Climate Change, Air Quality, and Human Health

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Abstract: Weather and climate play important roles in determining patterns of air quality over multiple scales in time and space, owing to the fact that emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorologic variables such as temperature, humidity, wind speed and direction, and mixing height. There is growing recognition that development of optimal control strategies for key pollutants like ozone and fine particles now requires assessment of potential future climate conditions and their influence on the attainment of air quality objectives. In addition, other air contaminants of relevance to human health, including smoke from wildfires and airborne pollens and molds, may be influenced by climate change. In this study, the focus is on the ways in which health-relevant measures of air quality, including ozone, particulate matter, and aeroallergens, may be affected by climate variability and change. The small but growing literature focusing on climate impacts on air quality, how these influences may play out in future decades, and the implications for human health is reviewed. Based on the observed and anticipated impacts, adaptation strategies and research needs are discussed.
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Introduction

Meteorologic variables such as temperature, humidity, wind speed and direction, and mixing height (the vertical height of mixing in the atmosphere) play important roles in determining patterns of air quality over multiple scales in time and space. These linkages can operate through changes in air pollution emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants. Policies to improve air quality and human health take meteorologic variables into account in determining when, where, and how to control pollution emissions, usually assuming that weather observed in the past is a good proxy for weather that will occur in the future, when control policies are fully implemented. However, policymakers now face the unprecedented challenge presented by changing climate baselines. There is growing recognition that development of optimal control strategies to control future levels of key health-relevant pollutants like ozone and fine particles (particulate matter, $PM_{2.5}$) should incorporate assessment of potential future climate conditions and their possible influence on the attainment of air quality objectives. Given the significant health burdens associated with ambient are pollution, getting the numbers right is critical for designing policies that maximize future health protection. Although not regulated as air pollutants, naturally occurring air contaminants of relevance to human health, including smoke from wildfires and airborne pollens and molds, also may be influenced by climate change. Thus there are a range of air contaminants, both anthropogenic and natural, for which climate change impacts are of potential interest.

It also should be recognized that anthropogenic emissions of air pollutants of direct health concern are, in many cases, associated with concurrent emission of pollutants that have important impacts on global climate (e.g., carbon dioxide, black carbon, sulfur dioxide, and others). This is particularly the case for combustion of fossil fuels such as coal and oil. Thus, efforts to mitigate climate impacts by reduced fossil fuel combustion also will often result in co-benefits from reduced direct health impacts of air pollution. This important interaction among climate, air quality, and health, is addressed elsewhere in this issue,[1] and is not discussed further here.

This study focuses on the ways in which health-relevant measures of air quality, including ozone, PM, and aeroallergens, may be affected by climate variability and change. Because many excellent reviews have been published on the human health impacts of air pollution, those impacts are only briefly summarized here. Instead, the small but growing literature focusing on climate impacts on air quality, how these influences may play out in future decades, and the implications for human health is reviewed. Based on the observed and

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anticipated impacts, adaptation strategies and research needs are also discussed.

Sources and Health Effects of Ozone, Fine Particles, and Aeroallergens

In spite of the substantial successes achieved since the 1970s in improving air quality in the U.S., millions in this country continue to live in areas that do not meet the health-based National Ambient Air Quality Standards for ozone and $PM_{2.5}$ (www.epa.gov/air/criteria.html). Ozone is formed in the troposphere mainly by reactions that occur in polluted air in the presence of sunlight. The key precursor pollutants for ozone formation are nitrogen oxides (emitted mainly by burning of fuels) and volatile organic compounds (VOCs, emitted both by the burning of fuels and evaporation from vegetation and stored fuels). Because ozone formation increases with greater sunlight and higher temperatures, it reaches unhealthy levels primarily during the warm half of the year. Daily peaks occur near midday in urban areas, and in the afternoon or early evening in downwind areas. It has been firmly established that breathing ozone can cause inflammation in the deep lung as well as short-term, reversible decreases in lung function. In addition, epidemiologic studies of people living in polluted areas have suggested that ozone can increase the risk of asthma-related hospital visits and premature mortality.[2–5] Vulnerability to ozone effects on the lungs is greater for people who spend time outdoors during ozone periods, especially those who engage in physical exertion, which results in a higher cumulative dose to the lungs. Thus, children, outdoor laborers, and athletes all may be at greater risk than people who spend more time indoors and who are less active. Asthmatics are also a potentially vulnerable subgroup.

Fine particulate matter, $PM_{2.5}$, is a complex mixture of solid and liquid particles that share the property of being less than 2.5μm in aerodynamic diameter. Because of its complex nature, $PM_{2.5}$ has complicated origins, including primary particles emitted directly from sources and secondary particles that form via atmospheric reactions of precursor gases. $PM_{2.5}$ is emitted in large quantities by combustion of fuels by motor vehicles, furnaces, power plants, wildfires, and, in arid regions, windblown dust.[6] Because of their small size, $PM_{2.5}$ particles have relatively long atmospheric residence times (on the order of days) and may be carried long distances from their source regions.[6,7] Figure 1 is a satellite image showing long-range transport of smoke over 1000 km (620 miles) from northern Quebec, Canada, to the city of Baltimore MD, on the east coast of the U.S. A corresponding time series of $PM_{2.5}$ concentrations in Baltimore clearly shows the impact of this event (Figure 2). Research on health effects in urban areas has demon-

