Disentangling interactions between atmospheric pollution and weather

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THE IMPACT OF CLIMATE CHANGE

The new Intergovernmental Panel on Climate Change (IPCC) report reaffirms the mounting threat of climate change.[1] The IPCC predicts that the global average surface temperature will increase by 1.4–5.8°C by the end of this century, depending on the pollution emission scenarios and the sensitivity of the climate to greenhouse gas perturbations.[1] Climate change perturbs not just surface temperatures, but also a suite of other meteorological variables important to human health, including absolute humidity, surface pressure, precipitation, and the duration and intensity of summertime weather. Forecasting studies suggest that in the northeast USA, the passage of summertime cold fronts will diminish in frequency in a warmer climate, leading to more persistent heat waves. Observations show that such a trend in cold front frequency in the northeast may have already begun. In a warming climate, absolute humidity will most likely increase due to the increased surface evaporation.[2] Air pollution emissions increase climate change, on the other hand in the Northeast heat waves are usually accompanied by, and can lead to increased secondary pollutants like ozone.[3] However, the impacts of climate change mitigation activities related to energy production, such as the increased use of wind, wave, solar and nuclear sources of power generation, as well as the reduction in greenhouse gas emissions are likely to reduce particulate and other air pollution emissions.

EPIDEMIOLOGICAL EVIDENCE FROM STUDIES ON WEATHER AND AIR POLLUTION

Increased mortality has been linked not only to heat wave episodes[4] but also to exposure to colder weather conditions.[4–7] In general, morbidity[8 9] and mortality[10 11] associated with heat depend on age, race, sex, class, home characteristics, access to air conditioning, general health and living in an urban area versus a rural area.[12] Greater susceptibility to extreme heat has been reported for: the elderly, children, impoverished populations/those with lower socioeconomic status, pregnant women, people with chronic health conditions (eg, diabetes, mobility and cognitive constraints) and outdoor workers.[8 11 13–16] Panel studies investigating associations between temperature and cardiac risk factors such as increased blood pressure,[17–19] markers of inflammations,[15 20–22] and cholesterol,[23 24] or changes in heart rate and repolarisation parameters,[25] have shown divergent results, suggesting that mechanisms for weather-related cardiovascular deaths are still to be elucidated. Inconsistent results in small observational studies with potentially susceptible individuals can have multiple sources including differences in panel composition and therefore underlying susceptibility as well as differences in exposure ranges depending on the season. The latter point may be of great importance as potential pathomechanisms of cold and hot weather responsible for associations with mortality and morbidity may differ. Cold temperatures may induce proinflammatory and procoagulatory states, while in contrast, evidence from patients with heat stress or heat stroke indicates anticoagulatory states to promote sweating and decrease in body temperatures.

Temperature is not the only weather parameter of exposure. Barometric pressure has been used as a covariate in several previous studies;[14 26] however, studies focusing on exposures to air pollution have often abstained from adjusting for it due to the fact that low-pressure periods in wintertime are the reason for elevated air pollution concentrations from local sources. The only two studies that examined the independent barometric pressure health effects found protective associations with mortality[26] and pulse rate.[27] Precipitation, in the form of snowfall, has been mainly related to shovel-related injuries and exercise-induced medical emergencies. In contrast, rainfall in moderate amounts may improve health by reducing ambient air pollution and pollen levels. Water vapour pressure, a measure of humidity, has been associated with ST-segment[9] and brachial artery diameter.[28] High humidity has been associated with hyperpyrexia, decline in physical strength and fatigue; reduction in alertness and mental capacity, but it often occurs when the temperature is high.

It is highly likely that temperature does not act alone in determining health, but rather in concert with other weather parameters, ambient air pollutants and aerosols of biological origin. For example, allergen patterns are also changing in response to climate change, and air pollution can modify the allergenic potential of pollens. However, the joint effects of multiple weather parameters and air pollutants on health have not been well explored. There are some studies indicating synergism between temperature and air pollution,[3 29–33] showing higher pollution effects with hotter weather, and also that the effects of temperature can be overstated if one fails to control for air pollution.[34] A recent review[35] showed that the methods used to assess the synergism between temperature and air pollution have been mainly focused on the estimation of air pollution health effects stratified by season or by interaction. Therefore, there is a need for development of studies optimising the collection of appropriate data and advancing methodological approaches to better assess the complex interplay between weather and ambient aerosols.

