean and Federal Ministry of Education (BONUS INTEGRAL; Grant No. 03F0773A)	GR
Germany, Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy – EXC 2037 'Climate, Climatic Change, and Society' – Project Number: 390683824	TI
Germany, Federal Ministry for Education and Research (BMBF)	GR
Germany, GEOMAR Helmholtz Centre for Ocean Research	SKL
Germany, German Federal Ministry of Education and Research under project "DArgo2025" (03F0857C)	AK
Germany, Helmholtz Association ATMO programme	PA
Germany, Helmholtz Young Investigator Group Marine Carbon and Ecosystem Feedbacks in the Earth System (MarESys), grant number VH-NG-1301	JH, OG
Germany, ICOS (Integrated Carbon Observation System) Germany	GR, NL
Hapag-Lloyd	TT

Ireland, Marine Institute	MC
Japan, Environment Research and Technology Development Fund of the Ministry of the Environment (JPMEERF21S20810)	YN
Japan, Global Environmental Research Coordination System, Ministry of the Environment (grant number E1751)	SN, TO, CW
Kuehne + Nagel International AG	TT
Mediterranean Shipping Company (MSc)	TT
Monaco, Fondation Prince Albert II de Monaco	TT
Monaco, Yacht Club de Monaco	TT
NASA Interdisciplinary Research in Earth Science Program.	BP
Netherlands Organization for Scientific Research (NWO; grant no. SH-312, 17616)	WP
New Zealand, NIWA MBIE Core funding	KIC
Norway, Norwegian Research Council (grant no. 270061)	JS
Norway, Research Council of Norway, ICOS (Integrated Carbon Observation System) Norway and OTC (Ocean Thematic Centre) (grant no. 245927)	SKL, MB, SDJ
PEAK6 Investments	SKL
Saildrone Inc.	SKL
South Africa, Department of Science and Innovation	LD
South Africa, National Science Foundation	LD
Swiss National Science Foundation (grant no. 200020_172476)	SL
UK Royal Society (grant no. RP\R1\191063)	CLQ
UK, CLASS ERC funding	TG
UK, National Centre for Atmospheric Science (NCAS)	PCM
UK, Natural Environment Research Council (SONATA: grant no. NE/P021417/1)	DW
UK, Natural Environmental Research Council (NE/R016518/1)	LF
UK, Newton Fund, Met Office Climate Science for Service Partnership Brazil (CSSP Brazil)	AJWi
UK, Royal Society: The European Space Agency OCEANFLUX projects	AJWa
UK, University of Reading Research Endowment Trust Fund	PCM
USA, Department of Commerce, Office of Oceanic and Atmospheric Research (OAR)'s / National Oceanic and Atmospheric Administration (NOAA)'s Global Ocean Monitoring and Observation Program (GOMO)	DRM, CS, DP, RW, SRA, RAF, AJS, NRB
USA, Department of Commerce, Office of Oceanic and Atmospheric Research (OAR)'s / National Oceanic and Atmospheric Administration (NOAA)'s Ocean Acidification Program	DP, RW, SRA, RAF, AJS
USA, Department of Energy, Office of Science and BER prg. (grant no. DE-SC000 0016323)	AKJ
USA, Department of Energy, SciDac (DESC0012972)	GCH, LPC
USA, NASA Carbon Monitoring System probram and OCO Science team program (80NM0018F0583) .	JL
USA, NASA Interdisciplinary Research in Earth Science (IDS) (80NSSC17K0348)	GCH, LPC
USA, National Science Foundation (grant number 1903722)	HT
USA, National Science Foundation (grant number PLR 1543457)	DRM, CS
USA, Princeton University Environmental Institute and the NASA OCO2 science team, grant number 80NSSC18K0893.	LR
Computing resources	
bwHPC, High Performance Computing Network of the State of Baden-Württemberg, Germany	PA
Cheyenne supercomputer, Computational and Information Systems Laboratory (CISL) at National Center for Atmospheric Research (NCAR)	DK
Deutsches Klimarechenzentrum (allocation bm0891)	JEMSN, JP
MRI (FUJITSU Server PRIMERGY CX2550M5)	YN

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Netherlands Organization for Scientific Research (NWO; NWO-2021.010)	ITL
NIES (SX-Aurora)	YN
NIES supercomputer system	EK
supercomputer 'Gadi' of the National Computational Infrastructure (NCI), Australia	JK
Supercomputing time was provided by the Météo-France/DSI supercomputing center.	RS, BD
TGCC under allocation 2019-A0070102201 made by GENCI	FC
UEA High Performance Computing Cluster, UK	MWJ, CLQ, DRW
UNINETT Sigma2, National Infrastructure for High Performance Computing and Data Storage in Norway (NN2980K/NS2980K)	JS

1

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Appendix B. Supplementary Figures

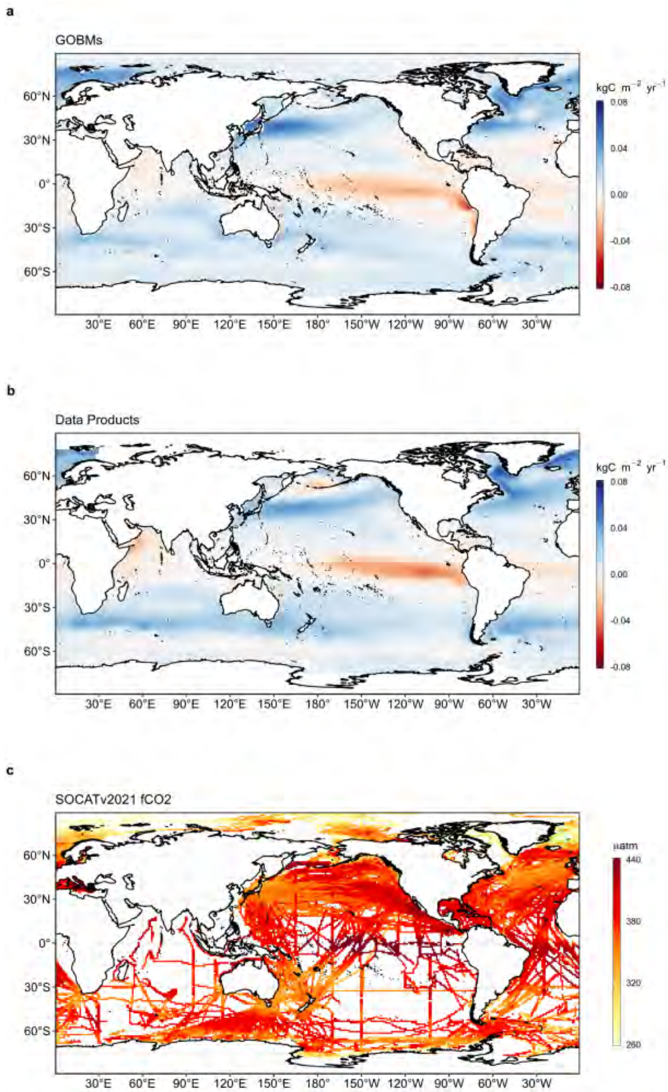

Figure B1. Ensemble mean air-sea CO_2 flux from a) global ocean biogeochemistry models and b) fCO_2 based data products, averaged over 2011-2020 period (kgC m^{-2} yr^{-1}). Positive numbers indicate a flux into the ocean. c) gridded SOCAT v2021 fCO_2 measurements, averaged over the 2011-2020 period (µatm). In (a) model simulation A is shown. The data-products represent the contemporary flux, i.e. including outgassing of riverine carbon, which is estimated to amount to 0.615 GtC yr^{-1} globally.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

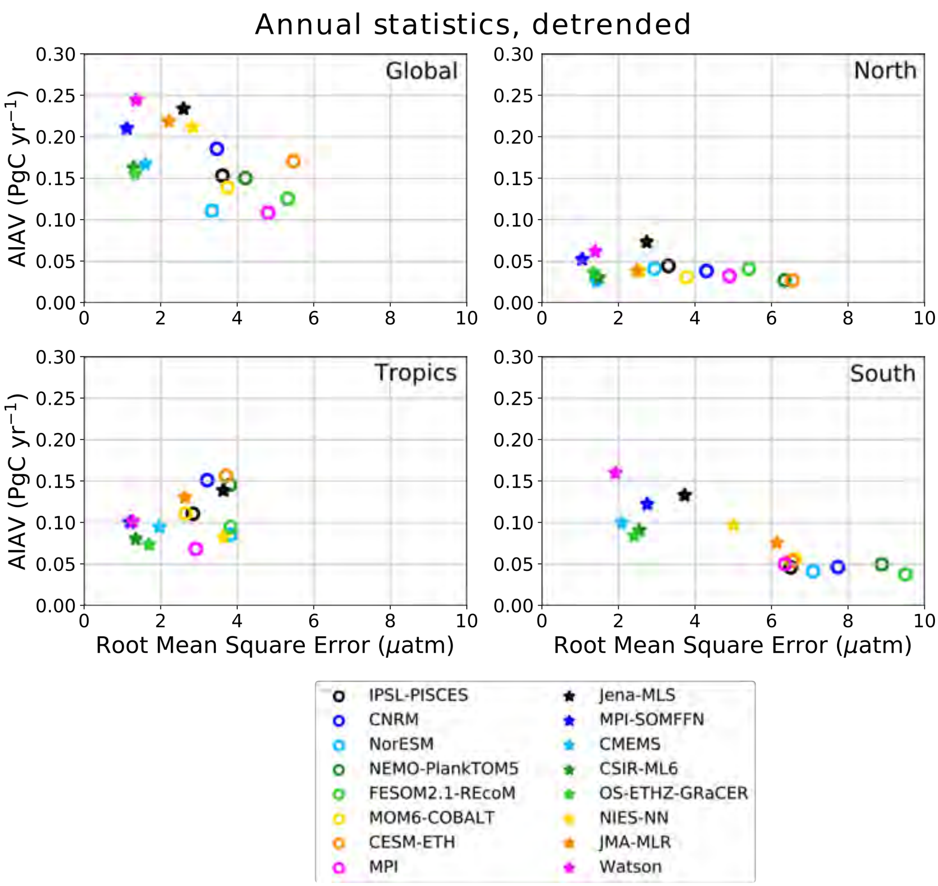

Figure B2. Evaluation of the GOBMs and data products using the root mean squared error (RMSE) for the period 1990 to 2020, between the individual surface ocean fCO_2 mapping schemes and the SOCAT v2021 database. The y-axis shows the amplitude of the interannual variability (A-IAV, taken as the standard deviation of a detrended time series calculated as a 12-months running mean over the monthly flux time series, Rödenbeck et al., 2015). Results are presented for the globe, north (>30°N), tropics (30°S-30°N), and south (<30°S) for the GOBMs (see legend circles) and for the fCO_2-based data products (star symbols). The fCO_2-based data products use the SOCAT database and therefore are not independent from the data (see section 2.4.1).

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

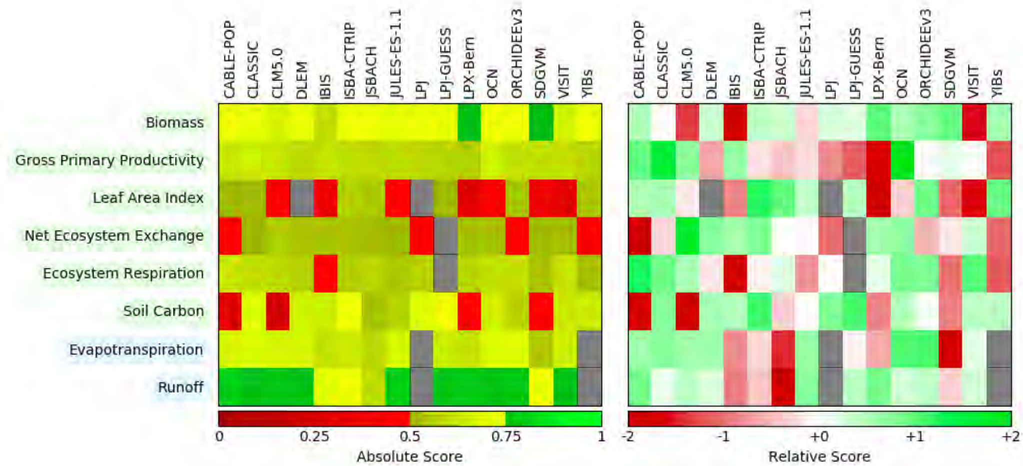

Figure B3. Evaluation of the DGVMs using the International Land Model Benchmarking system (ILAMB; Collier et al., 2018) (left) absolute skill scores and (right) skill scores relative to other models. The benchmarking is done with observations for vegetation biomass (Saatchi et al., 2011; and GlobalCarbon unpublished data; Avitabile et al., 2016), GPP (Jung et al., 2010; Lasslop et al., 2010), leaf area index (De Kauwe et al., 2011; Myneni et al., 1997), net ecosystem exchange (Jung et al., 2010;Lasslop et al., 2010), ecosystem respiration (Jung et al., 2010;Lasslop et al., 2010), soil carbon (Hugelius et al., 2013;Todd-Brown et al., 2013), evapotranspiration (De Kauwe et al., 2011), and runoff (Dai and Trenberth, 2002). For each model-observation comparison a series of error metrics are calculated, scores are then calculated as an exponential function of each error metric, finally for each variable the multiple scores from different metrics and observational data sets are combined to give the overall variable scores shown in the left panel. Overall variable scores increase from 0 to 1 with improvements in model performance. The set of error metrics vary with data set and can include metrics based on the period mean, bias, root mean squared error, spatial distribution, interannual variability and seasonal cycle. The relative skill score shown in the right panel is a Z-score, which indicates in units of standard deviation the model scores relative to the multi-model mean score for a given variable. Grey boxes represent missing model data.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

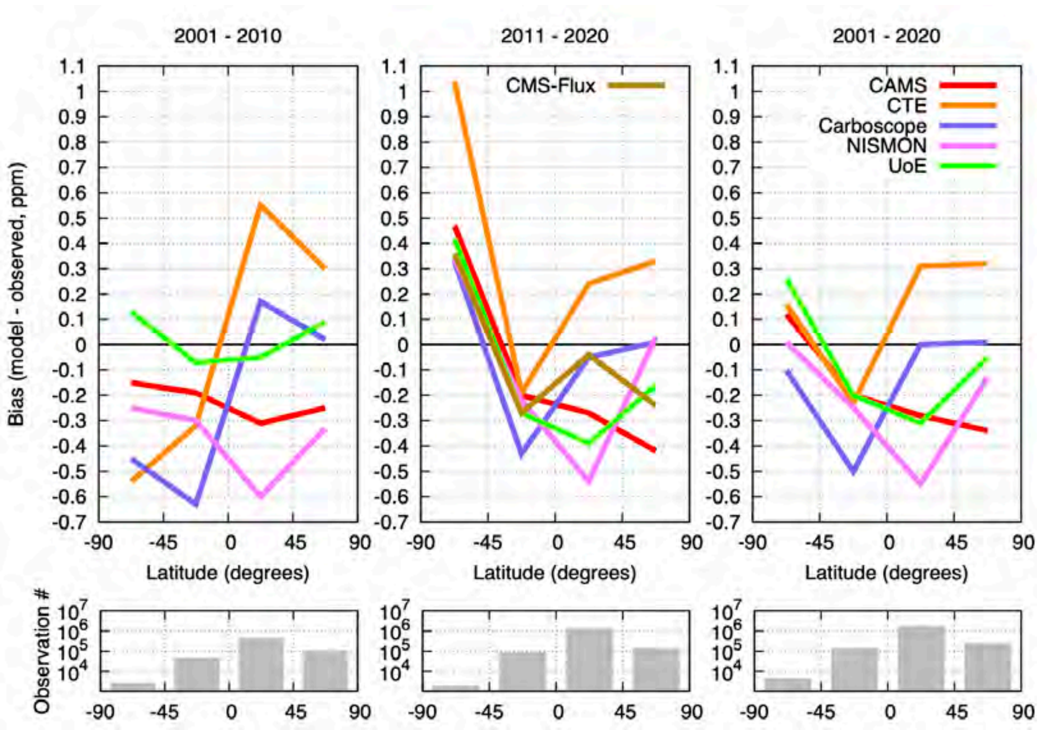

Figure B4. Evaluation of the atmospheric inversion products. The mean of the model minus observations is shown for four latitude bands in three periods: (left) 2001-2010, (centre) 2011-2020, (right) 2001-2020. The six models are compared to independent CO_2 measurements made onboard aircraft over many places of the world between 2 and 7 km above sea level. Aircraft measurements archived in the Cooperative Global Atmospheric Data Integration Project (CGADIP; Cox et al., 2021) from sites, campaigns or programs that cover at least 9 months between 2001 and 2020 and that have not been assimilated, have been used to compute the biases of the differences in four 45° latitude bins. Land and ocean data are used without distinction, and observation density varies strongly with latitude and time as seen on the lower panels.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

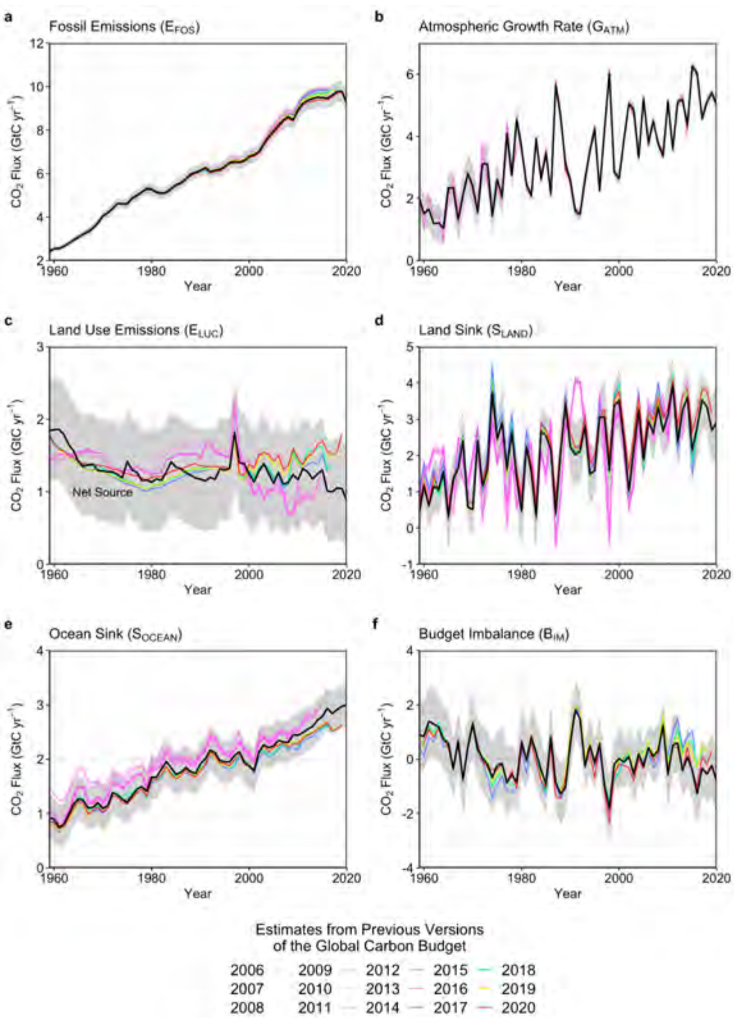

Figure B5. Comparison of the estimates of each component of the global carbon budget in this study (black line) with the estimates released annually by the GCP since 2006. Grey shading shows the uncertainty bounds representing ±1 standard deviation of the current global carbon budget, based on the uncertainty assessments described in Appendix C. CO_2 emissions from (a) fossil CO_2 emissions (E_{FOS}), and (b) land-use change (E_{LUC}), as well as their partitioning among (c) the atmosphere (G_{ATM}), (d) the land (S_{LAND}), and (e) the ocean (S_{OCEAN}). See legend for the corresponding years, and Tables 3 and A7 for references. The budget year corresponds to the year when the budget was first released. All values are in GtC yr^{-1}.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Appendix C. Extended Methodology

Appendix C.1 Methodology Fossil Fuel CO_2 emissions (E_{FOS})

C.1.1 Cement carbonation

From the moment it is created, cement begins to absorb CO_2 from the atmosphere, a process known as 'cement carbonation'. We estimate this CO_2 sink, as the average of two studies in the literature (Cao et al., 2020; Guo et al., 2021). Both studies use the same model, developed by Xi et al. (2016), with different parameterisations and input data, with the estimate of Guo and colleagues being a revision of Xi et al (2016). The trends of the two studies are very similar. Modelling cement carbonation requires estimation of a large number of parameters, including the different types of cement material in different countries, the lifetime of the structures before demolition, of cement waste after demolition, and the volumetric properties of structures, among others (Xi et al., 2016). Lifetime is an important parameter because demolition results in the exposure of new surfaces to the carbonation process. The main reasons for differences between the two studies appear to be the assumed lifetimes of cement structures and the geographic resolution, but the uncertainty bounds of the two studies overlap. In the present budget, we include the cement carbonation carbon sink in the fossil CO_2 emission component (E_{FOS}).

C.1.2 Emissions embodied in goods and services

CDIAC, UNFCCC, and BP national emission statistics 'include greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction' (Rypdal et al., 2006), and are called territorial emission inventories. Consumption-based emission inventories allocate emissions to products that are consumed within a country, and are conceptually calculated as the territorial emissions minus the 'embodied' territorial emissions to produce exported products plus the emissions in other countries to produce imported products (Consumption = Territorial – Exports + Imports). Consumption-based emission attribution results (e.g. Davis and Caldeira, 2010) provide additional information to territorial-based emissions that can be used to understand emission drivers (Hertwich and Peters, 2009) and quantify emission transfers by the trade of products between countries (Peters et al., 2011b). The consumption-based emissions have the same global total, but reflect the trade-driven movement of emissions across the Earth's surface in response to human activities. We estimate consumption-

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

based emissions from 1990-2018 by enumerating the global supply chain using a global model of the economic relationships between economic sectors within and between every country (Andrew and Peters, 2013; Peters et al., 2011a). Our analysis is based on the economic and trade data from the Global Trade and Analysis Project (GTAP; Narayanan et al., 2015), and we make detailed estimates for the years 1997 (GTAP version 5), 2001 (GTAP6), and 2004, 2007, and 2011 (GTAP9.2), covering 57 sectors and 141 countries and regions. The detailed results are then extended into an annual time series from 1990 to the latest year of the Gross Domestic Product (GDP) data (2018 in this budget), using GDP data by expenditure in current exchange rate of US dollars (USD; from the UN National Accounts main Aggregrates database; UN, 2021) and time series of trade data from GTAP (based on the methodology in Peters et al., 2011a). We estimate the sector-level CO_2 emissions using the GTAP data and methodology, include flaring and cement emissions from CDIAC, and then scale the national totals (excluding bunker fuels) to match the emission estimates from the carbon budget. We do not provide a separate uncertainty estimate for the consumption-based emissions, but based on model comparisons and sensitivity analysis, they are unlikely to be significantly different than for the territorial emission estimates (Peters et al., 2012a).

C.1.3 Uncertainty assessment for E_{FOS}

We estimate the uncertainty of the global fossil CO2 emissions at ±5% (scaled down from the published ±10 % at ±2σ to the use of ±1σ bounds reported here; Andres et al., 2012). This is consistent with a more detailed analysis of uncertainty of ±8.4% at ±2σ (Andres et al., 2014) and at the high-end of the range of ±5-10% at ±2σ reported by (Ballantyne et al., 2015). This includes an assessment of uncertainties in the amounts of fuel consumed, the carbon and heat contents of fuels, and the combustion efficiency. While we consider a fixed uncertainty of ±5% for all years, the uncertainty as a percentage of emissions is growing with time because of the larger share of global emissions from emerging economies and developing countries (Marland et al., 2009). Generally, emissions from mature economies with good statistical processes have an uncertainty of only a few per cent (Marland, 2008), while emissions from strongly developing economies such as China have uncertainties of around ±10% (for ±1σ; Gregg et al., 2008; Andres et al., 2014). Uncertainties of emissions are likely to be mainly systematic errors related to underlying biases of energy statistics and to the accounting method used by each country.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

C.1.4 Growth rate in emissions

We report the annual growth rate in emissions for adjacent years (in percent per year) by calculating the difference between the two years and then normalising to the emissions in the first year: (EFOS(t0+1)-EFOS(t0))/EFOS(t0)×100%. We apply a leap-year adjustment where relevant to ensure valid interpretations of annual growth rates. This affects the growth rate by about 0.3% yr-1 (1/366) and causes calculated growth rates to go up approximately 0.3% if the first year is a leap year and down 0.3% if the second year is a leap year.

The relative growth rate of E_{FOS} over time periods of greater than one year can be rewritten using its logarithm equivalent as follows:

$$\frac{1}{E_{FOS}}\frac{dE_{FOS}}{dt} = \frac{d(lnE_{FOS})}{dt} \qquad (2)$$

Here we calculate relative growth rates in emissions for multi-year periods (e.g. a decade) by fitting a linear trend to *ln*(E_{FOS}) in Eq. (2), reported in percent per year.

C.1.5 Emissions projection for 2021

To gain insight on emission trends for 2021, we provide an assessment of global fossil CO_2 emissions, E_{FOS}, by combining individual assessments of emissions for China, USA, the EU, and India (the four countries/regions with the largest emissions), and the rest of the world. We provide full year estimates for two datasets: IEA (2021b) and our own analysis. This approach differs from last year where we used four independent estimates including our own, because of the unique circumstances related to the COVID-19 pandemic. This year's analysis is more in line with earlier budgets.

Previous editions of the Global Carbon Budget (GCB) have estimated YTD emissions, and performed projections, using sub-annual energy consumption data from a variety of sources depending on the country or region. The YTD estimates have then been projected to the full year using specific methods for each country or region. The methods described in detail below.

China: The method for the projection uses: (1) the sum of monthly domestic production of raw coal, crude oil, natural gas and cement from the National Bureau of Statistics (NBS, 2021), (2) monthly net imports of coal, coke, crude oil, refined petroleum products and natural gas from the General Administration of Customs of the People's Republic of China (2021); proprietary monthly estimates of sectoral coal consumption by the consultancy SX Coal (2021); and (3) annual energy

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

consumption data by fuel type and annual production data for cement from the NBS, using data for 2000-2020 (NBS, 2021), with the last year being a preliminary estimate. We estimate the full-year growth rate for 2021 using a Bayesian regression for the ratio between the annual energy consumption data (3 above) from 2014 through 2019, and monthly production plus net imports through August of each year (1+2 above) or the corresponding estimate from SX Coal for coal. The uncertainty range uses the standard deviations of the resulting posteriors. Sources of uncertainty and deviations between the monthly and annual growth rates include lack of or incomplete monthly data on stock changes and energy density, variance in the trend during the last three months of the year, and partially unexplained discrepancies between supply-side and consumption data even in the final annual data.

Note that in recent years, the absolute value of the annual growth rate for coal energy consumption, and hence total CO_2 emissions, has been consistently lower (closer to zero) than the growth or decline suggested by the monthly, tonnage-based production and import data, and this is reflected in the projection. This pattern is only partially explained by stock changes and changes in energy content, and it is therefore not possible to be certain that it will continue in any given year. For 2020 and 2021, COVID-19-related lockdown and reopening in China, similar but delayed restrictions in major export markets, unusual amounts of flooding and extreme weather during the summer months and extraordinarily high local and global prices of many energy products imply that seasonal patterns and correlations between supply, stock changes and consumption may be quite different this year than in the previous years that the regression is based on. Shocks in the housing market and heightened perceptions of political risk among investors may also affect consumption patterns. This adds a major but unquantified amount of uncertainty to the estimate.

USA: We use emissions estimated by the U.S. Energy Information Administration (EIA) in their Short-Term Energy Outlook (STEO) for emissions from fossil fuels to get both YTD and a full year projection (EIA, 2021). The STEO also includes a near-term forecast based on an energy forecasting model which is updated monthly (last update with preliminary data through September 2021), and takes into account expected temperatures, household expenditures by fuel type, energy markets, policies, and other effects. We combine this with our estimate of emissions from cement production using the monthly U.S. cement clinker production data from USGS for January-June 2021, assuming changes in cement production over the first part of the year apply throughout the year.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

India: We use monthly emissions estimates for India updated from Andrew (2020b) through August 2021. These estimates are derived from many official monthly energy and other activity data sources to produce direct estimates of national CO_2 emissions, without the use of proxies. Emissions from coal are then extended to September using a regression relationship based on power generated from coal, coal dispatches by Coal India Ltd., the composite PMI, time, and days per month. For the last 3-4 months of the year, each series is extrapolated assuming typical trends.

EU: We use a refinement to the methods presented by Andrew (2021), deriving emissions from monthly energy data reported by Eurostat. Some data gaps are filled using data from the Joint Organisations Data Initiative (JODI, 2021). Sub-annual cement production data are limited, but data for Germany and Poland, the two largest producers, suggest a small decline. For fossil fuels this provides estimates through July. We extend coal emissions through September using a regression model built from generation of power from hard coal, power from brown coal, total power generation, and the number of working days in Germany and Poland, the two biggest coal consumers in the EU. These are then extended through the end of the year assuming typical trends. We extend oil emissions by building a regression model between our monthly CO2 estimates and oil consumption reported by the EIA for Europe in its Short-Term Energy Outlook (October edition), and then using this model with EIA's monthly forecasts. For natural gas, the strong seasonal signal allows the use of the bias-adjusted Holt-Winters exponential smoothing method (Chatfield, 1978).

Rest of the world: We use the close relationship between the growth in GDP and the growth in emissions (Raupach et al., 2007) to project emissions for the current year. This is based on a simplified Kaya Identity, whereby E_{FOS} (GtC yr^{-1}) is decomposed by the product of GDP (USD yr^{-1}) and the fossil fuel carbon intensity of the economy (I_{FOS}; GtC USD^{-1}) as follows:

$$E_{FOS} = GDP \times I_{FOS} \quad (3)$$

Taking a time derivative of Equation (3) and rearranging gives:

$$\frac{1}{E_{FOS}}\frac{dE_{FOS}}{dt} = \frac{1}{GDP}\frac{dGDP}{dt} + \frac{1}{I_{FOS}}\frac{dI_{FOS}}{dt} \quad (4)$$

where the left-hand term is the relative growth rate of E_{FOS}, and the right-hand terms are the relative growth rates of GDP and I_{FOS}, respectively, which can simply be added linearly to give the overall growth rate.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

The I_{FOS} is based on GDP in constant PPP (Purchasing Power Parity) from the International Energy Agency (IEA) up to 2017 (IEA/OECD, 2019) and extended using the International Monetary Fund (IMF) growth rates through 2020 (IMF, 2021). Interannual variability in I_{FOS} is the largest source of uncertainty in the GDP-based emissions projections. We thus use the standard deviation of the annual I_{FOS} for the period 2009-2019 as a measure of uncertainty, reflecting a ±1σ as in the rest of the carbon budget.

World: The global total is the sum of each of the countries and regions.

Appendix C.2 Methodology CO_2 emissions from land-use, land-use change and forestry (E_{LUC})

The net CO_2 flux from land-use, land-use change and forestry (E_{LUC}, called land-use change emissions in the rest of the text) includes CO_2 fluxes from deforestation, afforestation, logging and forest degradation (including harvest activity), shifting cultivation (cycle of cutting forest for agriculture, then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture. Emissions from peat burning and drainage are added from external datasets (see section C.2.1 below). Only some land-management activities are included in our land-use change emissions estimates (Table A1). Some of these activities lead to emissions of CO_2 to the atmosphere, while others lead to CO_2 sinks. E_{LUC} is the net sum of emissions and removals due to all anthropogenic activities considered. Our annual estimate for 1960-2020 is provided as the average of results from three bookkeeping approaches (Section C.2.1 below): an estimate using the Bookkeeping of Land Use Emissions model (Hansis et al., 2015; hereafter BLUE) and one using the compact Earth system model OSCAR (Gasser et al., 2020), both BLUE and OSCAR being updated here to new land-use forcing covering the time period until 2020, and an updated version of the estimate published by Houghton and Nassikas (2017) (hereafter updated H&N2017). All three data sets are then extrapolated to provide a projection for 2021 (Section C.2.5 below). In addition, we use results from Dynamic Global Vegetation Models (DGVMs; see Section 2.5 and Table 4) to help quantify the uncertainty in E_{LUC} (Section C.2.4), and thus better characterise our understanding. Note that in this budget, we use the scientific E_{LUC} definition, which counts fluxes due to environmental changes on managed land towards S_{LAND}, as opposed to the national greenhouse gas inventories under the UNFCCC, which include them in E_{LUC} and thus often report

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

smaller land-use emissions (Grassi et al., 2018; Petrescu et al., 2020). However, we provide a methodology of mapping of the two approaches to each other further below (Section C.2.3).

C.2.1 Bookkeeping models

Land-use change CO_2 emissions and uptake fluxes are calculated by three bookkeeping models. These are based on the original bookkeeping approach of Houghton (2003) that keeps track of the carbon stored in vegetation and soils before and after a land-use change (transitions between various natural vegetation types, croplands, and pastures). Literature-based response curves describe decay of vegetation and soil carbon, including transfer to product pools of different lifetimes, as well as carbon uptake due to regrowth. In addition, the bookkeeping models represent long-term degradation of primary forest as lowered standing vegetation and soil carbon stocks in secondary forests, and include forest management practices such as wood harvests.

BLUE and the updated H&N2017 exclude land ecosystems' transient response to changes in climate, atmospheric CO_2 and other environmental factors, and base the carbon densities on contemporary data from literature and inventory data. Since carbon densities thus remain fixed over time, the additional sink capacity that ecosystems provide in response to CO_2-fertilization and some other environmental changes is not captured by these models (Pongratz et al., 2014). On the contrary, OSCAR includes this transient response, and it follows a theoretical framework (Gasser and Ciais, 2013) that allows separating bookkeeping land-use emissions and the loss of additional sink capacity. Only the former is included here, while the latter is discussed in Appendix D4. The bookkeeping models differ in (1) computational units (spatially explicit treatment of land-use change for BLUE, regional-/ mostly country-level for the updated H&N2017 and OSCAR), (2) processes represented (see Table A1), and (3) carbon densities assigned to vegetation and soil of each vegetation type (literature-based for the updated H&N2017 and BLUE, calibrated to DGVMs for OSCAR). A notable difference between models exists with respect to the treatment of shifting cultivation. The update of H&N2017 changed the approach over the earlier H&N2017 version: H&N2017 had assumed the "excess loss" of tropical forests (i.e., when FRA indicated a forest loss larger than the increase in agricultural areas from FAO) resulted from converting forests to croplands at the same time older croplands were abandoned. Those abandoned croplands began to recover to forests after 15 years. The updated H&N2017 now assumes that forest loss in excess of increases in cropland and pastures represented an increase in shifting cultivation. When the excess loss of forests was negative, it was assumed that shifting cultivation was returned to forest.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

Historical areas in shifting cultivation were extrapolated taking into account country-based estimates of areas in fallow in 1980 (FAO/UNEP, 1981) and expert opinion (from Heinimann et al., 2017). In contrast, the BLUE and OSCAR models include sub-grid-scale transitions between all vegetation types. Furthermore, the updated H&N2017 assume conversion of natural grasslands to pasture, while BLUE and OSCAR allocate pasture proportionally on all natural vegetation that exists in a grid-cell. This is one reason for generally higher emissions in BLUE and OSCAR. Bookkeeping models do not directly capture carbon emissions from peat fires, which can create large emissions and interannual variability due to synergies of land-use and climate variability in Southeast Asia, particularly during El-Niño events, nor emissions from the organic layers of drained peat soils. To correct for this, the updated H&N2017 includes carbon emissions from burning and draining of peatlands in Indonesia, Malaysia, and Papua New Guinea (based on the Global Fire Emission Database (GFED4s; van der Werf et al., 2017) for fire and Hooijer et al. for drainage. Further, estimates of carbon losses from peatlands in extra-tropical regions are added from Qiu et al. (2021). We add GFED4s peat fire emissions to BLUE and OSCAR output as well as the global FAO peat drainage emissions 1990-2018 from croplands and grasslands (Conchedda and Tubiello, 2020), keeping post-2018 emissions constant. We linearly increase tropical drainage emissions from 0 in 1980, consistent with H&N2017's assumption, and keep emissions from the often old drained areas of the extra-tropics constant pre-1990. This adds 9.0 GtC for FAO compared to 5.6 GtC for Hooijer et al. (2010). Peat fires add another 2.0 GtC over the same period.

The three bookkeeping estimates used in this study differ with respect to the land-use change data used to drive the models. The updated H&N2017 base their estimates directly on the Forest Resource Assessment of the FAO which provides statistics on forest-area change and management at intervals of five years currently updated until 2020 (FAO, 2020). The data is based on country reporting to FAO and may include remote-sensing information in more recent assessments. Changes in land-use other than forests are based on annual, national changes in cropland and pasture areas reported by FAO (FAOSTAT, 2021). On the other hand, BLUE uses the harmonised land-use change data LUH2-GCB2021 covering the entire 850-2020 period (an update to the previously released LUH2 v2h dataset; Hurtt et al., 2017; Hurtt et al., 2020), which was also used as input to the DGVMs (Sec. 2.2.2). It describes land-use change, also based on the FAO data as well as the HYDE3.3 dataset (Goldewijk et al., 2017a, 2017b), but provided at a quarter-degree

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

spatial resolution, considering sub-grid-scale transitions between primary forest, secondary forest, primary non-forest, secondary non-forest, cropland, pasture, rangeland, and urban land (Hurtt et al., 2020; Chini et al., 2021). LUH2-GCB2021 provides a distinction between rangelands and pasture, based on inputs from HYDE. To constrain the models' interpretation on whether rangeland implies the original natural vegetation to be transformed to grassland or not (e.g., browsing on shrubland), a forest mask was provided with LUH2-GCB2021; forest is assumed to be transformed to grasslands, while other natural vegetation remains (in case of secondary vegetation) or is degraded from primary to secondary vegetation (Ma et al., 2020). This is implemented in BLUE. OSCAR was run with both LUH2-GCB2021 and FAO/FRA (as used by Houghton and Nassikas, 2017), where emissions from the latter were extended beyond 2015 with constant 2011–2015 average values. The best-guess OSCAR estimate used in our study is a combination of results for LUH2-GCB2021 and FAO/FRA land-use data and a large number of perturbed parameter simulations weighted against an observational constraint. All three bookkeeping estimates were extended from 2020 to provide a projection for 2021 by adding the annual change in emissions from tropical deforestation and degradation and peat burning and drainage to the respective model's estimate for 2020 (van der Werf et al., 2017, Conchedda & Tubiello, 2020).

For E_{LUC} from 1850 onwards we average the estimates from BLUE, the updated H&N2017 and OSCAR. For the cumulative numbers starting 1750 an average of four earlier publications is added (30 ± 20 PgC 1750-1850, rounded to nearest 5; Le Quéré et al., 2016).

We provide estimates of the gross land use change fluxes from which the reported net land-use change flux, E_{LUC}, is derived as a sum. Gross fluxes are derived internally by the three bookkeeping models: Gross emissions stem from decaying material left dead on site and from products after clearing of natural vegetation for agricultural purposes, wood harvesting, emissions from peat drainage and peat burning, and, for BLUE, additionally from degradation from primary to secondary land through usage of natural vegetation as rangeland. Gross removals stem from regrowth after agricultural abandonment and wood harvesting. Gross fluxes for the updated H&N2017 2016-2020 and for the 2021 projection of all three models were based on a regression of gross sources (including peat emissions) to net emissions for recent years.

Due to an artifact in the HYDE3.3 data causing large abrupt transitions, an unrealistic peak in emissions occurs around 1960 in BLUE and OSCAR. To correct for this, we replace the estimates for 1959-1961 by the average of 1958 and 1962 in each BLUE and OSCAR. Abrupt transitions will immediately influence gross emissions, which have a larger instantaneous component. Processes with longer timescales, such as slow legacy emissions and regrowth, are inseparable from the carbon dynamics due to subsequent land-use change events. We therefore do not adjust gross removals, but only gross emissions to match the corrected net flux. Since DGVMs estimates are only used for an uncertainty range of E_{LUC}, which is independent of land-use changes, no correction is applied to the DGVMs data.

C.2.2 Dynamic Global Vegetation Models (DGVMs)

Land-use change CO_2 emissions have also been estimated using an ensemble of 17 DGVMs simulations. The DGVMs account for deforestation and regrowth, the most important components of E_{LUC}, but they do not represent all processes resulting directly from human activities on land (Table A1). All DGVMs represent processes of vegetation growth and mortality, as well as decomposition of dead organic matter associated with natural cycles, and include the vegetation and soil carbon response to increasing atmospheric CO_2 concentration and to climate variability and change. Most models explicitly simulate the coupling of carbon and nitrogen cycles and account for atmospheric N deposition and N fertilisers (Table A1). The DGVMs are independent from the other budget terms except for their use of atmospheric CO_2 concentration to calculate the fertilization effect of CO_2 on plant photosynthesis.