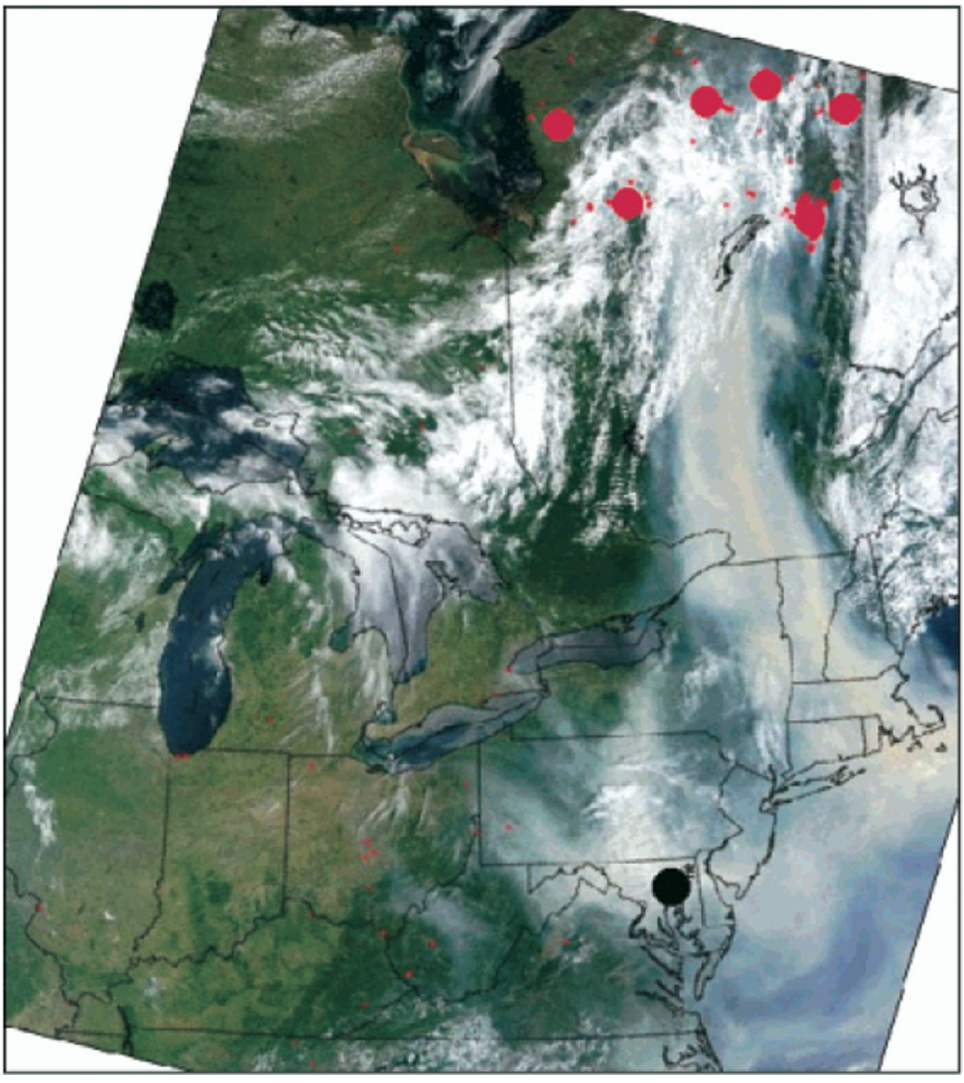

Figure 1. NASA MODIS satellite image taken July 7, 2002, 10:35 EDT, showing areas of high forest fire activity (red dots) and the affected area (Baltimore MD)[7]
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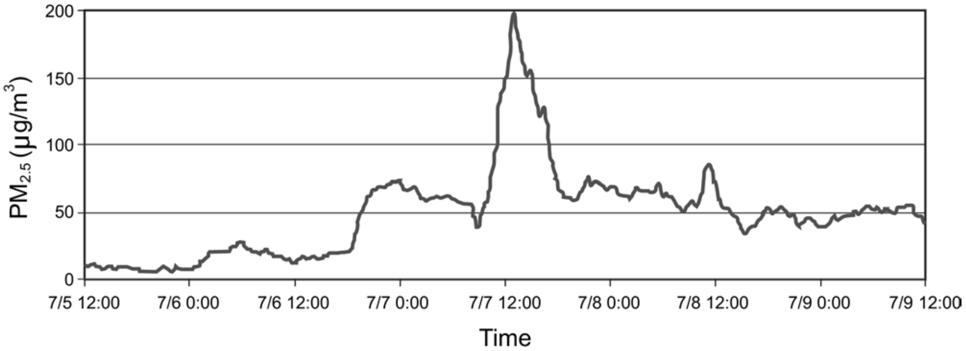

Figure 2. Outdoor $PM_{2.5}$ concentrations in Baltimore before, during, and after July 7, 2002[7]
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strated associations between both short-term and long-term average ambient $PM_{2.5}$ concentrations and a variety of adverse health outcomes, including premature deaths related to heart and lung diseases.[8–10] In addition, smoke from wildfires has been associated with increased hospital visits for respiratory problems in affected communities.[11–13]

Airborne allergens (aeroallegens) are substances present in the air that, upon inhalation, stimulate an allergic response in sensitized individuals. Aeroallergens can be broadly classified into pollens (e.g., from trees, grasses, and/or weeds); molds (both indoor and outdoor); and a variety of indoor proteins associated with dust mites, animal dander, and cockroaches. Pollens are released by plants at specific times of the year that depend to varying degrees on temperature, sunlight, and moisture. Allergy is assessed in humans either by skin prick testing or by a blood test, both of which involve assessing reactions to standard allergen preparations. A nationally representative survey of allergen sensitization spanning the years 1988–1994 found that 40% of Americans are sensitized to one or more outdoor allergens, and that prevalence of sensitization had increased compared with data collected in 1976–1980.[14] For example, for these two surveys, Figure 3 plots the percentage of the population sensitized to ragweed pollen as a function of age.