MOVING FORWARD

We hypothesise that the health impact associated with exposure to air pollution and weather jointly is larger than the risk estimated based on the health effects of air pollution and weather alone. The comprehensive assessment of the short-term variation of air pollution and weather on health seems to be highly challenging, but the joint impact on a regional scale and over longer time periods has not been explored as yet. Specifically, we hypothesise that weather variability together with elevated long-term exposures to ambient air pollution is contributing to the burden of chronic diseases. Addressing these hypotheses poses a number of challenges which we would like to examine more closely in the following sections.

Varying exposure contrasts around the world

Ambient air pollution mixtures differ between seasons and regions (table 1). Not only does the composition of fine particulate matter ($PM_{2.5}$, particulate matter smaller than 2.5 μm in aerodynamic diameter), the single pollutant with the largest

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Table 1 Schematic description of differences in environmental conditions between seasons in temperate climates of the Northern hemisphere

	Winter	Spring	Summer	Fall
North America temperate regions	Low temperatures, cold spells Particles of local and regional origin Moderate NO_2	Unusually cold or hot days Intermediate pollution Pollen	High temperature, heat waves High particles of regional origin Wildfires High ozone	Unusually cold or hot days Intermediate pollution
Europe temperate regions	Low temperatures High particles of local and regional origin High NO_2	Unusually cold or hot days Intermediate pollution Pollen	High temperature, heat waves High ozone	Unusually cold or hot days Intermediate pollution
Asia temperate regions	Low temperatures High particles of local and regional origin High NO_2 High SO_2	Unusually cold or hot days Intermediate pollution Pollen Wildfires Dust storms	High temperature Moderate ozone	Unusually cold or hot days Intermediate pollution

health impact, differ, but also the co-occurring gaseous pollutants differ. In addition, exposure ranges differ by season when comparing the evidence on a global scale.

The highest $PM_{2.5}$ concentrations are observed during the summer months in Northern America, being dominated by regional transported secondary aerosols for which sulfates are a marker. In contrast, the highest concentrations of $PM_{2.5}$ are reported during the winter months in Europe, resulting from a combination of local sources and regional transport for which black carbon can be considered a marker. Behavioural changes modify population average exposures as well. During cold seasons, air exchange rates decrease and therefore exposures to air pollution from outdoor origin decreases as well. In the presence of widespread air conditioner use, the exposure to air pollution is reduced in the summer months while increasing energy consumption. Obviously, outside the tropics, temperatures differ by season as well. Generally, perceived temperatures differ by accompanying weather conditions such as humidity or wind chill. These modifying conditions are summarised in measures such as apparent temperature.

Short-term exposure-response function

A substantial additional challenge which becomes important when studying interactions is the fact that the exposure-response functions differ greatly when considering ambient air pollution and temperatures. The associations between ambient air pollution and health outcomes are considered to be linear in the low-to-medium exposure range with a potential flattening of the function at very high concentrations.[36] In contrast, associations between temperature and health outcomes are reported to be U-shaped or J-shaped with some variation across different climate zones.[7] Interestingly, the optimal temperature range seemed to vary by climate zones. In figure 1, we show our hypothesis that the combination of temperature and air pollution increases mortality in winter as well as in the summer/spring. As summarised in table 1, the impact of temperature and air pollution in winter originates from the cold and local pollution. In summer, the heat and secondary pollution on a regional (particulate matter) and local scale (ozone) are responsible for the increased risk. In polluted climates and hot climates, we hypothesise that the risk is larger than the sum of the individual risks (figure 1, brown line).

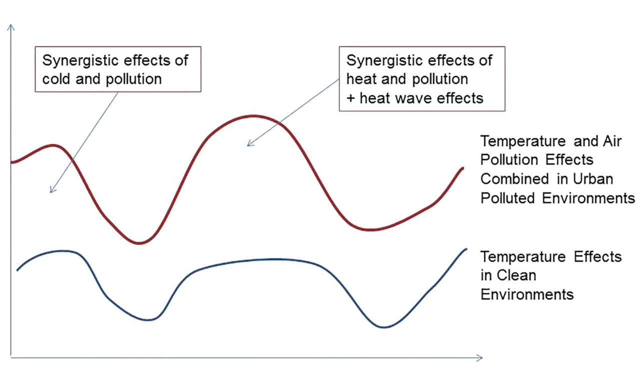

Figure 1 Hypothetical relationship between mortality and the combination of temperature and air pollution by season.

Short-term effect's lag structure and susceptibility

Studies assessing the short-term health effects of environmental exposures explored different lag structures and found evidence that air pollutants may have very immediate effects on some specific disease outcomes such as myocardial infarctions, while other disease outcomes such as chronic obstructive disease mortality may have stronger associations with cumulative exposures over several days. Similarly, immediate and cumulative responses to temperature changes were observed and the lag structures were documented to differ between cold and hot periods. Therefore, models to assess interactions with different lag structures are needed.