DGVMs that do not simulate subgrid scale transitions (i.e., net land-use emissions; see Table A1) used the HYDE land-use change data set (Goldewijk et al., 2017a, 2017b), which provides annual (1700-2019), half-degree, fractional data on cropland and pasture. The data are based on the available annual FAO statistics of change in agricultural land area available until 2015. The new HYDE3.3 cropland/grazing land dataset which now in addition to FAO country-level statistics is constrained spatially based on multi-year satellite land cover maps from ESA CCI LC. Data from HYDE3.3 is based on a FAO which includes yearly data from 1961 up to and including the year 2017. After the year 2017 HYDE extrapolates the cropland, pasture, and urban data, based on the trend over the previous 5 years, to generate data until the year 2020. HYDE also uses satellite imagery from ESA-CCI from 1992 – 2018 for more detailed yearly allocation of cropland and grazing land. The 2018 map is also used for the 2019-2020 period. The original 300 meter resolution data from ESA was aggregated to a 5 arc minute resolution according to the classification scheme as described in Klein Goldewijk et al (2017a). DGVMs that simulate subgrid

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

scale transitions (i.e., gross land-use emissions; see Table A1) also use the LUH2-GCB2021 data set, an update of the more comprehensive harmonised land-use data set (Hurtt et al., 2020), that further includes fractional data on primary and secondary forest vegetation, as well as all underlying transitions between land-use states (850-2020; Hurtt et al., 2011, 2017, 2020; Chini et al., 2021; Table A1). This new data set is of quarter degree fractional areas of land-use states and all transitions between those states, including a new wood harvest reconstruction, new representation of shifting cultivation, crop rotations, management information including irrigation and fertilizer application. The land-use states include five different crop types in addition to the pasture-rangeland split discussed before. Wood harvest patterns are constrained with Landsat-based tree cover loss data (Hansen et al. 2013). Updates of LUH2-GCB2021 over last year's version (LUH2-GCB2020) are using the most recent HYDE/FAO release (covering the time period up to 2021 included). We also use the most recent FAO wood harvest data for all years from 1961 to 2019. After the year 2019 we extrapolated the wood harvest data until the year 2020. The HYDE3.3 population data is also used to extend the wood harvest time series back in time. Other wood harvest inputs (for years prior to 1961) remain the same in LUH2.

DGVMs implement land-use change differently (e.g., an increased cropland fraction in a grid cell can either be at the expense of grassland or shrubs, or forest, the latter resulting in deforestation; land cover fractions of the non-agricultural land differ between models). Similarly, model-specific assumptions are applied to convert deforested biomass or deforested area, and other forest product pools into carbon, and different choices are made regarding the allocation of rangelands as natural vegetation or pastures.

The difference between two DGVMs simulations (See Section C4.1 below), one forced with historical changes in land-use and a second with time-invariant pre-industrial land cover and pre-industrial wood harvest rates, allows quantification of the dynamic evolution of vegetation biomass and soil carbon pools in response to land-use change in each model (E_{LUC}). Using the difference between these two DGVMs simulations to diagnose E_{LUC} means the DGVMs account for the loss of additional sink capacity (around 0.4 ± 0.3 GtC yr-1; see Section 2.7.4, Appendix D4), while the bookkeeping models do not.

As a criterion for inclusion in this carbon budget, we only retain models that simulate a positive E_{LUC} during the 1990s, as assessed in the IPCC AR4 (Denman et al., 2007) and AR5 (Ciais et al., 2013). All DGVMs met this criterion, although one model was not included in the E_{LUC} estimate

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

from DGVMs as it exhibited a spurious response to the transient land cover change forcing after its initial spin-up.

C.2.3 Mapping of national GHG inventory data to E_{LUC}

For the first time, an approach is implemented to reconcile the large gap between ELUC from bookkeeping models and land use, land-use change and forestry (LULUCF) from national GHG Inventories (NGHGI) (see Tab. A8). This gap is due to different approaches to calculating "anthropogenic" CO_2 fluxes related to land-use change and land management (Grassi et al. 2018). In particular, the land sinks due to environmental change on managed lands are treated as non-anthropogenic in the global carbon budget, while they are generally considered as anthropogenic in NGHGIs ("indirect anthropogenic fluxes"; Eggleston et al., 2006). Building on previous studies (Grassi et al. 2021), the approach implemented here adds the DGVMs estimates of CO_2 fluxes due to environmental change from countries' managed forest area (part of the S_{LAND}) to the original E_{LUC} flux. This sum is expected to be conceptually more comparable to LULUCF than simply E_{LUC}.

ELUC data are taken from bookkeeping models, in line with the global carbon budget approach. To determine S_{LAND} on managed forest, the following steps were taken: Spatially gridded data of "natural" forest NBP (S_{LAND} i.e., due to environmental change and excluding land use change fluxes) were obtained with S2 runs from DGVMs up to 2019 from the TRENDY v9 dataset. Results were first masked with the Hansen forest map (Hansen et al. 2013), with a 20% tree cover and following the FAO definition of forest (isolated pixels with maximum connectivity less than 0.5 ha are excluded), and then further masked with the "intact" forest map for the year 2013, i.e. forest areas characterized by no remotely detected signs of human activity (Potapov et al. 2017). This way, we obtained the S_{LAND} in "intact" and "non-intact" forest area, which previous studies (Grassi et al. 2021) indicated to be a good proxy, respectively, for "unmanaged" and "managed" forest area in the NGHGI. Note that only 4 models (CABLE-POP, CLASSIC, YIBs and ORCHIDEE-CNP) had forest NBP at grid cell level. Two models (OCN and ISBA-CTRIP) provided forest NEP and simulated disturbances at pixel level that were used as basis, in addition to forest cover fraction, to estimate forest NBP. For the other DGVMs, when a grid cell had forest, all the NBP was allocated to forest.

LULUCF data from NGHGIs are from Grassi et al. (2021) until 2017, updated until 2019 for Annex I countries. For non-Annex I countries, the years 2018 and 2019 were assumed equal to the average 2013-2017. This data includes all CO2 fluxes from land considered managed, which in principle

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

encompasses all land uses (forest land, cropland, grassland, wetlands, settlements, and other land), changes among them, emissions from organic soils and from fires. In practice, although almost all Annex I countries report all land uses, many non-Annex I countries report only on deforestation and forest land, and only few countries report on other land uses. In most cases, NGHGI include most of the natural response to recent environmental change, because they use direct observations (e.g., national forest inventories) that do not allow separating direct and indirect anthropogenic effects (Eggleston et al., 2006).

To provide additional, largely independent assessments of fluxes on unmanaged vs managed lands, we include a DGVM that allows diagnosing fluxes from unmanaged vs managed lands by tracking vegetation cohorts of different ages separately. This model, ORCHIDEE-MICT (Yue et al., 2018), was run using the same LUH2 forcing as the DGVMs used in this budget (Section 2.5) and the bookkeeping models BLUE and OSCAR (Section 2.2). Old-aged forest was classified as primary forest after a certain threshold of carbon density was reached again, and the model-internal distinction between primary and secondary forest used as proxies for unmanaged vs managed forests; agricultural lands are added to the latter to arrive at total managed land.

Tab. A8 shows the resulting mapping of global carbon cycle models' land flux definitions to that of the NGHGI (discussed in Sec. 3.2.2). Note that estimates in this table are based on the global carbon budget estimates from Friedlingstein et al. (2020), which estimated higher emissions from the net land-use change flux (E_{LUC}) and a larger natural terrestrial sink. ORCHIDEE-MICT estimates for SLAND on intact forests are expected to be higher than based on DGVMs in combination with the NGHGI managed/unmanaged forest data because the unmanaged forest area, with about 27 mio km2, is estimated to be substantially larger by ORCHIDEE-MICT than, with less than 10 mio km2, by the NGHGI, while managed forest area is estimated to be smaller (22 compared to 32 mio km2). Related to this, S_{LAND} on non-intact lands plus E_{LUC} is a larger source estimated by ORCHIDEE-MICT compared to NGHGI. We also show as comparison FAOSTAT emissions totals (FAO, 2021), which include emissions from net forest conversion and fluxes on forest land (Tubiello et al., 2021) as well as CO_2 emissions from peat drainage and peat fires.

C.2.4 Uncertainty assessment for E_{LUC}

Differences between the bookkeeping models and DGVMs models originate from three main sources: the different methodologies, which among others lead to inclusion of the loss of additional sink capacity in DGVMs (see Appendix D1.4), the underlying land-use/land cover data set, and the different processes represented (Table A1). We examine the results from the DGVMs models and of the bookkeeping method and use the resulting variations as a way to characterise the uncertainty in E_{LUC}.

Despite these differences, the E_{LUC} estimate from the DGVMs multi-model mean is consistent with the average of the emissions from the bookkeeping models (Table 5). However there are large differences among individual DGVMs (standard deviation at around 0.5 GtC yr^{-1}; Table 5), between the bookkeeping estimates (average difference 1850-2020 BLUE-updated H&N2017 of 0.8 GtC yr^{-1}, BLUE-OSCAR of 0.4 GtC yr^{-1}, OSCAR-updated H&N2017 of 0.3 GtC yr^{-1}), and between the updated estimate of H&N2017 and its previous model version (Houghton et al., 2012). A factorial analysis of differences between BLUE and H&N2017 attributed them particularly to differences in carbon densities between natural and managed vegetation or primary and secondary vegetation (Bastos et al., 2021). Earlier studies additionally showed the relevance of the different land-use forcing as applied (in updated versions) also in the current study (Gasser et al., 2020).

The uncertainty in E_{LUC} of ±0.7 GtC yr^{-1} reflects our best value judgment that there is at least 68% chance (±1σ) that the true land-use change emission lies within the given range, for the range of processes considered here. Prior to the year 1959, the uncertainty in E_{LUC} was taken from the standard deviation of the DGVMs. We assign low confidence to the annual estimates of E_{LUC} because of the inconsistencies among estimates and of the difficulties to quantify some of the processes in DGVMs.

C.2.5 Emissions projections for E_{LUC}

We project the 2021 land-use emissions for BLUE, the updated H&N2017 and OSCAR, starting from their estimates for 2020 assuming unaltered peat drainage, which has low interannual variability, and the highly variable emissions from peat fires, tropical deforestation and degradation as estimated using active fire data (MCD14ML; Giglio et al., 2016). Those latter scale almost linearly with GFED over large areas (van der Werf et al., 2017), and thus allows for tracking fire emissions in deforestation and tropical peat zones in near-real time. During most years, emissions during January-September cover most of the fire season in the Amazon and Southeast Asia, where a large part of the global deforestation takes place, and our estimates capture emissions until the end of September.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Appendix C.3 Methodology Ocean CO_2 sink

C.3.1 Observation-based estimates

We primarily use the observational constraints assessed by IPCC of a mean ocean CO_2 sink of 2.2 ± 0.7 GtC yr^{-1} for the 1990s (90% confidence interval; Ciais et al., 2013) to verify that the GOBMs provide a realistic assessment of S_{OCEAN}. This is based on indirect observations with seven different methodologies and their uncertainties, using the methods that are deemed most reliable for the assessment of this quantity (Denman et al., 2007; Ciais et al., 2013). The observation-based estimates use the ocean/land CO_2 sink partitioning from observed atmospheric CO_2 and O_2/N_2 concentration trends (Manning and Keeling, 2006; Keeling and Manning, 2014), an oceanic inversion method constrained by ocean biogeochemistry data (Mikaloff Fletcher et al., 2006), and a method based on penetration time scale for chlorofluorocarbons (McNeil et al., 2003). The IPCC estimate of 2.2 GtC yr^{-1} for the 1990s is consistent with a range of methods (Wanninkhof et al., 2013). We refrain from using the IPCC estimates for the 2000s (2.3 ± 0.7 GtC yr^{-1}), and the period 2002-2011 (2.4 ± 0.7 GtC yr^{-1}, Ciais et al., 2013) as these are based on trends derived mainly from models and one data-product (Ciais et al., 2013). Additional constraints summarized in AR6 (Canadell et al., 2021) are the interior ocean anthropogenic carbon change (Gruber et al., 2019) and ocean sink estimate from atmospheric CO_2 and O_2/N_2 (Tohjima et al., 2019) which are used for model evaluation and discussion, respectively.

We also use eight estimates of the ocean CO_2 sink and its variability based on surface ocean fCO_2 maps obtained by the interpolation of surface ocean fCO_2 measurements from 1990 onwards due to severe restriction in data availability prior to 1990 (Figure 9). These estimates differ in many respects: they use different maps of surface fCO_2, different atmospheric CO_2 concentrations, wind products and different gas-exchange formulations as specified in Table A3. We refer to them as fCO_2-based flux estimates. The measurements underlying the surface fCO_2 maps are from the Surface Ocean CO_2 Atlas version 2021 (SOCATv2021; Bakker et al., 2021), which is an update of version 3 (Bakker et al., 2016) and contains quality-controlled data through 2020 (see data attribution Table A5). Each of the estimates uses a different method to then map the SOCAT v2021 data to the global ocean. The methods include a data-driven diagnostic method (Rödenbeck et al., 2013; referred to here as Jena-MLS), three neural network models (Landschützer et al.,

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

2014; referred to as MPI-SOMFFN; Chau et al., 2021; Copernicus Marine Environment Monitoring Service, referred to here as CMEMS-LSCE-FFNN; and Zeng et al., 2014; referred to as NIES-FNN), two cluster regression approaches (Gregor et al., 2019; referred to here as CSIR-ML6; and Gregor and Gruber, 2021, referred to as OS-ETHZ-GRaCER), and a multi-linear regression method (Iida et al., 2021; referred to as JMA-MLR). The ensemble mean of the fCO_2-based flux estimates is calculated from these seven mapping methods. Further, we show the flux estimate of Watson et al. (2020) who also use the MPI-SOMFFN method to map the adjusted fCO_2 data to the globe, but resulting in a substantially larger ocean sink estimate, owing to a number of adjustments they applied to the surface ocean fCO_2 data and the gas-exchange parameterization. Concretely, these authors adjusted the SOCAT fCO_2 downward to account for differences in temperature between the depth of the ship intake and the relevant depth right near the surface, and included a further adjustment to account for the cool surface skin temperature effect. The Watson et al. flux estimate hence differs from the others by their choice of adjusting the flux to a cool, salty ocean surface skin. Watson et al. (2020) showed that this temperature adjustment leads to an upward correction of the ocean carbon sink, up to 0.9 GtC yr^{-1}, that, if correct, should be applied to all fCO_2-based flux estimates. So far, this adjustment is based on a single line of evidence and hence associated with low confidence until further evidence is available. The Watson et al flux estimate presented here is therefore not included in the ensemble mean of the fCO_2-based flux estimates. This choice will be re-evaluated in upcoming budgets based on further lines of evidence.

The CO_2 flux from each fCO_2-based product is either already at or above 98% areal coverage (Jena-MLS, OS-ETHZ-GRaCER), filled by the data-provider (using Fay et al., 2021a, method for JMA-MLR; and Landschützer et al., 2020, methodology for MPI-SOMFFN) or scaled for the remaining products by the ratio of the total ocean area covered by the respective product to the total ocean area (361.9e6 km^2) from ETOPO1 (Amante and Eakins, 2009; Eakins and Sharman, 2010). In products where the covered area varies with time (e.g., CMEMS-LSCE-FFNN) we use the maximum area coverage. The lowest coverage is 93% (NIES-NN), resulting in a maximum adjustment factor of 1.08 (Table A3, Hauck et al., 2020).

We further use results from two diagnostic ocean models, Khatiwala et al. (2013) and DeVries (2014), to estimate the anthropogenic carbon accumulated in the ocean prior to 1959. The two approaches assume constant ocean circulation and biological fluxes, with S_{OCEAN} estimated as a response in the change in atmospheric CO_2 concentration calibrated to observations. The

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

uncertainty in cumulative uptake of ±20 GtC (converted to ±1σ) is taken directly from the IPCC's review of the literature (Rhein et al., 2013), or about ±30% for the annual values (Khatiwala et al., 2009).

C.3.2 Global Ocean Biogeochemistry Models (GOBMs)

The ocean CO_2 sink for 1959-2019 is estimated using eight GOBMs (Table A2). The GOBMs represent the physical, chemical, and biological processes that influence the surface ocean concentration of CO_2 and thus the air-sea CO_2 flux. The GOBMs are forced by meteorological reanalysis and atmospheric CO_2 concentration data available for the entire time period. They mostly differ in the source of the atmospheric forcing data (meteorological reanalysis), spin up strategies, and in their horizontal and vertical resolutions (Table A2). All GOBMs except one (CESM-ETHZ) do not include the effects of anthropogenic changes in nutrient supply (Duce et al., 2008). They also do not include the perturbation associated with changes in riverine organic carbon (see Section 2.7.3).

Three sets of simulations were performed with each of the GOBMs. Simulation A applied historical changes in climate and atmospheric CO_2 concentration. Simulation B is a control simulation with constant atmospheric forcing (normal year or repeated year forcing) and constant pre-industrial atmospheric CO_2 concentration. Simulation C is forced with historical changes in atmospheric CO_2 concentration, but repeated year or normal year atmospheric climate forcing. To derive S_{OCEAN} from the model simulations, we subtracted the annual time series of the control simulation B from the annual time series of simulation A. Assuming that drift and bias are the same in simulations A and B, we thereby correct for any model drift. Further, this difference also removes the natural steady state flux (assumed to be 0 GtC yr^{-1} globally without rivers) which is often a major source of biases. Simulation B of IPSL had to be treated differently as it was forced with constant atmospheric CO_2 but observed historical changes in climate. For IPSL, we fitted a linear trend to the simulation B and subtracted this linear trend from simulation A. This approach assures that the interannual variability is not removed from IPSL simulation A.

The absolute correction for bias and drift per model in the 1990s varied between <0.01 GtC yr^{-1} and 0.26 GtC yr^{-1}, with six models having positive biases, and one model having essentially no bias (NorESM). The remaining model (MPI) uses riverine input and therefore simulates outgassing in simulation B, i.e., a seemingly negative bias. By subtracting simulation B, also the ocean carbon

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

sink of the MPI model follows the definition of S_{OCEAN}. This correction reduces the model mean ocean carbon sink by 0.03 GtC yr^{-1} in the 1990s. The ocean models cover 99% to 101% of the total ocean area, so that area-scaling is not necessary.

C.3.3 GOBM evaluation and uncertainty assessment for S_{OCEAN}

The ocean CO_2 sink for all GOBMs and the ensemble mean falls within 90% confidence of the observed range, or 1.5 to 2.9 GtC yr^{-1} for the 1990s (Ciais et al., 2013) after applying adjustments. An exception is the MPI model, which simulates a low ocean carbon sink of 1.38 GtC yr^{-1} for the 1990s in simulation A owing to the inclusion of riverine carbon flux. After adjusting to the GCB's definition of S_{OCEAN} by subtracting simulation B, the MPI model falls into the observed range with an estimated sink of 1.69 GtC yr^{-1}.

The GOBMs and data products have been further evaluated using the fugacity of sea surface CO_2 (fCO_2) from the SOCAT v2021 database (Bakker et al., 2016, 2021). We focused this evaluation on the root mean squared error (RMSE) between observed and modelled fCO_2 and on a measure of the amplitude of the interannual variability of the flux (modified after Rödenbeck et al., 2015). The RMSE is calculated from detrended, annually and regionally averaged time series calculated from GOBMs and data-product fCO_2 subsampled to open ocean (water depth > 400 m) SOCAT sampling points to measure the misfit between large-scale signals (Hauck et al., 2020) The amplitude of the S_{OCEAN} interannual variability (A-IAV) is calculated as the temporal standard deviation of the detrended CO_2 flux time series (Rödenbeck et al., 2015, Hauck et al., 2020). These metrics are chosen because RMSE is the most direct measure of data-model mismatch and the A-IAV is a direct measure of the variability of S_{OCEAN} on interannual timescales. We apply these metrics globally and by latitude bands. Results are shown in Fig. B2 and discussed in Section 3.5.5.

We quantify the 1-σ uncertainty around the mean ocean sink of anthropogenic CO_2 by assessing random and systematic uncertainties for the GOBMs and data-products. The random uncertainties are taken from the ensemble standard deviation (0.3 GtC yr^{-1} for GOBMs, 0.3 GtC yr^{-1} for data-products). We derive the GOBMs systematic uncertainty by the deviation of the DIC inventory change 1994-2007 from the Gruber et al (2019) estimate (0.5 GtC yr^{-1}) and suggest these are related to physical transport (mixing, advection) into the ocean interior. For the data-products, we consider systematic uncertainties stemming from uncertainty in fCO_2 observations (0.2 GtC yr^{-1}, Takahashi et al., 2009; Wanninkhof et al., 2013), gas-transfer velocity (0.2 GtC yr^{-1}, Ho et al., 2011; Wanninkhof et al., 2013; Roobaert et al., 2018), wind product (0.1 GtC yr^{-1}, Fay et al., 2021a), river flux adjustment (0.2 GtC yr^{-1}, Jacobson et al., 2007; Resplandy et al., 2018), and fCO_2 mapping (0.2 GtC yr^{-1}, Landschützer et al., 2014). Combining these uncertainties as their squared sums, we assign an uncertainty of ± 0.6 GtC yr^{-1} to the GOBMs ensemble mean and an uncertainty of ± 0.5 GtC yr^{-1} to the data-product ensemble mean. These uncertainties are propagated as $\sigma(S_{OCEAN}) = (1/2^2 * 0.6^2 + 1/2^2 * 0.5^2)^{1/2}$ GtC yr^{-1} and result in an ± 0.4 GtC yr^{-1} uncertainty around the best estimate of S_{OCEAN}.

We examine the consistency between the variability of the model-based and the fCO_2-based data products to assess confidence in S_{OCEAN}. The interannual variability of the ocean fluxes (quantified as A-IAV, the standard deviation after detrending, Figure B2) of the seven fCO_2-based data products plus the Watson et al. (2020) product for 1990-2020, ranges from 0.16 to 0.26 GtC yr^{-1} with the lower estimates by the three ensemble methods (CSIR-ML6, CMEMS-LSCE-FFNN, OS-ETHZ-GRaCER). The inter-annual variability in the GOBMs ranges between 0.10 and 0.19 GtC yr^{-1}, hence there is overlap with the lower A-IAV estimates of three data-products.

Individual estimates (both GOBMs and data products) generally produce a higher ocean CO_2 sink during strong El Niño events. There is emerging agreement between GOBMs and data-products on the patterns of decadal variability of S_{OCEAN} with a global stagnation in the 1990s and an extra-tropical strengthening in the 2000s (McKinley et al., 2020, Hauck et al., 2020). The central estimates of the annual flux from the GOBMs and the fCO_2-based data products have a correlation *r* of 0.94 (1990-2020). The agreement between the models and the data products reflects some consistency in their representation of underlying variability since there is little overlap in their methodology or use of observations.

Appendix C.4 Methodology Land CO_2 sink

C.4.1 DGVM simulations

The DGVMs model runs were forced by either the merged monthly Climate Research Unit (CRU) and 6 hourly Japanese 55-year Reanalysis (JRA-55) data set or by the monthly CRU data set, both providing observation-based temperature, precipitation, and incoming surface radiation on a 0.5°x0.5° grid and updated to 2020 (Harris et al., 2014, 2020). The combination of CRU monthly data with 6 hourly forcing from JRA-55 (Kobayashi et al., 2015) is performed with methodology used in previous years (Viovy, 2016) adapted to the specifics of the JRA-55 data.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

New to this budget is the revision of incoming short-wave radiation fields to take into account aerosol impacts and the division of total radiation into direct and diffuse components as summarised below.

The diffuse fraction dataset offers 6-hourly distributions of the diffuse fraction of surface shortwave fluxes over the period 1901-2020. Radiative transfer calculations are based on monthly-averaged distributions of tropospheric and stratospheric aerosol optical depth, and 6-hourly distributions of cloud fraction. Methods follow those described in the Methods section of Mercado et al. (2009), but with updated input datasets.

The time series of speciated tropospheric aerosol optical depth is taken from the historical and RCP8.5 simulations by the HadGEM2-ES climate model (Bellouin et al., 2011). To correct for biases in HadGEM2-ES, tropospheric aerosol optical depths are scaled over the whole period to match the global and monthly averages obtained over the period 2003-2020 by the CAMS Reanalysis of atmospheric composition (Inness et al., 2019), which assimilates satellite retrievals of aerosol optical depth.

The time series of stratospheric aerosol optical depth is taken from the climatology by Sato et al. (1993), which has been updated to 2012. Years 2013-2020 are assumed to be background years so replicate the background year 2010. That assumption is supported by the Global Space-based Stratospheric Aerosol Climatology time series (1979-2016; Thomason et al., 2018). The time series of cloud fraction is obtained by scaling the 6-hourly distributions simulated in the Japanese Reanalysis (Kobayashi et al., 2015) to match the monthly-averaged cloud cover in the CRU TS v4.03 dataset (Harris et al., 2021). Surface radiative fluxes account for aerosol-radiation interactions from both tropospheric and stratospheric aerosols, and for aerosol-cloud interactions from tropospheric aerosols, except mineral dust. Tropospheric aerosols are also assumed to exert interactions with clouds.

The radiative effects of those aerosol-cloud interactions are assumed to scale with the radiative effects of aerosol-radiation interactions of tropospheric aerosols, using regional scaling factors derived from HadGEM2-ES. Diffuse fraction is assumed to be 1 in cloudy sky. Atmospheric constituents other than aerosols and clouds are set to a constant standard mid-latitude summer atmosphere, but their variations do not affect the diffuse fraction of surface shortwave fluxes.

In summary, the DGVMs forcing data include time dependent gridded climate forcing, global atmospheric CO_2 (Dlugokencky and Tans, 2021), gridded land cover changes (see Appendix C.2.2), and gridded nitrogen deposition and fertilisers (see Table A1 for specific models details).

Four simulations were performed with each of the DGVMs. Simulation 0 (S0) is a control simulation which uses fixed pre-industrial (year 1700) atmospheric CO2 concentrations, cycles early 20th century (1901-1920) climate and applies a time-invariant pre-industrial land cover distribution and pre-industrial wood harvest rates. Simulation 1 (S1) differs from S0 by applying historical changes in atmospheric CO2 concentration and N inputs. Simulation 2 (S2) applies historical changes in atmospheric CO_2 concentration, N inputs, and climate, while applying time-invariant pre-industrial land cover distribution and pre-industrial wood harvest rates. Simulation 3 (S3) applies historical changes in atmospheric CO2 concentration, N inputs, climate, and land cover distribution and wood harvest rates.

S2 is used to estimate the land sink component of the global carbon budget (S_{LAND}). S3 is used to estimate the total land flux but is not used in the global carbon budget. We further separate S_{LAND} into contributions from CO_2 (=S1-S0) and climate (=S2-S1-S0).

C.4.2 DGVM evaluation and uncertainty assessment for S_{LAND}

We apply three criteria for minimum DGVMs realism by including only those DGVMs with (1) steady state after spin up, (2) global net land flux (S_{LAND} – E_{LUC}) that is an atmosphere-to-land carbon flux over the 1990s ranging between -0.3 and 2.3 GtC yr^{-1}, within 90% confidence of constraints by global atmospheric and oceanic observations (Keeling and Manning, 2014; Wanninkhof et al., 2013), and (3) global E_{LUC} that is a carbon source to the atmosphere over the 1990s, as already mentioned in section 2.2.2. All 17 DGVMs meet these three criteria.

In addition, the DGVMs results are also evaluated using the International Land Model Benchmarking system (ILAMB; Collier et al., 2018). This evaluation is provided here to document, encourage and support model improvements through time. ILAMB variables cover key processes that are relevant for the quantification of S_{LAND} and resulting aggregated outcomes. The selected variables are vegetation biomass, gross primary productivity, leaf area index, net ecosystem exchange, ecosystem respiration, evapotranspiration, soil carbon, and runoff (see Fig. B3 for the results and for the list of observed databases). Results are shown in Fig. B3 and discussed in Section 3.6.5.

https://doi.org/10.5194/essd-2021-386
Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

For the uncertainty for S_{LAND}, we use the standard deviation of the annual CO_2 sink across the DGVMs, averaging to about ± 0.6 GtC yr^{-1} for the period 1959 to 2019. We attach a medium confidence level to the annual land CO_2 sink and its uncertainty because the estimates from the residual budget and averaged DGVMs match well within their respective uncertainties (Table 5).

Appendix C.5 Methodology Atmospheric Inversions

Six atmospheric inversions (details of each in Table A4) were used to infer the spatio-temporal distribution of the CO_2 flux exchanged between the atmosphere and the land or oceans. These inversions are based on Bayesian inversion principles with prior information on fluxes and their uncertainties. They use very similar sets of surface measurements of CO_2 time series (or subsets thereof) from various flask and in situ networks. One inversion system also used satellite xCO_2 retrievals from GOSAT and OCO-2.

Each inversion system uses different methodologies and input data but is rooted in Bayesian inversion principles. These differences mainly concern the selection of atmospheric CO_2 data and prior fluxes, as well as the spatial resolution, assumed correlation structures, and mathematical approach of the models. Each system uses a different transport model, which was demonstrated to be a driving factor behind differences in atmospheric inversion-based flux estimates, and specifically their distribution across latitudinal bands (Gaubert et al., 2019; Schuh et al., 2019).

The inversion systems prescribe same global fossil fuel emissions for E_{FOS}; specifically, the GCP's Gridded Fossil Emissions Dataset version 2021 (GCP-GridFEDv2021.2; Jones et al., 2021b), which is an update through 2020 of the first version of GCP-GridFED presented by Jones et al. (2021a). GCP-GridFEDv2021.2 scales gridded estimates of CO_2 emissions from EDGARv4.3.2 (Janssens-Maenhout et al., 2019) within national territories to match national emissions estimates provided by the GCP for the years 1959-2020, which were compiled following the methodology described in Appendix C.1 based on all information available on 31st July 2021 (R. Andrew, *pers. comm.*).

Typically, the GCP-GridFED adopts the seasonal variation in emissions (the monthly distribution of annual emissions) from EDGAR and applies small corrections based on heating or cooling degree days to account for the effects of inter-annual climate variability on the seasonality emissions (Jones et al., 2021a). However, strategies taken to deal with the COVID-19 pandemic during 2020 mean that the seasonality of emissions diverged substantially in 2020 from a typical year. To account for this change, GCP-GridFEDv2021.2 adopts the national seasonality in emissions from Carbon Monitor (Liu et al., 2020a,b) during the years 2019-2020 (Jones et al. 2021b).

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Preprint. Discussion started: 4 November 2021

Open Access Earth System Science Data Discussions

The consistent use of GCP-GridFEDv2021.2 for E_{FOS} ensures a close alignment with the estimate of E_{FOS} used in this budget assessment, enhancing the comparability of the inversion-based estimate with the flux estimates deriving from DGVMs, GOBMs and fCO_2-based methods. To account for small differences in regridding, and the use of a slightly earlier file version (GCP-GridFEDv2021.1) for 2000-2018 in CarbonTracker Europe, small fossil fuel corrections were applied to all inverse models to make the estimated uptake of atmospheric CO2 fully consistent. Finally, we note that GCP-GridFEDv2021.2 includes emissions from cement production, but it does not include the cement carbonation CO_2 sink (Xi et al., 2016; Cao et al., 2020; Guo et al. 2021) that is applied to the GCB estimate of E_{FOS} in Table 6.

The land and ocean CO_2 fluxes from atmospheric inversions contain anthropogenic perturbation and natural pre-industrial CO_2 fluxes. On annual time scales, natural pre-industrial fluxes are primarily land CO_2 sinks and ocean CO_2 sources corresponding to carbon taken up on land, transported by rivers from land to ocean, and outgassed by the ocean. These pre-industrial land CO_2 sinks are thus compensated over the globe by ocean CO_2 sources corresponding to the outgassing of riverine carbon inputs to the ocean, using the exact same numbers and distribution as described for the oceans in Section 2.4. To facilitate the comparison, we adjusted the inverse estimates of the land and ocean fluxes per latitude band with these numbers to produce historical perturbation CO_2 fluxes from inversions. Finally, for the presentation of the comparison in Figure 11 we modified the FF-corrected and riverine-adjusted land sinks from the inversions further, by removing a 0.2 $GtCyr^{-1}$ CO_2 sink that is ascribed to cement carbonation in the GCB, rather than to terrestrial ecosystems. The latter is not applied in the inversion products released through GCB or the original data portals of these products.

All participating atmospheric inversions are checked for consistency with the annual global growth rate, as both are derived from the global surface network of atmospheric CO2 observations. In this exercise, we use the conversion factor of 2.086 GtC/ppm to convert the inverted carbon fluxes to mole fractions, as suggested by Prather (2012). This number is specifically suited for the comparison to surface observations that do not respond uniformly, nor immediately, to each year’s summed sources and sinks. This factor is therefore slightly smaller than the GCB conversion factor in Table 1 (2.142 GtC/ppm, Ballantyne et al., 2012). Overall, the inversions agree with the growth rate with biases between 0.03-0.08 ppm (0.06-0.17 $GtCyr^{-1}$) on the decadal average.

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The atmospheric inversions are also evaluated using vertical profiles of atmospheric CO_2 concentrations (Fig. B4). More than 30 aircraft programs over the globe, either regular programs or repeated surveys over at least 9 months, have been used in order to draw a robust picture of the model performance (with space-time data coverage irregular and denser in the 0-45°N latitude band; Table A6). The six models are compared to the independent aircraft CO_2 measurements between 2 and 7 km above sea level between 2001 and 2020. Results are shown in Fig. B4, where the inversions generally match the atmospheric mole fractions to within 0.6 ppm at all latitudes, except for CT Europe in 2010-2020 over the more sparsely sampled southern hemisphere.

Appendix D Processes not included in the global carbon budget

Appendix D.1 Contribution of anthropogenic CO and CH_4 to the global carbon budget

Equation (1) includes only partly the net input of CO_2 to the atmosphere from the chemical oxidation of reactive carbon-containing gases from sources other than the combustion of fossil fuels, such as: (1) cement process emissions, since these do not come from combustion of fossil fuels, (2) the oxidation of fossil fuels, (3) the assumption of immediate oxidation of vented methane in oil production. However, it omits any other anthropogenic carbon-containing gases that are eventually oxidised in the atmosphere, such as anthropogenic emissions of CO and CH_4. An attempt is made in this section to estimate their magnitude and identify the sources of uncertainty. Anthropogenic CO emissions are from incomplete fossil fuel and biofuel burning and deforestation fires. The main anthropogenic emissions of fossil CH_4 that matter for the global (anthropogenic) carbon budget are the fugitive emissions of coal, oil and gas sectors (see below). These emissions of CO and CH_4 contribute a net addition of fossil carbon to the atmosphere.

In our estimate of E_{FOS} we assumed (Section 2.1.1) that all the fuel burned is emitted as CO_2, thus CO anthropogenic emissions associated with incomplete fossil fuel combustion and its atmospheric oxidation into CO_2 within a few months are already counted implicitly in E_{FOS} and should not be counted twice (same for E_{LUC} and anthropogenic CO emissions by deforestation fires). Anthropogenic emissions of fossil CH_4 are however not included in E_{FOS}, because these fugitive emissions are not included in the fuel inventories. Yet they contribute to the annual CO_2 growth rate after CH_4 gets oxidized into CO_2. Emissions of fossil CH_4 represent 30% of total anthropogenic CH_4 emissions (Saunois et al. 2020; their top-down estimate is used because it is

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Preprint. Discussion started: 4 November 2021

consistent with the observed CH_4 growth rate), that is 0.083 GtC yr^{-1} for the decade 2008-2017. Assuming steady state, an amount equal to this fossil CH_4 emission is all converted to CO_2 by OH oxidation, and thus explain 0.083 GtC yr^{-1} of the global CO_2 growth rate with an uncertainty range of 0.061 to 0.098 GtC yr^{-1} taken from the min-max of top-down estimates in Saunois et al. (2020). If this min-max range is assumed to be 2 σ because Saunois et al. (2020) did not account for the internal uncertainty of their min and max top-down estimates, it translates into a 1-σ uncertainty of 0.019 GtC yr^{-1}.

Other anthropogenic changes in the sources of CO and CH_4 from wildfires, vegetation biomass, wetlands, ruminants, or permafrost changes are similarly assumed to have a small effect on the CO_2 growth rate. The CH_4 and CO emissions and sinks are published and analysed separately in the Global Methane Budget and Global Carbon Monoxide Budget publications, which follow a similar approach to that presented here (Saunois et al., 2020; Zheng et al., 2019).

Appendix D.2 Contribution of other carbonates to CO_2 emissions

Although we do account for cement carbonation (a carbon sink), the contribution of emissions of fossil carbonates (carbon sources) other than cement production is not systematically included in estimates of E_{FOS}, except at the national level where they are accounted for in the UNFCCC national inventories. The missing processes include CO_2 emissions associated with the calcination of lime and limestone outside cement production. Carbonates are also used in various industries, including in iron and steel manufacture and in agriculture. They are found naturally in some coals. CO_2 emissions from fossil carbonates other than cement are estimated to amount to about 1% of E_{FOS} (Crippa et al., 2019), though some of these carbonate emissions are included in our estimates (e.g., via UNFCCC inventories).

Appendix D.3 Anthropogenic carbon fluxes in the land-to-ocean aquatic continuum

The approach used to determine the global carbon budget refers to the mean, variations, and trends in the perturbation of CO_2 in the atmosphere, referenced to the pre-industrial era. Carbon is continuously displaced from the land to the ocean through the land-ocean aquatic continuum (LOAC) comprising freshwaters, estuaries, and coastal areas (Bauer et al., 2013; Regnier et al., 2013). A substantial fraction of this lateral carbon flux is entirely 'natural' and is thus a steady state component of the pre-industrial carbon cycle. We account for this pre-industrial flux where appropriate in our study (see Appendix C.3). However, changes in environmental conditions and

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land-use change have caused an increase in the lateral transport of carbon into the LOAC – a perturbation that is relevant for the global carbon budget presented here.

The results of the analysis of Regnier et al. (2013) can be summarized in two points of relevance for the anthropogenic CO_2 budget. First, the anthropogenic perturbation of the LOAC has increased the organic carbon export from terrestrial ecosystems to the hydrosphere by as much as 1.0 ± 0.5 GtC yr^{-1} since pre-industrial, mainly owing to enhanced carbon export from soils. Second, this exported anthropogenic carbon is partly respired through the LOAC, partly sequestered in sediments along the LOAC and to a lesser extent, transferred to the open ocean where it may accumulate or be outgassed. The increase in storage of land-derived organic carbon in the LOAC carbon reservoirs (burial) and in the open ocean combined is estimated by Regnier et al. (2013) at 0.65 ± 0.35GtC yr^{-1}. The inclusion of LOAC related anthropogenic CO_2 fluxes should affect estimates of S_{LAND} and S_{OCEAN} in Eq. (1) but does not affect the other terms. Representation of the anthropogenic perturbation of LOAC CO_2 fluxes is however not included in the GOBMs and DGVMs used in our global carbon budget analysis presented here.