Allergic diseases include allergic asthma, hay fever, and atopic dermatitis. More than 50 million Americans suffer from allergic diseases, costing the U.S. healthcare system over $18 billion annually.[15] For reasons that remain unexplained, the prevalence of allergic diseases has increased markedly over the past 3–4 decades. Asthma is the major chronic disease of childhood, with almost 4.8 million U.S. residents affected. It is also the principal cause for school absenteeism and hospitalizations among children.[16] Mold and pollen exposures and home dampness have been associated with exacerbation of allergy and asthma, as has air pollution.[17–20]

Climate and Air Quality

The influence of meteorology on air quality is substantial and well established,[21] giving rise to the expectation that changes in climate are likely to alter patterns of air pollution concentrations. Higher temperatures hasten the chemical reactions that lead to ozone and secondary particle formation. Higher temperatures, and perhaps elevated carbon dioxide (CO_2) concentrations, also lead to increased emissions of ozone-relevant VOC precursors by vegetation.[22] Weather patterns influence the movement and dispersion of all pollutants in the atmosphere through the action of winds, vertical mixing, and rainfall. Air pollution episodes can occur with atmospheric conditions that limit both vertical and horizontal dispersion. For example, calm winds and cool air aloft limits dispersion of traffic emission during morning rush hour in winter.

Emissions from power plants increase substantially during heat waves, when air conditioning use peaks. Weekday emissions of nitrogen oxides (NO_x) from selected power plants in California more than doubled on days when daily maximum temperatures climbed from 75°F to 95°F in July, August, and September of 2004.[23] Changes in temperature, precipitation, and wind affect windblown dust, as well as the initiation and

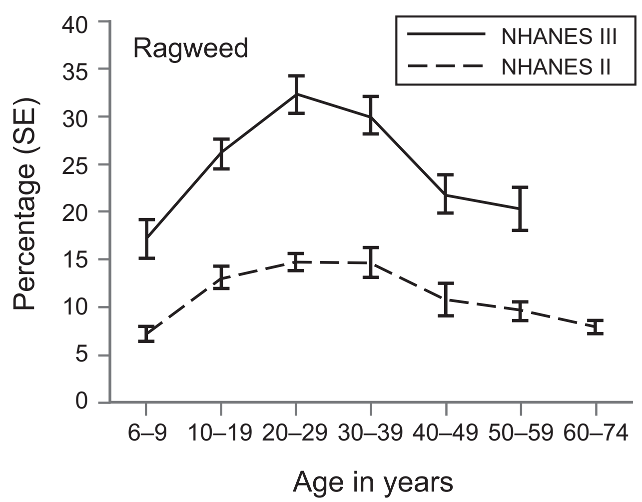

Figure 3. Percentage of the population by age with positive skin test reactivity to ragweed pollen in NHANES II (dashed line) and NHANES III (solid line)[14]
NHANES, National Health and Nutrition Examination Survey
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movement of forest fires. Finally, the production and distribution of airborne allergens such as pollens and molds are highly influenced by weather phenomena, and also have been shown to be sensitive to atmospheric CO_2 levels.[24] The timing of such phenologic events such as flowering and pollen release are closely linked with temperature.

Human-induced climate change is likely to alter the distributions over both time and space of all the meterologic factors mentioned. There is little question that air quality will be influenced by these changes. The challenge is to understand these influences better and to quantify the direction and magnitude of resulting air quality and health impacts.

Potential Climate Influences on Air Pollution: Findings from Emerging Studies

A variety of methods have been used to study the influences of climatic factors on air quality, ranging from relatively simple statistical analyses of empirical relationships in the historical record to sophisticated integrated modeling of future air quality resulting from climate change. Empirical and/or episode modeling studies have examined influences of temperature and other meteorologic parameters on concentrations of ozone and fine particles, the risk of wildfires, pollen, and, to a lesser extent, mold concentrations. Most integrated modeling studies to date have focused on climate effects on ozone concentrations. Some of the key approaches and findings from this emerging body of research are reviewed here briefly.

Empirical studies have examined statistical relationships between meteorologic parameters and observed ozone concentrations, and used these relationships to infer potential future changes in air quality as climate changes.[25–28] For example, the California Climate Change Center developed an ozone prediction equation based on ambient temperature and then used this equation to estimate ozone concentrations for future time periods using daily temperature outputs for California from a global scale general circulation model.[23] Another “historical” approach uses atmospheric models to explore the sensitivity of air pollution levels to changes in meterologic inputs during known episode periods in the past.[23,29,30] Most such studies have shown that higher temperatures typically result in higher simulated ozone concentrations. However, $PM_{2.5}$ responses are variable.[29,31] Another recent study examined the sensitivity of ozone to a range of temperature, humidity, and other conditions that could occur with climate change in California.[31] Other studies have used global and/or regional climate models to examine future distributions of weather patterns known to be conducive to air pollution episodes, such as stagnating high pressure systems.[32]

Integrated modeling links air quality simulation models to climate simulation models to examine potential air quality under alternative scenarios of future global climate change.[33] Although more complex and computer-intensive than the methods discussed above, a key advantage of integrated modeling is the ability to account for the complex influences of climate, emissions, and atmospheric chemistry on air quality patterns, and in particular, to evaluate how air quality might change under a variety of assumptions regarding both climate change and emissions of precursor pollutants. Several integrated modeling studies have used large-scale global chemistry/climate models to examine how air quality may be influenced by future climate change over the twenty-first century.[34–36]

Hogrefe and colleagues[37,38] were the first to report results of a local-scale analysis of air pollution impacts of future climate changes using an integrated modeling approach. In this work, a global climate model was used to simulate hourly meteorologic data from the 1990s through the 2080s based on two different greenhouse gas emissions scenarios, one representing high emissions and the other representing moderate emissions. The global climate outputs were downscaled to a 36 km (22 mile) grid over the eastern U.S. using regional climate and air quality models. When future ozone projections were examined, summer-season daily maximum 8-hour concentrations averaged over the modeling domain increased by 2.7, 4.2, and 5.0 parts per billion (ppb) in the 2020s, 2050s, and 2080s, respectively, as compared to the 1990s, due to climate change alone (Figure 4). The impact of climate on mean ozone values was similar in magnitude to the influence of rising global background ozone by the 2050s, but climate had a dominant impact on hourly peaks.