Study the interactions of long-term exposures

Mounting evidence suggests that long-term exposure to air pollution has major health impacts; nevertheless, the long-term effect of weather changes due to weather is nearly unexplored. A study was performed by Zanobetti *et al*,[37] who assessed the impact of temperature variability on mortality in a prospective analysis of Medicare data. They found that particularly among the elderly (age greater than 74 years) and chronically ill individuals, variability in temperature was consistently associated with mortality. No investigations have assessed the associations between long-term exposures to temperature and air pollution jointly. An assessment of the joint effects of long-term exposure of air pollution and weather is difficult because the exposure-response functions on the margins are not well developed and investigated. The same is true for an assessment of the relevant time window of exposure.

Integrating designs and methods for short-term and long-term studies

Integrated concepts to assess the health effects of short-term and long-term exposures seem to be the way forward to revolutionise the assessment of weather and urban ambient air jointly. Innovative study designs and methods are needed. Specifically, there is a need to evaluate short-term and long-term temperature–pollution interactions, and the disease development due to temperature–pollution interactions in large cohorts with well characterised populations in different areas of the world. This would permit one to study how the synergistic effect may vary among cities according to local weather characteristics, activity patterns and physical adaptation. In addition, a focus on large cohorts would allow one to study susceptible individuals with pre-existing diseases to evaluate short-term and long-term effects.

Ideally, newly emerging methods should be systematically applied to large-scale cohorts, capturing the health effects of weather variability and pollution mixture, together with their interaction around the world. Statistical methods addressing the challenges described above are under way, especially using spline methodologies for interactions; integrating the exposure-response functions with distributed lag models; and applying the Bayesian hierarchical model addressing short-term and long-term exposures jointly; as well as others.

OUTLOOK

In conclusion, the combined analysis of ambient air pollution and weather jointly poses more challenges than currently acknowledged by most attempts to tackle them. However, owing to the large variation in space and time, carefully designed multicentre studies are considered potent to meet the challenges at hand. Leveraging the variation in exposures on a global scale would allow one to capture the interactions between weather and ambient air pollution jointly to a full extent. In addition, these studies will provide novel stimuli for promoting measures to slow climate change and improve air pollution in urban areas and, in particular, in megacities around the world.