Appendix D.4 Loss of additional land sink capacity

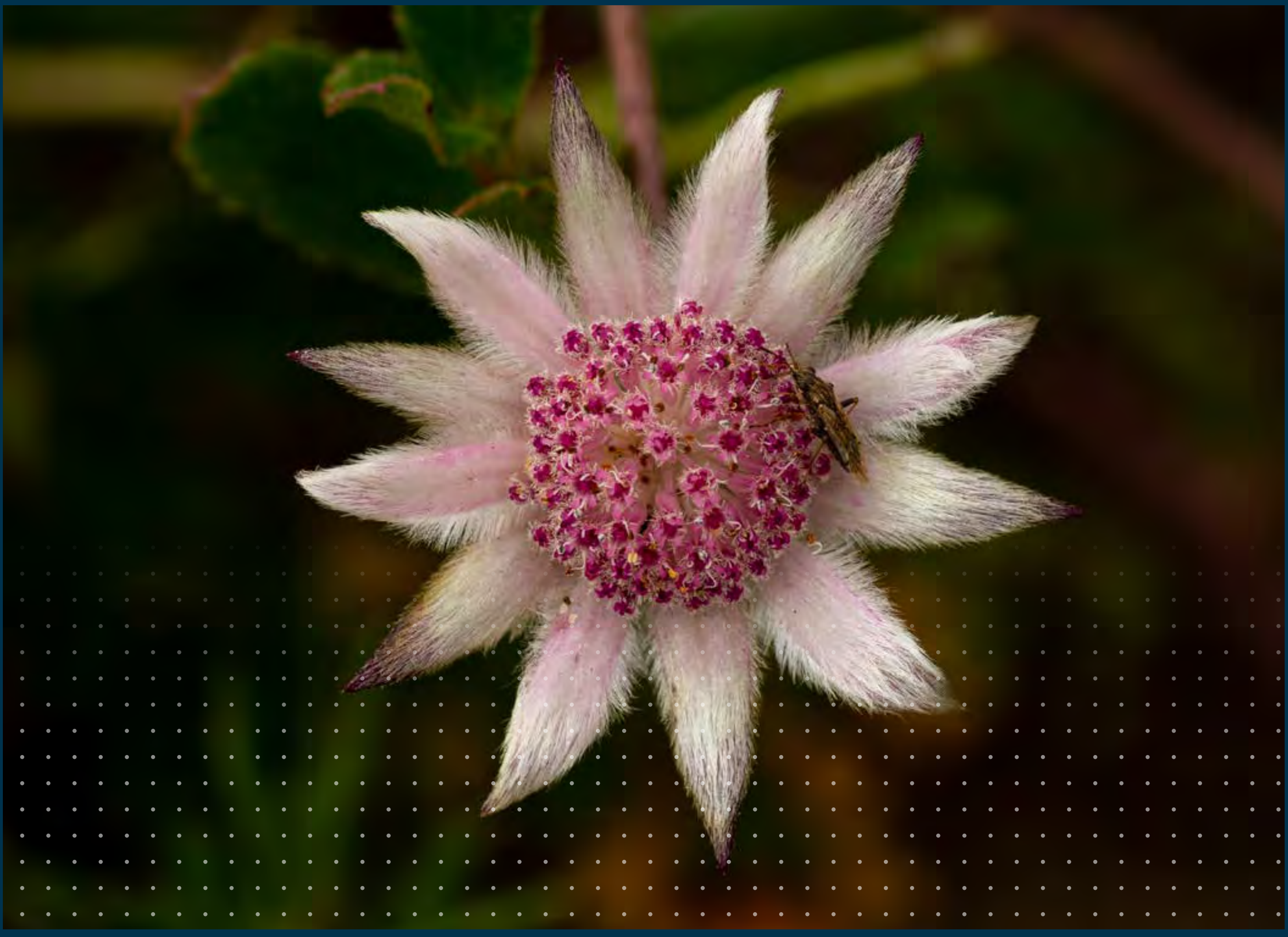
Historical land-cover change was dominated by transitions from vegetation types that can provide a large carbon sink per area unit (typically, forests) to others less efficient in removing CO_2 from the atmosphere (typically, croplands). The resultant decrease in land sink, called the 'loss of additional sink capacity', can be calculated as the difference between the actual land sink under changing land-cover and the counterfactual land sink under pre-industrial land-cover. This term is not accounted for in our global carbon budget estimate. Here, we provide a quantitative estimate of this term to be used in the discussion. Seven of the DGVMs used in Friedlingstein et al. (2019) performed additional simulations with and without land-use change under cycled pre-industrial environmental conditions. The resulting loss of additional sink capacity amounts to 0.9 ± 0.3 GtC yr^{-1} on average over 2009-2018 and 42 ± 16 GtC accumulated between 1850 and 2018 (Obermeier et al., 2021). OSCAR, emulating the behaviour of 11 DGVMs finds values of the loss of additional sink capacity of 0.7 ± 0.6 GtC yr^{-1} and 31 ± 23 GtC for the same time period (Gasser et al., 2020). Since the DGVM-based ELUC estimates are only used to quantify the uncertainty around the bookkeeping models' ELUC we do not add the loss of additional sink capacity to the bookkeeping estimate.

DOCUMENT 6

NSW Environment Protection Authority

NSW State of the Environment 2021

Tabled Report



soe.epa.nsw.gov.au

Acknowledgement of Country

Aboriginal people have a spiritual and cultural connection and an inherent right to protect the land, waters, sky and natural resources of New South Wales. This connection goes deep and has been since the dreaming. The entire landscape, including traditional lands, fresh water and seas, has spiritual and cultural significance to Aboriginal people. If the cultural and spiritual values of Aboriginal people are sustained by providing protection, respect, quantity and quality, then many other components of Aboriginal life will be healthy. By this understanding there is no separation of country, culture, waters and wellbeing. The health of the natural environment, fresh waters, land animals, marine animals and people are intimately connected.

In compiling this report the NSW Environment Protection Authority (EPA) acknowledges this and that Aboriginal people as the first protectors have continuously cared for Country and the natural environment of NSW for thousands of generations. The EPA acknowledges the custodians and honours the ancestors, the Elders both past and present and extend that respect to other Aboriginal people in NSW.

Dharawal Country, Royal National Park, NSW

EPA Statement of Commitment

We, the NSW Environment Protection Authority, acknowledge Aboriginal peoples as the enduring Custodians of the land, sea, waters and sky of New South Wales.

We recognise the entire NSW landscape, including the lands, waters, plant and animal species and seas, has spiritual and cultural significance to all Aboriginal people of NSW. By this understanding there is no separation of nature, wellbeing, and Culture. The health of the natural environment, land animals, marine animals and the health of people and Culture are intimately connected.

Upon the release of the NSW 2021 SoE Report and in the spirit of reconciliation, the EPA is committed to:

- Work in respectful partnership with Aboriginal peoples
- Actively learn from and listen to Aboriginal voices, Culture and Knowledge
- Respect Aboriginal people's knowledge and science as an equal to western science.
- Weave Aboriginal Knowledges and Science with conventional science into the EPA's decision making.
- Act boldly and bravely to play our part to mend and heal Country together
- Ensure Aboriginal Knowledge, Science and Indigenous Cultural and Intellectual Property (ICIP) is protected, and Aboriginal people have Free, Prior Informed Consent
- Address both the tangible and intangible cultural elements of environmental protection
- Deliver on results that have direct benefits for Aboriginal communities
- Embed consistent, meaningful, and trustworthy engagement with Aboriginal communities
- Develop Aboriginal cultural competency across the agency
- Increase Aboriginal employment across the agency to exceed public sector Aboriginal employment targets and to identify specific occupational gaps
- Monitor the impact of the commitment to Aboriginal peoples, Country, culture and spirit.

Gumbainggir Country, Clarence floodplain coastal backswamp (wetland) northern NSW.
Photo Stuart Murphy.

Cover: Tim Johnson, Pink flannel flower, Murramarang National Park, Yuin Country.

Published by:

NSW Environment Protection Authority
4 Parramatta Square
12 Darcy Street, Parramatta NSW 2150
Locked Bag 5022, Parramatta NSW 2124

Phone: +61 2 9995 5000 (switchboard)
Phone: 131 555 (NSW only – environment information and publications requests)
Fax: +61 2 9995 5999
TTY users: phone 133 677, then ask for 131 555
Speak and listen users: phone 1300 555 727, then ask for 131 555

Email: info@epa.nsw.gov.au
Website: www.soe.epa.nsw.gov.au

Report pollution and environmental incidents
Environment Line: 131 555 (NSW only) or info@epa.nsw.gov.au
See also www.epa.nsw.gov.au

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Foreword

I am pleased to present the EPA's eleventh *NSW State of the Environment*. This report describes the status and trends in the quality of the NSW natural environment and implications for environmental and human health.

The condition of our natural environment is a major determinant of our quality of life – the air we breathe, the water we drink, the soil so essential for our land and agriculture, the raw materials for industry and economic growth and the natural beauty that sustains public amenity and tourism. Reporting on the state of our environment helps us take stock of environmental conditions in our state, identify emerging issues and act effectively for the benefit of future generations and the environment itself.

This report is published every three years and provides a valuable time-series of data on our natural environment. The accompanying interactive online portal includes more frequent updates as a resource for the general community and to support policy-makers in determining outcomes for the environment.

I am grateful this year for the generous involvement of the Aboriginal Peoples Knowledge Group in preparing this report. In 2021, the EPA invited the views, values and knowledge of Aboriginal people to enhance our understanding of the health of the NSW environment. The Aboriginal Peoples Knowledge Group has, in a short time, made an invaluable contribution to this report and will continue to guide further engagement for wider representation from Aboriginal people in this kind of reporting. As the Knowledge Group has acknowledged so powerfully:

'Everything is connected. How we use and care for the land/Country impacts its health. Healthy land/Country means not only healthy plants, animals and ecosystems but also healthy people.'

So, what does the report tell us about our environment?

Over the past three years our environment has too frequently been in the news as a series of natural events and disasters has played out – severe droughts and water shortages for many remote communities, several major fish kills in the Darling River system, the worst bushfires ever recorded in NSW, followed by widespread flooding.

This demonstrates how sensitive and vulnerable the environment is to disturbance and harm, often caused by humans, and how important it is to protect it so our own and future generations can continue to enjoy its many benefits.

But it is not all bad news and *NSW State of the Environment 2021* identifies that many aspects of the environment are in good condition.

Air quality continues to be generally good, with low concentrations of lead, carbon monoxide and sulfur dioxide, although particle pollution from smoke and dust soared in 2019 due to the continuing drought and extensive bushfires. Ozone and particle pollution levels require ongoing attention in some situations.

The **industry and household waste** disposed of to landfill is decreasing while recycling of garden and food waste is on the increase. The NSW Government is combating illegal dumping and supporting emergency clean-ups of hazardous waste such as illegally dumped asbestos.

There are also many opportunities for innovative solutions that benefit both the environment and the economy. An example of this is the *Return and Earn* **container deposit scheme**, which was established in December 2017. Previously, drink container rubbish made up almost half of the total litter volume in NSW. By September 2021, over 8.1 billion containers had been returned, resulting in a 52% reduction in drink container litter.

Electricity generation has seen a strong increase in the share of renewable energy sources in the NSW electricity supply from around 16% in 2017 to 19% in 2020. In the three years to June 2020, total NSW and ACT electricity generation remained stable with a slight increase of 0.5% as the population continued to grow, while electricity consumption per capita declined by about 6%.

Impacts from **population** growth and our use of natural resources can have a profound effect on our environment. Some of the principal challenges identified in previous *NSW State of the Environment* reports remain.

Climate change continues to pose a significant threat to both the environment and population of NSW. Its effects are already being felt and are anticipated to become more severe over the coming decades. International collaboration will be required to make the deep reductions in greenhouse gas emissions necessary to counteract these effects. NSW is doing its part by supporting a number of programs and initiatives under *Net Zero Plan Stage 1: 2020–2030*, which aims to strengthen the prosperity and quality of life of our people, while helping to achieve the objective of delivering a 50% cut in emissions by 2030 compared to 2005 levels.

The number of **threatened species** in NSW continues to rise. More than 1,000 native plant and animal species and 112 ecological communities are currently listed as threatened under state legislation. The main threats to these species are habitat loss due to permanent clearing and degradation of native vegetation and the spread of invasive pests and weeds.

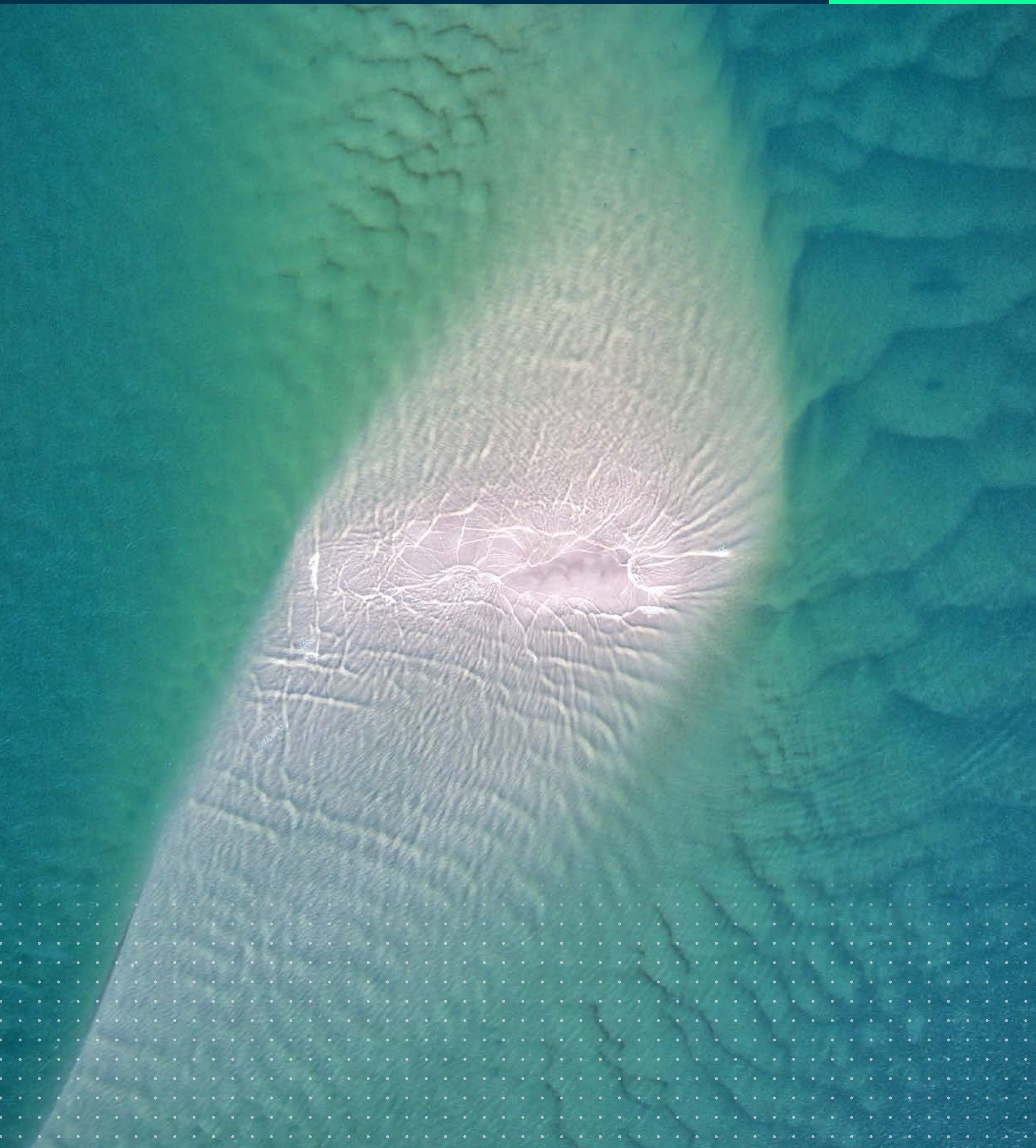
Preparation of this report has relied on extensive contributions from within the EPA as well as from many other NSW Government agencies. Data and information have been validated by the contributing organisations and independent experts, through an extensive process of review. An important inclusion this year is the views, values and knowledge of Aboriginal people to enhance understanding of the health of the NSW environment.

My sincere thanks to everyone who contributed to this report.

Tracy Mackey
Chief Executive Officer
NSW Environment Protection Authority

Contents

About the Report



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About this report

NSW State of the Environment 2021 (SoE 2021) has been prepared by the EPA to provide a snapshot in time of the status of the main environmental issues facing the state. The SoE is updated every three years and brings together information and data from across all NSW Government agencies with responsibility for managing the state's environmental assets.

This information is assembled and compiled within an SoE online reporting system. A new version of the SoE system has been created following completion of the three-yearly data update in December 2021. This SoE 2021 report was extracted from the system for tabling in the NSW Parliament as a more concise report without the interactive functionality, online linkages and supplementary resources available in the 2021 online version.

How to use this report

Structure and linkages

NSW State of the Environment 2021 is structured around six broad themes and 22 separate topics within those themes. The six themes are all related and the SoE online system allows for seamless transition from content in one topic to another. Each topic has a structure consistent with the Status and Trends – Pressures – Responses model for SoE reporting.

Indicator summaries

SoE 2021 assesses the current status and trends of each of 77 environmental indicators, along with the reliability of the information used to provide an indicator rating. Any new information or data is generally assessed over the reporting period between the previous and current SoE report, taking into account previous data whenever possible to help understand the level of background variation that may be present.

Key to the indicator summaries

Indicator status

'Indicator status' refers to the environmental condition of the indicator.

Indicator rating	Interpretation
 GOOD	**Green:** Good – the data shows a positive or healthy environmental condition.
 MODERATE	**Blue:** Moderate – the data shows that the environmental condition is neither good nor poor, or results may be mixed.
 POOR	**Red:** Poor – the data indicates poor environmental condition or condition under significant stress.
 UNKNOWN	**Grey:** Unknown – insufficient data or information is available to make an assessment.

Indicator trend

'Indicator trend' describes the direction of significant change in environmental condition, where this can be differentiated from natural background variation. The trend is usually judged over the three years of the reporting period, but with a greater focus on the latest and most current data.

However, longer term data is also considered, where available, as it helps to gauge the level of background variation that occurs naturally and interpret the significance of any change. The trend reported, if maintained, may have an impact on the overall status of the indicator in the future.

Indicator trend	Interpretation
Getting better	The trend in environmental condition for the indicator is clearly improving (environmental impacts are decreasing). However, while a trend may be positive in direction, it may still be many years before the change is enough to warrant a revision to the status.
Stable	No significant change in condition is evident, usually allowing for some level of fluctuation due to the background variability that occurs in most naturally occurring systems.
Getting worse	The trend in environmental condition for the indicator is clearly deteriorating (environmental impacts are increasing).

Indicator reliability

'Indicator reliability' describes the level of confidence in the data or information used to make these assessments. It considers the statewide extent of data coverage, the accuracy and 'fitness for use' of the data, and the reliability of the information and its interpretation in assessing the status and trend for the indicator. This is represented by the symbols below.

Indicator reliability	Interpretation
✓✓✓	**Three ticks:** Good – the data or information is sufficient to interpret the outcome with confidence.
✓✓	**Two ticks:** Reasonable – the data coverage may not be complete or the supporting information drawn on is not ideally fit for purpose (often it is collected for some other purpose) but is still adequate for use in this context and the interpretations are sound.
✓	**One tick:** Limited – the data coverage is patchy and uneven in quality or there may be some inconsistencies in the supporting information, so caution is needed in considering the ratings and interpretations.

Credits

Preparation of *NSW State of the Environment 2021* has relied on contributions, appraisal and validation from many sources.

EPA Aboriginal Peoples Knowledge Group

In 2021, the EPA invited the views, values and knowledge of Aboriginal people to enhance its understanding of the health of the NSW environment.

The SoE Aboriginal Peoples Knowledge Group was established to improve representation of Aboriginal people during preparation of the 2021 report. This included, among other things, providing introductions to the six environmental themes, sharing cultural stories, reviewing the Fire topic and setting a process to deliver future enhancements to the website.

This has been an important step to better recognise outcomes and impacts to Aboriginal people and cultures. The group will continue to guide further engagement for wider representation from Aboriginal people across NSW in State of the Environment reporting.

For this report the Aboriginal Peoples Knowledge Group comprised members of:

- EPA Aboriginal Initiatives
- EPA Governance Risk and Planning
- Department of Planning, Industry and Environment.
- NSW Aboriginal Land Council.*

And two independent members:

- Wally Stewart, Walbunja man from the south coast of NSW
- Associate Professor Bradley Moggridge, Kamilaroi Water Scientist.

*Established under the *Aboriginal Land Rights Act 1983* (NSW), the NSW Aboriginal Land Council is the peak representative body for Aboriginal people in NSW.

'We talk about Country as Aboriginal people. We talk about Country as a being. The thing for us is you hear people like to say "This is my country" and it's not like it's "I take, it's no one else's". It's "This is the Country I'm connected to. This is the being I'm connected to".'
– Andrew Beach (Wonnarua): Acting Unit Head Regulatory Operations

'Our Country is our soul, is our mother and if that's gone, we're gone too.'
– Denise O'Donnell (Malyangapa, Ngiyampaa & Barkindji): EPA Liaison

Future Opportunities raised by the Group

Throughout the report, the Aboriginal Peoples Knowledge Group has identified future opportunities for management authorities to learn more and apply how Aboriginal cultures and practices improve the care, protection and management of the environment.

The Group has also identified the following as being important:

- That Aboriginal knowledges and cultures are valued and promoted alongside western sciences.
- Inclusion of Aboriginal people in decision making and programs that aim to sustain healthy native vegetation, animals and Country.
- That more scientific, biodiversity and conservation (environmental management) committees include membership of Aboriginal people, and that this outcome be measured through a future additional SoE indicator.

Agency contributors

Preparation of *NSW State of the Environment 2021* has relied on contributions, appraisal and validation from many NSW Government agencies and from within the EPA.

The EPA is grateful for the assistance of NSW agencies who contributed the majority of content for other topics, particularly:

- Department of Planning, Industry and Environment
- Department of Regional NSW
- Forestry Corporation of NSW
- Hunter Water Corporation
- NSW Rural Fire Service
- Sydney Water Corporation
- Transport for NSW.

Review assistance was also provided by the Department of Premier and Cabinet and NSW Ministry of Health.

Independent expert reviewers

Independent expert review enhances the value and transparency of the report by ensuring that the most up-to-date and appropriate information is included; analysis and interpretation of the material is appropriate; and content adequately covers new and emerging issues.

The EPA acknowledges the contribution of the following experts who reviewed content and data relevant to their expertise:

- Associate Professor Howard Bridgman, University of Newcastle
- Associate Professor Mathew Crowther, University of Sydney
- Dr Scott Dwyer, Institute for Sustainable Futures
- Dr Damien Giurco, Institute for Sustainable Futures
- Dr Ben Gooden, CSIRO
- Dr Richard Greene, Australian National University
- Dr Mike McLaughlin, University of Adelaide
- Professor Andrew Pitman, University of NSW
- Associate Professor Owen Price, Director of the Centre for Environmental Risk Management of Bushfire Risk, University of Wollongong
- Professor David Stern, Australian National University
- Mr Rob Sturgiss, Australian Department of Environment and Energy
- Professor Martin Thoms, University of New England
- Mr Ian Varley, Water Resources and Environmental Management
- Professor Stuart White, Institute for Sustainable Futures
- Bhiamie Williamson, Euahlayi man and Associate Lecturer Centre for Aboriginal Economic Policy Research, Australian National University
- Associate Professor Jane Williamson, Macquarie University
- Kerryn Wilmot, Institute for Sustainable Futures

Photo credits

The EPA is on a journey to inclusiveness of Aboriginal people and cultures and notes the names of traditional Country may be contestable and should not be regarded as fact and has been used to demonstrate EPAs commitment.

- **Front Cover:** Tim Johnson, Pink flannel flower, Murramarang National Park, Yuin Country
- **About the Report:** Roger Laird, Harrington sandbar, Harrington, Biripi Country
- **Key Findings:** Pauline Choppin, Plant with water drops, Warrumbungles, Gamilaroi, Wiradjuri and Weilwan Country
- **Drivers:** istock image, Pitt Street shops, Sydney, Gadigal Country
- **Human Settlement:** istock image, Suburb from above, Sydney, Gadigal Country
- **Climate and Air:** Kevin Dodds, Misty town and hills, Tumut valley, Walgalu/Wolgalu, Wiradjuri, and Ngungawal Country
- **Land:** Claudia Abbott, Green hills, Megalong Valley, Dharug and Gundungurra Country
- **Biodiversity:** Jennifer O'Meara, Green and gold bell frog, Sydney Olympic Park, Wangal Country
- **Water and Marine:** Simon Walsh. Marshes, Boulder Beach, Nyangbul Bundjalung Country
- **Appendix:** Sarah Winter, Waterfall, Great Otway National Park, Gulidjan and Gadubanud people

Key Findings

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Key Findings

Key Findings in State of the Environment 2021

The 2021 report looks at 22 environmental topics across six broad themes covering *Drivers*, *Human Settlement*, *Climate and Air*, *Land*, *Biodiversity* and *Water and Marine.* The report shows population growth and human activity have influenced air and water quality, ecosystems and threatened species.

Key findings in this SoE report include:

- Air quality is generally good, drinking water quality has been maintained at a high quality and the recreational water quality of our beaches continues to be good.
- The overall rate of greenhouse gas emissions has fallen 17% since 2005.
- The proportion of electricity generated from renewable resources has grown steadily from about 16% in 2017 to 19% in 2020. Growth in renewables (solar and wind power) has more than doubled over the past five years to 2020.
- The NSW economy is now predominantly services based and is therefore less reliant on the consumption of natural resources. There is clear evidence that carbon emissions have been decoupling from economic growth over an extended period of time and that growth in the economy is not being achieved at the expense of the environment.
- The NSW Government's *Waste Less, Recycle More* program has continued to be effective in managing waste, with littering down and new recycling facilities opening for problem wastes.
- About 9.6% of NSW is conserved in the public reserve system. The rate of new reservations has increased markedly, with around 305,000 ha being added to reserves since 2018. Joint management agreements are in place with Aboriginal traditional owners across about 30% of the parks estate.

Ongoing Challenges

Many of the challenges reported in previous SoE reports remain in the 2021 report findings. These include:

- The growing population of NSW continues to exert pressure on the environment, although there has been a temporary respite due to reduced activity and human caused disturbance during the COVID-19 pandemic. Innovative ways to use our natural resources more sustainably and to protect fragile ecosystems must continue to be found.
- The effects of climate change are already evident, but these will become broader and intensify in the future.
- The extreme weather conditions, drought and floods of the recent reporting period (2017–2021) put pressure on water resources and infrastructure in regional areas, cities and towns.
- The number of species listed as threatened in NSW continues to rise. These species are at the greatest risk from threats including vegetation clearing, the spread of invasive species and the mounting impacts of climate change.
- NSW is still heavily dependent on non-renewable sources of energy such as coal for power generation. Transport has become established as the largest (and fastest growing) sector for energy use.
- The condition of most native vegetation continues to deteriorate. Since the Black Summer fires of 2019, 62% of vegetation in the fire zone is under pressure from too much burning.
- The state's major inland river systems continue to be affected by water extraction, altered river flows, loss of connectivity and catchment changes such as altered land use and vegetation clearing. These affect water availability, river health and ecosystem integrity.
- Our love of coastal living and recreation continues to put pressure on the condition of coastal estuaries and lakes.

Key Responses

The NSW Government undertook a number of significant environmental reforms during the reporting period. The responses to major environmental issues are described under each topic (go to theme page and select topic). Some key responses include:

- The ***Net Zero Plan Stage 1: 2020–2030*** was released in March 2020, which provides the foundation for NSW Government action on climate change over the next decade. Emissions in 2030 are projected to fall be 47–52% lower than 2005 levels under the current policy settings. Policies under the net zero plan are also being delivered as part of the NSW Electricity Infrastructure Roadmap, the Electric Vehicle Strategy and the NSW Waste and Sustainable Materials Strategy 2041.
- The NSW Water Strategy was launched in September 2021. This strategy proposes more than 40 actions across seven priority areas, focused on improving the security, reliability, quality and resilience of the state's water resources. A key action of the strategy is investing over $500 million over the next eight years to help local water utilities reduce risks in urban water systems through the Safe and Secure Water Program.
- $175 million has been allocated to the S***aving our Species*** (SoS) program for the 10 years to 2026. The number of plants and animals and communities being managed under the SoS program is steadily rising, with 465 projects in 2018–19 covering roughly 40% of all listed entities (species, populations or communities).
- $240 million has been allocated over five years to support a greater commitment to long-term conservation of biodiversity on private land.
- The NSW Bushfire Inquiry was instigated following the Black Summer fires. All 76 recommendations were accepted by the NSW Government and around $460 million in funding allocated to their implementation, including for new bushfire risk management plans, increased hazard reduction works, enhanced rapid response capacity, improved bushfire modelling and upgraded fire trails.

Drivers

Drivers

The key drivers of human induced change to the environment are the economy and a growing population.

Introduction to Drivers

The first theme of the report describes the key drivers of human-induced change in the environment: population growth and economic trends. While these drivers lead to a cumulative build-up of threats and pressures on the environment, their effects are diffuse and manifested through a multitude of pathways, making it difficult to directly attribute changes in the environment to their effects.

The population of NSW generally continues to grow, despite a slowdown (and possible temporary reversal) due to the COVID-19 pandemic. Trends in population growth, settlement patterns and residential densities are described in the Population topic.

Achieving sustainable economic growth requires an understanding of the relationship between the economy and the environment. Trends in economic growth and the interaction between the economy and resource consumption, waste production and environmental disturbance are discussed in the Economic activity and the environment topic, along with new economic instruments and accounting systems that will enhance environmental management and decision-making.

In this report:

- The population of NSW is expected to reach 10.57 million people by 2041 with most growth in Greater Sydney. Population growth is the main driver of environmental issues.
- Since 1990, the NSW economy has grown by 2.4% a year and has shifted over time from a resource-intensive industry base to being 70% services-based.
- Between 2010 and 2019, carbon emissions fell by 13% while the economy grew by 26%, indicating a decoupling of carbon emissions from economic growth.

Aboriginal Perspectives

As the NSW environment faces increasing pressures due to economic trends and a growing population, decision-makers need to work with Aboriginal people, whose knowledge, cultures and practices can help shape a more sustainable environment.

As one of the largest landowners in NSW, Aboriginal people and organisations are well placed to provide input on future social and development planning tools and concepts for regional growth areas that maximise positive environmental and social outcomes and protect open spaces, as well as reducing negative environmental impacts from intensive development in major cities.

Many Aboriginal services have a regional focus for delivery and planning. Careful development of future regional growth areas can help reduce impacts in major centres with Aboriginal communities leading development and growth in these areas.

Population

Population growth is a key driver of changes to the environment caused by humans.

NSW's population is expected to reach

10.57 million

people by 2041

Greater Sydney's population was

5.02 million

people as at June 2020

People per sq km in NSW

7.4%

increase between 2015 and 2020

The NSW population grew by

550,000

people from 2015 to 2020

The NSW population has continued to increase at an annual average growth rate of 1.4% between 2015 and 2020.

Why population growth is a driver of environmental change

Population growth can be a significant driver of environmental impacts. In NSW, a rising population accompanied by growing urbanisation has led to greater demand for housing, land, energy, water, consumer products and transport services, and can increase energy, water and resource use, and the generation of waste and emissions.

Status and Trends

By June 2020, 8.17 million people were living in NSW, 61% of whom resided in Greater Sydney. Over the five-year period from June 2015 to June 2020, the state's population grew by more than 550,000 people. However, the rate of growth has started to slow.

Spotlight figure 1 shows population growth rising at a steady rate between 2010 and 2016, with a peak in 2016–17 (coinciding with a peak in the number of overseas students studying in NSW) and growth at a slower rate between 2017 and 2020.

Population density in NSW has also risen. In June 2020, there were an average of 10.2 people per square kilometre – a 7.4% rise since 2015. Across Greater Sydney, the average density reached almost 480 people per square kilometre – 41 more than in 2015.

By 2041, the NSW population is expected to grow to 10.57 million with most of the increase in Greater Sydney. The challenge will be to manage projected population growth alongside environment protection and conservation, and maintain liveability.

Spotlight figure 1: Population growth in NSW, Greater Sydney* and regional NSW 2009–20

Notes:
* Greater Sydney extends from Hawkesbury River in the north to Royal National Park in the south and includes the Blue Mountains, Wollondilly and Hawkesbury local government areas in the west. The historic results have been updated to reflect the definition of Greater Sydney as not including the Central Coast.
** 2019 figures are revised ABS estimates and subject to change.
^ 2020 figures are preliminary ABS estimates and subject to change.

Source:
ABS 2020a; calculations by DPIE

Pressures

Over the past 40 years, natural population increases have been fairly stable while overseas migration has been a significant contributor to growth. However, during the closure of international borders due to the COVID-19 pandemic, overseas migration was temporarily not a major driver of population growth. The 2021 NSW Budget forecast negative population growth for the state of –0.1% in 2021–22, before a gradual rise to 1.2% in 2024–25.

Response

The NSW Government has developed long-term plans for Greater Sydney and regional NSW. The plans aim to provide for sustainable and resilient development with a balanced approach to the use of land and water resources, while enhancing liveability and protecting the natural environment.

Other strategies for reducing environmental impacts of urbanisation and a growing population include the Waste and Sustainable Materials Strategy , the Sydney Green Grid framework for enhancing quality of open space, Future Transport 2056 , NSW Government's Net Zero Plan and the NSW Water Strategy .

Related topics: Energy Consumption | Transport | Urban Water Supply | Waste and Recycling

Economic Activity and the Environment

The health of the NSW economy is strongly linked to the condition of the environment and natural resources, although the economy is becoming less resource-intensive.

Carbon emissions

Carbon emissions fell by **13%** while NSW GSP grew by **26%** between 2010 and 2019

Service-based economy

~ 70%

of the NSW economy is service-based

A steady reduction in resource dependency and lower carbon emissions from energy production are two areas where economic growth is not being achieved at the expense of the environment.

Why economic activity and the environment are important

Over the past 30 years, the NSW economy has been shifting from a resource-intensive industry base to a service-based economy that has reduced environmental impacts.

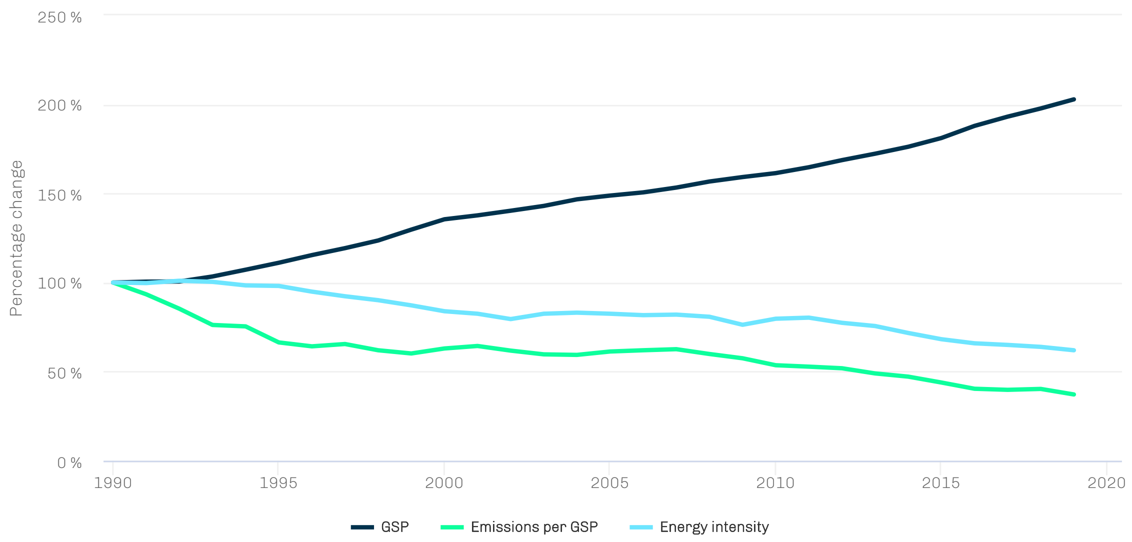
Environmental-economic accounts, which supplement conventional economic accounts, can enhance decision-making by enabling environmental factors to be considered in decisions that have traditionally been based on economic factors alone.

Status and Trends

Since 1990, the NSW economy has grown by almost 2.4% per annum. Gross State Product (GSP) has increased in real terms by about $23,400 per capita over the same period. Carbon emissions fell by 13% from 156,594 kilo tonnes (kt) to 136,579 kilo tonnes (kt), while the NSW GSP grew by 26% between 2010 and 2019. Around 70% of the NSW economy is service-based, becoming less resource-intensive.

The decrease in emissions in the 1990's was largely due to having avoided primary forest clearing, with the land sector going from a significant source of emissions in 1990 to a net sink of carbon that decade. Emissions from stationary energy and transport and re-clearing of land for agriculture continued to increase until about a decade ago. Emission reduction from electricity generation, mining fugitives, waste and net sequestration by the land sector contributed to emission reductions over the past decade, although transport emissions continue to increase.

Spotlight figure 2: Relative change in NSW economic, emission and energy intensity 1990–2019



Source:
ABS 2020a (cat. no. 5220.0), Science, energy and Resources, National Greenhouse Accounts 2019 and Australian Energy Statistics, Table F

The **Spotlight figure 2** shows how economic performance (measured as GSP), carbon emissions intensity and energy intensity (both measured in tonnes per dollar of GSP) have changed relative to 1990 levels. Relative to economic activity, overall carbon emission and energy intensity has steadily declined since 1990, indicative of a decoupling between emissions and economic growth.

The trends over the past decade indicate reductions in the carbon emissions intensity of the NSW economy. These reductions are based on the emissions intensity of stationary energy decreasing due to improved power generation efficiencies, an increase in the share of renewable energy, greater energy efficiency and fuel switching.

Pressures

The impacts of processing and use of resources, the production of goods and services, transport and waste generation, including greenhouse gas emissions, are central to how economic activity generates environmental pressures. Decoupling environmental pressures from economic growth is critical to creating a sustainable future.

Responses

The NSW Government uses various economic tools to manage its environmental resources, including cost-benefit analysis, market-based instruments and program evaluations.

Economic instruments, such as levies or taxes, subsidies, tradeable permits and performance-based regulatory charges, use market-based responses rather than traditional regulatory approaches to offer a more flexible way to meet environmental quality objectives. A major initiative that relies on a market-based scheme is the container deposit scheme Return and Earn.

Related topics: Population | Energy Consumption | Waste and Recycling

Human Settlement

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Human Settlement

Human settlement is our most heavily modified and intensively used environment and presents specific challenges in the use of resources and services and the management of pollution and waste.

Introduction to Human Settlement

The Human Settlements theme addresses issues that arise in the urban environment in which most of the people of NSW live, including energy use, transport patterns, urban water use, management of waste and recycling and contaminated sites.

The growth in population and the economy described in the Drivers theme leads to the consumption of energy, water and land resources and the generation of waste. The production and use of energy has been identified as the largest source of greenhouse gas emissions in NSW, with electricity generation and transport being responsible for most of these emissions. Energy production and use is described in the Energy Consumption topic, while trends in the use of public and private transport are discussed in Transport.

Communities, industry and agriculture all require access to reliable sources of water. Drinking water quality and patterns of potable water use are described in the Urban Water Supply topic. Trends in waste generation, recycling and litter prevention are covered in Waste and Recycling, while management of legacy pollution of land and groundwater is outlined in the Contaminated Sites topic.

In this report:

- Energy consumption per capita in the NSW and the ACT decreased by 3.2% from 2017 to 2019 while the share of renewable energy sources in the NSW electricity supply reached 19% in 2020, a rise of 3% since 2017.
- In contrast, energy use for transport continues to rise at a steady rate, together with transport-related emissions.
- Litter has dropped by 43% over the past six years while the percentage of waste diverted for recycling has increased slightly.
- Sustained efforts have seen the number of notified and regulated contaminated sites, and the number of sites remediated grow.
- Water use per person per day in NSW has been stable since 2009, but pressure from population growth and weather events continues.

Aboriginal Perspectives

Country is everywhere, including within human and urban environments. It is living and breathing underneath all the buildings and connected to Aboriginal people through stories and culture. Aboriginal people still hold a strong responsibility to care for these places. For people to be healthy, the urban environments we live in need to be healthy too. From the beginning, Country has sustained Aboriginal peoples and Aboriginal peoples have sustained Country. The whole landscape, including all animals, plants and soils, were cared for and used sustainably according to stories and culture.

The arrival of Europeans brought many changes for Aboriginal people, the landscape and ways of life. Aboriginal people were excluded from planning decisions and most now live in heavily modified and intensively used environments that face many challenges.

As these places face increasing pressures, there is a need to work with Aboriginal people and recognise cities and urban environments as Country too. Aboriginal people's knowledge, cultures and practices can help shape healthy urban and human environments across NSW. The responsibility to care for Country and nourish our human settlements is on all of us.

Energy Consumption

As NSW moves from fossil fuels to renewable energy sources, the aim is to connect communities to reliable and affordable energy while reaching net zero carbon emissions by 2050.

Energy consumption decreased by

↓ 2%

in NSW and the ACT between 2010 and 2019

Renewable energy sources shared

19%

of total energy generation in NSW and the ACT in 2019–20

Transport remains the biggest energy user, representing

47%

of total energy use in NSW and the ACT in 2018–19

Energy consumption per capita in NSW and the ACT decreased by

↓ 3.2%

between 2017 and 2019

Energy consumption decreased by 2% from 1,169 to 1,142 petajoules (PJ) between 2010 and 2019 and per capita consumption decreased by 3.2% between 2017–19.

Of the 19% of electricity supplied by renewable sources, solar and wind combined provided 14% and hydro 3%. The transport sector remained the biggest energy user at 47% of the total energy use in NSW and the ACT.

Why energy consumption is important

The percentage of renewable energy in the NSW electricity supply is increasing. Between 2015 and 2020 the amount of wind and solar energy in NSW electricity generation more than doubled, partly due to generation from rooftop solar panels and large-scale solar and wind farms. NSW is one of the leading states in adding renewable energy to the electricity market.

Four out of the five coal-fired power stations supplying around three-quarters of the state's electricity are scheduled to close in the next 15 years. We are moving towards a two-way energy system where more consumers are installing their own rooftop solar systems and exporting energy back to the grid. Communities are looking to new local renewable energy technologies and models, such as trading energy and sharing solar energy with their neighbours.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Total NSW non-renewable energy consumption	POOR	Stable	✓✓✓
Transport sector use of non-renewable energy	POOR	Stable	✓✓✓
Renewable electricity generation in NSW	MODERATE	Getting better	✓✓✓
Per capita residential energy consumption	MODERATE	Getting better	✓✓✓

Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

In 2019–20, 81% of electricity in NSW came from non-renewable sources such as oil, coal and gas. This was a 7% decline since the 2018 State of the Environment report.