Climate change shifted the distribution of ozone concentrations toward higher values, with larger relative increases in future decades occurring at higher ozone concentrations. The finding of larger climate impacts on extreme ozone values was confirmed in a recent study in Germany[39] that compared ozone in the 2030s and the 1990s using a downscaled integrated modeling system. Daily maximum ozone concentrations increased by 2–6 ppb (6%–10%) across the study region. However, the number of cases where daily maximum ozone exceeded 90 ppb increased by nearly fourfold, from 99 to 384 (Figure 5).

More recently, the influence of climate change on $PM_{2.5}$ and its component species have been examined using an integrated modeling system.[40] Results showed that $PM_{2.5}$ concentrations increased with climate change, but that the effects differed by component species, with sulfates and primary PM increasing markedly but with organic and nitrated components decreasing, mainly due to movement of these volatile species from the particulate to the gaseous phase.

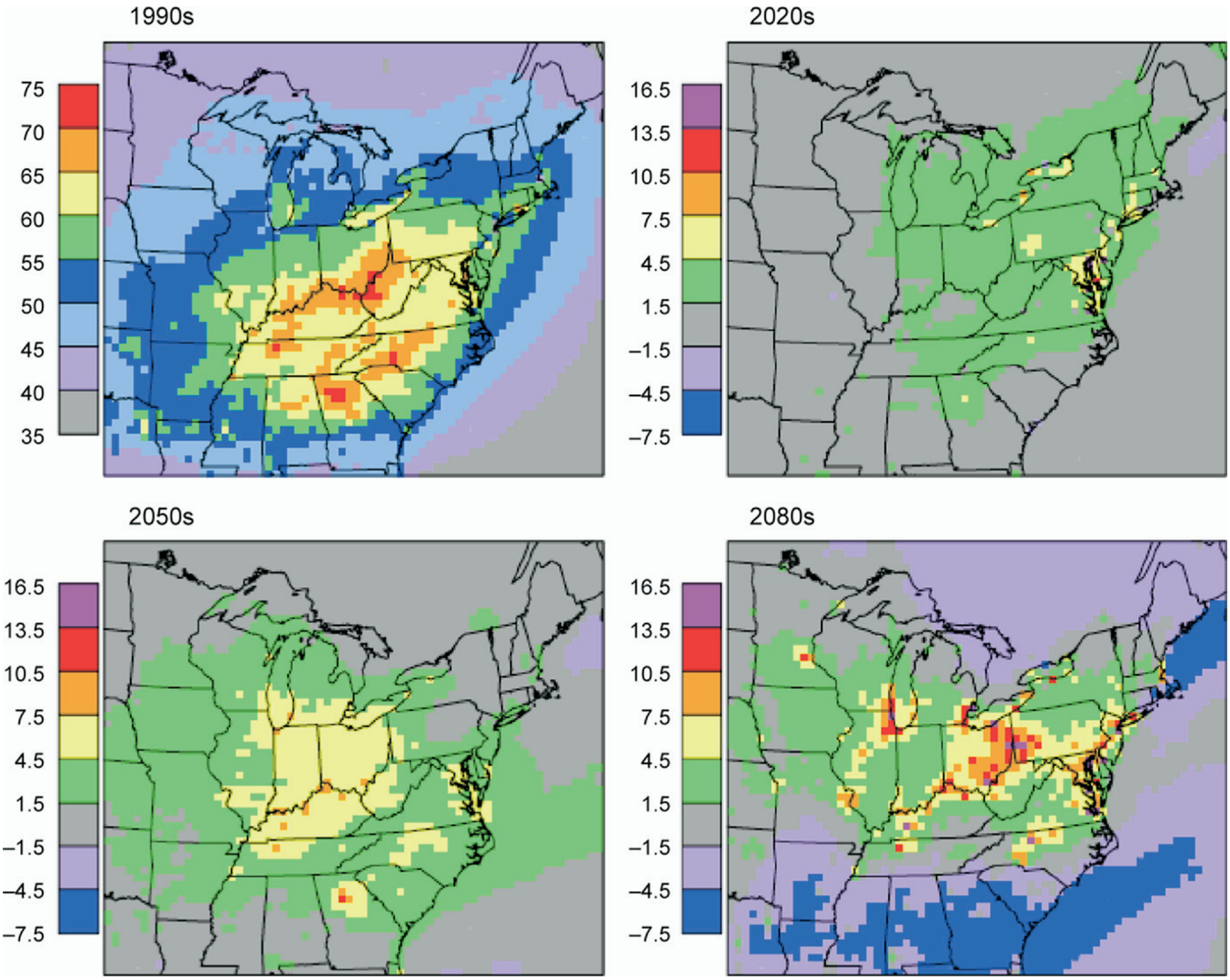

Figure 4. Summertime average daily maximum 8-hour ozone concentrations for the 1990s and changes in same for the 2020s, 2050s, and 2080s, based on the IPCC A2 CO_2 scenario relative to the 1990s, in ppb. Five consecutive summer seasons were simulated in each decade.[38]
IPCC, Intergovernmental Panel on Climate Change; ppb, parts per billion
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As can be seen in the above literature review, the trend in recent years has been toward increasingly sophisticated, integrated, policy-relevant regional-scale modeling studies of the possible future impacts of climate change on air quality. Most work to date has focused on ozone, for which reliable models have been available for some time. The more complex challenge of modeling climate impacts on fine particle concentrations has only recently been attempted, taking advantage of new chemistry models that include mechanisms related to the formation of PM component species. Research suggests that urban and regional ozone concentrations in the U.S. may increase approximately 5%–10% between now and the 2050s as a result of climate change alone, holding anthropogenic precursor emissions and global background concentrations constant. Relatively smaller changes (2.5%–5%) might be observed by 2030, and larger changes by the end of the century. It is important to note that trends in actual ozone concentrations will depend as much or more on control of precursor emissions as on climate change. The picture for $PM_{2.5}$ remains uncertain, with somewhat conflicting results from the few studies to date.