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REFERENCES

1 IPCC. Climate Change 2014: Impacts, Adaptation, and Vulnerability. IPCC Working Group II Contribution to AR5. 2014. http://ipcc-wg2.gov/AR5/ (accessed 30 Apr 2014).
2 Mickley LJ. Effects of future climate change on regional air pollution episodes in the United States. *Geophys Res Lett* 2004;31:L24103.
3 Kinney PL. Climate change, air quality, and human health. *Am J Prev Med* 2008;35:459–67.
4 Kaiser R, Le Tertre A, Schwartz J, *et al*. The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality. *Am J Public Health* 2007;97 (Suppl 1):S158–62.
5 McGeehin MA, Mirabelli M. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ Health Perspect* 2001;109:185–9.
6 Breitner S, Wolf K, Devlin RB, *et al*. Short-term effects of air temperature on mortality and effect modification by air pollution in three cities of Bavaria, Germany: a time-series analysis. *Sci Total Environ* 2014;485–486:49–61.
7 Von Klot S, Zanobetti A, Schwartz J. Influenza epidemics, seasonality, and the effects of cold weather on cardiac mortality. *Environ Health* 2012;11:74.
8 Michelozzi P, Accetta G, De Sario M, *et al*. High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities. *Am J Respir Crit Care Med* 2009;179:383–9.
9 Schneider A, Schuh A, Maetzel F-K, *et al*. Weather-induced ischemia and arrhythmia in patients undergoing cardiac rehabilitation: another difference between men and women. *Int J Biometeorol* 2008;52:535–47.
10 Basu R. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 2009;8:40.
11 Curriero FC, Heiner KS, Samet JM, *et al*. Temperature and mortality in 11 cities of the eastern United States. *Am J Epidemiol* 2002;155:80–7.
12 Kloog I, Nordio F, Zanobetti A, *et al*. Short term effects of particle exposure on hospital admissions in the mid-Atlantic states: a population estimate. *PLoS ONE* 2014;9:e88578.
13 Schwartz J. Who is sensitive to extremes of temperature? A case-only analysis. *Epidemiology* 2005;16:67–72.
14 O'Neill MS, Zanobetti A, Schwartz J. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *J Urban Health* 2005;82:191–7.
15 Hampel R, Breitner S, Rückerl R, *et al*. Air temperature and inflammatory and coagulation responses in men with coronary or pulmonary disease during the winter season. *Occup Environ Med* 2010;67:408–16.
16 Balbus JM, Malina C. Identifying vulnerable subpopulations for climate change health effects in the United States. *J Occup Environ Med* 2009;51:33–7.
17 Halonen JI, Zanobetti A, Sparrow D, *et al*. Relationship between outdoor temperature and blood pressure. *Occup Environ Med* 2011;68:296–301.
18 Alpérovitch A, Lacombe J-M, Hanon O, *et al*. Relationship between blood pressure and outdoor temperature in a large sample of elderly individuals: the Three-City study. *Arch Intern Med* 2009;169:75–80.
19 Lanzinger S, Hampel R, Breitner S, *et al*. Short-term effects of air temperature on blood pressure and pulse pressure in potentially susceptible individuals. *Int J Hyg Environ Health* 2014;217:775–84.
20 Halonen JI, Zanobetti A, Sparrow D, *et al*. Associations between outdoor temperature and markers of inflammation: a cohort study. *Environ Health* 2010;9:42.
21 Schäuble CL, Hampel R, Breitner S, *et al*. Short-term effects of air temperature on blood markers of coagulation and inflammation in potentially susceptible individuals. *Occup Environ Med* 2012;69:670–8.
22 Schneider A, Panagiotakos D, Picciotto S, *et al*. Air temperature and inflammatory responses in myocardial infarction survivors. *Epidemiology* 2008;19:391–400.
23 Yamamoto H, Zheng KC, Ariizumi M. Influence of heat exposure on serum lipid and lipoprotein cholesterol in young male subjects. *Ind Health* 2003;41:1–7.
24 Halonen JI, Zanobetti A, Sparrow D, *et al*. Outdoor temperature is associated with serum HDL and LDL. *Environ Res* 2011;111:281–7.
25 Hampel R, Schneider A, Brüske I, *et al*. Altered cardiac repolarization in association with air pollution and air temperature among myocardial infarction survivors. *Environ Health Perspect* 2010;118:1755–61.
26 Schwartz J. The distributed lag between air pollution and daily deaths. *Epidemiology* 2000;11:320–6.
27 Dockery DW, Pope CA III, Kanner RE, *et al*. Daily changes in oxygen saturation and pulse rate associated with particulate air pollution and barometric pressure. *Res Rep Health Eff Inst* 1999;(83):1–8.
28 Zanobetti A, Luttmann-Gibson H, Horton ES, *et al*. Brachial artery responses to ambient pollution, temperature, and humidity in people with type 2 diabetes: a repeated-measures study. *Environ Health Perspect* 2014;122:242–8.
29 Stafoggia M, Schwartz J, Forastiere F, *et al*. Does temperature modify the association between air pollution and mortality? A multicity case-crossover analysis in Italy. *Am J Epidemiol* 2008;167:1476–85.
30 Mehta AJ, Kloog I, Zanobetti A, *et al*. Associations between changes in city and address specific temperature and QT interval—the VA normative aging study. *PLoS ONE* 2014;9:e106258.
31 Park AK, Hong YC, Kim H. Effect of changes in season and temperature on mortality associated with air pollution in Seoul, Korea. *J Epidemiol Community Health* 2011;65:368–75.
32 Jhun I, Fann N, Zanobetti A, *et al*. Effect modification of ozone-related mortality risks by temperature in 97 US cities. *Environ Int* 2014;73:128–34.
33 Zanobetti A, Schwartz J. Temperature and mortality in nine US cities. *Epidemiology* 2008;19:563–70.
34 O'Neill MS, Hajat S, Zanobetti A, *et al*. Impact of control for air pollution and respiratory epidemics on the estimated associations of temperature and daily mortality. *Int J Biometeorol* 2005;50:121–9.
35 De Sario M, Katsouyanni K, Michelozzi P. Climate change, extreme weather events, air pollution and respiratory health in Europe. *Eur Respir J* 2013;42:826–43.
36 Schwartz J, Zanobetti A. Using meta-smoothing to estimate dose-response trends across multiple studies, with application to air pollution and daily death. *Epidemiology* 2000;11:666–72.
37 Zanobetti A, O'Neill MS, Gronlund CJ, *et al*. Summer temperature variability and long-term survival among elderly people with chronic disease. *Proc Natl Acad Sci USA* 2012;109:6608–13.