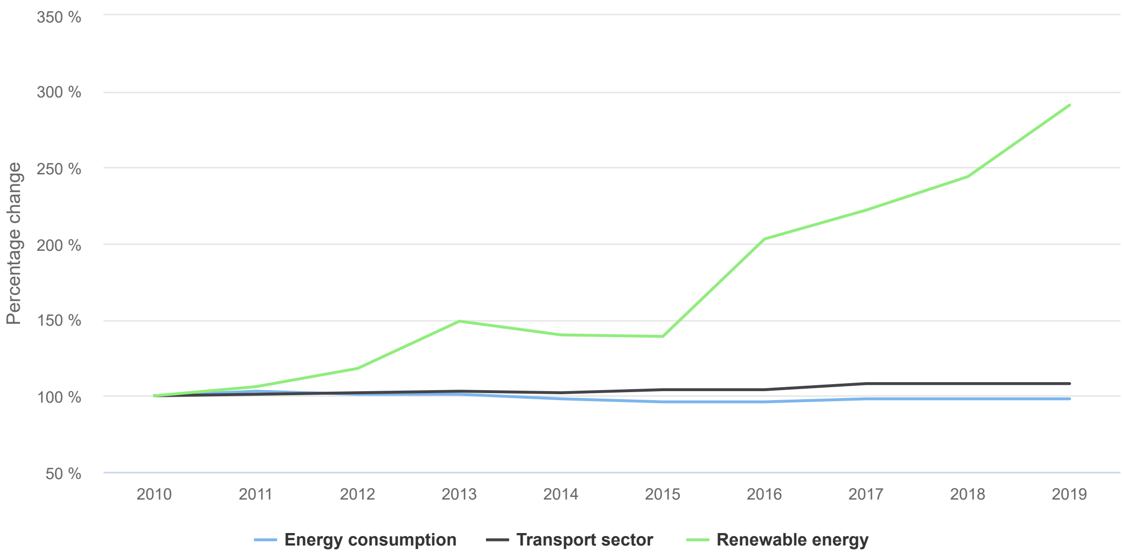
From June 2017 to June 2020, total NSW and ACT electricity generation remained stable with a slight increase of 0.5% as the population continued to grow, while electricity consumption per capita declined by about 6%. The Gross State Product (GSP), which experienced above trend growth for the four years to 2018–19, contracted by 0.7% in 2019–20, likely due to impacts of COVID-19. However, the economy has since rebounded, growing by 2.4% from June 2020 to June 2021. Since then, the state has experienced a faster than expected rebound in economic activity and continues to see a strong recovery from the pandemic-driven collapse in the middle of 2020.

In 2018–19, the transport sector used almost half (47%) of the total energy used in NSW and the ACT – up from 43% in 2008–09.

The industrial sector used 33% of energy, with the residential and commercial sectors accounting for 11% and 9% respectively.

Electric vehicles (EV) – which both use and store energy – will become increasingly common. Currently, the sale of EVs is low (about 0.8% of new vehicle sales) but is projected to increase rapidly, with two million EVs expected on Australian roads by the mid-2030s.

Spotlight figure 3: Measures of energy consumption, transport sector energy use and renewable energy source



Source:
Derived from Department of the Environment and Energy, Australian Energy Statistics, Table O, June 2021, Table F, October 2020

The **Spotlight figure 3** shows the change between 2010–19 in energy consumption, energy use by the transport sector and the contribution of renewable energy sources to total energy demand. Total energy consumption generally decreased between 2010–19 with slight fluctuation, while the transport sector share of energy use slightly increased by 4%.

The contribution of renewable energy sources to the state's total electricity generation increased substantially between 2015–19.

Pressures

The electricity grid was designed to operate as a one-way power delivery system through big energy generators, such as coal-fired power stations, delivering electricity via poles and wires to homes and businesses.

While electricity demand from the grid is expected to decline with increasing adoption of energy efficient appliances and machinery and rooftop solar and battery systems, it is expected to increase with the predicted growth in electric vehicle charging and related infrastructure.

However, the increase in rooftop solar photovoltaics (PV) sending power back into the grid and other distributed energy resources (DER), such as battery storage, electric vehicles and chargers and smart meters, means these behind the meter systems need a power system that can evolve and allow DER to be integrated. Demand for DER is predicted to grow; by 2050, it may contribute up to 45% of the nation's electricity generation capacity.

The current absence of an overarching national policy to guide the closure and replacement of coal-fired plants means states and territories must manage changes needed to properly coordinate energy generation, transmission, storage and investment.

Without national coordination, renewable energy generation and storage projects may not come online within planned timeframes, which could delay bringing clean energy into the grid.

Responses

The NSW Government continues to implement policies to encourage energy efficiency and use of renewable energy, such as the *Net Zero Plan Stage 1: 2020-2030* released in March 2020, and the Energy Security Safeguard that supports energy efficiency and reduction in demand at peak times. A range of clean energy initiatives is being delivered, such as the Emerging Energy Program to encourage investment in new generation technology and the Solar for Low Income Households program.

On 9 November 2020, the NSW Government released the Electricity Infrastructure Roadmap – a plan to transition the NSW electricity sector into one that is cheaper, cleaner and more reliable. The Roadmap is enabled by the *Electricity Infrastructure Investment Act 2020* and builds on the foundations of the 2019 Electricity Strategy and 2018 Transmission Infrastructure Strategy.

The roadmap will:

- deliver five Renewable Energy Zones (REZs) in Central-West Orana, New England, South West, Hunter-Central Coast and Illawarra regions
- attract up to $32 billion of private investment in regional energy infrastructure by 2030
- support the private sector to bring 12 gigawatts of renewable energy and 2 gigawatts of storage, such as pumped hydrogen, online
- help NSW deliver on its ambitions to reach net zero emissions by 2050
- reduce NSW electricity emissions by 90 million tonnes by 2030.

The NSW Government released the Electric Vehicle (EV) Strategy in June 2021, to help increase EV sales to more than 50% of new car sales by 2030–31 and help NSW achieve net zero emissions by 2050. EVs also present opportunities to increase the proportion of renewable energy used in the transport sector.

The NSW Government's Hydrogen Strategy, released on 13 October 2021, will provide up to $3 billion in incentives to develop the NSW green hydrogen industry, including:

- investing $70 million in hydrogen hubs in the Illawarra and Hunter regions
- providing exemptions from electricity network and government scheme charges
- expanding the scope of the Energy Security Safeguard to include hydrogen
- rolling out hydrogen refuelling stations.

Related topics: Economic Activity and the Environment | Population | Greenhouse Gas Emissions | Climate Change

Transport

The demand for transport has increased as the population grows. There has been a modal shift as people rethink their travel needs during the 2020–21 COVID-19 lockdown periods.

Average distance travelled per vehicle

12,000 km

in 2019–20

COVID-19 saw public transport patronage in Greater Sydney drop by

41.6%

in 2020–21, compared to 2018–19 levels

Transport sector greenhouse gas emissions increased by

16%

since 2005

Electric vehicles made up

0.1%

of light vehicles on NSW roads as at March 2021

The demand for transport has increased as the population grows. Total vehicle kilometres travelled for light duty vehicles, primarily passenger vehicles, peaked in 2018–19 and dropped due to COVID-19 travel restrictions. The transport sector (road, rail, ship and air) is one of the major contributors to greenhouse gas emissions and air pollution in NSW. Electric Vehicle (EV) sales are expected to increase as a result of the NSW Electric Vehicle Strategy which aims to make the state the easiest place to buy and use an EV in Australia. Electrifying the NSW fleet is integral in reaching net zero emissions by 2050.

Why transport is important

Transport plays a key role in the movement of people and goods. Transport assists participation in social life and fulfils an essential economic function. However, the construction and operation of transport infrastructure may have negative environmental impacts, including:

- reliance on non-renewable resources for fuel
- greenhouse gas emissions
- noise and air pollution
- land clearing.

Private modes of transport, such as cars, generally have greater impacts on the environment than trains, buses, ferries and light rail. This is because they are less efficient at moving large numbers of people and mostly rely on polluting energy sources. Walking and cycling are the most energy efficient transport modes. Current major public transport delivery programs will reduce fuel consumption and congestion and lead to lower environmental impacts caused by private cars.

Freight transport by rail can have a lower environmental impact than moving freight by road because it is more efficient at carrying larger volumes of goods. Environment protection licences held by rail freight operators and rail infrastructure owners help manage environmental impacts such as noise.

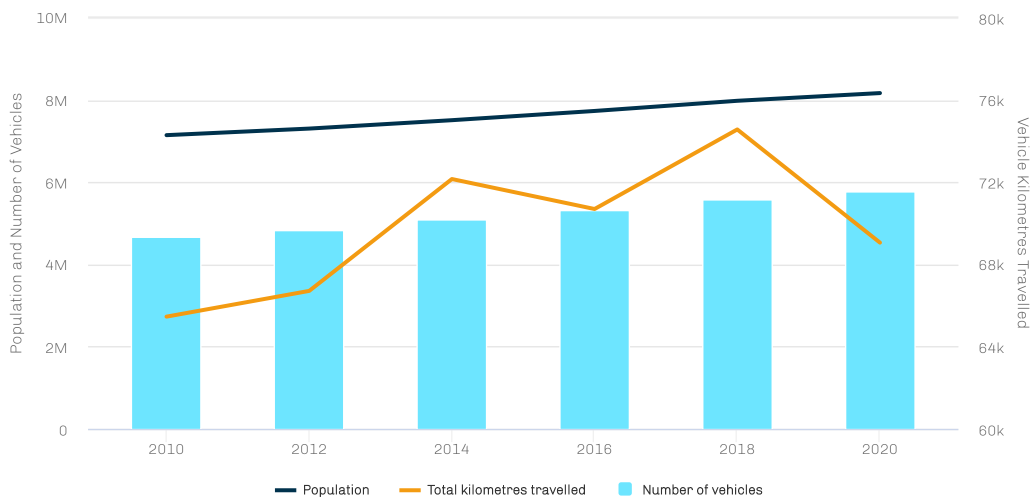
NSW indicators			
Indicator and status		Environmental trend	Information reliability
Vehicle kilometres travelled (total)	POOR	Stable	✓✓✓
Vehicle kilometres travelled (per person)	MODERATE	Stable	✓✓✓
Public transport use overall trips	GOOD	Getting better	✓✓✓
Percentage of electric vehicles of the NSW car fleet	POOR	Getting better	✓✓✓

Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

The total distance travelled by motor vehicles in NSW increased by 13% in the eight-year period between 2009–10 and 2017–18 and then dipped 10% during 2019–20 because of statewide COVID-19 restrictions on travel (ABS 2020b). Heavy truck vehicle kilometres travelled (VKT) increased 8% between 2017–18 and 2019–20 while passenger vehicle VKT decreased by 16%. In this time, NSW's population grew by 12.5% (ABS 2021a). (see **Spotlight figure 4**).

Spotlight figure 4: NSW total number of registered vehicles, population and vehicle kilometres travelled 2009–10 to 2019–20



Notes:
Terms and symbols used above are defined in How to use the report.

Source:
ABS 2008, 2010, 2020b

In 2019–20, around 6.2 million Greater Sydney residents made 18.6 million trips by all modes of transport on an average weekday – around three trips per person per day. Private motor vehicles remained the dominant mode of transport in NSW, accounting for 68% of all trips on an average weekday by Sydney residents and over 80% of trips by Hunter and Illawarra residents (TfNSW 2021a).

Transport emissions are currently the second largest component of NSW greenhouse gas emissions. Since 1990, transport emissions have increased from 19Mt to 28 Mt (DISER 2021a), with 2019 emissions 48% higher than 1990 levels (Adapt NSW 2021). This is an average increase in transport emissions of 1.65% per year. This reflects activity increases across transport modes due to population and economic growth. Petrol and diesel-fuelled vehicles are the main sources of oxides of nitrogen (NOx) emissions in Greater Sydney and the second largest source of population exposure to fine particles (Broome et al 2020). Other potential environmental impacts include noise pollution and fragmentation of ecosystems.

Pressures

The NSW population is expected to grow to 10.57 million by 2041, which without government action will lead to more vehicles on the roads and more demand for public transport. In spite of the projected increase in VKT, the strong reduction in vehicle emission rates due to tightening national vehicle emission standards has resulted in significant reductions in total fleet emissions to date, and these reductions are projected to continue over the next 10–20 years (EPA 2018). However, due to the contribution of non-exhaust particle emissions from road brake and tyre wear, total particle emissions will begin to increase from around 2026. Together with increasing population and population density, total population exposure to transport fine particle emissions is likely to increase without the rapid uptake of zero-emission vehicles and improvement in transport efficiency.

Urban sprawl leads to greater reliance on private vehicles. Construction of new roads can have significant impacts on wildlife and can lead to a direct loss of mature trees and canopy, which in turn exacerbates the urban heat island effect (Landcom 2020). Tyres and brake linings, petrol and oil deposits are a major source of heavy metals which can be washed into the stormwater systems during rain, eventually polluting waterways.

Ballast water, sewage, and wastes from international shipping vessels have environmental impacts on our coastal ecosystems.

Responses

A range of transport infrastructure service and technology initiatives are being delivered under *Future Transport 2056* which aims to encourage travel by public and active transport (such as walking and cycling), rather than by private car, which can help reduce traffic congestion and greenhouse gas emissions. These initiatives aim to increase the proportion of electric vehicles in the state. The NSW Electric Vehicle Strategy is the State government's plan to accelerate the NSW vehicle fleet of the future. The State government's Future Energy Strategy commits to securing energy needs from sustainable sources, supporting the transition of the transport sector to net zero emissions by 2050. For example, the electrified rail network was moved to renewable energy in mid-2021 and planning is also under way for the transition of the full NSW bus fleet of over 8,000 buses to zero emissions buses.

The environmental impacts of transport can be lessened by reducing the distance people need to travel to workplaces and essential facilities. *Future Transport 2056: Greater Sydney services and Infrastructure Plan* (TfNSW 2018) sets out a vision for achieving this by shifting from one central business district to a metropolis of three cities: The Eastern Harbour City, the Central River City and the Western Parkland City. The aim is for people to more conveniently access jobs and services by travel to one of these cities within 30 minutes from home.

Strategies to manage environmental impacts of road and related infrastructure are part of project planning, design, construction, operation and maintenance. Strategies include minimising the use of non-renewable resources, managing erosion and sediment during construction works, protecting biodiversity via planning approvals and conditions, implementing additional wildlife protection features, such as fauna fencing and fauna crossings (Biosis 2016) and reducing energy use and greenhouse gas emissions through LED traffic lights.

Related topics: Climate Change| Energy Consumption | Greenhouse Gas Emissions | Population

Urban Water Supply

A high-quality and secure water supply is essential to sustain communities and support economic growth.

Summary

Drinking water quality

100%

compliance with water quality guidelines for the last three years

Water use per person per day (Greater Sydney)

276 litres

stable overall since 2009

Annual water consumption

43% reduction

in regional NSW since 2005–06 through water efficiency measures

Water supply

~50

NSW town and city water supplies at risk of failure in 2019–20 due to drought

Climate change and more intense droughts are increasing risks to the water security of NSW cities and towns. Increasing the proportion of rainfall independent water supply and implementing programs to improve water efficiency and reduce system leakage are key strategies for improving the resilience of water systems and water security.

Why urban water supply systems are important

A sustainable supply of water to urban areas is fundamental to the health, wellbeing and economic growth of communities, and to maintaining the health of aquatic systems.

While households in NSW generally use 16% or less of all water consumed in the state (ABS 2020), the implications of failing to provide a secure supply of water to communities are significant.

Water supplies to urban areas are under constant pressure from growing populations and variable weather conditions, including droughts and flooding, which are being exacerbated by climate change. Urban water supply systems must be managed to ensure different and changing water needs for households, businesses, communities and the environment can be met now and in the future.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Proportion of the metropolitan and regional water supply meeting national guidelines	GOOD	Getting better	✓✓✓
Total and per person water consumption for metropolitan and regional centres	MODERATE	Getting better	✓✓✓
Water recycling - major utilities	MODERATE	Stable	✓✓✓
Water recycling - local water utilities	MODERATE	Getting better	✓✓✓

Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

For the last 10 years (2010–11 to 2019–20), the average volume of residential water supplied per connected property has been relatively stable for Sydney Water ranging between 189 kilolitres per property (kL/prop) and 215 kL/prop, and Hunter Water ranging between 156p and 181 kL/prop. For regional water utilities, the volume supplied has shown a greater variability over the same period, ranging between 167 and 238 kL/prop).

Overall demand for water decreased substantially during the Millennium Drought (from 2002–2009) in Greater Sydney. Subsequently, demand has slowly increased in line with the city's population growth, except for the period between mid-2019 to the end of 2020 when water restrictions were in place to manage water supplies during the drought period. Overall demand stayed relatively constant in the Lower Hunter and regional centres due to decreased consumption per person.

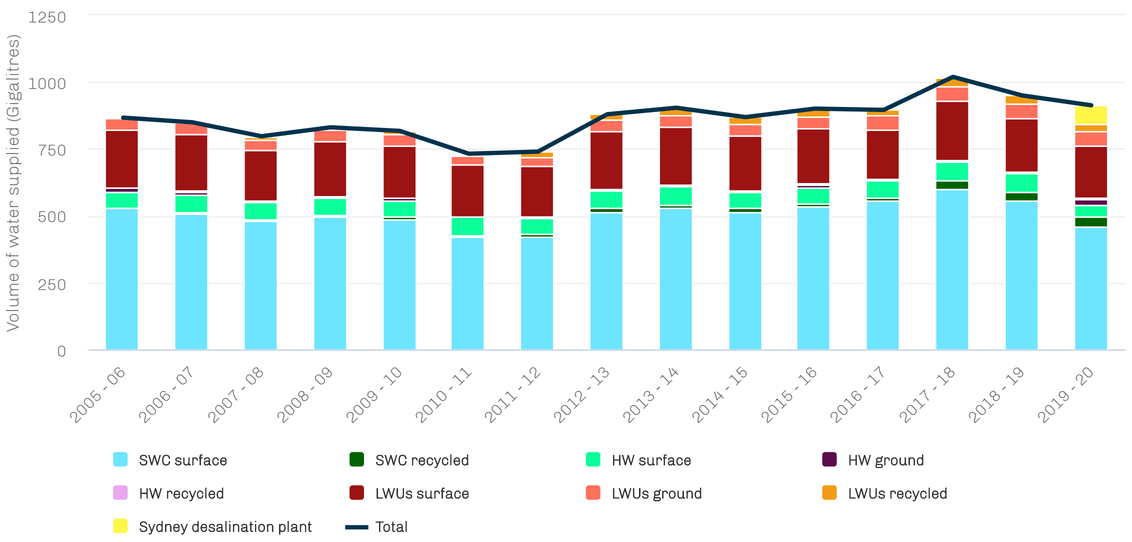
The 2017–20 drought saw water supplies across cities and towns under significant stress. The situation prompted the State and local governments to rethink their approaches to water security and to escalate their investment in water infrastructure.

At the beginning of 2020, 100% of NSW was in drought, resulting in a drop in the average volume of residential water supplied per connected property compared to the previous year. There was a -5.5% drop for Sydney Water, -11% for Hunter Water and -14.5% for the median of all the local water utilities in regional NSW. Sydney's residential water use was 12% lower in 2019–20 than in 2017–18 following the introduction of voluntary and enforced drought response measures between February 2019 and December 2020.

Spotlight figure 6 tracks the volumes of water taken from different sources since 2005–06, including:

- supply reservoirs
- in-stream sources
- groundwater aquifers
- recycled water schemes
- the Sydney desalination plant.

Spotlight figure 6: Urban water supplied, by source



Notes:

Includes Sydney Water Corporation (SWC), Hunter Water (HW) and all local water utilities (LWUs) in regional NSW, and the Sydney desalination plant.

Source:

DPIE 2021a | BOM 2018 | BOM 2020

Pressures

Australia is the driest inhabited continent in the world and has a highly variable climate. It faces difficulties with changing rainfall patterns and drought as a result of natural climate variability and climate change. NSW is already experiencing trends of higher average temperatures and reduced cool season rainfall. There are indications from climate models that drought conditions may become more frequent and severe.

The recent drought has highlighted the vulnerability of metropolitan and regional water supplies across NSW. Between July 2017 and February 2020, Greater Sydney's water storages were impacted by one of the worst droughts on record. Sydney's water storages declined rapidly over two and a half years, reducing dam levels to around 40% of capacity. Some inland storage levels fell to as low as 10%. This rate of decline in water storages had not been experienced in the historical record and was not anticipated in the 2017 Metropolitan Water Plan which was prepared to secure water for Greater Sydney. It demonstrated that storages can deplete rapidly in a severe drought and highlighted the risks associated with relying mainly on dam levels to trigger key decisions and drought response measures.

Poor water quality affects its suitability for human use, increases the cost of treatment for supply and may affect the health of aquatic ecosystems. Stormwater runoff, wastewater discharge and development in catchment areas are a significant risk to water quality and can alter habitats for species and ecological communities that depend on healthy water. Bushfires in catchments also pose a risk to water quality and impact on water supplies. Dry periods followed by extreme wet weather and high flows bring additional hazards to catchments.

Responses

The NSW Government has developed a 20-year *NSW Water Strategy* as part of a suite of long-term strategies being developed to maintain the resilience of the state's water services and resources over the coming decades. This statewide, high-level strategy works with 12 regional water strategies and two metropolitan water strategies, the Greater Sydney Water Strategy and the Lower Hunter Water Security Plan .

These strategies are setting the direction for and informing the best mix of water-related policy, planning and infrastructure investment decisions over the next 20 to 40 years. They aim to balance different and changing water needs and make sure that households, businesses, towns and cities, communities and the environment have access to the right amount of water for the right purpose at the right times.

Related topics: Population | Water Resources | River Health | Groundwater | Climate Change

Waste and Recycling

As NSW transitions to a circular economy, we need to transform the way we use and manage our resources to make them as productive as possible and reduce the environmental and human health impacts of waste.

Per person waste generation

↑ 9%

increase since 2015–16 to 2.65 tonnes per year

Total waste generation

↑ 17%

increase since 2015–16 to 21.9 million tonnes per year

Recycling

64%

of waste diverted for recycling in 2019–20

Litter volume

↓ 43%

decrease against the 2013–14 benchmark

Since 2015–16, the total amount of waste recycled and disposed of has increased. The amount recycled has increased at a higher rate than waste disposed of. Construction and demolition (C&D) waste accounts for the most waste disposed and recycled. Between 2013–14 and 2019–20, the volume of litter in NSW decreased by 43%.

Why waste and recycling is important

Waste and littering can have widespread and damaging effects on the environment and human health. As consumption grows, so does the amount of waste that needs to be effectively managed. Waste can vary in scale and type, from littered cigarette butts and single-use plastics to discarded food and garden organics, illegal dumping of unwanted household items, construction and demolition waste and hazardous waste materials, including asbestos and chemical contaminants.

Recycling and reuse of discarded items and materials is an effective way of managing some of this waste (if waste streams are non-hazardous) and also contributes to a circular economy. Community awareness of recycling options has steadily increased over the last few years as more and more waste is successfully diverted from landfill.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Total waste generation	**MODERATE**	Getting worse	✓✓✓
Per person waste generation	**MODERATE**	Getting worse	✓✓✓
Total and per person solid waste disposal	**GOOD**	Getting worse	✓✓✓
Total and per person solid waste recycled	**GOOD**	Getting better	✓✓✓
Litter items per 1,000 m^2	**GOOD**	Getting better	✓✓✓

Notes:
Terms and symbols used above are defined in About this report.

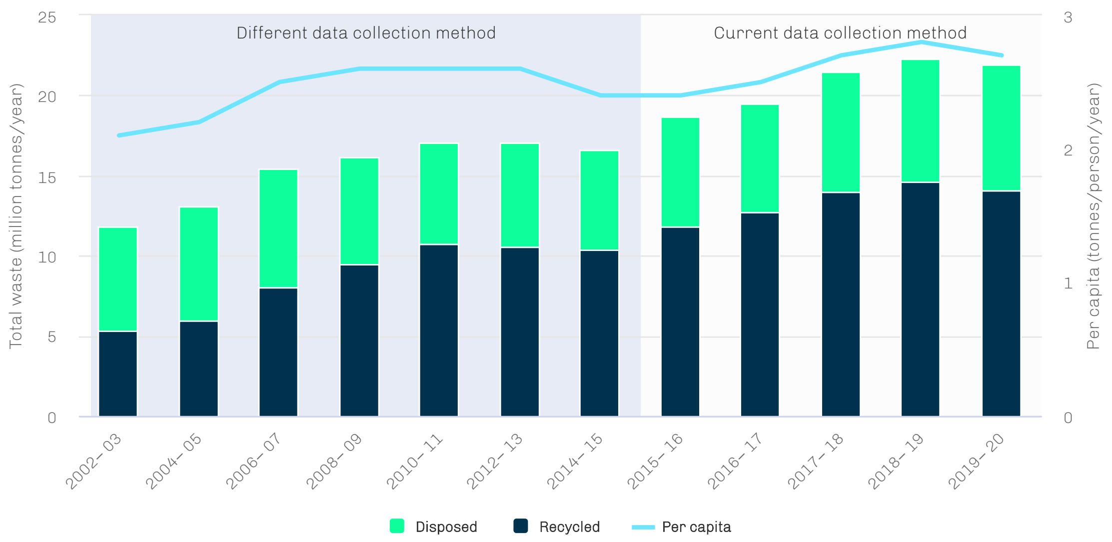
In 2019–20, the proportion of waste diverted for recycling was 64%, an increase of one percent over five years. The construction and demolition (C&D) waste stream accounted for the largest proportion of both waste generated and waste recycled in 2019–20: 12.5 million tonnes of C&D waste were generated, of which 9.6 million tonnes were recycled. The volume of C&D waste has fallen by 9.5% since 2018–19.

The volume of litter in NSW decreased by 43% in six years and the number of littered items decreased by 19%. The largest category of littered items in volume were drink bottles and cans at 35% of the total in 2020. However, since the start of *Return and Earn* scheme in 2017, the volume of litter from these eligible containers has decreased by 52%.

In 2019–20, household waste was the most common type of illegally dumped material at 62% of all incidents recorded in EPA's Report Illegal Dumping online system. Since 2016–17, the total number of recorded illegal dumping incidents increased by 15% from 16,802 to 19,355 reports. However, the number of incidents involving illegal dumping of asbestos has been decreasing since 2016–17.

An estimated 2 million tonnes of hazardous waste was generated in NSW in 2019–20. Asbestos and contaminated soils accounted for 72% of this. Approximately 3% of hazardous waste was exported interstate from NSW in 2019–20. This included zinc compounds moved to SA for recovery, oil to Queensland for recycling, and a range of other waste types to mainly Queensland and Victoria for destruction, disposal, recovery, recycling and reuse. Reasons for interstate export included economics, waste infrastructure gaps and proximity to suitable waste facilities outside NSW.

Spotlight figure 7: Total waste disposed and recycled and waste generated per capita – 2002–03 to 2018–19



Source:
EPA Waste and Resource Reporting Portal (WARRP) data 2021

Spotlight figure 7 shows that between 2016 and 2020, total waste disposed of in NSW steadily increased, while the total tonnes recycled grew at a much higher rate. The total waste disposed of increased from 6.9 million tonnes in 2015–16 to 7.8 million tonnes in 2019–20. In the same period, the total waste recycled increased from 11.8 million tonnes to 14.1 million tonnes. Since 2015, the overall recycling rate remained relatively unchanged.

The volume of litter in NSW decreased by 43% in the six years to 2019–20, while the number of littered items also fell by 19%. Drink bottles and cans remained the largest category of littered items by volume at 35% of the total in 2020. However, the trend has been down since the start of the *Return and Earn* container deposit scheme in 2017. As at September 2021, over 6.1 billion containers had been returned through the scheme's network and over 2 billion returned from kerbside recycling, resulting in a 52% reduction in drink container litter.

In 2019–20, household waste was the most common type of illegally dumped material at 62% of all incidents reported to the EPA's Illegal Dumping Online system. Since 2016–17, the total number of recorded illegal dumping incidents increased by 15% to 19,355 reports. However, the number of incidents involving illegal dumping of asbestos has decreased since 2016–17.

An estimated 2 million tonnes of hazardous waste were generated in NSW in 2019–20. Asbestos and contaminated soils accounted for 72% of this. Approximately 3% of hazardous waste was exported interstate from NSW in 2019–20. Reasons for interstate export included cost efficiency, waste infrastructure gaps and proximity to suitable waste facilities outside NSW.

Pressures

Over the next 20 years, the volume of waste generated in NSW annually is expected to grow from 21 million tonnes in 2021 to nearly 34 million tonnes by 2041. This is due to the continued increase in population and economic growth. Managing high volumes of waste each year is challenging and over time will require more efficient and suitable infrastructure boosted by advances in technology. Facilities for the storage, treatment and disposal of hazardous waste, landfill and liquid waste are approaching capacity.

NSW has also joined an agreement to ban the export of unprocessed plastic, paper, glass and tyres in a bid to move towards a circular economy, increasing the need for adequate infrastructure and processing on shore.

Responses

The NSW Government is committed to the state becoming a circular economy and fulfilling the targets and actions set by the *National Waste Policy*.

The *NSW Waste and Sustainable Materials Strategy 2041* sets out a 20-year vision for reducing waste and changing how the NSW economy produces, consumes and recycles products and materials. The vision and actions in the *NSW Plastics Action Plan* are a key component of this and address each step of the plastics life cycle.

After achieving the Premier's Priority Target to reduce litter by 40% by 2020, a new state target to cut litter items by 60% by 2030 has been announced. NSW will also be using new, more robust measurement tools for tracking terrestrial and marine litter. Anti-littering campaigns such as *Don't be a Tosser!* and new programs for reducing cigarette butt and marine litter will focus on changing public attitudes and behaviour. The *Return and Earn* container deposit scheme has resulted in over 556,000 tonnes of materials being recycled since 2017 and a 52% reduction in drink container.

In alignment with *Net Zero Plan Stage 1: 2020–2030*, the NSW Government has set a goal of net zero emissions from organic waste to landfill by 2030. This includes targets for all NSW food-generating businesses to have a source-separated service for organic waste by 2025 and all households by 2030.

Related topics: Population | Economic Activity and the Environment

Contaminated Sites

Contaminated land can threaten human health, the environment and the Aboriginal cultural values of the land, limit land use and increase development costs. It is typically found on sites of past industrial or agricultural use or where chemicals are stored, such as at service stations.

Remediated sites

30

EPA-regulated significantly contaminated sites were remediated from 2018–20

Notified contaminated sites

139

contaminated sites were notified to the EPA from 2018–20

Petroleum or service station sites

53%

of sites the EPA declared as significantly contaminated from 2018–20 are petroleum industry or service station sites

Regulated sites

36

The EPA declared 36 new sites as significantly contaminated from 2018–20

Between 2018–20, the number of notified and regulated contaminated sites steadily increased. This was matched by an increase in the number of remediated sites. The petroleum industry and service stations represented the largest number of sites declared significantly contaminated by the EPA.

Why managing contaminated land is important

Industrial, agricultural and other commercial activities can result in the discharge of substances to land which contaminate it by accumulating in soil, sediments, groundwater, surface water or air. Some of these substances can remain in the environment for a long time, have an adverse impact on human health or the environment and degrade the productive use of land or water.

Contaminated land must be managed to ensure there are no unacceptable risks to human health or the environment from the contamination and to ensure that land is suitable for its current or approved use.

The SoE Aboriginal Peoples Knowledge Group has noted that legacy land contamination can be an issue on Crown land transferred to Aboriginal people under the *Aboriginal Land Rights Act 1983*. This is a concern among Aboriginal communities and land holders.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Number of regulated contaminated sites*	MODERATE	Getting better	✓✓✓
Number of regulated contaminated sites remediated**	MODERATE	Getting better	✓✓✓

Notes:
Terms and symbols used above are defined in About this report.

*An increase in the number of contaminated sites being regulated is a positive indicator because it means there has been an increase in regulatory oversight of contamination.

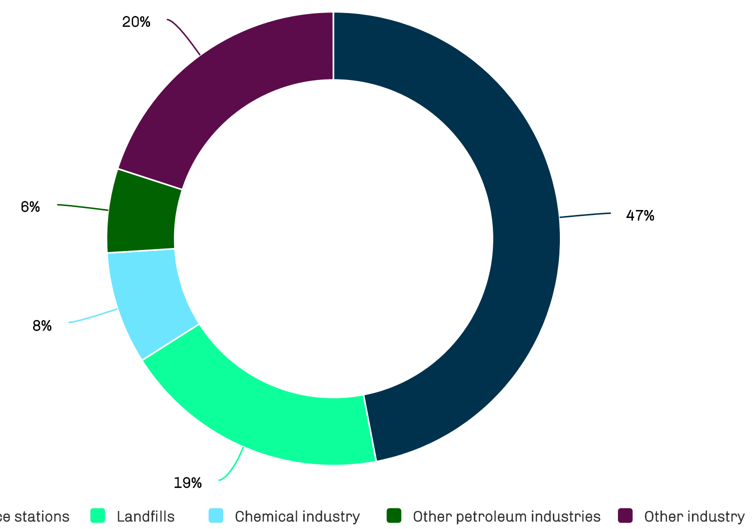
**An increase in the number of regulated contaminated sites remediated is a positive indicator because a remediated site is no longer significantly contaminated, that is, the number of significantly contaminated sites has decreased.

Status and Trends

As at December 2020, 1,805 contaminated sites had been notified to the EPA, of which 388 required regulation. Of these regulated sites, 185 have been remediated.

Between January 2018 and December 2020, 139 new sites were notified to the EPA, of which 36 were significantly contaminated. Service stations and other petroleum industries accounted for 53% of the new sites (see **Spotlight figure 9**).

Spotlight figure 9: Number of newly regulated sites between January 2018 and December 2020 under the Contaminated Land Management Act by contamination type



Source:
EPA data 2021

Pressures

Sites in the major coastal cities, particularly Sydney, are remediated more quickly than in rural areas as there is more demand for land in cities for residential and commercial development. However, the extent of contamination beneath the surface of the land is often difficult to identify and manage, so characterising the risks and costs of remediation can be challenging and time consuming.

Responses

The EPA manages land declared as 'significantly contaminated' under the *Contaminated Land Management Act 1997*. Land that is not declared as 'significantly contaminated' is regulated by planning authorities, including local councils, who generally deal with the contamination under their planning and development processes.

To respond to the contamination challenges from service stations and petroleum industries, the NSW Government introduced the Protection of the Environment Operations (Underground Petroleum Storage Systems) Regulation in 2008, which required operators of UPSS to install tanks and pipes for underground fuel systems in accordance with industry best practice, and to monitor those systems for leaks.

When the UPSS Regulation was first made, the EPA was declared to be the Appropriate Regulatory Authority (ARA) for all UPSS-related matters. On 1 September 2019 local councils resumed responsibility for regulating most UPSS sites in their local areas, which are mostly service stations. The EPA continues to publish technical and guideline documents to support management and clean-up of these sites.

In March 2021, the use of PFAS firefighting foam was banned in most situations to reduce its impact on the environment. However, it can still be used when responding to catastrophic fires by relevant authorities and exempt entities. The Protection of the Environment Operations (General) Amendment (PFAS Firefighting Foam) Regulation 2021, was published in March 2021 and is the first step in the NSW Government's commitment to gradually replace PFAS-containing firefighting foams with appropriate alternatives.

The EPA is leading an investigation program to assess the legacy of PFAS use across NSW, focusing on sites where large quantities of PFAS were used in the past. As at June 2021, the EPA had conducted 914 investigations.

DPIE Crown Lands endeavours to identify and appropriately deal with contamination issues on land prior to determination of any Aboriginal land claim or transfer of ownership under the *Aboriginal Land Rights Act 1983*. Given the size and nature of the Crown estate, it is not always possible to resolve all issues prior to transfer, especially with illegal dumping which can occur at unknown locations. Since 2016 DPIE Crown Lands has adopted a Contaminated Land Management Strategy to help reduce occurrence of this issue and, where necessary, remediate contaminated sites to an extent consistent with their existing purpose or use. The onus to remediate or clean up transferred Crown Land (under the Aboriginal Land Rights Act) does not transfer with the land, foremost remaining with the person responsible for the contamination where land is determined to be significantly contaminated under the Contaminated Land Management Act.

Climate and Air

soe.epa.nsw.gov.au

Climate and Air

The emissions that we release into the atmosphere affect the quality of the air we breathe and may build up in the atmosphere contributing to climate change.

Introduction to Climate and Air

The topics in this theme describe air quality in NSW and the effects of carbon emissions on our climate, as well as how climate change already affects many aspects of our environment.

Energy generation, industrial and manufacturing processes and transport give rise to emissions of air pollutants and greenhouse gases. Ensuring that air quality remains safe and healthy is essential to provide a clean living environment and maintain the wellbeing of the NSW population. While air quality is generally good in NSW, the levels of the major pollutants and the issues that can arise in some situations are discussed in the Air Quality topic.

The build-up of greenhouse gases in the atmosphere since the start of the industrial age is causing our climate to change with potentially serious consequences. The overall levels and trends in greenhouse gas emissions in NSW are described in the Greenhouse Gas Emissions topic. The changes in current temperature and weather patterns in NSW and future projections of change are discussed in Climate Change, as well as the impacts of these changes on the environment more generally.

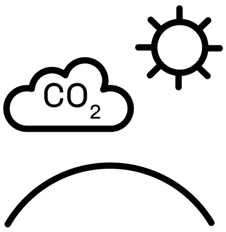
In this report:

- The effects of climate change, especially increases in temperature, are already being felt and will become more intense in the future.
- NSW greenhouse gas emissions in 2018–19 were 136.6 million tonnes of carbon dioxide equivalent (CO_2-e), which is 17% lower than in 2005.
- By 2030, emissions are projected to be 47–52% lower than 2005 levels with current policies implemented.
- NSW air quality is generally good, although particle pollution soared in 2019 due to the continuing drought and unprecedented and extensive bushfires.

Aboriginal Perspectives

Over tens of thousands of years, Aboriginal people and cultures have been able to live effectively with changing climates. Intergenerational knowledge handed down through vibrant cultures has meant Aboriginal peoples have intimate and detailed knowledges of their respective Country and climates. This knowledge has also resulted in effective understanding and management of place, including seasonal calendars which relate to specific lands and waters that guide Aboriginal people on climate matters.

Aboriginal communities and peoples are, and continue to grow as, major landowners, developers and caretakers across NSW. Decision-makers need to recognise and work with these opportunities to further develop outcomes that Aboriginal peoples are presenting in their land management practices, including those that contribute to a reduced carbon footprint.



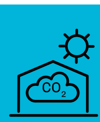
Greenhouse Gas Emissions

Although generating and using energy from non-renewable sources in NSW continues to produce greenhouse gas emissions, their levels are decreasing. With current policies implemented, emissions by 2030 are projected to be 47–52% lower than 2005 levels.

Greenhouse gas emissions in NSW were

136.6 million tonnes

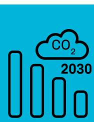
of CO_2-e in 2019, representing 26% of Australia's total emissions



After peaking in 2007, greenhouse gas emissions in 2019 in NSW were

↓ 17%

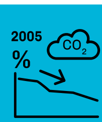
lower than in 2005



Greenhouse gas emissions in NSW are projected to be

78.9–87.6 million tonnes

of CO_2-e in 2030



Greenhouse gas emissions in 2030 are projected to be

↓ 47–52%

lower than in 2005

In 2018–19, NSW recorded net greenhouse gas emissions of 136.6 million tonnes carbon dioxide equivalent (CO_2-e). Emissions peaked in 2007 and were 17% lower in 2019 than in 2005. Emissions have declined across most economic sectors, with the exception of transport, which has undergone almost uninterrupted growth in emissions.

By 2030, with current NSW Government policies implemented, greenhouse gas emissions are projected to fall to 78.9–87.6 million tonnes CO_2-e, a 47–52% reduction from 2005 levels. Electricity generation emissions are forecast to reduce significantly as a result of an increased share of renewable energy as the state's coal-fired power stations are retired.

Why managing greenhouse gas emissions is important

Burning and extracting fossil fuels and certain chemical processes release greenhouse gases which build up in the atmosphere causing extra heat to be trapped by the atmosphere and resulting in global warming. Human activities are estimated to account for global warming of between 0.8°C and 1.3°C above pre-industrial levels. Unless deep reductions in greenhouse gas emissions occur, global warming will exceed 1.5–2°C during the 21st century (IPCC 2021).

Managing the amount of greenhouse gas emissions released and sequestered will be vital to the ongoing health of our state's ecosystems and viability of key economic sectors.