Wildfires

Because the risk of wildfire initiation and spread is enhanced with higher temperatures, decreased soil moisture, and extended periods of draught, it is possible that climate change could increase the impact of wildfires in terms of frequency and area affected.[41,42] Among the numerous health and economic impacts brought about by these more frequent and larger fires,

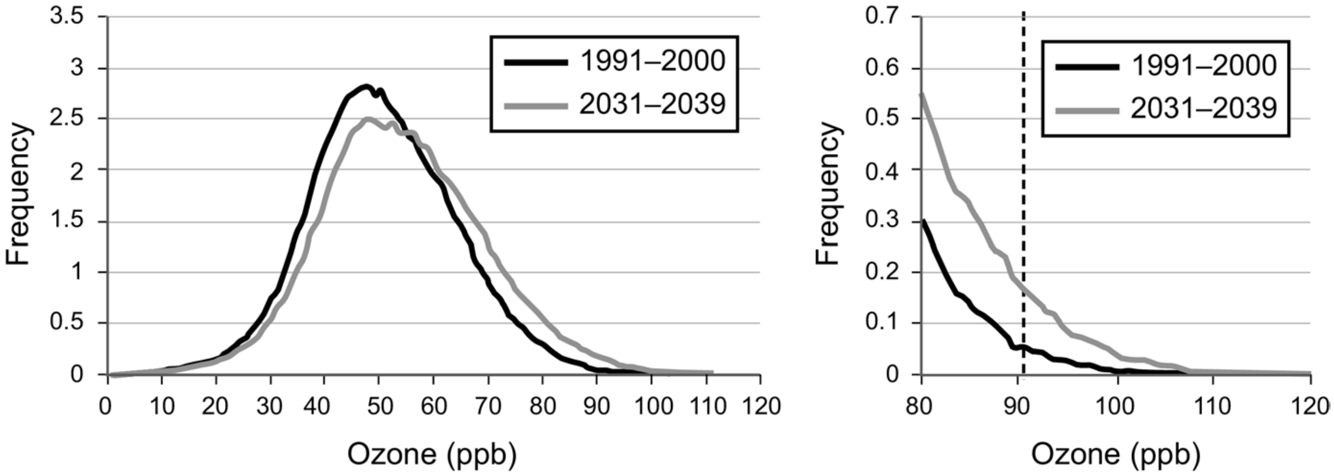

Figure 5. Left: frequency distribution of the simulated daily ozone maxima averaged over southern Germany during summer (June–August) for the years 1991–2000 and 2031–2039. Right: a zoom of the high-ozone portion of the curve.[39] Reprinted with permission.

increases in fine particulate air pollution are an important concern, both in the immediate vicinity of fires as well as in areas downwind of the source regions. Several studies have been published in recent years examining trends in wildfire frequency and area burned in Canada and the U.S. Most such studies report upward trends in the latter half of the twentieth century that are consistent with changes in relevant climatic variables.[42–44] Interpretation of trends in relation to climate change is complicated by concurrent changes in land cover and in fire surveillance and control. However, similar trends were seen in areas not affected by human interference,[42] or under consistent levels of surveillance over the follow-up period.[44]

How might these trends play out in the future with continued climate change? Integrated modeling studies have examined fire risk associated with climatic variables projected under alternative CO_2 scenarios, mainly in Canada. Most studies have projected increases in fire frequency and/or area burned over future decades in relation to 2x or 3x CO_2 growth scenarios, due to increases in average temperatures, longer growing seasons, and/or increased aridity.[45–47] For example, Flannigan and colleagues[47] projected 74%–118% increases in area burned in different regions of Canada by the end of the present century with 3x CO_2, but with considerable variation across different ecologic regimes. One study projected general reductions in future fire burn rates in Canada, although some regions showed the opposite trend.[48] Authors suggested that increased precipitation outweighed increased temperatures in regions where fire risk was projected to be lower. It should be noted that climate change will interact with changes in land cover, the frequency of lightning and other initiators, and topography in determining future damage risks to forests.[41] Air quality impacts related to projected future wildfires under a changing climate have yet to be evaluated.

Aeroallergens

Aeroallergens that may respond to climate change include outdoor pollens generated by trees, grasses, and weeds, and spores released by outdoor or indoor molds. Because climatologic influences differ for these different classes of aeroallergens, they are discussed separately here.

Historical trends in the onset and duration of pollen seasons have been examined extensively in recent studies, mainly in Europe. Nearly all species and regions analyzed have shown significant advances in seasonal onset that are consistent with warming trends.[49–58] There is more limited evidence for longer pollen seasons or increases in seasonal pollen loads for birch[55] and Japanese cedar tree pollen.[56] Grass pollen season severity was greater with higher pre-season temperatures and precipitation.[59] What remains unknown is whether and to what extent recent trends in pollen seasons may be linked with upward trends in allergic diseases (e.g., hay fever, asthma) that have been seen in recent decades.

In addition to earlier onset of the pollen season and possibly enhanced seasonal pollen loads in response to higher temperatures and resulting longer growing seasons, there is evidence that CO_2 rise itself may cause increases in pollen levels. Experimental studies have shown that elevated CO_2 concentrations stimulate greater vigor, pollen production, and allergen potency in ragweed.[24,60,61] Ragweed is arguably the most important pollen in the U.S., with up to 75% of hay fever sufferers sensitized.[15] Significant differences in allergenic pollen protein were observed in comparing plants grown under historical CO_2 concentrations of 280 ppb, recent concentrations of 370 ppb, and potential future concentrations of 600 ppb.[61] Interestingly, significant differences in ragweed productivity were observed in outdoor plots situated in urban, suburban, and rural locales where measurable gradients were observed in both CO_2 concentrations and temperatures. Cities are not only heat islands but also CO_2 islands, and thus to some extent represent proxies for a future warmer, high-CO_2 world.[24]

With warming over the longer term, changing patterns of plant habitat and species density are likely, with gradual movement northward of cool-climate species like maple and birch, as well as northern spruce.[62] Although these shifts are likely to result in altered pollen patterns, to date they have not been assessed quantitatively.

As compared with pollens, molds have been much less studied.[50] This may reflect in part the relative paucity of routine mold monitoring data from which trends might be analyzed, as well as the complex relationships among climate factors, mold growth, spore release, and airborne measurements.[63] One study examining the trends in *Alternaria* spore counts between 1970 and 1998 in Derby England observed significant changes in seasonal onset, peak concentrations, and season length. These trends parallel gradual warming observed over that period.

In addition to potential effects on outdoor mold growth and allergen release related to changing climate variables, there is also concern about indoor mold growth in association with rising air moisture and especially after extreme storms, which can cause widespread indoor moisture problems from flooding and leaks in the building envelope. Molds need high levels of surface moisture to become established and flourish.[64] In the aftermath of Hurricane Katrina, very substantial mold problems were noted, causing unknown but likely significant impacts on respiratory morbidity.[65] There is growing evidence for increases in both the number and intensity of tropical cyclones in the north Atlantic since 1970, associated with unprecedented warming of sea surface temperatures in that region.[62,66]

Taken as a whole, the emerging evidence from studies looking at historic or potential future impacts of climate change on aeroallergens led Beggs to state:

> [This] suggests that the future aeroallergen characteristics of our environment may change considerably as a result of climate change, with the potential for more pollen (and mould spores), more allergenic pollen, an earlier start to the pollen (and mould spore) season, and changes in pollen distribution.[50]

Health Implications and Adaptive Responses

The emerging findings from a small but growing body of literature provides an initial evidence base on which to assess air quality and associated health implications of climate variability and change. Although much more research is needed before firm, quantitative conclusions can be drawn, the limited available evidence suggests that climate change is likely to exacerbate some anthropogenic and naturally occurring pollutants including ozone, smoke from wildfires, and some pollens. To the extent that such impacts occur where large numbers of people are exposed, which is more likely to be the case for ozone and pollen than for smoke from wildfires, additional adverse health effects can be anticipated. People with existing asthma, allergies, and other respiratory diseases may be especially vulnerable to respiratory impacts.

To reduce future air quality impacts of climate-related trends, more aggressive emissions controls, both in the U.S. and elsewhere, will be needed to make progress toward reducing ozone concentrations below health-based standards. The adaptation measures needed are the same as those already in place: reduced emissions of key ozone precursors, especially NOx. Because the transport sector plays an increasingly prominent role in urban NOx emissions, efforts to reduce emissions per mile from motor vehicles should be a high priority. Substantial gains are possible with improved fleetwide fuel efficiency. Tightened emissions controls can play a role as well, as can the use of cleaner, high efficiency fuels such as biofuels. Breakthrough technologies such as electric and fuel cell vehicles could have significant benefits in the longer run. In the case of wildfires, maintenance and enhancement of existing surveillance and early response programs will be critical to mitigate the impacts of potentially increased risks caused by climate change.

Air conditioning is an adaptive response to ozone—reducing indoor exposures compared to those outdoors—but exacerbates the problem of pollution emissions from the utility sector. Caution is advised in relying on air conditioning as a primary adaptive response, in the absence of a corresponding program to reduce the resulting emissions from power plants.

In the case of aeroallergens, ensuring complete and equitable access to available medications will be important, as will stronger education programs directed at allergen avoidance. Use of innovative air handling and filtration equipment for reducing the penetration of outdoor pollens into indoor spaces may also be valuable. Greater awareness of the impacts of indoor moisture on molds and associated respiratory diseases should provide additional incentive to shift housing development away from flood-prone areas. There is a pressing need for improved surveillance of pollen and mold levels.

Research Needs

With respect to integrated modeling of future air quality under a changing climate, there is a need for greater use of model ensembles that capture the full range of uncertainties in future impacts. The literature to date provides mainly selective analyses of particular models and scenarios, preventing a comprehensive quantitative evaluation of central tendencies and variability around the center.

Further advances in climate/air quality modeling are in progress, taking advantage of the continuing progress in computer processor speeds. Complex integrated models that took a week to run 5 years ago can now be run in less than 1 day. These advances will make it possible to look at finer geographic and temporal scales, and to begin modeling the two-way "fully coupled" interactions between climate and air quality.

The study of climate influences on pollen, mold, and other aeroallergens in the U.S. has been extremely limited to date, due in large part to the lack of routinely available, consistently monitored data on aeroallergen levels. An improved surveillance system would begin to alleviate this constraint. Once the empirical relationships are established, integrated modeling studies could be used to examine potential future impacts of climate change.