The impacts of increased greenhouse gas concentrations and climate change to NSW are explored in the Climate Change topic.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Atmospheric concentrations of greenhouse gases	POOR	Getting worse	✓✓✓
Annual NSW greenhouse gas emissions	POOR	Getting better	✓✓✓
Annual NSW per capita greenhouse gas emissions	POOR	Getting better	✓✓✓

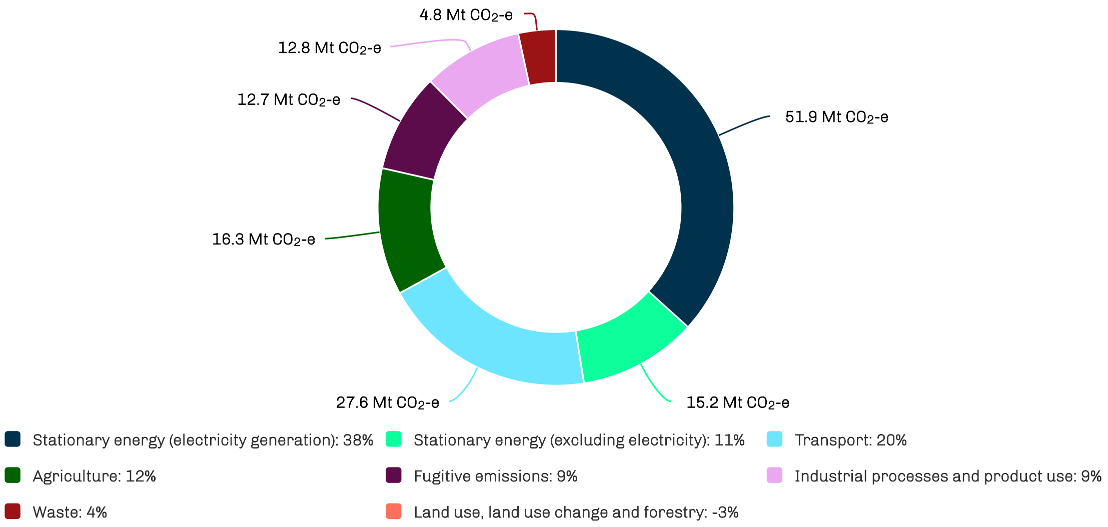
Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

In 2018–19, per capita NSW greenhouse gas emissions, including land use, land-use change and forestry, were 16.9 tonnes CO_2-e. While this is below the national average of 20.9 tonnes per capita, both are much higher than the global per capita average of 6.6 tonnes last recorded in 2014.

Stationary energy, primarily from electricity generation, is the largest source of greenhouse gas emissions in NSW at 38%, followed by emissions from transport (20%), agriculture (12%), industrial processes and product use (9%) and fugitive emissions from coal and gas (9%) (**Spotlight figure 5**). The land use, land-use change and forestry sector is currently a carbon 'sink' as it stores more carbon than it emits and thus reduces the state's emissions by 3%.

Spotlight figure 5: NSW greenhouse gas emissions by UNFCCC key categories, 2018–2019



Notes:
The sum of percentages shown above will be greater than 100% as values are rounded and it does not show removals from the land use, land-use change and forestry sectors, which equate to approximately 3% of emissions (4.7Mt CO_2-e).

Source:
Australian Department of Industry, Science, Energy and Resources (DISER 2021f)

By 2030, emissions from electricity generation are expected to fall substantially as initiatives to increase renewable energy take effect. These initiatives are projected to reduce NSW greenhouse gas emissions by 23–31%. Transport is projected to become the largest source (33–36%) of NSW emissions by that time, with emission reductions from the uptake of light duty electric vehicles and the electrification of buses offset by increasing emissions from aviation and trucks. Emissions from agriculture will represent 18–20%, fugitive emissions from fuels 12–14% and industrial processes and product 9–10% of NSW emissions. Net carbon sequestration by the land sector is projected to increase, reducing NSW emissions by 8–9%.

Pressures

Economic activity and population growth are key drivers of greenhouse gas emissions. Most emissions are from energy use, transport, land clearing and agriculture.

Responses

The *Net Zero Plan Stage 1: 2020–2030* (DPIE 2020a) sets out the NSW Government's long-term objective to achieve net zero emissions by 2050. Base case trends in NSW emissions, and initiatives under the plan's first stage are projected to achieve a 47–52% reduction in emissions by 2030, compared with 2005 levels as reported in the *Net Zero Plan Stage 1: 2020–2030 Implementation Update* (DPIE 2021f).

Related topics: Energy Consumption | Climate Change | Net Zero Plan Stage 1 2020–2030

Air Quality

Good air quality is essential for providing a clean environment and maintaining the health of the NSW population.

Particle concentrations in regional areas exceeded national standards up to

151 days a year

between 2018 and 2020

Ground level ozone in Sydney exceeded national standards up to

28 days a year

between 2018 and 2020 in Sydney

NSW air quality was generally good in 2018 and most of 2020. However, particle pollution soared in 2019 due to the continuing drought and unprecedented extensive bushfires. Concentrations of carbon monoxide, nitrogen dioxide, lead and sulfur dioxide generally complied with national air quality standards, but levels of particles and ozone pollution continued to be of concern.

Why managing air pollution is important

Air pollution is the release of particles and gases into the air that can adversely affect human health and the environment. Short-term exposure to elevated air pollutants worsens respiratory and cardiovascular problems and increases the risk of acute symptoms, hospitalisation and even death. Longer-term exposure can lead to chronic respiratory and cardiovascular disease and mortality and permanently affect lung development in children.

The impacts of air pollution can vary according to its source, location and the weather conditions. Pollution may spread over large areas and affect many people or it may be concentrated on communities at a smaller, more local scale. High levels of air pollution can cause severe health conditions, but even low levels of pollution that meet air quality standards can potentially harm those exposed over the long term. Vulnerable people, including the elderly, children and those with chronic health conditions, are generally the most affected.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Concentrations of ozone	MODERATE	Stable	✓✓✓
Concentrations of particles (PM_{10}*)	MODERATE	Stable	✓✓✓
Concentrations of particles ($PM_{2.5}$**)	MODERATE	Stable	✓✓✓
Concentrations of carbon monoxide	GOOD	Stable	✓✓✓
Concentrations of nitrogen dioxide	GOOD	Stable	✓✓✓
Concentrations of sulfur dioxide	GOOD	Stable	✓✓✓
Concentrations of lead	GOOD	Stable	✓✓

Notes:
Terms and symbols used above are defined in About this report.

* PM_{10} refers to particles which are 10 micrometres (10µm) or less in diameter.

** $PM_{2.5}$ refers to particles which are 2.5 micrometres (2.5µm) or less across.

Status and Trends

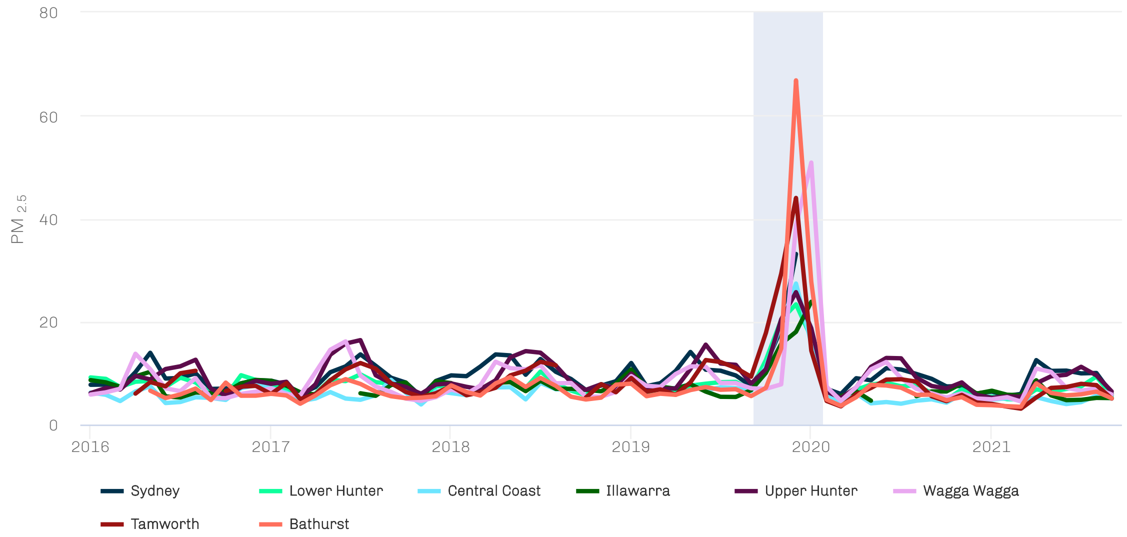
Smaller particles in the air are invisible to the naked eye and can be inhaled deep into the lungs. Two sizes of airborne particles are monitored: PM_{10} with particles 10 micrometres or less in diameter and even tinier $PM_{2.5}$ particles which are 2.5 micrometres or less across. Growing evidence about the adverse health impacts of these particles prompted a tightening of national air quality standards to better address this issue.

Particle pollution generally meets national air quality standards in Sydney, except when natural events such as bushfires or dust storms occur and during hazard reduction burns. Between 2018 and 2020, PM_{10} and $PM_{2.5}$ concentrations exceeded the national air quality standards on up to 58 days a year in Sydney and up to 151 days a year in regional areas of NSW. These maximum readings were largely due to dust storms and the 2019–20 'Black Summer' bushfires and were the highest in NSW since 1996.

Concentrations of ground-level ozone, a key component of photochemical smog, exceeded national air quality standards in Sydney on six or fewer days in 2018 and 2020 – similar to most years since 2010 – but climbed to a record 28 days in 2019. Nitrogen oxides and volatile organic compounds are the main precursors of ozone and they generally originate in emissions from industrial facilities, power stations and motor vehicle exhausts. The elevated ozone levels in 2019 reflected that year's warm dry weather and emissions from extensive bushfires.

The levels of other pollutants of potential concern, such as nitrogen dioxide and sulfur dioxide, are typically 25–75% lower than the national air quality standards across NSW.

Spotlight figure 8: Monthly average $PM_{2.5}$(fine particulate matter) levels over 5 years from select monitoring stations



Notes:
Plot band highlights the 2019–2020 bushfires. Monitoring stations with 5 years of data and representative of the region's air quality have been selected.

Source:
DPIE calculation from NEMP Air Quality monitoring stations.

Monthly average $PM_{2.5}$ (fine particulate matter) readings in **Spotlight figure 8** show that while on average NSW has good air quality, there are measurable impacts on air quality from:

- bushfires, notably the unprecedented Black Summer bushfires in late 2019 through to early 2020
- seasonal variability with higher concentrations in winter, from the use of wood heaters, agricultural burning, as well as the natural impact of less air movement during cooler months due to temperature inversions
- drought conditions in 2017 to 2020, where vegetation coverage was lower, and topsoil was more easily picked up by
- wind impact of longer term weather factors, such as improvements from mid-2020 onwards due to wetter conditions caused by La Nina.

Pressures

Everyday activities can affect air quality in NSW. The transport we use, how we heat our homes and the industries producing our goods and services – all generate a range of air pollutants that can threaten our health.

Exposure to hazardous levels of air pollution can be expected during extreme events, such as the increasing number of bushfires and dust storms. Climate change is likely to result in changes to more and different air pollution episodes, which could be characterised by high pollutant levels lasting up to several days extending over wider areas. Air quality in our cities is also under pressure from population and economic growth.

Responses

The NSW air quality monitoring network is the largest in Australia with more than 90 long-term stations, well in excess of the number recommended by the *National Environment Protection (Ambient Air Quality) Measure* .

The NSW Government regulates industry emissions to air and also monitors and delivers coal mine dust management compliance campaigns. These are to ensure open cut coal mines in the upper Hunter minimise particle emissions. Other campaigns include regulating the sale of wood heaters, supporting local councils in managing wood smoke from domestic wood heaters through periodic Wood Smoke Reduction Programs and providing community education materials.

The NSW Government also implements strategies such as the Summer Petrol Volatility Program and the Vapour Recovery Program to reduce petrol emissions from service stations. The national air quality standards for ozone were revised in 2021 to reflect health evidence and Australia's climate.

Air quality is also a key component of other government strategies. These include the Net Zero Plan, NSW Electricity Strategy, NSW Electric Vehicle Strategy, NSW Hydrogen Strategy, Greater Sydney Regional Plan - A Metropolis of Three Cities, NSW Freight and Ports Plan, Future Transport 2056 and NSW Electricity Infrastructure Roadmap. These strategies all include goals and actions to improve air quality. The government, through DPIE and the EPA, also conducts air quality research and modelling and advocates at the national level for improved air quality standards.

Related topics: Climate Change | Energy Consumption | Greenhouse Gas Emissions | Transport

Climate Change

The effects of climate change on the people and the environment of NSW are expected to become greater as warming continues.

Sea level rise

↑ 3.4mm

rise in sea level per year at Port Kembla tidal gauge since 1991, equating to a total increase in mean sea level of around 10 cm

Long-term rainfall trends

~15% decline

in April to October rainfall over southern NSW during the last 20 years (2000–19) relative to 1900–99, despite strong natural variability

Increase in temperature

↑ ~1.1°C

increase in mean NSW temperature from 1961–90 to 2011–20

Significant climate related risks to human and natural systems risk increase at

1.5°C

average global warming and above

The climate of NSW is changing due to global warming. The effects of climate change on the people and environment of NSW are expected to become more pronounced as the climate continues to change over this century.

Why climate change is important

Emissions of CO_2 and other greenhouse gases from human activity including power generation, industry, transport, land-use and land cover change, and agriculture, accumulate in the atmosphere, trapping heat and leading to global warming.

Without substantial, concerted action, climate change poses a major threat to humanity and most living systems on Earth. While impacts are being observed now, they will become more pronounced over time. Extreme events such as extreme heat, dangerous fire weather and heatwaves are projected to increase in duration, magnitude and frequency with impacts on communities and infrastructure.

In 2016, 194 nations (98%) signed the Paris Climate Agreement, which focuses on limiting global warming to well below 2°C and aims to limit warming to 1.5°C. Each country has pledged to make national contributions to reducing greenhouse gas emissions. However, concentrations are continuing to increase at rates that will increase temperatures beyond the

Paris Agreement targets. Cuts in emissions well beyond those pledged under the agreement will be necessary to meet the target. Even with global warming of 1.5°C, climate-related risks for human and natural systems will be higher than they are today (IPCC 2021). The extent of the impacts of climate change will ultimately be determined by the concerted actions taken by nations globally to reduce greenhouse gas emissions.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Annual mean temperature (present)	MODERATE	Getting worse	✓✓✓
Sea level rise (present)	MODERATE	Getting worse	✓✓✓
Rate of temperature warming	POOR	Stable	✓✓✓
Annual mean temperature (2070): projected outcomes	POOR	Getting worse	✓✓
Sea level rise (2070): projected outcomes	POOR	Getting worse	✓✓

Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

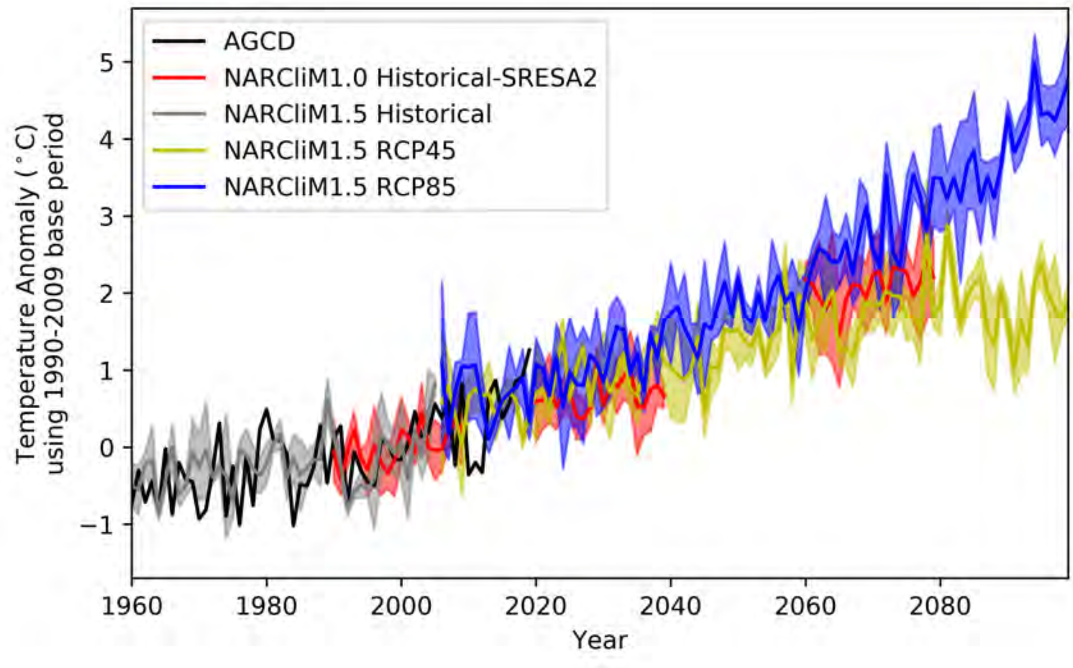
Globally, warming has increased by approximately 1.1°C since industrialisation (1850–1900). Based on current trajectories, global temperature will likely increase by approximately 1.5°C by around 2030. Exceeding this target will result in more serious and frequent heat extremes and bushfires, and fewer cold extremes.

In NSW, the mean temperature for 2011–2020 was about 1.1°C higher than late last century (1961–90), with 2018 and 2019 being the warmest years on record. Mean temperatures during 2020 in NSW were generally above average, with the exception of the state's south-west. Black Summer fires peaked in December 2019–January 2020, causing widespread destruction and prolonged poor air quality in Sydney and Canberra.

Other observed changes include increased seasonal variability in rainfall and increases in some extreme weather events such as heatwaves.

The changes to climate are expected to become more severe over time. Regional climate projections over NSW suggest that by 2070 mean temperature will have risen by a further 2.1°C relative to a 1990–2009 baseline period, with much larger increases in extreme temperatures (**Spotlight figure 21**).

Spotlight figure 21: Observed and projected changes in annual mean temperatures for NSW and the ACT



Notes:

Projected changes in annual mean temperatures use data from two generations of NARCliM regional climate simulations, NARCliM1.0 and NARCliM1.5. Together, these simulations are designed to complement each other and provide a range of plausible climate futures.

AGCD data is from http://www.bom.gov.au/climate/austmaps/about-agcd-maps.shtml0

Source:

DPIE NSW and ACT Regional Climate modelling (NARCliM) project. Adapted from Nishant et al. 2021, Figure 12.

Since the late 20th century, sea surface temperatures (SST) in the western Tasman Sea have increased by 0.2–0.5°C per decade. For the Sydney area, SST have increased by 0.2°C per decade since 1945.

The rate of sea level rise has nearly doubled. From an average rate of 1.7 mm per year during most of the 20th century, sea levels at the Port Kembla Baseline Sea Level Monitoring Station now indicate an average 3.4 mm increase per year since 1991. Globally, sea levels are expected to rise by a half to one metre by the end of the 21st century.

Pressures

The future effects of climate change will be extensive, including more extreme weather events, increasing coastal erosion and inundation and greater impacts on infrastructure, human health and wellbeing. The survival of many species and ecosystems, water availability, and the productivity of some agricultural systems will be affected.

Responses

Effective action to counteract the effects of climate change depends on concerted action globally. The extent of climate change impacts will be determined by mitigation and adaptation actions and the time taken to reduce greenhouse gas emissions.

The NSW Climate Change Policy Framework released in 2016 sets targets for NSW to achieve net zero emissions by 2050, become more resilient to a changing climate and adapt to climate change.

The AdaptNSW website provides guidance on implementing adaptation actions. Integrated Regional Vulnerability Assessments have been completed across NSW to identify regional areas where adaptation actions are needed.

The NSW and ACT Regional Climate Modelling project (NARCliM) (Evans et al. 2014, Nishant et al. 2021) provides high resolution projections of plausible future climate changes regionally for NSW and south-eastern Australia and has informed many of the projections in this chapter. NARCliM regional climate projections are available at the NSW Climate Data Portal .

Related topics: Economic Activity and the Environment | Energy Consumption | Greenhouse Gas Emissions | Transport

Land

Land

How our land is used and managed is the main determinant of its condition and the health of native species and ecosystems.

Introduction to Land

The topics in this theme describe the condition of our land and its ability to provide ecosystem services and suitable habitat for native species and ecosystems.

The natural environment is subject to disturbance from human uses of the land and associated land management practices. Managing the land sustainably and maintaining the quality of habitat for natural ecosystems and wildlife enhances their prospects for survival in the longer term. Fire is an integral part of the natural environment and essential to the growth and reproduction of many natural systems and Country, but altered fire regimes are a threat to the sustainability of ecosystems and species.

Healthy soils provide essential ecosystem services and the primary productivity that supports natural ecosystems and the economic prosperity of the state. The health of soils in NSW and recent changes in condition are described in the Soil Condition topic. Changes in the extent and condition of native vegetation and the quality of habitat it provides, as well as recent trends in clearing rates, are discussed in Native vegetation. The preservation of ecosystem,s and habitats is covered in the Protected Areas and Conservation topic. The impacts of fire and altered patterns of burning on the health of ecosystems and species, especially too much fire, are discussed in the Fire topic.

In this report:

- While native vegetation covers 69% of NSW, the ecological carrying capacity of this vegetation is estimated at just 31% of natural levels in the aftermath of the 2019–20 Black Summer fires.
- Since 2018, more than 300,000 hectares have been added to the public reserve system, which now covers around 9.6% of land in NSW.
- In contrast, permanent clearing of native woody vegetation in NSW has increased about three-fold since 2015 and stands at an average of 35,000 ha cleared each year. Permanent clearing of non-woody vegetation, such as native shrubs and ground covers, occurs at an even higher rate.
- Soil resources in NSW are generally in a moderate condition. Ongoing declines are mainly due to acidification caused by intensified land use, with the added recent hazard of wind erosion levels which has increased four-fold over the past three years due to prevailing weather conditions.
- The Black Summer fire season was the most severe ever recorded in NSW with about 5.5 million hectares burnt. It is estimated more than a billion animals were killed, burnt or displaced in NSW. Where fire history is available, an estimated 62% of vegetation is now under pressure from too much fire.

Aboriginal Perspectives

Everything is connected. How we use and care for the land/Country impacts on its health. Healthy land/Country means not only healthy plants, animals and ecosystems but also healthy people.

Country is more than a place. It is our soul and our identity. We speak about Country like we are speaking about a person, taking care of our lives in every aspect – spiritually, physically, emotionally, socially and culturally.

In 2021, NAIDOC invited the nation to 'heal Country!' – a call for stronger measures to recognise, protect and maintain all aspects of Aboriginal and Torres Strait Islander cultures and heritage. To understand the state of our environment is to understand what the environment means to Aboriginal people. Caring for Country is not just an ambition, it is Aboriginal Lore. From the beginning, Aboriginal people have protected Country. This has included the use of cultural burning, also known as fire-stick farming, which has helped to shape the biodiversity, ecology and character of our Country.

For generations, Aboriginal peoples have been calling for stronger action and to be a part of protecting all Country. To do this better and to learn requires understanding, recognition, respect and promotion of Aboriginal people's rights to culture and Country and working with Aboriginal peoples as partners in the development and implementation of policies and programs.

Aboriginal peoples have been caring for the land and Country from the beginning and they embrace the opportunity to teach the wider community about Aboriginal culture and land management practices. The combination of Aboriginal cultures and western sciences into all types of land management will enhance environmental outcomes.

The NSW *Our Place on Country Aboriginal Outcomes Strategy 2020–23* outlines ways to respectfully embed Aboriginal cultural knowledge and empower Aboriginal voices in decision-making. The strategy encourages working together to advocate for and celebrate the living history of Aboriginal communities that have existed within our state for thousands of generations.

In the spirit of NAIDOC in 2021, and in recognition of our people, we say heal Country, heal our nation.

Soil Condition

Healthy soil resources support natural biomes, provide essential ecosystem services and productivity that enable the agricultural industry to prosper.

Wind erosion

There was more than **400%** average increase in dust hours between 2017 and 2020 compared to the previous 10-year average

Loss of soil organic carbon

3.1%

of natural carbon stocks have been lost across NSW since 2006

Between 2017 and 2020, wind erosion was a major issue with significantly elevated dust levels and loss of topsoil arising from recent drought conditions across western and central NSW.

The main ongoing issues contributing to deterioration in soil condition and productivity across NSW are increasing acidification and the continuing decline of soil organic carbon in agricultural soils due to the intensification of land use.

Why soil condition is important

Soils make a significant contribution to the ecological integrity of the environment and economic prosperity of NSW. Healthy soils deliver essential ecosystem services, including:

- nutrient transformation and cycling
- water infiltration and filtering
- climate regulation through carbon storage and cycling
- providing habitat for biota
- supporting natural ecosystems
- enabling farming for food and resources.

Soil is a non-renewable resource, as its formation is an extremely slow process beyond human timeframes (Bui et al. 2010; Stockmann et al. 2014). Therefore, to maintain productivity and ecosystem services, soils must be managed sustainably to prevent them becoming degraded.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Soil pH (acidification)	MODERATE	Getting worse	✓✓

NSW indicators

Indicator and status		Environmental trend	Information reliability
Organic carbon	MODERATE	Getting worse	✓✓
Wind erosion	POOR	Getting worse	✓✓
Hillslope erosion	MODERATE	Stable	✓✓
Salinisation	MODERATE	Stable	✓✓
Acid sulfate soils	MODERATE	Getting better	✓✓

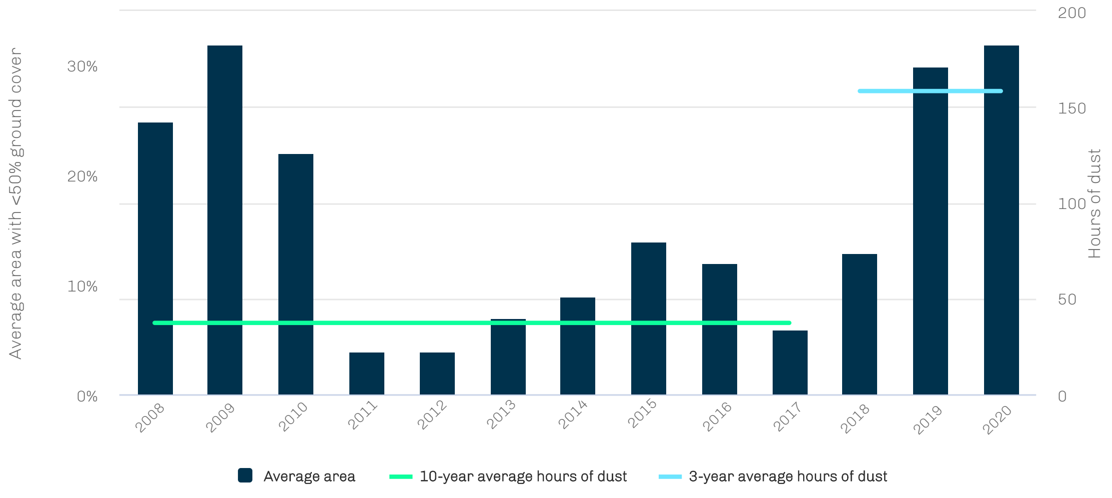
Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

The increasing intensity of land use, climate variability and extreme weather events, are the greatest risk factors in maintaining soil condition and the provision of ecosystem services.

Conservation farming practices introduced over recent decades, including the maintenance of groundcover vegetation and reduced tillage, are helping to mitigate erosion and declines in some soil condition parameters in the face of ongoing and increasing pressures.

Spotlight figure 10: Average dust hours and area with less than 50% total vegetation cover recorded at NSW DustWatch stations



Notes:
Years shown are financial years and so cover the 12 months ending 30 June of that year.

Source:
DustWatch data 2020

the Spotlight figure 10 shows dust hours recorded were 4.2 times the average levels of the previous 10 years and wind erosion worsened across NSW with negative impacts on soil loss and air quality.

The average area of less than 50% groundcover has increased from the previous 10-year average of 14% to 25% over the past three years, attributable to extreme climate conditions.

Pressures

While land management practices have generally improved, the pressure on soil condition continues due to the increasing intensity of land use across NSW. There is, therefore, a greater need to ensure that soils and land are managed sustainably and within their inherent physical capacity to handle a specific level of disturbance or use.

While soil may be managed sustainably with little risk of degradation in normal weather, the unpredictability and variability of severe weather events can rapidly reduce its capacity to absorb disturbance, leading to loss of soil condition and degradation.

Due to a changing climate, these conditions are likely to occur more frequently, leading to a greater focus on how to retain and manage groundcover.

Responses

Legislation and policies to regulate soil conservation and the clearing of native vegetation include the:

- *Soil Conservation Act 1938*
- *Local Land Services Act 2013*
- *Biodiversity Conservation Act 2016*

These laws aim to achieve a balance between land use and biodiversity conservation in NSW.

Policies for sustainable soil management in NSW include:

- *State Environmental Planning Policy (Rural Lands) 2008*
- the *Policy for Sustainable Agriculture in NSW* (NSW Agriculture 1998)

NSW is a signatory to the *National Soil Strategy* which provides a national framework for coordinated action on soil by governments, industry and stakeholders.

Eleven regional natural resource management bodies, under Local Land Services (LLS), are working with local farmers, landholders and communities, including Landcare groups, to develop strategies and programs to improve natural resource management and sustainable land use across NSW.

Farmers and landholders are also independently adopting improved land management practices, due to a greater awareness of, and commitment to, sustaining their operations and protecting environmental values.

Related topics: Climate Change | Native Vegetation

Native Vegetation

Maintaining native vegetation in good condition is critical to the survival of the species and ecosystems that depend on it.

Summary

Permanent clearing of woody vegetation

35,000 ha each year

on average from 2017 to 2019, compared to 13,000 ha on average each year from 2009 to 2015

Intact native vegetation cover in NSW

69%

comprising 50% woody vegetation and 19% non-woody native vegetation

Ecological condition of overall vegetation habitat

42%

2% decrease following the bush fires in 2020

Ecological carrying capacity of overall vegetation habitat

31%

2% decrease following the bush fires in 2020

Following the Black Summer bushfires it is estimated 31% of the ecological carrying capacity of native vegetation in NSW remains, compared to pre-European settlement. The rate of loss of vegetation in NSW due to clearing has steadily increased since 2015.

Why native vegetation matters

Native vegetation provides essential habitat for plant and animal species, and is an integral component of healthy, functioning ecosystems. For tens of thousands of years, First Nations peoples have been stewards of the natural landscape which helped to shape the biodiversity and character of our Country.

Clearing of native vegetation, and the destruction of habitat that is associated with it, has been identified as the single greatest threat to biodiversity in NSW (Coutts-Smith & Downey 2006).

NSW indicators

Indicator and status		Environmental trend	Information reliability
Permanent clearing rate for woody native vegetation	MODERATE	Getting worse	✓✓✓
Extent of native vegetation	MODERATE	Getting worse	✓✓✓
Condition of native vegetation	MODERATE	Getting worse	✓✓
Ecological carrying capacity	MODERATE	Getting worse	✓✓
Levels of pressure on the condition of native vegetation	MODERATE	Stable	✓

Notes:
Terms and symbols used above are defined in About this report

Status and Trends

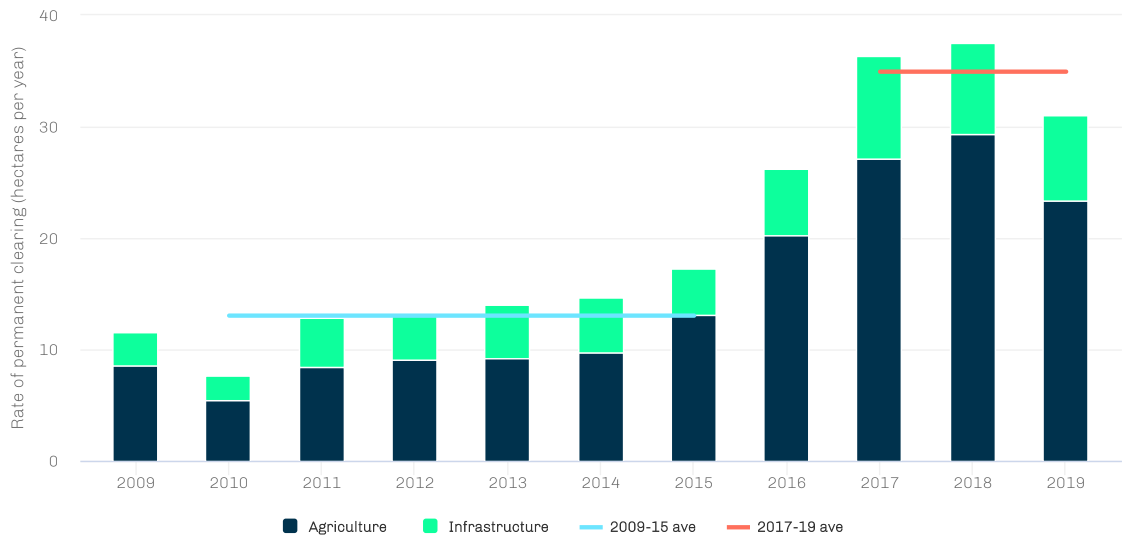
The state has 49.8% woody native vegetation cover and 19% non-woody vegetation cover in which the structure has not been substantially altered. Woody vegetation includes heathlands, forests, woodlands and shrublands higher than two metres. Non-woody vegetation includes grasses, small shrubs, herbs and groundcover. While structurally intact, vegetation condition across both woody and non-woody extents is declining largely due to the effects of different land uses and land management practices.

Habitats in National Parks and Wildlife (NPWS) reserves across the State remain relatively intact, with 63% of their original ecological carrying capacity remaining. Habitats in all other land tenures retain only 30% of their original ecological carrying capacity, but areas of native vegetation are also being protected through private land conservation.

The pattern of habitat loss and degradation varies between bioregions and across tenures. Habitat in the Australian Alps, South East Corner and NSW North Coast bioregions has remained the most intact relative to other bioregions with 53% to 62% of their original ecological carrying capacity remaining. Land has been used more intensively in the NSW South Western Slopes, Brigalow Belt South and Riverina bioregions, resulting in less remaining and more fragmented habitat relative to other bioregions, and therefore, less remaining ecological carrying capacity overall (15% to 25%).

The Black Summer bushfires of the spring and summer 2019–20 altered large areas of habitat for species and ecosystems in NSW. Following the fires in 2020, overall ecological condition and ecological carrying capacity for NSW both decreased by 2%, to 42% and 31% respectively. Within the immediate fire ground, ecological condition decreased from 72% in 2013 to 44%, a 39% reduction, while ecological carrying capacity decreased from 62% to 38%, a 24% reduction. The longer term impacts are still being assessed and the recovery process will continue for many years.

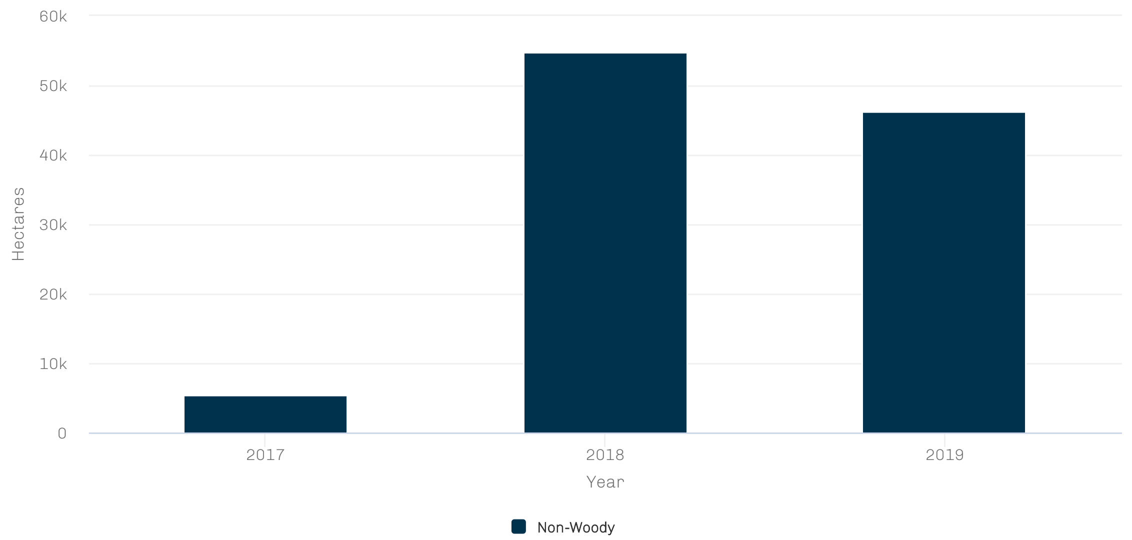
Spotlight figure 13a: Permanent clearing of woody vegetation each year in NSW 2009–2019



Notes:

Rate of permanently removal of woody vegetation from DPIE analysis of satellite imagery to classify landcover types. Satellite imagery used for this analysis was captured by SPOT and Sentinel 2 remote sensing.

Spotlight figure 13.b: Non-woody vegetation clearing on regulated land



Notes:

Regulated land is where authorisation may be required from Local Land Services for native vegetation clearing. This category makes up around 54% of land in NSW. The non-woody vegetation removal figures above depict only clearing that occurs on Category 2 regulated land. Additional clearing of non-woody vegetation, on excluded or category 1 exempt land, has not been included. Landholders also have a range of allowable clearing activities available to them for use without approval from Local Land Services.

Pressures

Land clearing is listed as a key threatening process under the *Biodiversity Conservation Act 2016*. The rate of permanent clearing of woody vegetation in NSW has been steadily increasing since 2015, with a slight decrease in 2019, the most recent reporting year. Precautions built into NSW legislation include limits on allowable land clearing, offset requirements, and government investment in private land conservation (see next section).

The average rate of permanent clearing over seven years from 2009 to 2015 was 13,028 hectares per year (Spotlight figure 13.1a). In area, 26,200 hectares of woody vegetation was permanently cleared in 2016, the year before the new regulatory framework (*Biodiversity Conservation Act 2016*) came into effect in August 2017. The subsequent rate of permanent clearing from 2017 to 2019 was 34,933 hectares per year on average. Some of this included agricultural clearing approved under the previous native vegetation framework.

In 2019, 46,300 hectares of non-woody vegetation were cleared on regulated land, and 54,760 hectares in 2018 (Spotlight figure 13.1b).

Land use changes and intensifying land use place significant pressure on the condition of remnant native vegetation. Other pressures on condition, which are likely to remain for the foreseeable future, include long-term effects of fragmentation, increasing threats from invasive species and worsening elements of climate change including impacts of fires. Native forest harvesting results in temporary vegetation change, but is not classified as land clearing because there is an acknowledgment that all harvested areas must be regrown.

Responses

Programs of restoration and revegetation are occurring at local and regional levels to enhance the extent and condition of native vegetation. However, there is a net loss of vegetation because these programs are not restoring native vegetation at the rate of permanent clearing.

In 2017, the NSW Government introduced the land management and biodiversity conservation framework, which included the new *Biodiversity Conservation Act 2016* and amendments to the *Local Land Services Act 2013*. A new biodiversity offsets framework was also introduced. The Biodiversity Offsets Scheme establishes a framework to avoid, minimise and offset the impacts on biodiversity from development or clearing. The NSW Biodiversity Values Map identifies land with high biodiversity value that is particularly sensitive to impacts from development and clearing.

The Biodiversity Offsets Scheme and the Biodiversity Conservation Trust's private land conservation program have been introduced to encourage landholders to protect and conserve biodiversity and vegetation habitat on private land. The *Biodiversity Conservation Act 2016* also enables the Minister for the Environment to declare Areas of Outstanding Biodiversity Value. These are special areas that contain irreplaceable biodiversity values that are important to the whole of NSW, Australia or globally.

The pressures that affect vegetation condition are likely to continue in the foreseeable future and the Government will conduct a statutory five-year review of the land management and biodiversity conservation framework commencing in 2022. The Government's ongoing monitoring of land clearing rates, the Biodiversity Indicator Program and the five-year review are opportunities to monitor the impacts and risks of land clearing on biodiversity.

Related topics: River Health | Wetlands | Coastal, Estuarine and Marine Ecosystems

Protected Areas and Conservation

Protected areas of land and water in original or nearly original natural condition are the foundation of nature conservation in NSW.

Private land conservation

4%

of privately-owned land in NSW was managed for conservation in 2020–21

Terrestrial reserve system comprehensiveness

39%

of bioregions met targets for adequate representation of each regional ecosystem in public reserves in 2020–21

Terrestrial reserve system representativeness

47%

of bio-subregions met targets for the adequate representation of each regional ecosystem in public reserves in 2020–21

Public conservation reserves

9.6%

of NSW was formally protected in terrestrial public reserves in 2020–21

The NSW terrestrial reserve system covers about 7.59 million hectares or approximately 9.6% of the state. Around 6.4% of the NSW marine estate is protected within sanctuary zones of marine protected areas.

Why protected areas and conservation are important

The state's terrestrial reserve system has a substantial network of protected areas, such as national parks and flora reserves, that:

- conserve representative areas of habitats and ecosystems, plant and animal species and significant geological features and landforms
- protect significant Aboriginal and European cultural heritage
- provide opportunities for recreation and education.

A network of marine-protected areas span the NSW marine estate which conserve marine biodiversity and maintain ecosystem integrity and function. They also:

- enable resources to be used in an ecologically sustainable manner
- enable parks and reserves to be used for scientific research and education
- provide opportunities for public appreciation and enjoyment
- support Aboriginal cultural uses.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Area of terrestrial reserve system	MODERATE	Getting better	✓✓✓
Growth in off-reserve protection	MODERATE	Getting better	✓✓
Protected areas jointly managed or owned by Aboriginal people	MODERATE	Getting better	✓✓✓
Proportion of marine waters protected in marine parks and reserves	MODERATE	Stable	✓✓✓

Notes:
Terms and symbols used above are explained in About this report.