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References

1. Younger M, Morrow-Almeida HR, Vindigni SM, Dannenberg AL. The built environment, climate change, and health: opportunities for co-benefits. Am J Prev Med 2008;35:517–26.
2. Peel JL, Tolbert PE, Klein M, et al. Ambient air pollution and respiratory emergency department visits. Epidemiol 2005;16:164–74.
3. Peel JL, Metzger KB, Klein M, Flanders WD, Mulholland JA, Tolbert PE. Ambient air pollution and cardiovascular emergency department visits in potentially sensitive groups. Am J Epidemiol 2007;165:625–33.
4. Kinney PL, Ozkaynak H. Associations of daily mortality and air pollution in Los Angeles County. Environ Res 1991;54:99–120.
5. Levy JI, Chemerynski SM, Sarnat JA. Ozone exposure and mortality: an empiric bayes metaregression analysis. Epidemiology 2005;16:458–68.
6. Prospero JM, Lamb PJ. African droughts and dust transport to the Caribbean: climate change implications. Science 2003;302:1024–7.
7. Sapkota A, Symons JM, Kleissl J, et al. Impact of the 2002 Canadian forest fires on particulate matter air quality in Baltimore city. Environ Sci Technol 2005;39:24–32.
8. Samet J, Zeger S, Dominici F, et al. The national morbidity, mortality, and air pollution study. Part II: morbidity and mortality from air pollution in the United States. www.healtheffects.org.
9. Pope CA 3rd, Burnett RT, Thun MJ, et al. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 2002;287:1132–41.
10. Schwartz J. Air pollution and daily mortality: a review and meta-analysis. Environ Res 1994;4:36–52.
11. Hoyt KS, Gerhart AE. The San Diego County wildfires: perspectives of healthcare providers [corrected]. Disaster Manag Response 2004;2:46–52.
12. Johnston FH, Kavanagh AM, Bowman DM, Scott RK. Exposure to bushfire smoke and asthma: an ecological study. Med J Aust 2002;176:535–8.
13. Moore D, Copes R, Fisk R, Joy R, Chan K, Brauer M. Population health effects of air quality changes due to forest fires in British Columbia in 2003: estimates from physician billing data. Can J Public Health 2006;97:105–8.
14. Arbes SJ Jr, Gergen PJ, Elliott L, Zeldin DC. Prevalences of positive skin test responses to 10 common allergens in the US population: results from the third National Health and Nutrition Examination Survey. J Allergy Clin Immunol 2005;116:377–83.
15. American Academy of Allergy, Asthma and Immunology. The allergy report: Vol. 1. Science based findings on the diagnosis and treatment of allergic disorders. Milwaukee WI: AAAAI, 2000.
16. O'Connell EJ. The burden of atopy and asthma in children. Allergy 2004;59(78S):7–11.
17. Gilmour MI, Jaakkola MS, London SJ, Nel AE, Rogers CA. How exposure to environmental tobacco smoke, outdoor air pollutants, and increased pollen burdens influences the incidence of asthma. Environ Health Perspect 2006;114:627–33.
18. IOM. Clearing the air: asthma and indoor air exposures. Washington DC: National Academies Press, 2000.
19. IOM. Damp indoor spaces and health. Washington DC: National Academies Press, 2004.
20. Jaakkola MS, Jaakkola JJK. Indoor molds and asthma in adults. Adv Appl Microbiol 2004;55:309–38.
21. Jacob DJ. Interactions of climate change and air quality: research priorities and new direction. Report from a workshop, April 26–27, 2005, Washington DC: Electric Power Research Institute.
22. Hogrefe C, Leung R, Mickley L, Hunt S, Winner D. Considering climate change in air quality management. Environ Manager 2005:19–23.
23. Drechsler DM, Motallebi N, Kleeman M, et al. Public health-related impacts of climate change in California. White paper, 2006.
24. Ziska LH, Gebhard DE, Frenz DA, Faulkner S, Singer BD, Straka JG. Cities as harbingers of climate change: common ragweed, urbanization, and public health. J Allergy Clin Immunol 2003;111:290–5.
25. Gaza R. Mesoscale meteorology and high ozone in the Northeast United States. Environ Manage 1998;37:961–77.
26. Vukovich F. Regional-scale boundary layer ozone variations in the eastern United States and their association with meteorological variations. Atmos Environ 1995;29:2259–73.
27. Lin, Jacob D, Fiore A. Trends in exceedances of the ozone air quality standard in the continental United States, 1980–1998. Atmos Environ 2001;35:3217–28.
28. Ordóñez C, Mathis H, Furger M, et al. Changes of daily surface ozone maxima in Switzerland in all seasons from 1992 to 2002 and discussion of summer 2003. Atmos Chem Phys 2005;5:1187–203.
29. Aw J, Kleeman M. Evaluating the first-order effect of intraannual temperature variability on urban air pollution. J Geophys Res 2003;108(D12):4365.
30. Bell M, Ellis H. Sensitivity analysis of tropospheric ozone to modified biogenic emissions for the Mid-Atlantic region. Atmos Environ 2004;38:1879–89.
31. Steiner A, Tonse S, Cohen R, Goldstein A, Harley R. Influence of future climate and emissions on regional air quality in California. J Geophys Res 2006;111:D18303.
32. Leung R, Gustafson W. Potential regional climate change and implications to US air quality. Geophys Res Lett 2005;32:L16711.
33. Kinney PL, Rosenthal J, Rosenzweig C, et al. Assessing the potential public health impacts of changing climate and land use: NY climate & health project. In: Ruth M, Donaghy K, Kirshen P, eds. Climate change and variability: impacts and responses. Cheltenham UK: Edward Elgar, 2006.
34. Mickley LJ, Jacob DJ, Field BD, Rind D. Effects of future climate change on regional air pollution episodes in the United States. Geophys Res Lett 2004;31:L24103.
35. Murazaki K, Hess P. How does climate change contribute to surface ozone change over the United States? J Geophys Res 2006;111:D05301.
36. Unger N, Shindell D, Koch D, Amann M, Cofala J, Streets D. Influences of man-made emissions and climate changes on tropospheric ozone, methane, and sulfate at 2030 from a broad range of possible futures. J Geophys Res 2006;111:D12313.
37. Hogrefe C, Biswas J, Lynn B, et al. Simulating regional-scale ozone climatology over the eastern United States: model evaluation results. Atmos Environ 2004;38:2627–38.
38. Hogrefe C, Lynn B, Civerolo K, et al. Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. J Geophys Res 2004;109:D22301.
39. Forkel R, Knoche R. Regional climate change and its impact on photooxidant concentrations in southern Germany: simulations with a coupled regional climate-chemistry model. J Geophys Res 2006;111:D12302.
40. Hogrefe C, Werth D, Avissar R, et al. Analyzing the impacts of climate change on ozone and particulate matter with tracer species, process analysis, and multiple regional climate scenarios. In: Borrego C, Renner E, eds. Air pollution modeling and its application XVIII: 28th NATO/CCMS international technical meeting on air pollution modeling and its application, May 15–19, 2006. Leipzig Germany: Elsevier, 2006.
41. Easterling WE, Aggarwal PK, Batima P, et al. Food, fibre, and forest products. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, eds. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report