Status and Trends

Since the NSW State of the Environment 2018, there were 84 additions to NPWS parks and reserves, by June 2021, totalling 304,629 hectares. The comprehensiveness and representativeness of formal protected areas in NSW is improving with significant additions of underrepresented areas, but some bioregions and vegetation classes are below target levels, particularly in the central and western regions.

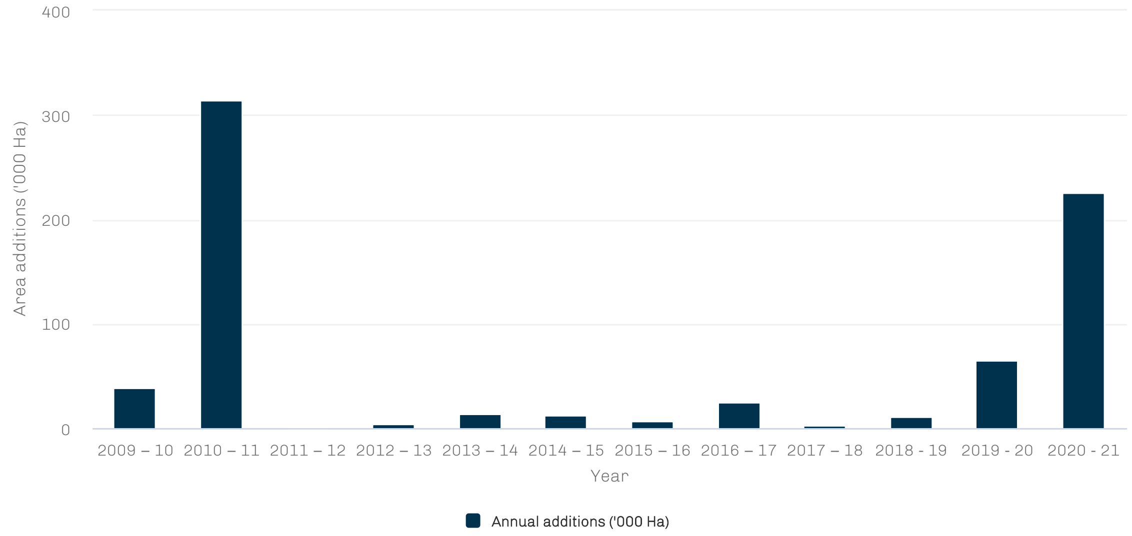
At 30 June 2021, terrestrial reserves covered about 7.59 million hectares, approximately 9.6% of NSW. Although this is below the rate of some other Australian states and territories such as Tasmania (42%), South Australia (30%), Northern Territory (24%), Western Australian (23%), and Victoria (18%), NSW also has a substantial State forest network managed by the Forestry Corporation which is subject to comprehensive regulatory prescriptions, exclusion arrangements and forestry practices based on ecologically sustainable forest management principles.These measures make a significant contribution to the overall protection of the environmental values of native forests in NSW. Almost 70,000 hectares of State forest are protected in formal reserves while 872,000 hectares are excluded from harvesting.

Conservation on private land and Crown land supplements the protected areas, provides vegetation corridors linking larger public reserves and protects some natural ecosystems that are under-represented or not present in public reserves.

Public land jointly managed or owned by Aboriginal people has increased through whole-of-government Indigenous Land Use Agreements. By June 2021, the National Parks and Wildlife Service (NPWS) had 33 joint management agreements with Aboriginal traditional owners, covering approximately 2.28 million hectares.

The network of marine protected areas includes marine parks (around 345,000 hectares), aquatic reserves (around 2,000 hectares) and national park and nature reserve areas below the high tide level (around 20,000 hectares). Over the past three years there has been a focus on improving the management of existing marine parks and aquatic reserves.

Spotlight figure 14: Annual additions in area (in thousands of hectares) of national parks and reserves in NSW since 2009



Notes:
The data in this figure only refers to areas in NSW national parks and reserves and does not include other protected areas or conservation on private land which also significantly contribute to protecting environmental values.

Source: NPWS data

Spotlight figure 14 shows annual additions in thousands of hectares to national parks and reserves since 2009. In 2020–21, 226,000 hectares of land had already been added to protected areas by January 2021.

Pressures

Pest animals and weeds are some of the greatest threats to threatened species and ecological communities in reserves and other protected areas, and also have impacts on Aboriginal Country and cultural sites. Other pressures include illegal activities on reserves (such as waste dumping) and land-use changes, including clearing of natural vegetation on private land near reserve boundaries which can make it difficult to maintain habitat connectivity between protected areas. Climate change impacts on plants and animals that have a restricted range or diminished capacity to adapt to significant temperature changes, and increases the likelihood and frequency of damaging bushfires.

Pressures on marine protected areas include modifications to estuary entrances, the clearing of riparian and adjacent habitat including wetland drainage (in estuaries), diffuse source runoff from agriculture and urban areas to estuaries, climate change including increased impacts on coastal reserves from storms and sea level rise, modified freshwater flows in estuaries and boating and foreshore development. These pressures, as well as others, have been indentified as priority threats to the NSW marine estate by the Marine Estate Management Authority (MEMA 2017).

Responses

Every year, NPWS acquires land for national parks by purchasing private land and through public land transfers, donations and bequests. In August 2019, the Minister for Energy and Environment committed to expanding the NSW reserve system by 200,000 hectares in two years. When this target was achieved in October 2020, the Minister committed to an additional 200,000 hectares, raising the overall target to 400,000 hectares by 2022.

Since 2018, an additional 30,901 hectares of State forest have been dedicated as flora reserves, also contributing to the formal reserve system.

Legislation, policies and programs protect the land and water in the NSW's public reserve system. For example, the *Marine Estate Management Act 2014* provides for strategic and integrated management of the entire NSW marine estate, and the marine parks and aquatic reserves within the marine estate. Reforms to Aboriginal cultural heritage and initiatives such as Our Place on Country Strategy provide legal and policy frameworks to improve management, conservation and participation of Aboriginal people in protecting Aboriginal cultural heritage in NSW and providing access to Country.

Threatened species are protected in public reserves through the *Saving our Species* program and partnerships with private and not-for-profit environment groups. For example, work is under way on turning 555 hectares of Shanes Park in the Blacktown Local Government Area into a predator-free area. Up to 30 locally extinct or threatened mammals, birds, reptiles and amphibians – including the eastern quoll and brush-tailed phascogale – will be reintroduced, making it one of the biggest urban wildlife restoration projects in the world.

Related topics: Invasive Species | Wetlands | Native Fauna | Threatened Species | Climate Change

Fire

Fire is an integral part of our environment. It is essential for the growth and reproduction of many natural systems and the health of Country but altered fire regimes are a threat to ecosystem health.

The 2019–20 Black Summer fires burnt

5.5 million hectares

of area across NSW

The 2019–20 Black Summer fires burnt or displaced

3 billion

vertebrate animals across south-east Australia

The 2019–20 Black Summer fires affected

62%

of NSW vegetation communities which are under pressure from too much burning

Fire generated thunderstorms

50%

increase in the total number of events recorded (since 1978) during the 2019–20 Black Summer fire season

The 2019–20 Black Summer fire season was the most severe ever recorded in NSW, and as the climate warms and dries such fire patterns are likely to become more frequent. Many vegetation communities are now under pressure from too much burning.

Why managing fire is important

Fire is a natural part of the Australian landscape and much of the flora of NSW depends on fire to assist in its reproduction and growth. Altered fire regimes as a result of European settlement – too much or too little fire or fire of too high an intensity – have had a major detrimental impact on the integrity, structure and sustainability of most ecosystems and many threatened species.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Proportion of mapped vegetation communities exceeding (minimum or maximum) vegetation fire interval thresholds		Getting worse	✓✓

Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

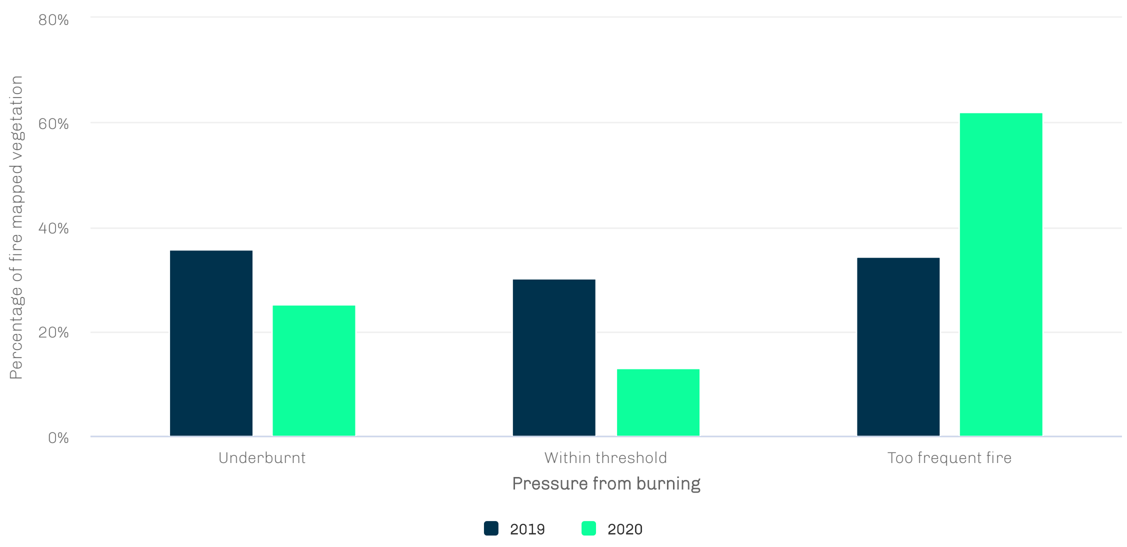
About 7% (5.5 million hectares) of NSW was burnt during the prolonged 2019–20 Black Summer fire season. The total area burnt was four times greater than the previous worst forest fires recorded in a fire season.

Over 450 threatened plant species and 293 threatened animal species occur in the footprint of the Black Summer fires. The prospects of long term survival of a significant proportion of these species have been impacted by the fires.

Rainforests have a low tolerance of fire and over 300,000 hectares or 37% of all NSW rainforest was burnt during the 2019–20 fire season.

Prior to the Black Summer fires, the fire interval status for vegetation communities was evenly spread - with about third each - within safe thresholds, or under pressure due to being too frequently burnt or insufficiently burnt. Following the fires, about 62% of vegetation communities are now under threat from too much burning and only 13% are within thresholds.

Spotlight figure 22: Vegetation fire interval status for 2019 and 2020 in NSW



Source:
Data from Bushfire Hub 2020

The **Spotlight figure 22** shows the change in status of vegetation fire intervals before and after the 2019–20 Black Summer fires. The time interval between fires is an indicator of the health of vegetation communities with the recommended time interval, which varies for different vegetation communities allowing for healthy regeneration and regrowth (apart from some specific communities, such as rainforest, where no fire is tolerated). If the time interval is not within the recommended threshold (i.e. it is too short or too long) this affects the condition and ultimately the integrity of the plant community.

Previously there was an even spread of fire interval status, but now they are strongly weighted towards overburning. This represents a fundamental shift in the ecological condition of vegetation communities and their response to fire.

Pressures

Increasing temperatures and the drying out of south-eastern Australia due to the effects of climate change are leading to longer fire seasons and more severe fire weather.

A trend is emerging for the more frequent development of fire-generated thunderstorms, where fires interact with the atmosphere to escalate the risk and spread of the blaze. Climate change is likely to amplify the conditions leading to the formation of such storms, through increasing dryness and atmospheric instability.

Over half of all bushfires in most years are started by humans, with arson a major cause. However, the Black Summer did not follow the usual pattern, with the majority of fires started by lightning, often in remote and inaccessible locations.

Responses

The key to achieving appropriate fire management is getting the balance right between maintaining natural ecosystems while ensuring community safety and protection of property, infrastructure and livestock.

All 76 recommendations from the NSW Bushfire inquiry announced in January 2020 were accepted by the NSW Government and around $460 million in funding allocated to their implementation in June 2020, including for new bushfire risk management plans, increased hazard reduction works, enhanced rapid response capacity, improved bushfire modelling and upgraded fire trails.

One of the principal tools for fire management is hazard reduction burning. The overall level of hazard reduction has increased over time but is quite variable from year to year, depending on assessed need and favourable conditions.

There is increasing interest in cultural burning, as part of the broader cultural practice of caring for Country in traditional Aboriginal land management. Cultural fire management protects and enhances ecosystems and cultural values, while reducing fuel loads.

Related topic: Climate Change

Biodiversity

soe.epa.nsw.gov.au

Biodiversity

The changes that have occurred to our natural environment affect the richness and diversity of the species and ecosystems found in NSW and their ability to survive into the future.

Introduction to Biodiversity

The topics in this theme describe how the native species and ecosystems of NSW are faring presently and the effects of introduced species.

Ensuring the long-term survival of the species and ecosystems of NSW means they will persist for the benefit and enjoyment of future generations. Many native species are considered to be threatened in NSW and the Threatened Species topic discusses current patterns in their status and trends. The broad patterns of survival and trends in animal populations are considered in Native Fauna.

The main threats to the survival of species are habitat destruction through the clearing of native vegetation and competition and predation by invasive species, with climate change an emerging and serious threat into the future. The impacts of invasive species on the survival of native species and ecosystems are discussed in the Invasive Species topic.

In this report:

- The number of species considered at risk of extinction continues to rise with 1,043 NSW species listed as threatened, 18 more than reported three years ago. A further 116 ecological communities are also listed as threatened.
- The conservation status of 64% of land-based NSW vertebrates is presently not considered to be threatened.
- Freshwater fish communities are in very poor condition across the state and are declining.
- Invasive species are widespread across the state's land and aquatic environments and regarded as a major threat.

Aboriginal Perspectives

From the beginning, Aboriginal people and cultures have cared for Country in a holistic way that ensures all animals and plants are able to thrive. Aboriginal cultural values and use of totems and kinship relationships with a range of species and special and sacred places impose obligations that protect these species and places.

Aboriginal people have seen many changes to the biodiversity of NSW and have for many years asked to be a part of decision-making. Biodiversity is central to Aboriginal people's cultures. Involvement would be a great opportunity to bring together Aboriginal knowledge and cultures with western science to promote better outcomes for the biodiversity of NSW.

Threatened Species

Programs that protect animals and plants and their habitats focus on threatened species, including those at greatest risk of extinction.

Extinct species

78

species are extinct in NSW (2020 data)

Number of threatened species

1,043

species are listed as threatened in NSW as at December 2020 (18 more species than in the last report)

Critically endangered species

116

critically endangered species were listed in NSW as at 2020 and face an extremely high risk of extinction in Australia in the immediate future

Increase in threatened species

↑ 2%

increase in species listed as threatened over the past three years

The number of species at risk of extinction continues to rise. As at 2020–21, 1,043 species and 115 ecological communities are listed as threatened under NSW legislation including 78 species declared extinct.

Why species and habitat are important

There has been a general pattern of decline in species diversity in NSW since European settlement. Some species of plants and animals, including fish, are at risk of extinction due to threatening processes such as removal of habitat. Conservation of threatened species is important to stabilise this loss of biodiversity. Programs such as ***Saving our Species*** are working to increase the number of species that will be secure in the wild for 100 years.

Aboriginal people attribute tremendous spiritual, cultural or symbolic value to many animals, plants and ecological communities, a value that is critical to identity and relationship with Country. The protection of these species and communities is fundamentally important in maintaining Aboriginal culture, language and knowledge.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Number of threatened species, communities and populations	 POOR	Getting worse	✓✓

Notes:
Terms and symbols used above are defined in About this report.

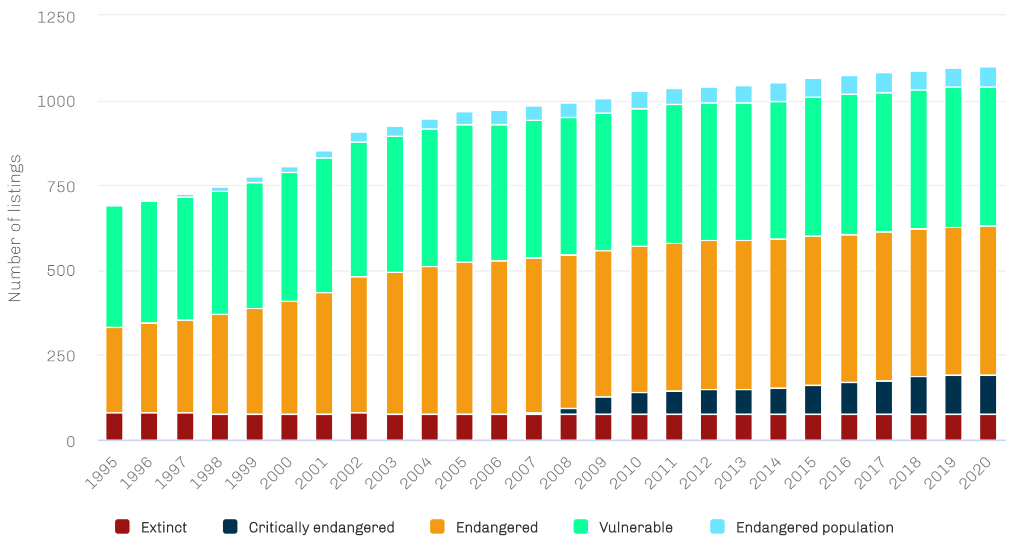
Status and Trends

In NSW in the three years to December 2020, the number of listings of threatened species increased by 18 (or 2%), with 1,043 species listed as threatened under the Biodiversity Conservation and Fisheries Management Acts (**Spotlight figure 11**).

The number of plants and animals and communities being managed under the ***Saving our Species*** program has steadily increased, with 465 projects in 2018–19 covering roughly 40% of the listed species, communities and populations in NSW.

However, modelling in the assessment of the NSW Biodiversity Indicator Program (BIP) predicts that only 496 or 50% of the 991 terrestrial species listed as threatened are predicted to survive in 100 years' time (DPIE 2020). Management and conservation efforts will not be enough to save many species without addressing key threats such as habitat removal and climate change.

Spotlight figure 11: Total listings of threatened species 1995–2020



Source:
Department of Planning, Industry and Environment (DPIE) and Department of Primary Industries (DPI) data

Pressures

A total of 47 key threatening processes have been identified as threatening the survival of species, communities and populations – 39 mainly terrestrial threats and eight aquatic. The most common threats are habitat loss due to the clearing and degradation of native vegetation and the spread of invasive pests and weeds. The capacity of species to adapt to these pressures is further constrained by climate change.

Altered fire regimes impact the ability of plant species and communities to regenerate or repropagate and extreme wildfires can decimate local animal populations. Water extraction and altered river flows and cycles affect a range of aquatic and bird species.

Responses

The Saving our Species (SoS) program is committed to maximising the number of threatened species and ecological communities secure in the wild for 100 years. In May 2018, the government released the NSW Koala Strategy to help secure the future of koalas in the wild.

Biodiversity legislation in NSW to protect threatened species includes the *Biodiversity Conservation Act 2016*, *Fisheries Management Act 1994* and the Common Assessment Method for national listing of threatened species.

Public national parks and reserves, the foundation of conservation efforts in NSW, play a vital role in protecting habitat and providing refuge for many threatened species that are sensitive to habitat disturbance. Threatened species are also increasingly being conserved on privately-owned land.

There are opportunities to further reintroduce locally extinct mammals in managed areas free of invasive species, such as foxes and cats, and assess longer term impacts of legislative change on threatened species and their natural habitats. There is a need to learn more about how Aboriginal cultures and practices improve the care, protection and management of species, their habitats and the overall environment. This includes qualitative data collection, oral stories and Aboriginal cultural knowledge. In this respect, the EPA Aboriginal Peoples Knowledge Group recommends that significant Aboriginal cultural species be included as an indicator for future State of the Environment reporting.

Related topics: Population | Greenhouse Gas Emissions | Native Vegetation | Protected Areas and Conservation | Native Fauna | Invasive Species | River Health

Native Fauna

It is important to preserve the full range of biodiversity in NSW and maintain healthy ecosystems for future generations. Healthy native fauna populations are an important factor in achieving these goals.

Decreased mammal ranges

64%

of native mammals have had long-term decreases in range

Survival of native vertebrate species

62%

of native terrestrial vertebrate species are not currently listed as threatened, but this is worsening

The overall diversity and richness of native species and communities in NSW remains under threat of further decline.

Why native animals are important

NSW has a rich biodiversity, much of which is recognised as being internationally significant. Shrinking distributions of species of mammals, birds, fish, reptiles and amphibians can indicate early that their populations are decreasing. Declines in population of many species have been under way for decades or longer but have largely gone unrecorded. Over the past three decades, heightened awareness of the plight of native fauna has revealed the extent of population declines and the threats that cause them.

Aboriginal people attribute tremendous spiritual, cultural or symbolic value to many animals, plants and ecological communities, a value that is critical to identity and relationship with Country. The protection of these species and communities is fundamentally important in maintaining Aboriginal culture, language and knowledge.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Native terrestrial mammals: Loss of long-term distribution over the past 200 years	POOR	Stable	✓
Native birds: Loss of long-term distribution over the past 200 years	MODERATE	Stable	✓

NSW indicators

Indicator and status		Environmental trend	Information reliability
Proportion of vertebrate fauna species that is presently non-threatened	MODERATE	Getting worse	✓✓
Birds: Decline in populations – short term (decades)	POOR	Getting worse	✓✓
Native fish communities	POOR	Getting worse	✓✓✓
Large kangaroos: Population	GOOD	Stable	✓✓✓

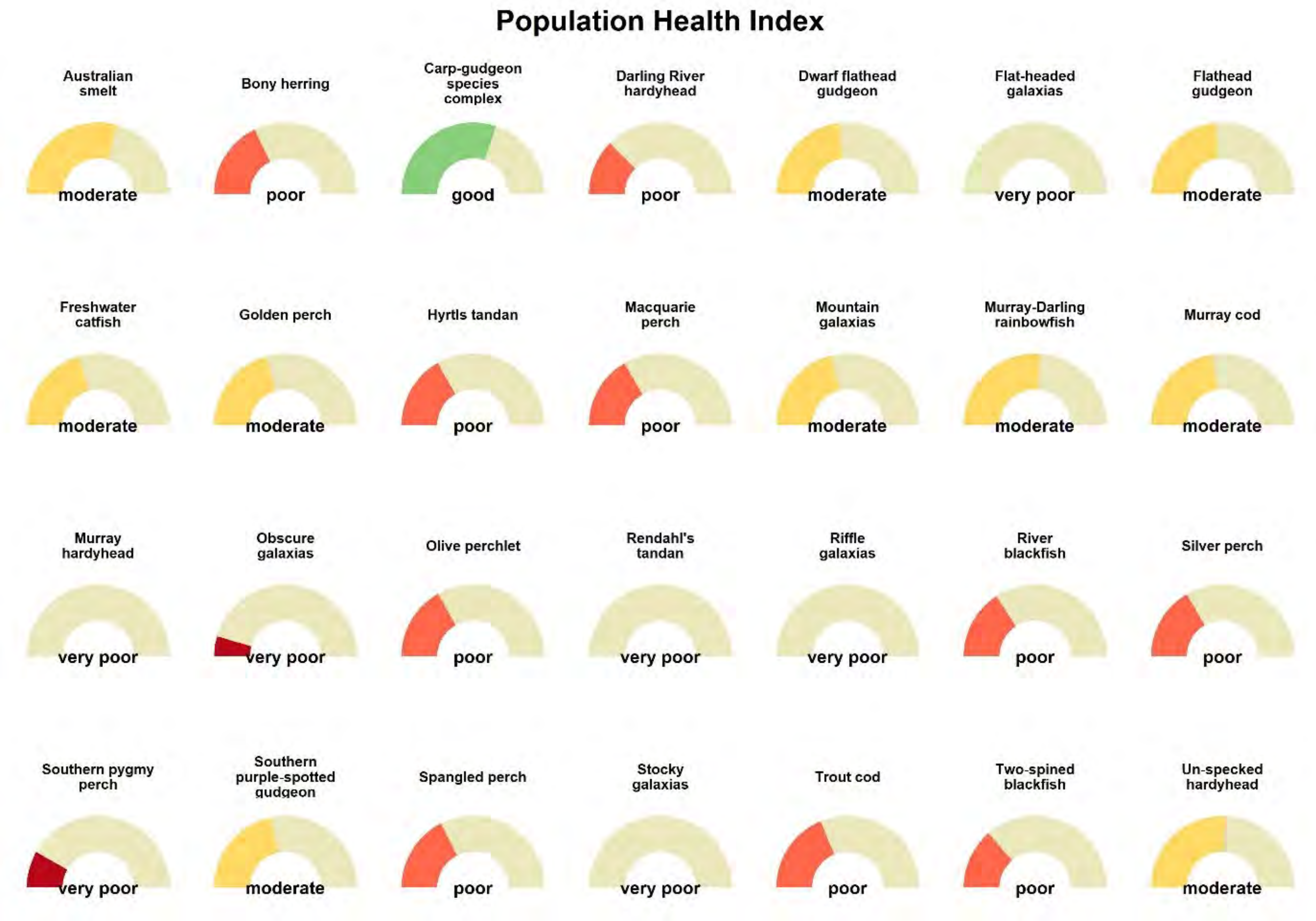
Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

A pattern of long-term decline in biodiversity is seen in the reduced range or abundance of many native vertebrate species. At the same time, many species less susceptible to current pressures have maintained their distributions, while a small number of adaptable species has flourished.

Over the past 200 years, birds have been more resistant to declines in range than mammals, which have experienced substantial declines, especially small- to medium-sized ground-dwelling species. However, over recent decades there is evidence that populations of some bird groups are declining.

Spotlight figure 12: Population health index (PHI) ratings for 28 native fish species in the NSW part of the Murray–Darling Basin in 2014–19



Notes:

Source: NSW DPI Fisheries

A good population health index (PHI) rating represents an overall improvement in general viability and resilience. In the **Spotlight figure**, only the carp-gudgeon species complex had a good PHI rating, meaning carp-gudgeons have a stable abundance, an improving distribution and adequate recruitment, and are in good individual condition.

Nine fish species had a moderate PHI rating, representing stable population health. The remaining 16 species (57%) were in poor or very poor population health, reflecting a substantial decline in one or more population health indicators and overall declining viability and resilience.

There are no PHI ratings for coastal fish species due to a lack of monitoring in coastal catchments.

Pressures

The decline in native fauna species is due to the cumulative impacts of threats such as vegetation clearing, habitat degradation and invasive species that prey on native animals and compete with them for habitat. Foxes and cats prey on native fauna on the mainland and introduced rodents affect species' survival on islands and on the mainland. Climate change is expected to be a major threat to the future survival of many species. Without significant action, climate change is expected to become one of the most significant of all the human-induced pressures.

Responses

The NSW Government has streamlined and integrated legislation for biodiversity conservation and protection. The main measures to address the decline in biodiversity are:

- conservation of native species in national parks and other reserves

- the Biodiversity Conservation Trust which funds landowners to manage, protect and conserve biodiversity on private land and through biodiversity offsets
- the *Saving our Species* program which aims to secure as many threatened species in the wild as possible
- an expanded NSW Biodiversity Offsets scheme to facilitate ecologically sustainable development.

Locally extinct mammals are being reintroduced in carefully managed areas in national parks and reserves kept free of invasive species, with more reintroductions planned for 2021–23 (see Protected Areas and Conservation).

There are opportunities to assess longer term impacts of legislative change on threatened species and their natural habitats, and to conserve threatened species on privately-owned land. There are also opportunities to continue to learn more about how Aboriginal cultures and practices improve the care, protection and management of species, their habitats and the overall environment. This includes qualitative data collection, oral stories and Aboriginal cultural knowledge.

Related topics: Threatened Species | Invasive Species | Native Vegetation | River Health

Invasive Species

Many invasive species are widespread across NSW. Once established, they are difficult to control. Invasive species prey on threatened native animals, take habitat from endangered ecological communities and threaten environmental health.

Pest animals and weeds threatened more than

70%

of threatened species and endangered ecological communities in NSW

Introduced carp dominated fish communities, making up more than

80%

of the biomass in some rivers in the Murray–Darling Basin in 2020–21

Pest animals cost the NSW economy

$170 million

every year in lost production and management costs

Weeds cost the NSW economy

$1.8 billion

each year in lost agricultural production and management costs

Invasive species are implicated in the decline of land and aquatic species and the extinction of many small Australian native mammals and birds.

Why managing invasive species is important

Australian native plants and animals have co-evolved over millions of years. As a result, the introduction of non-native pests and weeds can seriously threaten native species because native species have not evolved ways to deal with them. Invasive species are implicated in the decline and extinction of many Australian native plants and animals in both land-based and water-based ecosystems.

For example, weeds such as lantana can drive out native flora species and change the population of ecosystems. Invasive animals such as feral cats can prey on threatened animals, drastically reducing their numbers. Pests and weeds can also impact on agricultural productivity, social wellbeing and ecotourism (DPI 2018b).

NSW indicators

Indicator and status		Environmental trend	Information reliability
Number of new invasive species detected	MODERATE	Stable	✓✓
Spread of emerging invasive species	MODERATE	Getting worse	✓
Impact of widespread invasive species	POOR	Stable	✓

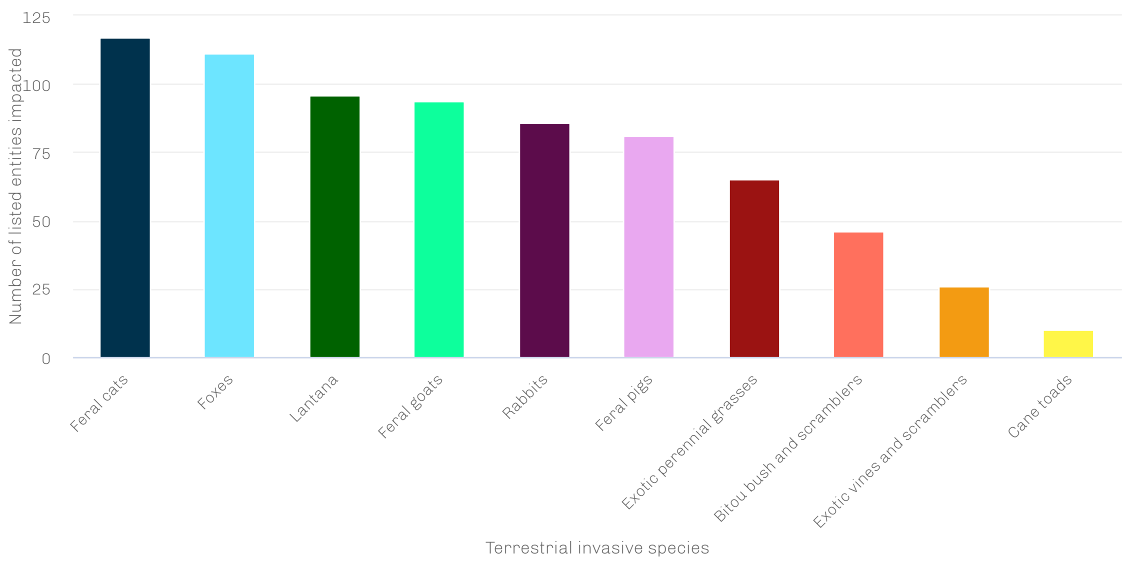
Notes:
Terms and symbols used above are defined in [About this report](#).

Status and Trends

The extinction or decline of numerous small- to medium-sized animals, particularly mammals, has largely been attributed to predation by foxes and cats, while rats introduced to Lord Howe Island caused nine of the 14 bird extinctions in NSW.

Grazing and browsing by introduced herbivores, such as rabbits, goats and deer, has led to habitat degradation and a decline in native vegetation diversity and productivity. Pest fish threaten native fish species and aquatic ecosystems, with carp dominating fish community biomass across most of the Murray–Darling Basin. Spotlight 15 shows species, populations and ecological communities threatened by key terrestrial invasive species.

Spotlight figure 15: Species, populations and ecological communities* threatened by key terrestrial invasive species**



Notes:
* Threatened species, populations and ecological communities listed under the *Biodiversity Conservation Act 2016*.
** The invasive species selected are generally those listed as [key threatening processes](#) .
Data compiled by aggregating the threats affecting each threatened species, identified at the time of listing, across all threatened species.

Source:
Modified form Coutts-Smith & Downey 2006 and Coutts-Smith et al. 2007

Considered individually, widespread pest animals, such as feral cats and foxes, have a far greater impact on threatened species than individual weed species. However, the overall number of weed species is much greater than pest animal species and their combined impact is broader than the impact of pest animals.

Pressures

Pest animals and weeds continue to spread, adding to other pressures on the natural environment such as addition of nutrients, changed hydrologic regimes, bushfires and climate change.

Invasive pathogens, particularly the root rot fungus (*Phytophthora*), myrtle rust and the amphibian chytrid fungus, are increasing threats to biodiversity.

New invasive species are being introduced by the black market pet trade, nursery industry and aquarium industry or as stowaways on boats. These newly introduced and emerging invasive species can have an impact on additional threatened flora and fauna, and potentially add to the cumulative impact of all invasive species on the environment.

Responses

The *NSW Invasive Species Plan 2018–2021* (DPI 2018a) sets out the priorities, goals, strategies and guidelines to exclude, eradicate or manage invasive species and their impacts. The *NSW Biosecurity Strategy 2013–2021* (DPI 2013) manages shared responsibility for effective biosecurity management, increases awareness of biosecurity issues in NSW and outlines ways in which the NSW Government works in partnership with other government agencies, industry and the community to manage biosecurity risks.

Response programs are important in mitigating the threats from invasive species. They include:

- the State Weed Committee which is responsible for ensuring a coordinated and strategic approach to weed management in NSW
- Regional Weed and Pest Animal Committees which coordinate regional pest and weed management activities
- Saving our Species which manages projects to protect threatened species from pests and weeds
- the National Carp Control Plan which helps manage carp populations.

Other initiatives include:

- improvements to surveillance and biosecurity measures to help prevent new invasive species threats
- a better understanding of pathogens which continue to emerge as an increasing threat
- schemes such as aerial baiting which have been successful in controlling foxes in some areas and may even help control feral cats.

Related topics: Threatened Species | Native Fauna | Native Vegetation | River Health

Water and Marine

soe.epa.nsw.gov.au

Water and Marine

Water is a valuable resource and the challenge is to find the right balance between extracting water for human uses, while retaining sufficient water to keep aquatic ecosystems healthy.

Introduction to Water and Marine

The topics in this theme describe how water resources are used in NSW and the condition of freshwater and marine ecosystems.

One of the greatest challenges facing NSW is continued access to reliable sources of good quality water. Water use needs to be managed to provide an equitable balance between the numerous beneficial uses of water and maintaining the health of rivers and aquatic ecosystems. How water resources are allocated and the share of water available for the environment is described in the Water Resources topic for surface water and in Groundwater for sub-surface water. River Health reports on the ecological health of rivers and the effects of water extraction and flow regulation while the health of NSW wetlands is examined in the Wetlands topic.

Most NSW rivers flow to the sea through estuaries and the Coastal, Estuarine and Marine Ecosystems topic covers the health and impacts of pressures on these environments.

In this report:

- The period from 2017 to 2020 saw some of the worst droughts in recent record. During this time, significantly less environmental water was available for delivery into inland rivers and wetlands.
- The overall environmental condition of rivers is moderate but waterbirds and fish communities are in poor condition. The major river systems of the Murray-Darling Basin are generally in poorer condition than coastal rivers.
- The abundance of waterbirds declined in 2020 to about 40% below their long-term median.
- Groundwater provides 27% of all metered water use in NSW, a notable increase from three years ago when it was 11%.
- Marine and coastal environments are in good condition overall, but the state of estuaries is more variable.

Aboriginal Water

Water is essential for life to exist in NSW and for Aboriginal people always was and always will be at the core of their culture and ways of knowing, being and doing. Cultural and spiritual values may relate to a range of uses and issues, including spiritual relationships, language, songlines, stories, sacred places, customary use, the plants and animals associated with water, drinking water, and recreational or commercial activities (DAWE 2018). Water is also strong through lore, song, dance and dreaming and plays a significant role in the health and wellbeing of its people (Moggridge & Thompson 2021).

Australia is the driest continent on earth and Aboriginal knowledge of water is essential to the survival of its people. With thousands of generations of connection and observation of all Countries, the many Aboriginal Nations of NSW must be a part of its protection, especially the quality of its waters.

More recently, Aboriginal people have felt much sadness in witnessing the destruction of Country, the diversion, over-extraction, storage and pollution of their waters while their voice and control over the quantity of water on-Country is diminished under water laws that benefit postcolonial settlers to this day (Hartwig, Jackson, Markham & Osborne 2021). Modern water planning must evolve and consider new ways to share water resources fairly to ensure Aboriginal people can thrive through self-determination with free and prior informed consent over water decisions that close the gap in water ownership and improve wellbeing and caring for their countries.

Our freshwater surface and groundwaters are both important assets with value not as a commodity but as the essence of life. Where our freshwater meets the saltwater Country, this is also an important place to protect.

Connection to Country (Marine)

Coastal Aboriginal people have a strong connection to the marine environment. It is important to saltwater people that we keep that connection strong and it comes with a responsibility that was handed down from our ancestors. It is our duty to look after the saltwater Country that has sustained our people for thousands of years, so the next generation can have the same enjoyment that we have. The responsibility of looking after saltwater Country is everybody's business, but to the Yuin nation it's more than just a responsibility – it's our spiritual connection to our dreamtime that connects us to our saltwater Country.

This is our Dreamtime story that I will share with you about why Yuin people are connected to the ocean and the land we live on.

TOONKOO and NGARDI

Here is the meaning put into Aboriginal context:

In the stillness of the night slowly bobbing to the rhythm of the waves, the night sky guides our dreaming, the moon predicts the destined tides. This is where the magic begins upon the ocean and its horizon. Even in the day, with the sunrise and the sunset when we look and see the ocean and its magic is still there and still alive – the magic of spirt that still today shows us the trail from where Aboriginal people first came.

(Our dreaming story is Toonkoo and Ngardi coming down from a star to this land. This story and many other stories from other Aboriginal peoples all over Australia share stories of their dreaming coming from the stars.)

The oceans are the balances to the land and when we sit between the 'balance' we see the path … to the Dreaming and creation.

The path to our dreaming is the magical space created in that balance which is called 'Mil-lum-ba-wa' or 'Mill-um-ba-wa' or 'Mill-um-bar-wa' which is interpreted as the 'sparkle of the waves'.

– Wally Stewart

Water Resources

A diversity of healthy and secure sources of water is essential to provide for a variety of beneficial water uses, including town water supplies and agriculture, while maintaining the condition of natural aquatic environments.

Water sharing plans

59

now developed, covering water extraction from all NSW water sources

Environmental water share

2,553 gigalitres

of entitlements, an increase of over 1,000 GL from 10 years ago

The period from 2018 to 2020 encompassed some of the most extreme weather ever experienced in NSW, including one of the worst droughts on record, followed by severe bushfires along the eastern seaboard. Water extraction fell quickly during this period and significantly less environmental water was delivered into inland rivers.

Why managing water resources is important

Water is a vital resource and effective management is necessary to balance competing human needs, maintain healthy and resilient aquatic environments, and protect river and groundwater systems.

A robust water resources management framework is important as it provides greater certainty about the water available for extraction, establishes rules for sharing water supplies between different types of uses, and allows for return of flows to the environment. NSW moves between extremes of weather, with abundant water quickly becoming scarce, making management and regulation of water resources both complex and critical.

This topic explores surface water resources, see the Groundwater topic for information on those resources.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Proportion of water extraction covered by water sharing plans	GOOD	Stable	✓✓✓

NSW indicators

Indicator and status		Environmental trend	Information reliability
Environmental share of available water	MODERATE	Stable	✓✓

Notes:
Terms and symbols used above are defined in About this report.