of the Intergovernmental Panel on Climate Change. Cambridge UK: Cambridge University Press, 2007. www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter5.pdf.

42. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. Warming and earlier spring increase western US forest wildfire activity. Science 2006; 313:940–3.
43. Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD. Detecting the effect of climate change on Canadian forest fires. Geophys Res Lett 2004;31:L18211.
44. Podur J, Martell DL, Knight K. Statistical quality control analysis of forest fire activity in Canada. Can J For Res 2002;32:195–205.
45. Lemmen DS, Warren FJ. Climate change impacts and adaptation: a Canadian perspective. Ottawa: Climate Change Impacts and Adaptation Directorate, 2004.
46. Williams AAJ, Karoly DJ, Tapper N. The sensitivity of Australian fire danger to climate change. Clim Change 2001;49:171–91.
47. Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ. Future area burned in Canada. Clim Change 2005;72:1–16.
48. Bergeron YM, Flannigan M, Gauthier S, Leduc A, Lefort P. Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. Ambio 2004;6:356–60.
49. Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. Fingerprints of global warming on wild animals and plants. Nature 2003;421:57–60.
50. Beggs PJ. Impacts of climate change on aeroallergens: past and future. Clin Exp Allergy 2004;34:1507–13.
51. Beggs PJ, Bambrick HJ. Is the global rise of asthma an early impact of anthropogenic climate change? Environ Health Perspect 2005;113:915–9.
52. Clot B. Trends in airborne pollen: An overview of 21 years of data in Neuchâtel (Switzerland). Aerobiologia 2003;19:227–34.
53. Emberlin J, Detandt M, Gehrig R, Jaeger S, Nolard N, Rantio-Lehtimaki A. Responses in the start of Betula (birch) pollen seasons to recent changes in spring temperatures across Europe. Int J Biometeorol 2002;46:159–70.
54. Galan C, Garcia-Mozo H, Vazquez L, Ruiz L, de la Guardia CD, Trigo MM. Heat requirement for the onset of the Olea europaea L. pollen season in several sites in Andalusia and the effect of the expected future climate change. Int J Biometeorol 2005;49:184–8.
55. Rasmussen A. The effects of climate change on the birch pollen season in Denmark. Aerobiologia 2002;18:253–65.
56. Teranishi J, Kenda Y, Katoh T, Kasuya M, Oura E, Taira H. Possible role of climate change in the pollen scatter of Japanese cedar Cryptomeria japonica in Japan. Clim Res 2000;14:65–70.
57. van Vliet AJH, Overeem A, DeGroot RS, Jacobs AFG, Spieksma FTM. The influence of temperature and climate change on the timing of pollen release in the Netherlands. Int J Climatology 2002;22:1757–67.
58. WHO. Phenology and human health: allergic disorders. Report on a WHO meeting, Rome. Rome: WHO, 2003.
59. Gonzalez Minero FJ, Candau P, Tomas C, Morales J. Airborne grass (Poaceae) pollen in southern Spain. Results of a 10-year study (1987–96). Allergy 1998;53:266–74.
60. Ziska LH, Caufield FA. Rising carbon dioxide and pollen production of common ragweed, a known allergy-inducing species: implications for public health. Aust J Plant Physiol 2000;27:893–8.
61. Singer BD, Ziska LH, Frenz DA, Gebhard DE, Straka JG. Increasing Amb a 1 content in common ragweed (Ambrosia artemisiifolia) pollen as a function of rising atmospheric CO_2 concentration. Funct Plant Biol 2005;32:667–70.
62. Rosenzweig C, Casassa G, Karoly DJ, et al. Assessment of observed changes and responses in natural and managed systems. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, eds. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge UK: Cambridge University Press, 2007. www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter1.pdf.
63. Katial RK, Zhang Y, Jones RH, Dyer PD. Atmospheric mold spore counts in relation to meteorological parameters. Int J Biometeorol 1997;41:17–22.
64. Burge HA. An update on pollen and fungal spore aerobiology. J Allergy Clin Immunol 2002;110:544–52.
65. Ratard Rea. Health concerns associated with mold in water-damaged homes after hurricanes Katrina and Rita—New Orleans LA, October 2005. MMWR 2006;55:41–4.
66. Emanuel K. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 2005;436:686–8.