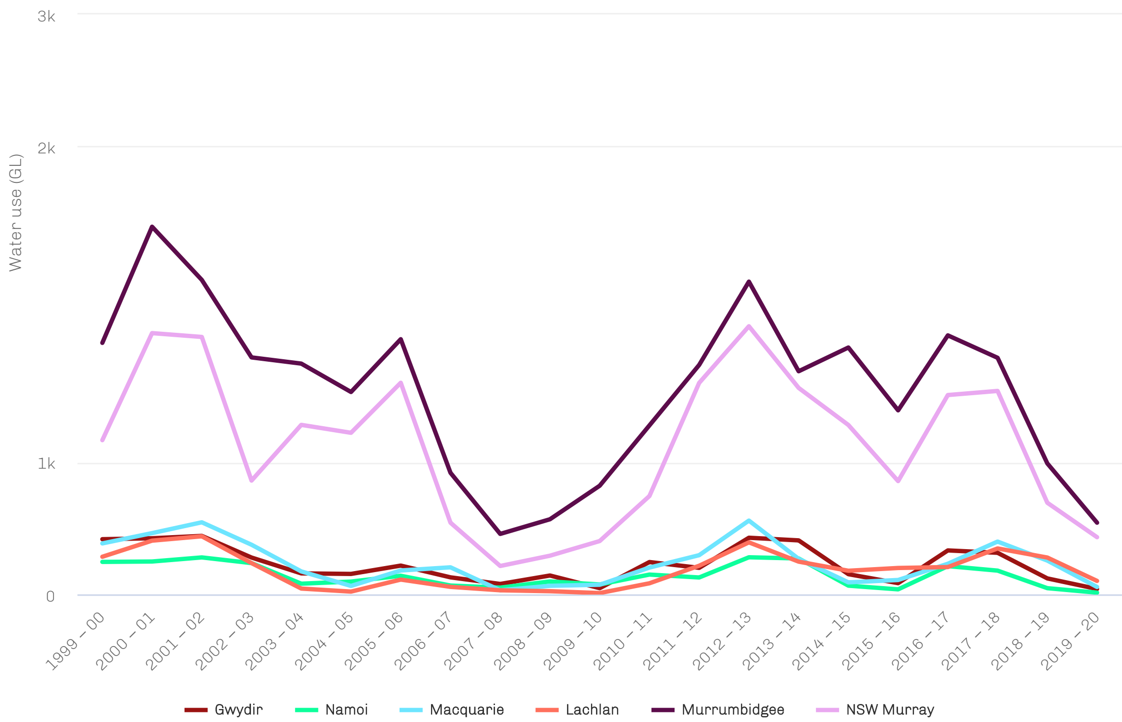
Status and Trends

After three years of severe drought, NSW climatic conditions and surface water availability improved after mid-2020. Water extraction and regulation alter river flows and continue to put pressure on the health of inland river systems. The impacts may be less severe during intermittent flooding events and periods of above-average rainfall.

About 80% of water used comes from regulated rivers, where flows are controlled by large water storages, while about 11% comes from groundwater and the balance is drawn from unregulated rivers. The amount of water extracted for use and the amount remaining in stream for environmental purposes differs significantly depending on annual rainfall and flow conditions.

Spotlight figure 16 shows water use by licensed users from 1999–00 to 2019–20 in all six major NSW inland regulated river valleys. All were quickly impacted by the extreme temperatures and very low rainfall experienced during the drought that occurred between 2018 and 2020.

Spotlight figure 16: Water use by licensed users in major NSW regulated valleys 1999–00 to 2019–20



Notes:
Water use is licensed account usage, including general security, high security, conveyance, water utilities, domestic and stock, and supplementary access. These use estimates include licensed water use for both consumptive and environmental purposes.
The Border Rivers valley is not included in the graph.

Source:
DPIE Water data 2021

The NSW Government's cumulative holdings of environmental water total about 902,400 megalitres (ML) within regulated rivers and about 27,500 ML in unregulated rivers. The Australian Government has also recovered substantial volumes of environmental water in the Murray–Darling Basin in NSW with current holdings of about 1,575,800 ML in regulated rivers and 46,000 ML in unregulated rivers. This gives a total of 2,553,000 ML of licensed environmental water for NSW.

During the three years 2017–18 to 2019–20, the volume of environmental water delivered back to locations across inland NSW was significantly less than in the previous three years. Volumes ranged from approximately 850,000 ML (2017–18) to 278,000 ML (2019–20), the lowest amount in a decade, and significantly less than the 1,396,000 ML peak in 2016–17. This highlights the impact of the recent drought and record-breaking high temperatures on water availability.

Pressures

Climate variability, periods of drought, above-average temperatures and low rainfall, and the increasing impact of climate change-related extreme weather events are significant pressures on water resources in NSW. More frequent drought conditions with only short periods of good rainfall in between dry periods reduce the ability of river systems and water storages to recover sufficiently.

Other pressures on water resources are the result of human intervention and activity. Water extraction can reduce total river flows and, particularly in times of reduced rainfall, these water diversions can affect water quality and ecosystem health.

The natural variability of river flows is also impacted by the regulation of rivers through structures that store or divert water such as dams and weirs. Although aquatic ecosystems in NSW are adapted to variable flow levels, changes to natural flow patterns and water temperatures, have contributed to biodiversity loss and declining aquatic health over time.

Another pressure on water resources is water pollution from catchment disturbances, land management practices and land-use changes including agriculture and urban expansion.

Responses

The state's water resources are managed through a framework of legislative instruments, strategies, policies and plans which aim to address and mitigate the pressures on water resources. Central to the management and control of demand are water sharing plans which are in force for all water sources in NSW. These plans provide a clear framework and rules for managing inland NSW basin water resources and coastal water resources and provide the basis for sharing water between the environment and extractive users. They play an important part in supporting water markets and enabling water trading for both commercial and environmental purposes. Water markets can help water managers to flexibly adapt to changing conditions and manage risk.

Water sharing plans are also an important component of regional water strategies which are currently being developed in NSW to understand how much water a region will need to meet future demand and identify the challenges and choices involved. Based on this, the plans will set out actions to manage risks to water security and reliability. They aim to consider the pressures on water resources in a region and bring together the latest climate evidence and a range of tools and solutions to plan and manage each region's water needs over the next 20 to 40 years.

Water sharing plans, with risk assessments, underpin 20 water resource plans developed by the NSW Government for both surface water and groundwater sources as part of its responsibilities for improving water resource management under the Murray–Darling Basin Plan.

The *NSW Water Strategy* was released by the NSW Government in September 2021 to draw the various water strategies and plans together into a strategic and integrated framework to better manage the state's water resources.

Related topics: River Health | Wetlands | Groundwater | Coastal, Estuarine and Marine Ecosystems

River Health

Healthy river ecosystems are vital for aquatic and terrestrial biodiversity and water quality, and to support human activities.

River condition index

38

out of 40 NSW river valleys have a 'moderate' or better rating

Health of fish communities

>90%

of Murray–Darling Basin river valleys are rated 'poor' or worse

Aquatic ecosystems in the major NSW rivers of the Murray–Darling Basin are generally in poorer condition than those in coastal rivers. The overall health of rivers across NSW is considered moderate.

Why river health is important

Healthy river ecosystems, comprising rivers, their riparian zones, floodplains and wetlands, are vital for aquatic and terrestrial biodiversity. Healthy rivers also provide the ecosystem services needed for good water quality and supply. They maintain cultural values, underpin economic growth and enable human activities, including agriculture, aquaculture, fishing, recreation and tourism.

Aboriginal culture and connection to Country rely on rivers to maintain traditional practices and communities.

A primary objective of effective river management in NSW is to preserve the integrity of natural systems while providing for a range of beneficial human uses.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Health of fish communities	POOR	Getting worse	✓✓
River condition index for NSW rivers *	MODERATE	Stable **	✓

NSW indicators

Indicator and status		Environmental trend	Information reliability
Salinity	GOOD	Stable	✓✓
Nitrogen and phosphorus levels	MODERATE	Stable	✓✓

Notes:
* Data for this indicator has not been updated during the last three years.
** Trend as at 2018. It has not been assessed for the latest reporting cycle.

Terms and symbols used above are defined in About this report.

Status and Trends

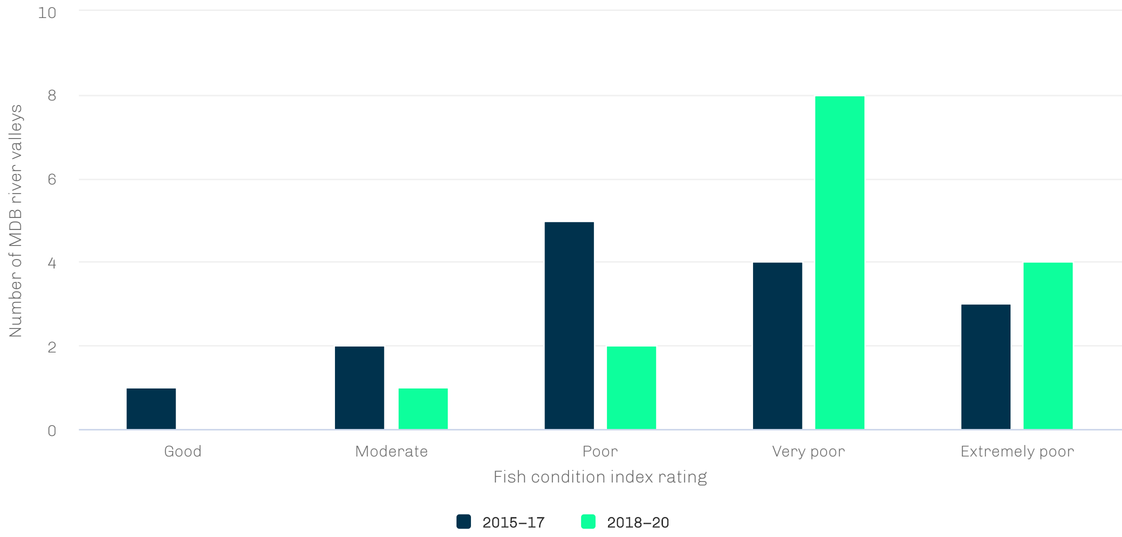
The period 2018 to early 2020 was marked by extreme weather events, including one of the worst droughts and the highest temperatures ever experienced in NSW, then severe bushfires along the eastern seaboard from September 2019 to February 2020. This was followed by intermittent heavy rain events and flooding in 2020, cooler and milder weather over the 2020–21 summer, and further rain events in 2021 resulting in improved river flows and replenished water catchments across NSW.

The state's major inland river systems have been affected by the ongoing impacts of water extraction, altered river flows, loss of connectivity caused by weirs and other instream structures and catchment changes such as altered land use and vegetation clearing. The greatest signs of ecosystem stress are generally where flow regimes have changed the most.

NSW coastal rivers are less affected by water extraction and flow regulation than inland rivers and are generally in better ecological health, except for their fish communities.

Fish communities are in poor condition across the state. They are declining in the Murray–Darling Basin where the widespread distribution of introduced carp, river regulation, degradation of habitat, and barriers to fish passage have reduced their health.

Spotlight figure 17: Summary of composite fish condition ratings for the 15 NSW Murray–Darling Basin valleys 2015–17 and 2018–20



Source:
DPI Fisheries data 2021

Spotlight figure 17 summarises the composite fish condition index rating for the 15 Murray–Darling Basin river valleys in NSW for the current and the previous reporting periods. The overall condition of freshwater fish communities in these river valleys deteriorated between the reporting periods 2015–17 and 2018–20 with more than 90% (14 out of 15 valleys) rated as poor, very poor or extremely poor during the current reporting period.

No freshwater species, populations or ecological communities in NSW were added to the threatened species lists in the 2018–20 reporting period, although none recovered sufficiently enough to be downgraded or removed from the list. The biggest threats to the health, abundance and diversity of fish in NSW include river regulation, destruction of habitat, and the cumulative impacts from a changing climate.

The instances of water quality being below the standards for the nutrients phosphorus and nitrogen decreased during 2018–20, though this was mainly due to less runoff washing nutrients into waterways during the extended drought. Salinity levels over time were relatively stable in most streams surveyed with some variability due to site-specific processes.

Pressures

Multiple pressures work together to influence river health in NSW. The key pressures fall into two broad categories: alterations to natural flow patterns and disturbances to river systems and catchments; and the impact of climate variability and change.

Alterations and disturbances, such as water extraction, changed river flows, infrastructure and blockages from dams, weirs and works on floodplains, all affect natural river processes. Agricultural and urban runoff, urban development, industrial uses, clearing of riparian vegetation and introduced aquatic species have had negative impacts on water quality and aquatic and terrestrial biodiversity.

Activities and structures that destroy aquatic vegetation, block channels and waterways, and disturb the balance between sediment and water flows in rivers and estuaries are also key threats to fish habitats.

Floods, droughts and fire have always brought pressures to the health of river systems. These natural events are now being exacerbated by climate change and resource competition. Climate change is adding to existing stressors, particularly water availability pressures, catchment and riparian condition and the impacts of altered river flows. Most climatic projections suggest an increase in the frequency and severity of drought in NSW, including more frequent prolonged droughts and more short, sharp droughts. Heavy, damaging rainfall is also expected to increase.

The predicted outcome of these continuing pressures is long-term decline in the ecological health of NSW rivers and aquatic ecosystems.

Responses

The NSW Government has developed a framework for improved water management which includes the *NSW Water Strategy* (released September 2021), regional water strategies and associated plans and risk assessments.

Water sharing plans, developed for all NSW water sources, continue to be central tools for addressing river health in NSW. They underpin water resource plans and are complemented by Long Term Water Plans. Both have been developed to meet requirements of the Murray–Darling Basin Plan to better align basin-wide and state-based water resource management, including water for the environment.

Water management initiatives and programs have been implemented to balance human uses of water with water for the environment to maximise the outcomes for river and wetland health. Examples of these include:

- *NSW Diffuse Source Water Pollution Strategy*
- floodplain management planning
- risk assessments for inland water resources and coastal water-dependent ecosystems
- Catchment Action NSW funding for approved environmental works by landholders.

In NSW, water has been purchased or recovered for the environment through water recovery programs funded by the NSW Government and the Australian Government. The cumulative total of licensed environmental water in NSW is approximately 2,478,812 shares or megalitres entitlement (ML) in regulated rivers and about 74,362 ML in unregulated rivers. Water released to the environment aims to restore, maintain and improve river and wetland sites across the state.

The NSW Government has invested in additional climate data and modelling to further develop an understanding of past and future climatic conditions. When combined with the NSW Government's NARCLiM climate change projections, the modelling helps with the analysis of climate variability and estimating risks to future water availability, mitigation of those risks and the benefits of medium and long-term solutions.

This modelling has been used in the development of NSW Regional Water Strategies to inform options for water management to improve river health.

Related topics: Threatened Species | Native Fauna | Invasive Species | Water Resources | Wetlands | Climate Change

Wetlands

Wetland ecosystems support high levels of biodiversity, providing habitat for a wide range of animals including waterbirds, fish, frogs, turtles, invertebrates, and water-dependent plants.

Waterbird abundance

162,824

birds in 2020, below the long-term median of 272,493

Wetland area index of eastern Australia

104,015

hectares in 2020, below the long-term median of 224,794 ha

A return to drier weather conditions from 2017 affected the health of some wetland areas and reduced opportunities for waterbird breeding.

Why wetlands are important

The protection and sustainable management and use of wetlands is important as they provide a range of benefits to both the natural environment and people.

Wetland ecosystems support high levels of biodiversity, providing habitat for a wide range of animals including waterbirds, fish, frogs, turtles, invertebrates and water-dependent plants.They also play a key role in keeping the environment healthy, for example by regulating regional water cycles and climate and reducing the impact of storm damage and flooding. Wetlands are culturally significant for Aboriginal people and provide them with a strong connection to Country. They also contribute to regional economies by providing environments for commercial fisheries, grazing and tourism.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Wetland extent	MODERATE	Getting worse	✓
Wetland condition	MODERATE	Getting worse	✓

NSW indicators

Indicator and status		Environmental trend	Information reliability
Waterbird abundance and diversity	 POOR	Getting worse	✓✓✓

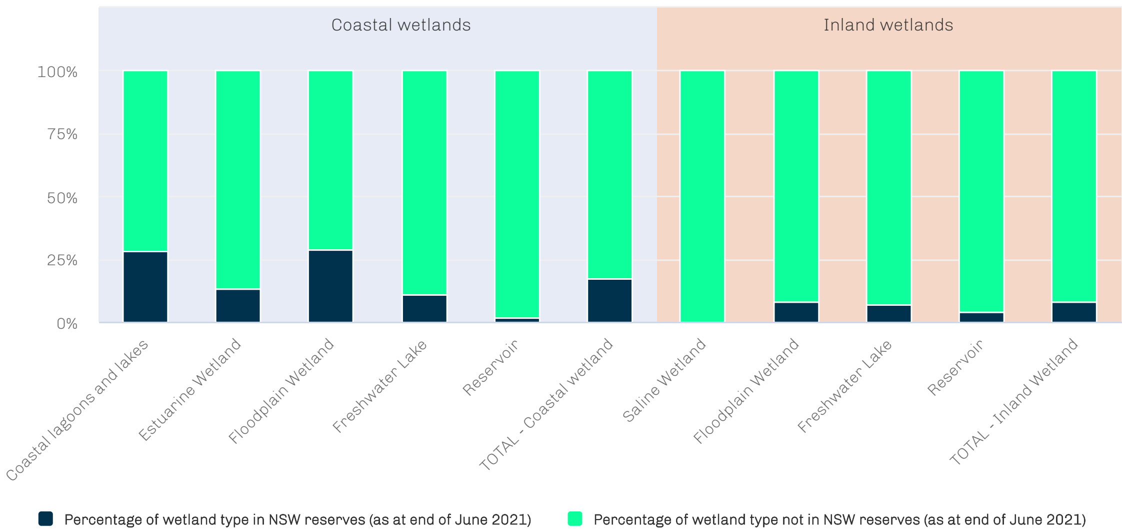
Notes:
Terms and symbols used above are defined in About this report.

Status and Trends

Eastern Australian Waterbird Survey data shows that the wetland area index across eastern Australia remained below the long-term median in 2020 and was the fifth-lowest since the survey began in 1983. However, the area of wetlands protected in the NSW parks estate increased between 2018 and 2020 with the addition of 209 hectares of coastal wetlands and 57,277 ha of inland wetlands.

Widespread rain and flooding during 2016 inundated many wetlands, increasing waterbird breeding. However, from 2017–19, drier conditions reduced the extent of wetland inundation and decreased waterbird breeding and waterbird abundance. Inland wetlands that have received water for the environment (held by the government and released in areas that need it) have acted as refuges for water-dependent species, including threatened frog species, during dry periods.

Spotlight figure 18: Percentage of coastal and inland wetland types in NSW reserves



Source:
East of the Great Dividing Range: Coastal Wetlands mapping | West of the Great Dividing Range: NSW Wetlands mapping | Reserves: National Parks and Wildlife Service

Spotlight figure 18 shows the percentage of coastal and inland wetland types protected in NSW reserves.

Pressures

Water availability is the most significant pressure on the health of many wetland ecosystems. Reduced water availability can be caused by altered flows from water extraction and the building of dams, levees and diversion structures, as well as by climate change, exacerbated by extreme weather events like heatwaves and droughts.

Other pressures on wetlands include human activities which can cause physical disturbance and adversely affect wetland water quality. For example, diffuse pollution from development and other land uses can raise the levels of nutrients and sediments entering wetlands. Lake bed cropping and floodplain clearing and grazing may also disturb soil, increase nutrients and impact vegetation and seed banks. Weed and invasive species are also threatening wetlands as they can affect wetland biodiversity and habitat value, ecosystem function and water quality.

Responses

A range of NSW Government legislation, policies and programs focus on protecting wetlands. For example, the *Water Management Act 2000* outlines requirements for water sharing plans for NSW rivers, one of the most important mechanisms for protecting wetlands; the NSW Wetlands Policy promotes the sustainable conservation, management and use of wetlands and the Marine Estate Management Strategy 2018–2028 and Catchment Action NSW improve and protect wetland water quality.

The Australian Clean Energy Regulator is currently finalising a method to enable landholders to claim carbon credits under the Emissions Reduction Fund for restoring some types of 'blue carbon' systems, specifically mangrove and saltmarsh. Any such future blue carbon projects in NSW would increase the state's wetland areas while removing carbon from the atmosphere and mitigating climate change.

Related topics: Water Resources | River Health

Groundwater

Used in agriculture and industry, groundwater is also the main water supply for many NSW regional communities and depended on for survival by important ecosystems.

Summary

Groundwater-dependent ecosystems

>90%

of the probable extent of dependent ecosystems in NSW has been mapped

Groundwater use in NSW

27%

of all metered water use comes from groundwater

Groundwater is often forgotten as it remains out of sight for most of its existence. It seeps (recharges) into the bedrock and may only appear as baseflow, adding to a river's flow, or emerging from a spring. Sometimes it may be tapped into by a bore or it might bubble up from a mound spring or at the coast through sands. Or it may sit just below the surface in shallow or perched permeable rock (aquifers).

Why groundwater is important

Groundwater can occur in dry landscapes across NSW and sometimes appears as a desert oasis and as the only source of water. Aboriginal people have always known about groundwater. It's been part their Dreaming, their stories, lore, dances and art for up to 65,000 years or since time immemorial (or Day One). The understanding Aboriginal people have of connected water through thousands of generations of observation is something to celebrate, especially knowing that deep groundwater, such as in the Great Artesian Basin, is very old or ancient water.

The cultural and spiritual connection Aboriginal people have with groundwater ranges from a source of water for survival or economic benefit, to dreaming stories where cultural heroes and creators exist, such as the Rainbow Serpent. With this strong Aboriginal connection, the SoE Aboriginal Peoples Knowledge Group has put forward that NSW water managers must protect groundwater quality and quantity from impactful drawdown, pollution from industry, mining and agriculture and over-extraction to ensure cultural values of groundwater are protected.

Overall average annual extraction from metered groundwater sources in NSW is being managed under the compliance rules in water sharing plans. Knowledge of NSW groundwater-dependent ecosystems has improved, but some uncertainty remains about their extent and condition.

In NSW there are water sharing plans that manage groundwater and surface water. There are 14 Regions identified by NSW, each with a number of surface water and groundwater plans. Aboriginal people currently have little say in groundwater management and even less ownership of groundwater resources. This is in spite of their long, deep connection with it.

Groundwater is an important source for communities' water supply, especially during droughts. Throughout NSW, 180 towns and villages rely on groundwater as their main water source for farming, irrigation and domestic use.

Certain ecosystems (groundwater-dependent ecosystems) depend either partially or mostly on the availability of groundwater to function when surface water is scarce.

NSW indicators

Indicator and status		Environmental trend	Information reliability
Long-term extraction limit: Entitlement	GOOD	Stable	✓✓
Aquifer integrity	GOOD	Stable	✓
Groundwater quality	MODERATE	Stable	✓
Condition of groundwater-dependent ecosystems*	UNKNOWN	Unknown	✓

Notes:
Terms and symbols used above are defined in
About this report
.

*While the condition of some groundwater-dependent ecosystems is known at a local level, the information in this report takes a statewide perspective

Spotlight figure 19 shows that groundwater extraction levels can fluctuate dramatically due to factors such as local sustainability levels and climatic conditions such as drought.

Status and Trends

Groundwater extraction increased between 2017–18 and 2019–20, reflecting significant demand for groundwater during a period of severe drought.

Water sharing plans ensure that groundwater use is managed within the long-term average annual extraction limit of the source. Extraction from some of the inland alluvial groundwater sources of the Murray–Darling Basin and one porous rock groundwater source fluctuates around local sustainability limits. However, the overall level of groundwater extracted from all metered groundwater sources in NSW is much lower than the cumulative sustainable extraction limits.

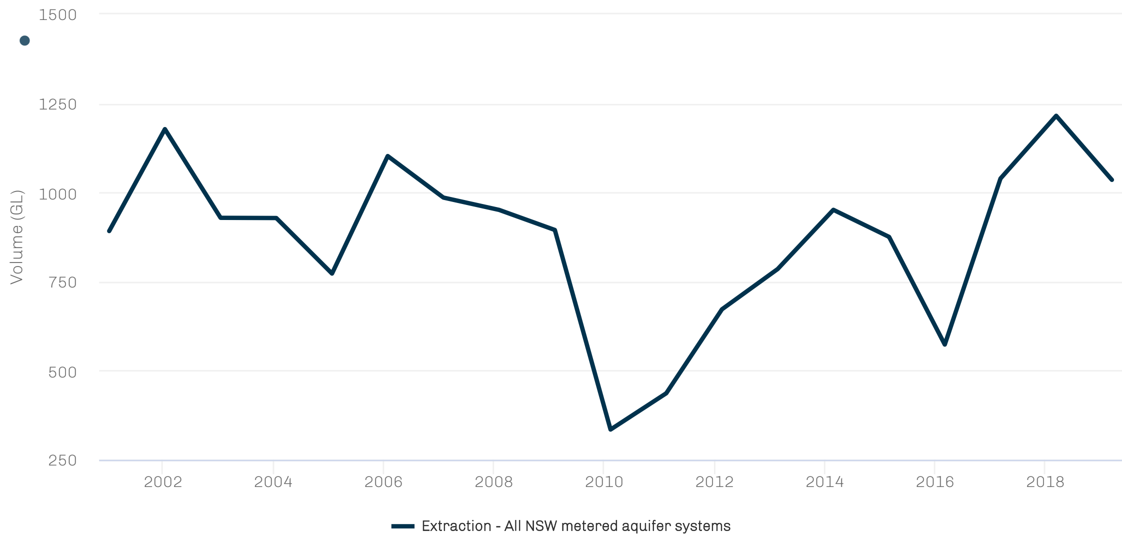
Eleven water resource plans focusing on groundwater sources in the Murray–Darling Basin were developed in 2020 and submitted for Commonwealth accreditation. These will set out arrangements to share water for consumptive uses, establish rules to meet environmental and water quality objectives and take into account potential and emerging risks to water.

Demand for groundwater increased significantly between 2017–18 and 2019–20 from roughly 11% of the state's overall metered water use to 27%, mainly due to extended and severe drought.

Overall, the quality of known groundwater sources is moderate, while the aquifer integrity is stable.

Water sharing plans rely heavily on groundwater sources. These plans manage the average annual extraction limits from metered groundwater sources under their compliance rules. Extraction from some inland alluvial groundwater sources in the Murray–Darling Basin and one porous rock groundwater source can at times exceed local sustainability limits. However, the overall level of groundwater extracted from all metered groundwater sources in NSW is much lower than the cumulative sustainable extraction limits.

Spotlight figure 19: Annual levels of NSW groundwater extraction from all metered groundwater systems 2001–02 to 2019–20



Source:
WaterNSW – Water accounting system data June 2021

Pressures

Factors affecting the quality and availability of groundwater include excessive demand and extraction, saline intrusion and chemical contamination.

Responses

The *Water Management Act 2000* legislates that all groundwater sources must be managed sustainably. Under the *Contaminated Land Management Act 1997*, contaminated groundwater must be reported to the Minister administering the Water Management Act.

Other responses include various policies and programs.

- The NSW State Groundwater Dependent Ecosystems Policy contains guidelines to protect and manage groundwater-dependent ecosystems.
- The NSW Aquifer Interference Policy balances the water requirements of towns, farmers, industry and the environment.
- The Cap and Pipe the Bores Program provides financial incentives for landowners to offset the costs of replacing uncapped artesian bores and open drains with rehabilitated bores and efficient pipeline systems.

Eleven water resource plans for groundwater sources in the Murray–Darling Basin were developed in 2020 and submitted for Commonwealth accreditation. These set out arrangements to share water, rules to meet environmental and water quality objectives and potential and emerging risks to groundwater quality and availability.

Related topics: Water Resources | Wetlands | Coastal, Estuarine and Marine Ecosystems

Coastal, Estuarine and Marine Ecosystems

The coastal, estuarine and marine waters of NSW contain high levels of biodiversity due to their wide range of oceanic, shoreline and estuarine habitats, and their subtropical and temperate current influences.

Recreational water quality

89%

of monitored swimming sites scored very good or good for recreational water quality in 2019–20

Marine species

47

marine species are listed as threatened under NSW legislation

Saltmarsh in estuaries

38%

of estuaries mapped in the past five years have shown a decrease in areas of saltmarsh

Estuarine water quality

71%

of estuaries in NSW had water quality rated as being in good condition

Water quality and ecosystem health in marine and beach environments are generally good. The condition of NSW estuaries, coastal lakes and lagoons is more variable with more disturbance and negative impacts.

Why coastal, marine and estuarine ecosystems are important

The coastal, marine and estuarine waters of NSW contain high levels of biodiversity due to their diverse range of oceanic, shoreline and estuarine habitats and the influence of subtropical and temperate currents. These varied environments and the habitats they support provide many important ecosystem services, such as:

- mitigating coastal and seabed erosion
- maintaining coastal water quality and healthy aquatic ecosystems
- acting as critical habitats for fish and other marine life
- providing recreation, visual amenity and food production.

NSW indicators			
Indicator and status		Environmental trend	Information reliability
Percentage of ocean and estuarine beaches with beach suitability grades for swimming of good or better	GOOD	Stable	✓✓✓
Estuarine water quality (chlorophyll *a* and turbidity)*	MODERATE	Stable	✓✓✓
Extent of estuarine macrophytes	MODERATE	Stable**	✓✓
Levels of estuarine catchment disturbance	MODERATE	Getting worse	✓✓

Notes:
Terms and symbols used above are defined in About this report.

* Water quality by algae (chlorophyll *a*) and water clarity (turbidity).
** Stable reflects a variable result with extent decreasing in some areas and increasing in others.

Status and Trends

Recreational water quality is rated as 'very good' or 'good' at 89% of NSW beaches. The Beachwatch program ratings are based on levels of pollution from stormwater runoff and sewage contamination (enterococci data). The results show that 98% of ocean beaches and 85% of estuaries are rated 'very good' or 'good' but that only 42% of coastal lakes and lagoons are rated at this level. This indicates that the majority of coastal lakes and lagoons were susceptible to faecal pollution, with water quality not always suitable for swimming.

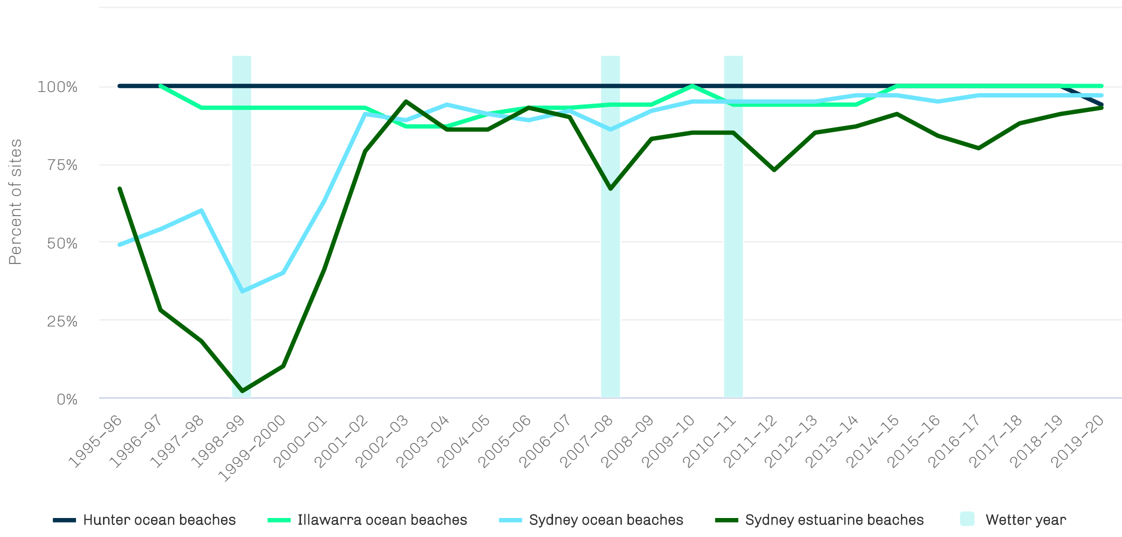
The condition of individual estuaries and coastal lakes is highly variable and depends on their level of resilience to change and the level of disturbance of their catchment. The health of estuarine ecosystems is heavily influenced by water quality. The NSW Government's Estuary Health Monitoring Program monitors estuarine water quality by algae (chlorophyll *a*) and water clarity (turbidity) showing 71% of estuaries are in good condition and 10% of estuaries are in poorer condition. Other parameters that impact water quality fall outside this program, such as acidity (pH), pesticides, herbicides, heavy metals and other contaminants.

Aquatic plants have a role in maintaining water quality and sediment stability and supporting aquatic biota. The impacts of climate change and sea temperature rise are contributing to loss of kelp. Kelp is also being lost from offshore reefs on the mid-north coast, correlating with increases in populations of herbivorous fish.

Long-term trends show mangroves have been spreading in many NSW estuaries, often into areas of saltmarshes, and may be related to various human activities and sea level rise. Matching upslope migration of saltmarsh is often constrained by public infrastructure and land uses; and also less evident than mangrove spread. The 2019–20 bush fire season saw some of the most extensive and intense fires recorded in NSW with blazes occurring in areas that would not have usually burnt due to the ferocity of the fires. In coastal areas, this can be seen in the burnt or heat effects on mangroves and varied impacts on saltmarsh. The largest areas affected by fire include 71% of saltmarsh and 32% of mangroves in Wonboyn Lake and 48% of saltmarsh at Berrara Creek, 40% at Lake Tabourie and 38% at Khappinghat Creek.

Forty-seven marine species or populations are currently listed as threatened under NSW legislation, including 22 marine seabird species, eight fish species, seven marine mammal species, three reptile species and seven other species. See Threatened Species topic.

Spotlight figure 20: Percentage of Sydney, Hunter and Illawarra beach and estuary monitoring sites rated with low levels of faecal contamination 1995–96 to 2019–20



Notes:
Includes Beachwatch Program data. Data from the Beachwatch Partnership Program is not included.

Source:
DPIE 2021

Spotlight figure 20 shows the percentage of sites with low levels of faecal contamination over the past 25 years at ocean and estuarine beaches in Sydney, the Hunter and the Illawarra. Microbial Assessment Categories are used to determine levels of enterococci found in faecal matter in water and, to determine levels over time, the categories have been applied to historical enterococci data. Microbial Assessment Categories A and B indicate generally low levels of faecal contamination, and are part of the assessment for a swimming site to achieve a beach suitability grade or rating of 'very good' or 'good'.

The trend shows a significant reduction in bacterial levels at swimming locations in the Sydney region since 1998–99, with most fluctuations due to rainfall patterns and the associated variation in the frequency and extent of stormwater and wastewater inputs. Significant changes in recreational water quality occurred around 2000 and was mostly attributed to large-scale sewage infrastructure works.

Pressures

The greatest threats to the coastal and marine environment come from land-use intensification, resource use activities and climate change. Most coastal and estuarine areas have been modified to some extent, increasing pressure on the species that depend on them. Coastal development and land use continue to affect the viability of faunal populations, including threatened species. Only about one in five estuaries and coastal lakes retains more than 90% of natural, uncleared vegetation in their catchments, mostly along the south coast.

The desirability of coastal lifestyles and increasing settlement along the coast are placing estuaries and coastal lakes under higher levels of stress. The waters and ecosystems near urban, industrial and agricultural areas are particularly exposed to the effects of pollution from urban and agricultural runoff, stormwater and sewage discharge. The main threats to coastal, estuarine and marine waters are:

- land-use intensification, point discharges, poor diffuse water quality discharges and hydrologic modification mostly via floodplain drainage
- resource use, activities including shipping, boating, fishing, aquaculture, recreation and tourism, dredging, mining, flow modification, entrance modification and infrastructure

- climate change resulting in altered ocean currents and nutrients, air and sea temperature rise, ocean acidification, altered storm and cyclone activity, sea level rise, coastal erosion, flooding and storm inundation (MEMA 2017).

Responses

NSW has frameworks and legislation to manage the marine estate, with objectives for coastal management, environment protection and fisheries management. Strategies in place include coastal management programs, the Marine Estate Management Strategy , Marine Water Quality Objectives, waterway health outcomes and risk-based frameworks to consider waterway health. Sustainability in the marine environment is also considered across commercial fisheries, harvest strategies and sustainable aquaculture strategies.

Marine-protected areas comprise a large network of marine parks and aquatic reserves to conserve biodiversity and maintain ecosystem function and the integrity of bioregions in NSW waters. See Protected Areas and Conservation topic.

Related topics: **Protected Areas and Conservation** | **Invasive Species** | **Climate Change** | **Fire** | **Threatened Species**

Appendices

soe.epa.nsw.gov.au

Net Zero Plan Stage 1: 2020–2030

The Net Zero Plan requires NSW State of the Environment to report on the plan's implementation and progress towards meeting its net zero emissions goal.

Summary

NSW greenhouse gas emissions projected to be abated by the plan

28.6–37.3 Mt CO_2-e

in 2030

Greenhouse gas emissions in 2030 are projected to be

47–52% lower

than in 2005

The NSW Government has an objective to achieve a 50% reduction in emissions on 2005 levels by 2030 and to reach net zero emissions by 2050. The *Net Zero Plan Stage 1: 2020–2030* is the foundation for NSW action on climate change. Under current policy settings, NSW emissions in 2030 are projected to be 47–52% lower than 2005 levels. This will put NSW on the path to achieving net zero emissions with further action and investment in decarbonisation initiatives needed to reach net zero emissions by 2050.

The *Net Zero Plan* highlights the NSW Government's commitment to maintaining a strong economy, improving the quality of life for the people of NSW and protecting the environment. Initiatives under the plan will reduce emissions and also grow the economy and create jobs over the next decade.

NSW greenhouse gas emissions in 2018–19 were inventoried to be 136.6 million tonnes carbon dioxide-equivalent (CO_2-e) or 16.9 tonnes CO_2-e per capita. Emissions peaked in 2007 and in 2019 were 17% lower than in 2005.

Projections show that taking a business-as-usual approach will reduce emissions to 30% below 2005 levels by 2030. NSW Government policies under the *Net Zero Plan*, including the *NSW Electricity Infrastructure Roadmap*, will deliver further emission reductions. Total NSW emissions are projected to fall to 78.9–87.6 Mt CO_2-e by 2030, which is 47–52% below 2005 levels. Overall output of carbon dioxide in the atmosphere will continue to rise under both scenarios, contributing to greater concentrations of carbon dioxide and amplifying the effects of climate change. However under the net zero plan CO_2-e emissions produced each year in NSW are projected to be 47–52% below 2005 levels, reducing the annual emissions rate to 78.9–87.6 Mt CO_2-e by 2030.

Stage 1 of the *Net Zero Plan* will put NSW on the path to achieving net zero emissions by 2050 through investment in new technologies, including energy systems and low emission ways of living. However projections show that further effort and investment will be required in the decades beyond 2030 to achieve the net zero emissions objective.

Related topics: Energy Consumption | Climate Change | Greenhouse Gas Emissions

Context

Released in March 2020, the *Net Zero Plan Stage 1: 2020–2030* (DPIE 2020a) is the foundation for NSW Government action on climate change over the next decade. It sets the state up to achieve its objective of halving emissions on 2005 levels by 2030 and its long-term objective of reaching net zero emissions by 2050.

The plan, which aims to strengthen the prosperity and quality of life for the people of NSW, has four key priorities. Priority

1: Drive the uptake of proven emissions reduction technologies

Priority 2: Empower consumers and businesses to make sustainable choices

Priority 3: Invest in the next wave of emissions reduction innovation

Priority 4: Ensure the NSW Government leads by example

These priorities support initiatives that will reduce emissions across the areas of electricity and energy efficiency, transport, primary industries and land, clean technology and industry innovation, buildings and planning systems, organic waste and sustainable finance.

The *Net Zero Plan* delivers on the objectives of the *NSW Climate Change Policy Framework* (OEH 2016), which sets out the policy directions for action to mitigate and adapt to climate change. This includes the long-term objectives of NSW being more resilient to a changing climate and achieving net zero emissions by 2050.

Policies under the plan are also being delivered as part of the *NSW Electricity Infrastructure Roadmap* , *NSW Electric Vehicle Strategy* and *NSW Waste and Sustainable Materials Strategy 2041* . For more about these and other plans and strategies, go to the Greenhouse Gas Emissions, Energy Consumption, Transport and Waste and Recycling topics.

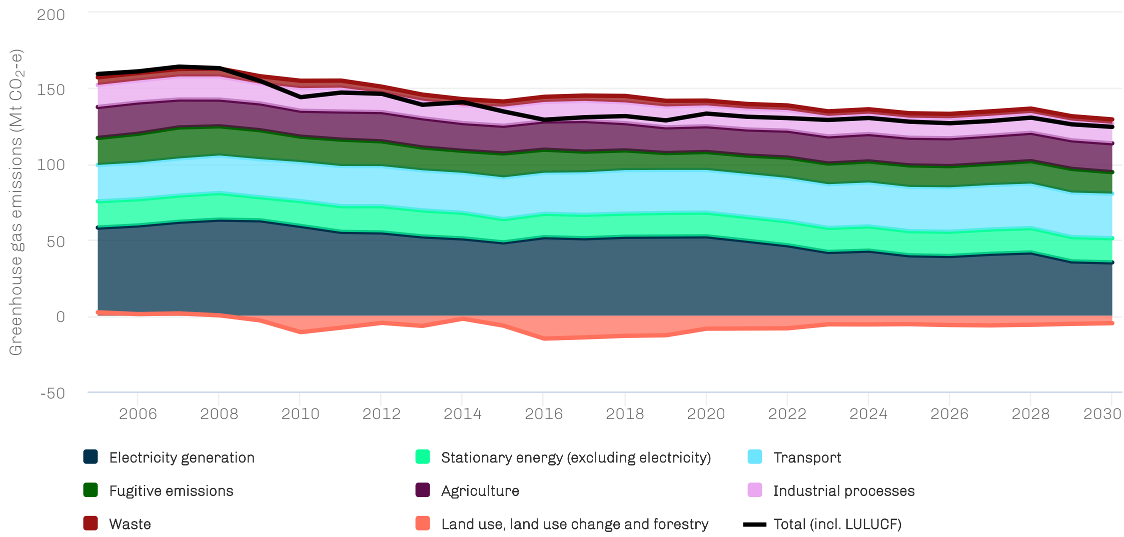
NSW emission projections

In 2018–19, NSW net greenhouse gas emissions were inventoried to be 136.6 megatonnes carbon dioxide-equivalent (CO_2-e), representing 26% of Australia's total emissions. Per capita NSW emissions, including land use, land-use change and forestry, stood at 16.9 tonnes CO_2-e, below the national average of 20.9 tonnes. Emissions peaked in 2007 and in 2019 were 17% lower than 2005 levels.

In 2018–19, stationary energy (mostly from electricity generation) was the largest source of emissions in NSW at 49% of the total, followed by emissions from transport (20%), agriculture (12%), industrial processes and product use (9%) and fugitives from coal and gas (9%) – see **Figure 23.1**. The land use, land-use change and forestry sector is currently a carbon 'sink' as it stores more carbon than it emits and thus reduces the state's emissions by 3%.

Four of NSW's five coal-fired power stations that currently provide around three-quarters of the state's energy supply are scheduled to close by 2035. This provides enormous potential to decarbonise the electricity sector.

Figure 23.1: Net NSW greenhouse gas emissions as inventoried (2005–2019) and projected with Net Zero Plan Stage 1 policies implemented (2020–2030)



Notes:
Non-CO_2 emissions are expressed as CO_2 equivalents using 100-year global warming potential values from the IPCC Fifth Assessment Report.
Emissions projections were prepared using the latest activity data and assumptions based on the advice of NSW and Australian government agencies. The projections are modelled to indicate what NSW future emissions could be if the assumptions underpinning the projection occur. It is dissimilar to a forecast, which predicts actual future events and changes. Projections are given as a range – for simplicity a central estimate of emission projections is shown for 2020–2030 and discussed in the related text.
References to a particular year refer to financial year, i.e. the 12 months ending 30 June of that year

Source:
Emissions to 2019 are as inventoried by the Australian Department of Industry, Science, Energy and Resources (Australian Greenhouse Emissions Information System).
| Emission projections for 2020 to 2030 are based on NSW Department of Planning, Industry and Environment modelling and analysis.

Projections show that, if a business-as-usual approach is followed, NSW emissions will fall to 30% below 2005 levels by 2030. This is because industry and the electricity sectors are already decarbonising by moving to more reliable and affordable sources of energy. Australia's three biggest trading partners, China, Japan and South Korea, have all committed to net zero emissions targets. It is important that NSW manages the risk this poses to our economy and takes advantages of new opportunities.

NSW Government policies under the *Net Zero Plan*, including the *NSW Electricity Infrastructure Roadmap* (DPIE 2020b), are projected to deliver further emission reductions taking the total to 78.9–87.6 Mt CO_2-e in 2030, which is 47–52% lower than in 2005.

Further information on the status of emissions in NSW and projected emissions to 2030 taking current policies in the plan into account is available in the Greenhouse Gas Emissions topic.

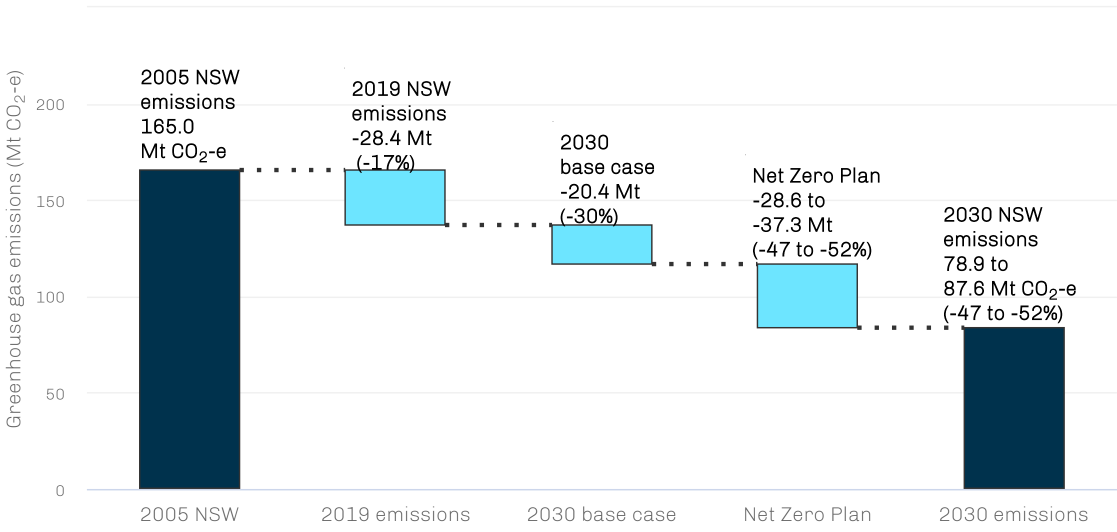
Impact of the Net Zero Plan

Emissions reduction

Upon its launch, the *Net Zero Plan Stage 1: 2020–2030* (DPIE 2020a) was forecast to reduce total NSW emissions by 35.8 Mt CO_2-e by 2030, which is 35% below 2005 levels. However, since the plan's publication, further modelling and analysis on trends in NSW emissions and the likely impact of the plan have revised projections significantly.

By 2019, total NSW emissions had already fallen by 28.4 Mt CO_2-e or 17% below 2005 levels (see **Figure 23.2**). 'Base case' trends in NSW emissions, which exclude the impact of the plan, are now projected to result in a further reduction of 20.3 Mt CO_2-e reduction in annual emissions by 2030 (**Figure 23.2**).

Figure 23.2: Projected reductions in annual NSW emissions in 2030 under base case and Net Zero Plan scenarios



Notes:
Emissions are expressed as CO_2 equivalents using 100-year global warming potential values from the IPCC Fifth Assessment Report and are given for financial year 2030. Emissions projections were prepared using the latest activity data and assumptions based on the advice of NSW and Australian government agencies. The projections are modelled to indicate what NSW future emissions could be if the assumptions underpinning the projection occur.

The graph depicts a central estimate of the emission reductions as a result of *Net Zero Plan Stage 1*, with lower and upper emission reduction projections referenced in the text on the graph.

Source:
Emission projections for 2020–2030 are based on NSW Department of Planning, Industry and Environment modelling and analysis.

Factors contributing to the downward revision of the NSW emissions trajectory include:

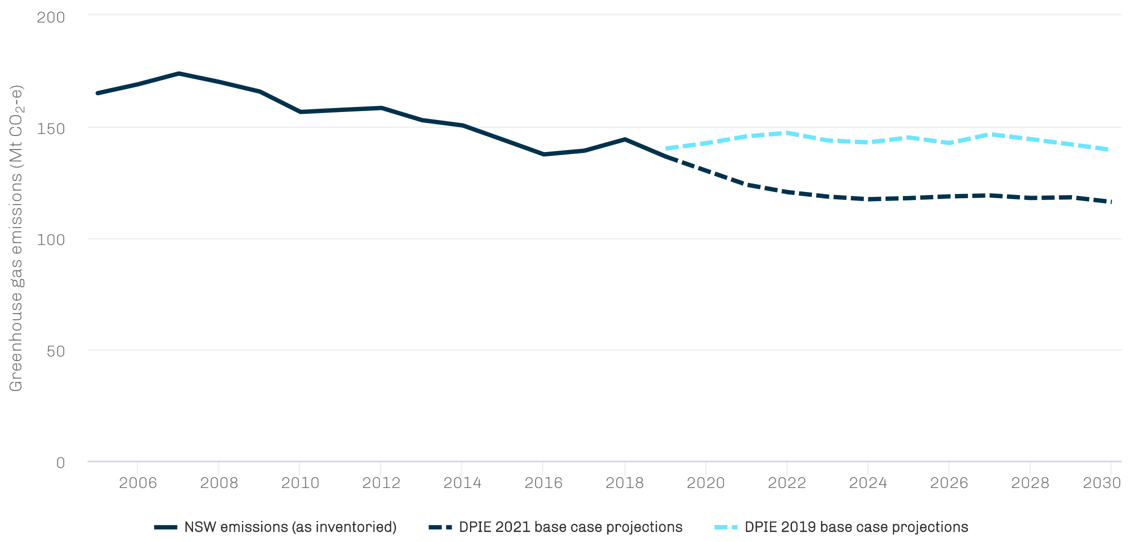
- lower electricity generation emissions due to a higher than expected increase in rooftop solar and updated projections by the Australian Energy Market Operator indicating more rapid growth in the renewables share of the National Electricity Market (AEMO 2021)
- lower agricultural emissions in the near term due to the impact of the recent drought on livestock numbers and crop productivity (DISER 2021b, 2021c)
- upgraded base case rates for electric vehicle uptake and downgraded coal production outlooks in response to global technology and energy market trends (IEA 2021).

Initiatives in the *Net Zero Plan* are projected to deliver further reductions in annual NSW emissions of between 28.6 and 37.3 Mt CO_2-e by 2030. Accounting for base case trends and NSW Government initiatives under the plan, total annual NSW emissions are projected to fall to 78.9–87.6 Mt CO_2-e in 2030, which is 47–52% lower than 2005 levels (**Figure 23.2**).

Forecast emission reductions under the plan include abatement from a range of initiatives including the *NSW Electricity Infrastructure Roadmap*, the Net Zero Industry and Innovation Program, *NSW Electric Vehicle Strategy*, and policies under the *NSW Waste and Sustainable Materials Strategy 2041*.

The projected emission reductions under *Net Zero Plan* initiatives do not include the impact of some policies still in development. For example, the estimate includes the impact of developing hydrogen hubs under the NSW Net Zero Industry and Innovation Program but does not account for the full impact of the NSW Hydrogen Strategy published in October 2021 or the NSW Renewable Gas Certification Scheme announced in June 2021. Both were still under development at the time of the modelling and analysis.

Figure 23.3: 2019 and 2021 base case projections for NSW emissions (that is, without the Net Zero Plan)



Notes:

Emissions are expressed as CO_2 equivalents using 100-year global warming potential values from the IPCC Fifth Assessment Report and are given for financial years.

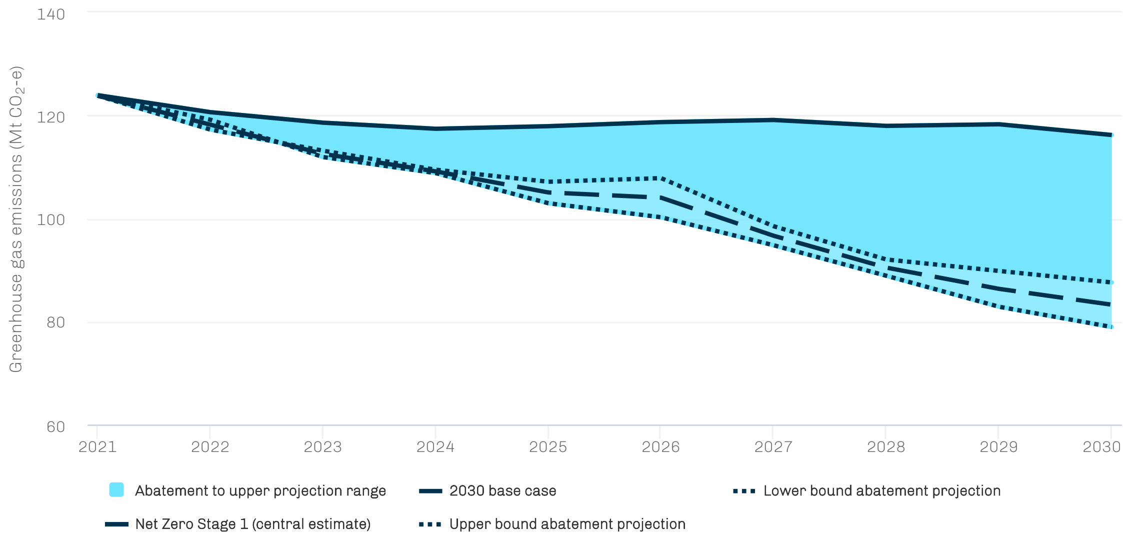
Emissions projections were prepared using the latest activity data, assumptions and advice at the time of their derivation. The projections are modelled to indicate what NSW future emissions could be if the assumptions underpinning the projection occur. The graph depicts NSW emissions as inventoried and published within the National Greenhouse Accounts (2005--2019) and base case projections developed by the NSW Department of Planning, Industry and Environment in 2019 and 2021.

Stage 1 of the *Net Zero Plan* will put NSW on the path to net zero emissions by 2050 through investment in proven and new emissions reduction technologies, energy systems and low emission ways of living (Figure 23.4). A large proportion of emission reductions this decade will come from reducing emissions associated with stationary energy.

Annual emission reductions to be delivered by the plan are projected to increase over the next decade as initiatives are implemented:

- coal-fired power stations close and renewable energy generation ramps up
- the share of electric vehicles on the road increases
- carbon markets expand, supporting greater carbon sequestration by the land sector
- technologies for abating agricultural, industrial and mining emissions mature
- more organic waste is diverted from landfill
- a growing number of households and businesses reduce their electricity and gas use under the expanded Energy Security Safeguard
- more consumers and businesses are empowered to make sustainable choices.

Figure 23.4: Projected reductions in NSW emissions due to NSW Government action between 2021 and 2030



Notes:
Emissions are expressed as CO_2 equivalents using 100-year global warming potential values from the IPCC Fifth Assessment Report and are given for financial years.
Emissions projections are prepared using the latest activity data and assumptions based on the advice of NSW and Australian government agencies. The projections are modelled to indicate what NSW future emissions could be if the assumptions underpinning the projection occur. The graph depicts base case and current policy projections to 2030 given emission reductions to be delivered by the Net Zero Plan Stage 1, including central estimates and upper and lower bound projections of the emission reductions.

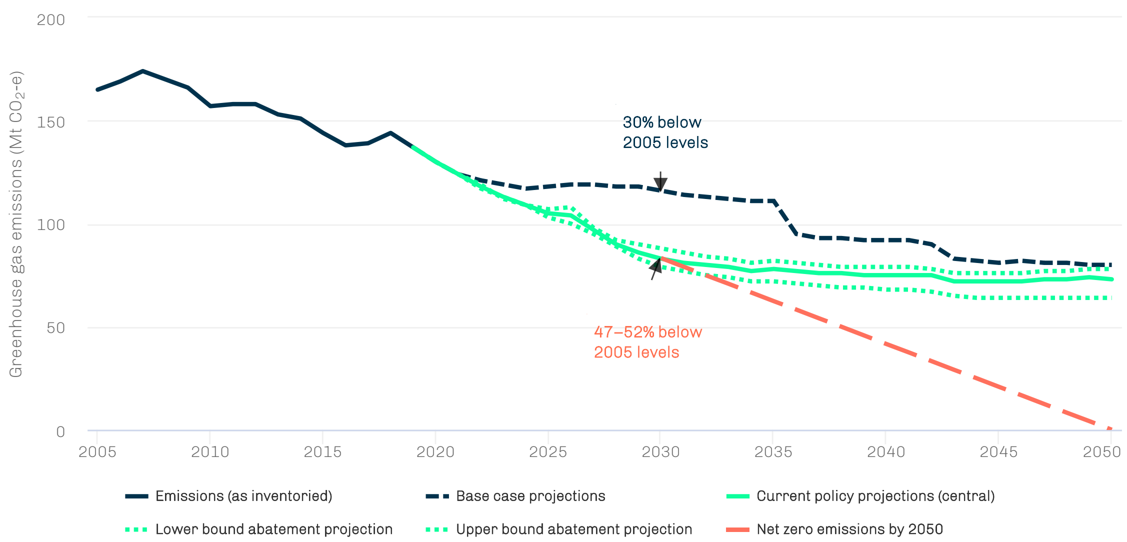
Emissions reduction beyond 2030

With the initiatives in Stage 1 of the *Net Zero Plan* implemented and emissions at 47–52% below 2005 levels, reductions will need to continue beyond 2030. Projections show that further effort and investment will be required in the following decades to achieve the reductions necessary to meet the net zero objective by 2050 (see Figure 23.5).

Projections indicate that action beyond current policies will be needed to address emissions from most sectors, including heavy duty vehicles, agriculture, stationary energy, industry, mining, aviation and land clearing (see Figure 23.6). More support may also be required to bolster carbon sequestration and support the expansion of premium carbon markets.

The International Energy Agency notes that, while technologies on the market today can offer immediate emission reductions, almost half the reductions needed to meet a global goal of net zero by 2050 will need to come from technologies that are currently at the demonstration or prototype phase (IEA 2021). This means that major innovation efforts will be required this decade to develop new technologies and bring them to market. Stages 2 and 3 of the Net Zero Plan will be developed ahead of 2030 and 2040 to address this challenge.

Figure 23.5: Projected NSW emissions to 2050 under base case and current policy scenarios and the path ahead to net zero emissions by 2050

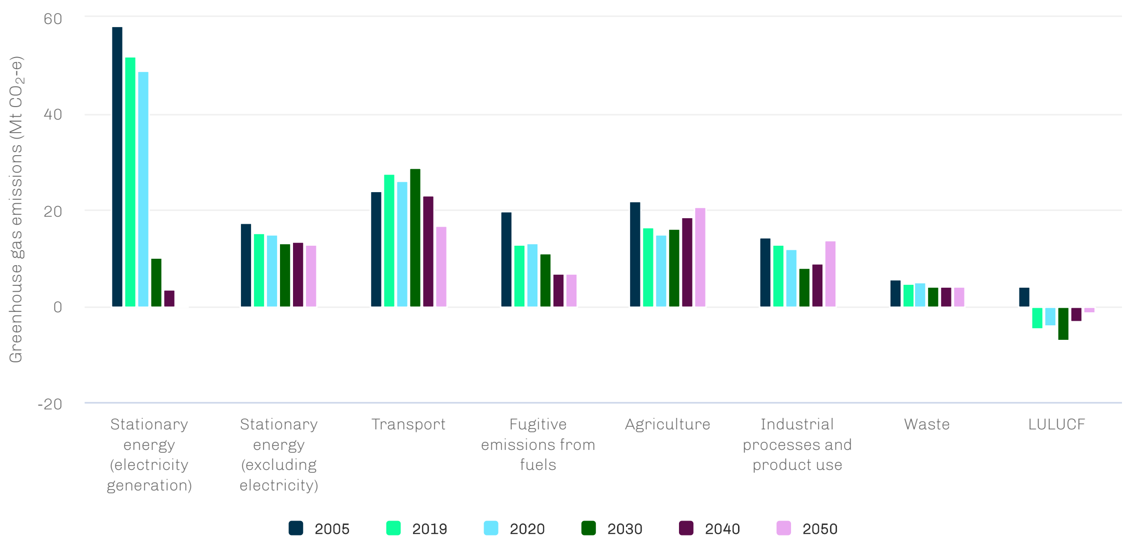


Notes:

Emissions are expressed as CO_2 equivalents using 100-year global warming potential values from the IPCC Fifth Assessment Report and are given for financial years.

Emissions projections are prepared using the latest activity data and assumptions based on the advice of NSW and Australian government agencies. The projections are modelled to indicate what NSW future emissions could be if the assumptions underpinning the projection occur. The graph depicts base case and current policy projections to 2050 given emission reductions to be delivered by *Net Zero Plan Stage 1*, including central estimates and upper and lower bound projections of the emission reductions.

Figure 23.6: Projected NSW emissions by sector with current policies implemented



Notes:

LULUCF = Land use, land-use change and forestry

Emissions are expressed as CO_2 equivalents using 100-year global warming potential values from the IPCC Fifth Assessment Report and are given for financial years.

Emissions projections are prepared using the latest activity data and assumptions based on the advice of NSW and Australian government agencies. The projections are modelled to indicate what NSW future emissions could be if the assumptions underpinning the projection occur. The graph depicts current policy projections taking into account central estimates of the emission reductions projected to be delivered by *Net Zero Plan Stage 1*.

A report by the Office of the NSW Chief Scientist and Engineer (OCSE) – Decarbonisation Innovation Study (OCSE 2020) – details economic opportunities associated with decarbonisation and climate adaptation across all sectors of the NSW economy, including services, electricity, industry, the built environment, land and transport. OCSE will update this report every two years to inform future policy and program design.

Economic impacts

Apart from helping to ameliorate the impacts of climate change by contributing to global reduction in emissions, current NSW efforts are expected to bring significant economic benefits to the state. These will be in the form of short- and long-term job creation as the result of increased economic activity. Likely benefits will not be confined to metropolitan areas, as significant investment is forecast in the regions. For example, planned Renewable Energy Zones, hydrogen hubs and land sector offset projects will primarily occur in regional NSW.

The following metrics will be reported on to determine the economic impact of the *Net Zero Plan*:

- $ per tonne of CO_2-e reduced
- jobs created in metropolitan and regional NSW
- government investment in metropolitan and regional NSW
- non-government investment in metropolitan and regional NSW
- increased economic activity in metropolitan and regional NSW.

Other environmental impacts

Initiatives under the *Net Zero Plan* will have environmental benefits, including improvements in air quality, biodiversity and soil health. The NSW Government will develop metrics to measure and evaluate the environmental impacts of these initiatives

Air quality

Air quality is determined by the types and amounts of pollutants emitted into the atmosphere. The main sources of human-made pollutants come from industry, motor vehicles, other transport and domestic wood smoke. Climate change also impacts air quality, with extreme climate-related events, such as bushfires and dust storms, worsening air pollution across large areas of the state.

Air pollution is known to shorten the lives of people in NSW. It has been estimated (Broome et al. 2020) that 5,900 years of life are lost each year due to long-term exposure to fine particles in the NSW Greater Metropolitan Region (GMR). This equates to a mortality effect equivalent to 420 premature deaths. Air pollution from fine particles is estimated to result in $3.3 billion in health costs each year in the GMR. Read more about the health impacts of air pollution in the Air Quality topic.

The *Net Zero Plan* will deliver improvements in air quality by supporting the transition to cleaner energy, industry and transport. This in turn will reduce the associated health costs, hospitalisations and deaths attributable to poor air quality.

As NSW transitions to net zero emissions, further work will develop measures to track the associated air quality and health benefits of reducing human exposure to fine particles and other air pollutants.

Electric vehicles, cleaner air and health benefits

Reducing tailpipe emissions from vehicles through initiatives outlined in the *NSW Electric Vehicle Strategy* will deliver significant health benefits for NSW. All vehicles contribute to air pollution through road, brake and tyre wear. The transition to battery and fuel cell electric vehicles will reduce the health impacts of air pollution with an end to tailpipe emissions of particle and gaseous air pollutants from petrol and diesel vehicles.

Statistics show that in 2013 motor vehicles accounted for 55% of Sydney's anthropogenic nitrogen oxide (NOx) emissions, 13% of volatile organic compound (VOC) emissions and 13% of particulate matter ($PM_{2.5}$) emissions (EPA 2019) – all of which have direct and indirect effects on the health of the community. Motor vehicles are also a significant contributor to fine particle and ozone pollution in the Sydney basin (Chang et al. 2019; Duc et al. 2018). Moreover, about 70 premature deaths each year are associated with long-term exposure to vehicle pollution in the NSW Greater Metropolitan Region, with vehicle exhaust emissions contributing 69% of the fine particle exposures associated with these deaths (Broome et al. 2020).

Biodiversity and soil health

Biodiversity refers to the variety of living animal and plant life and the complex interactions that make up the natural environment. Soil degradation is the decline in soil condition caused by its improper use or poor management, usually for agricultural, industrial or urban purposes. Soils and native vegetation are natural carbon sinks.

Climate change, pollution, invasive species and habitat clearing through intensified agricultural activity and urban expansion are pressures that are having an impact on biodiversity in NSW. Likewise, business-as-usual land management practices and climate change will exacerbate the loss of the soil's organic carbon and thus reduce productivity. It is important to protect biodiversity and soil heath so that environmental services which support human health, wellbeing and traditional cultures can continue to provide and thrive for future generations.

Initiatives under the *Net Zero Plan* in the agriculture and land sectors will support landholders and traditional owners to protect and manage biodiversity and soil health on their lands while reducing emissions. Carbon farming is one example of this. It aims to reduce greenhouse gas emissions by sequestering or capturing emissions in vegetation and soils. Such initiatives can mitigate land degradation by encouraging landholders to retain and enhance native vegetation on their land, improve groundcover, and manage stock, crops and waste in more sustainable ways.

The increase in soil organic carbon content derived from carbon farming has many co-benefits including greater productivity resulting from improved soil structure, increased nutrient cycling and greater diversity of soil organisms (Kragt et al 2016; Baumber et al 2019). Premium carbon projects have environmental and social co-benefits, such as biodiversity outcomes, coastal and wetland regeneration and Aboriginal community development. (DPIE 2020). For traditional owners, carbon farming may also have the added benefit of caring for Country. These activities are done in return for carbon credits which landholders can sell in carbon markets to businesses to offset emissions.

The opportunity to improve soil health is not just confined to agricultural land. Pollution from waste can greatly impact soil and contaminate urban lands. A focus on re-use, recycling and reducing waste will result in lower emissions and positive outcomes for soils. Better management of organic waste by diverting it from landfill will help reduce the release of nutrients that pollute soils and waterways. Where organics are properly sorted and processed, they can be turned into compost and natural fertilisers, which can enrich soils when used in farming or gardening.

Indicators have been developed to measure the condition of biodiversity and ecological integrity at statewide and regional scales through the Biodiversity Indicator Program . The NSW Department of Primary Industries is also developing indicators to measure the co-benefits of carbon farming, including biodiversity, soil health and other socio-economic benefits (DPI 2021). Building on these indicators will help to develop measures of the impact of the plan's initiatives.

Status of initiatives

Since the *Net Zero Plan* was released in March 2020, extensive scoping and development of initiatives to support NSW's transition to net zero emissions have been underway. This section outlines how key sectors are being transformed and tracks their performance across the plan's priority areas:

Energy

Initiative	Status
The *Net Zero Plan* includes a range of lower emissions energy initiatives being delivered as part of the *NSW Electricity Infrastructure Roadmap* (DPIE 2020b). The roadmap supports the development of new electricity infrastructure in NSW. It will support the private sector to bring 12 gigawatts of renewable energy and two gigawatts of storage, such as pumped hydro, online by 2030. The roadmap will help NSW deliver on its ambitions to reach net zero emissions by 2050 by reducing NSW electricity emissions by up to 90 million tonnes CO2-e over the period to 2030. The roadmap will support the development of five Renewable Energy Zones (REZs) in the Central-West Orana, New England, South West, Hunter-Central Coast and Illawarra regions of NSW. The Central-West Orana REZ is expected to be shovel-ready by the end of 2022 to unlock up to 3,000 megawatts of new electricity capacity by the mid-2020s and bring as much as $5.2 billion in private investment to the region by 2030.	**Being delivered** *First REZ to be shovel-ready by 2022 and plans for two more REZs announced*
Under the *Net Zero Plan*, the Energy Savings Scheme (ESS) has been extended through to 2050 to continue to encourage energy savings. The country's longest running energy efficiency certificate trading scheme has saved an estimated 15 megatonnes of greenhouse gas emissions between 2009 and 2019 by: • encouraging the private sector to develop products and services that are scalable and sustainable • helping households and businesses to reduce their energy use. The ESS is now a component of the new Energy Security Safeguard with energy savings targets gradually increasing from 2022 and an expanded set of eligible activities. From late 2022, the safeguard will also include a new Peak Demand Reduction Scheme (PDRS) to create incentives for activities that reduce electricity demand at peak times. The PDRS will help improve the sustainability of electricity by increasing load flexibility in response to variable renewable generation. Initiatives are also being developed under the *Net Zero Plan* to accelerate the transition of businesses and industry to the new safeguard.	**Being delivered** *Scheme expanded and new energy savings targets set* *Expanded Safeguard is in design*
The majority of energy initiatives so far are delivering outcomes that support Priority 1 of the *Net Zero Plan* which is to drive the uptake of proven emission reduction technologies. Other initiatives are designed to empower customers to make informed decisions about their energy use, which addresses Priority 2 of the plan. Energy Saver provides information about how households and businesses can switch to lower emission retailers and energy solutions that best fit their needs.	**In design**

Transport

Initiative	Status
The *NSW Electric Vehicle Strategy* (DPIE 2021a) was launched in June 2021, giving effect to the state's commitment to increase the uptake of electric vehicles (EVs). Targets include growing EV sales of new passenger and light commercial vehicles to 52% of the market by 2030–31 and the vast majority by 2035. The strategy includes: • targeted rebates for purchasing EVs • phased removal of stamp duty on EVs • targets for the uptake of EVs for the NSW Government passenger fleet • incentives to increase EVs in council and private fleets • investment to ensure widespread and world-class EV charging infrastructure across the state. Rebates of $3000 were available on sales of the first 25,000 EVs valued at under $68,750 from 1 September 2021*.These rebates are designed to encourage EV uptake and are targeted to the cars more people can afford. Stamp duty has also been removed from EVs under $78,000 purchased from 1 September 2021 and from all other EVs and plug-in hybrids from 1 July 2027 or when EVs reach at least 30% of new car sales, at which time a road user charge will be introduced. These initiatives will support Priorities 1, 2 and 4 of the *Net Zero Plan* by driving the uptake of proven emission reduction technologies, supporting consumers to make sustainable choices, as well as reducing government transport emissions.	**Being delivered** *Rebates and tax incentives available for EVs*

*Due to the COVID-19 pandemic, NSW Parliament's normal operations were suspended in August. As a result, some legislation was delayed. This included the *Electric Vehicles (Revenue Arrangements) Bill 2021*. To avoid potential delays to the uptake of electric vehicles, the NSW Treasurer announced that stamp duty exemptions and rebates would retrospectively be available from 1 September 2021.

Industry	
Initiative	**Status**
The Net Zero Industry and Innovation Program was announced by the NSW Government in March 2021. Delivery of programs are now in the market-sounding stage. The $750-million program focuses on supporting NSW industry and business to capitalise on the opportunities in the global transition to net zero. The program has three areas of focus: • New Low Carbon Industry Foundations will lay the foundations for low emissions industries by building enabling infrastructure and increasing the capability of NSW supply chains. The program will also support the establishment of low emissions manufacturing precincts to help grow low carbon industries. • High Emitting Industries will support existing, high-emitting industrial facilities in NSW to transition their plant, equipment and other assets to low-emission alternatives. • Clean Technology Innovation will support the development and continued innovation of emerging clean technologies by enabling knowledge sharing, capacity building and collaboration between researchers, industry and government. As part of this stream, the Office of the NSW Chief Scientist and Engineer will establish a Decarbonisation Innovation Hub to support research collaboration that develops the technologies of the future. The *Net Zero Plan* committed to a coal innovation program that would provide incentives for coal mines to reduce their fugitive emissions and support the development and commercialisation of new fugitive abatement technologies. Under the Net Zero Industry and Innovation Program, coal mines will be eligible to apply for incentives to implement large-scale abatement projects.	**In design** *Industry consultation underway with over 400 registrations of interest received*
The *Net Zero Plan* set an aspirational target of up to 10% hydrogen blending in the gas network by 2030. Streams across the Net Zero Industry and Innovation Program will help scale up hydrogen as an energy source and feedstock. As part of the New Low Carbon Industry Foundations stream, at least $70 million has been allocated to develop hydrogen hubs in the Hunter and Illawarra regions. These hubs will combine demand from existing and emerging hydrogen users to deliver the fuel in a coordinated fashion that will drive scale, reduce costs, focus innovation and grow workforce skills. The hubs aim to accelerate the growth of the state's clean hydrogen industry and unlock the heavy transport sector as a key new market for clean hydrogen demand. The NSW Hydrogen Strategy is a plan to support scientists, researchers and industries to rapidly increase the scale and competitiveness of green hydrogen in NSW. As well as delivering the $70 million to develop the state's hydrogen hubs in the Illawarra and the Hunter outlined above, the NSW Hydrogen Strategy will provide up to $3 billion in support for the hydrogen industry through: • exemptions for green hydrogen production from government charges • a 90% exemption from electricity network charges for green hydrogen producers who connect to parts of the network with spare capacity • incentives for green hydrogen production • a hydrogen refuelling station network to be rolled out across the state. The strategy is expected to attract up to $80 billion of investment to NSW and to drive deep decarbonisation.	**Being delivered** *Hydrogen hubs will help deliver on gas target*
These industry initiatives will support Priorities 1 and 3 of the *Net Zero Plan* by driving the uptake of proven emission reduction technologies and investing in innovative future emissions reduction technologies.	**Being delivered** *Businesses supported to implement energy efficiency measures*

Waste

Initiative	Status
In June 2021, the NSW Government launched the *NSW Waste and Sustainable Materials Strategy 2041: Stage 1 2021–2027* (DPIE 2021b). The strategy outlines the NSW Government's approach to making the transition to a circular economy over the next 20 years and outlines actions to achieve the organic waste target of net zero emissions from landfill by 2030, as outlined in the *Net Zero Plan*. The $356-million strategy will help deliver priority programs and policy reforms that minimise waste and value resources while decarbonising the economy. Strategy actions include: • mandating the collection of food and garden organics for all NSW households by 2030 and select businesses by 2025, with $65 million to help with the transition • introducing regulatory measures to require gas capture and net zero emissions from landfills with $7.5 million invested in the installation of landfill gas capture infrastructure • investigating a new regulatory framework to incentivise the uptake of anaerobic digestion facilities and biogas production with the $37-million Carbon Abatement and Recycling fund including funding to support biogas recovery from waste. The Waste and Sustainable Materials Strategy contributes to the plan's Priorities 1 and 2 to drive the uptake of emission reduction technologies and empower consumers and businesses to make sustainable choices.	In design *Strategy launched and programs in development* *Target: Net zero emissions from organic waste to landfill by 2030*

Land use

Initiative	Status
NSW has abundant land, a strong agricultural sector, technical expertise and a rigorous financial and legal infrastructure, all of which should allow the state to take advantage of the opportunities provided by carbon markets and the transition to net zero while enhancing the state's productivity and wellbeing. The *Net Zero Plan* is supported by joint funding from the NSW and Commonwealth Governments, as agreed in the NSW Energy Package Memorandum of Understanding. As part of the MoU, the Commonwealth has committed $450 million through the Climate Solutions Fund to support NSW businesses, farms and land managers to take practical, low-cost actions to reduce emissions. This commitment will provide important environmental, economic and social benefits to local businesses and communities.	
Under the plan, the NSW Government is working to improve the management of carbon across all land tenures through the Primary Industries Productivity and Abatement Program . Among other things, initiatives will be developed to: • support the uptake of proven technologies and practices in the primary industries and land sectors to increase abatement of emissions and optimise productivity • support farmers and land managers to access revenue from carbon markets and realise a market advantage from low-emission products. These will work to achieve the plan's Priorities 1, 2 and 3 to drive the uptake of proven emission-reduction technologies, and empower consumers and businesses to make sustainable choices and invest in innovative future reduction technologies.	In design

Built environment

Initiative	Status
Launched in early 2021, the Low Emissions Building Materials Program is a partnership with industry to grow the demand for these building materials in the construction and infrastructure sectors by driving the modification, adoption and use of voluntary standards. To achieve this, the Materials & Embodied Carbon Alliance (MELCA) has been formed in partnership with the World Wide Fund and includes professionals from the building industry and government. Organisations that are big purchasers of steel, concrete and other materials are actively participating in the development of agreed standards for low-emission alternatives.	**Being delivered** *Over 50 industry bodies have joined MELCA*
The National Australian Built Environment Rating System (NABERS) is a rating system that measures the energy, water, waste and indoor environmental impact of buildings in Australia using a six-star scale. NABERS can be used to rate a variety of buildings, including offices, apartments, shopping centres, hotels and data centres. Since the highly regarded program began in 1999, NABERS has helped users save over $1 billion in energy bills and 6 billion litres of water and remove 7 million tonnes of CO_2 emissions – equivalent to one year's worth of power from 93,430 homes (based on Office Energy ratings only). Currently 78% of Australia's office space is rated with NABERS. In 2020–21, NABERS offered NSW building owners free energy and carbon neutral ratings through the Energy Starters and Carbon Neutral Leaders pilots. This supported NSW building owners to overcome barriers to energy efficiency by enabling them to obtain their first NABERS energy rating and streamlining access to the NSW Energy Savings Scheme. NABERS is also working with industry to investigate an embodied carbon framework for commercial buildings and how this can align with existing building ratings, such as NABERS and Green Star. These initiatives address Priority 2 of the *Net Zero Plan* by empowering consumers and businesses to make sustainable choices in designing and using the built environment.	**Being delivered** *NABERS is accelerating the transition to net zero buildings*

Government

Initiative	Status
Under the NSW Government Resource Efficiency Policy, all NSW Government agencies are required to achieve resource-efficiency targets to reduce energy use, water consumption, waste disposal and air emissions. The policy seeks to achieve significant cost savings from over $400 million of government expenditure. The *Net Zero Plan* set a new target for government buildings to generate 126,000 megawatt hours per annum of solar energy by 2024. Feasibility assessments for statewide deployment of rooftop solar systems are underway to deliver this ambitious solar generation target. Government land assets also present an enormous opportunity to support investment in renewable energy infrastructure, including solar, wind, pumped-hydro, battery storage and a range of other renewable energy technologies, that will contribute to the transition of the electricity sector. Agencies have been encouraged to identify sites that could support diverse renewable energy infrastructure developments in partnership with business and communities.	**Being delivered** *Feasibility assessments for solar and other renewables on government property are underway*
As part of a 10-year contract with Shell Energy, a 100-megawatt battery is being constructed to help power schools, hospitals and government buildings across NSW under the state's new electricity supply contract. The battery will be near Darlington Point in the Riverina. It will be built and operated by Edify by November 2023 and will support up to 35 jobs during construction.	**In design** *100 megawatt battery due to be built by 2023*
In addition to electricity, other whole-of-government procurement policies and processes are also being reviewed to include sustainable and low carbon procurement for goods, services and infrastructure projects. Under the *NSW Waste and Sustainable Materials Strategy 2041* (DPIE 2021b), NSW Government departments will be required to preference products that contain recycled content, including building materials and office fit-outs and supplies, on an 'if not, why not' basis. By 2026, all NSW Government-owned and leased buildings over 1,000 square metres will need to obtain and publish a NABERS Waste Rating.	**In design** *Programs in development*
The *Net Zero Plan* identified commitments to transition the NSW public transport system to low emissions, including the replacement of the state's 8,000-vehicle bus fleet with electric buses. Transport for NSW rolled out over 50 electric buses across Sydney in early 2021 in the first phase of this work. The *NSW Electric Vehicle Strategy* (DPIE 2021a) commits $33 million to electrify the NSW Government passenger fleet by 2030. It sets an interim target of 50% EV procurement for the fleet by 2026. These initiatives are in line with Priority 4 of the plan for the Government to lead by example on the road to net zero emissions.	**Being delivered** *8000 new electric buses in Sydney* *$33 million to transition government fleet to EVs*

How we are keeping track

The status of initiatives in the *Net Zero Plan* are being reported in this and future NSW State of the Environment Reports.

The NSW Government's action on climate change is informed by science and economics. It will continue to refine the forecast emission reduction figures to reflect data validations in the national emissions accounts. This, along with program evaluations, may lead to improved understanding and adjustment of programs.

The NSW Government is also looking ahead to determine what it will need to do in the next decades to reduce emissions and get to net zero. The Office of the NSW Chief Scientist and Engineer (OCSE) will prepare a report every two years on emerging technologies that reduce emissions and are commercially competitive. The first of these reports, the *NSW Decarbonisation Innovation Study* (OCSE 2020), was published in August 2020.

The NSW Net Zero Emissions and Clean Economy Board is an advisory body established under section 34W of the *Energy and Utilities Administration Act 1987*. The Board will provide advice on the implementation and development of net zero policy and programs, development of emission reduction technologies, low emissions research and other relevant matters.

Units

Quantity	Unit	Symbol
Acidity/alkalinity	pH	pH
Area	hectare	ha
	square kilometre	km^2
Electrical conductivity	microsiemens per centimetre	µS/cm
Length	micrometre	µm
	millimetre	mm
	centimetre	cm
	metre	m
	kilometre	km
Mass	microgram	µg
	kilogram	kg
	tonne	t
	megatonne	Mt
	gigatonne	Gt
Power	megawatt	MW
	kilowatt-hour	kWh
	gigawatt-hour	GWh
Time	second	s
	hour	hr
	day	d
	year	y
Velocity and speed	kilometres per hour	km/hr
	metres per second	m/s

Quantity	Unit	Symbol
Volume	cubic metre	m^3
Volume (fluids)	litre	L
	kilolitre	kL
	megalitre	ML
	gigalitres	GL
	gigalitres per year	GL/y
Work and energy	petajoule	PJ
Other abbreviations	carbon dioxide equivalent units	CO_2-e
	parts per million	ppm
	micrograms per cubic metre	$\mu g/m^3$

Prefixes for SI units

Fraction	Prefix	Symbol
10^{-6}	micro	μ
10^3	kilo	k
10^6	mega	M
10^9	giga	G
10^6	peta	P

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