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Commentary

The Future of Climate Epidemiology: Opportunities for Advancing Health Research in the Context of Climate Change

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In the coming decades, climate change is expected to dramatically affect communities worldwide, altering the patterns of many ambient exposures and disasters, including extreme temperatures, heat waves, wildfires, droughts, and floods. These exposures, in turn, can affect risks for a variety of human diseases and health outcomes. Climate epidemiology plays an important role in informing policy related to climate change and its threats to public health. Climate epidemiology leverages deep, integrated collaborations between epidemiologists and climate scientists to understand the current and potential future impacts of climate-related exposures on human health. A variety of recent and ongoing developments in climate science are creating new avenues for epidemiologic contributions. Here, we discuss the contributions of climate epidemiology and describe some key current research directions, including research to better characterize uncertainty in climate health projections. We end by outlining 3 developing areas of climate science that are creating opportunities for high-impact epidemiologic advances in the near future: 1) climate attribution studies, 2) subseasonal to seasonal forecasts, and 3) decadal predictions.

adaptation; climate; climate change; climate epidemiology; climate projections; extreme events; temperature; weather

Abbreviations: CMIP, Climate Model Intercomparison Project; S2S, subseasonal to seasonal.

In recent decades, climate change has altered environmental exposures worldwide, with anthropogenic greenhouse gases attributed as a main cause (1, 2). Climate change is expected to continue over the next century, leading to increases in average land and sea surface temperatures and rising sea levels (1–4). These changes will likely degrade air quality, especially through the photochemical formation of ozone (5–7). The frequency and intensity of extreme weather events—including heat waves, wildfires, and droughts—are also projected to increase (1, 2, 7, 8).

These changes will almost certainly affect human health. Rising temperatures and extreme weather events directly influence physical and mental health (1, 3, 9), whereas disaster-related damage to infrastructure and health systems can have indirect impacts (10). Changes in climate conditions affect the distribution of disease vectors such as mosquitoes and ticks (1, 4, 11), thus influencing patterns of malaria (12), West Nile virus (11), Lyme disease (11), and other diseases (1, 13). Changes in water temperature, precipitation, and flooding may influence water-related diseases like cholera (14–16). Climate change can also exacerbate conflict and migrations (8), as well as alter food production (1, 8, 17) and water availability (1). Though the direct and indirect effects of climate change threaten health worldwide, the impact will likely be particularly high in developing countries (1, 3, 4).

Climate epidemiology leverages deep, integrated collaborations between epidemiologists and climate scientists to understand the current and potential future impacts of climate-related exposures on human health. A variety of recent and ongoing developments in climate science are creating new avenues for epidemiologic contributions. Here, we discuss the contributions of climate epidemiology, describe some key current research directions, and outline developing areas of climate science that are creating opportunities for high-impact epidemiologic advances in the near future.

CONTRIBUTIONS OF CLIMATE EPIDEMIOLOGY

Climate epidemiology studies augment the evidence base that is communicated to governments and policymakers on the potential impacts of climate change, through reports such as the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (4) and the regular climate-health assessment report from the US Global Change Research Program (2). Under a common framework defined by the World Climate Research Programme through the Climate Model Intercomparison Project (CMIP) (18–20), climate scientists explore how current choices and policies might affect future climates by running climate models for several different scenarios of greenhouse gas emissions and land use (1). Climate epidemiologists have combined the output of CMIP climate model runs to project the potential health impacts of different emissions scenarios (12, 15, 21–24). These projections help clarify how current national and international policy choices might limit the adverse health impacts of climate change, and epidemiologic research also informs this policymaking by investigating how policies to reduce greenhouse gas emissions might immediately benefit human health through reduced ambient exposure to air pollution (25, 26).

Climate epidemiology also informs policies and measures aimed at adapting communities to changing climate exposures (1, 27), including implementation of warning systems that combine weather forecasts with epidemiologic knowledge (4, 27). For example, the European heat wave of 2003, and epidemiologic evidence of its health impacts, triggered the creation of heat preparedness plans and heat health warning systems (27, 28). Local epidemiologic studies help identify appropriate thresholds for deploying warning systems; local thresholds may differ substantially from those in national guidelines, as was found in a recent study of New England communities (29).

KEY CURRENT RESEARCH DIRECTIONS IN CLIMATE EPIDEMIOLOGY

Incorporating uncertainty from climate model outputs into estimations of health effects

When epidemiologists project the health impacts of climate change on the future, they are building on projections of future exposures generated by climate models. Each run of a climate model results in a single time series of projected exposures. This output captures 1 plausible instance of exposures in the future, but does not capture the range of plausible exposures.

To present a plausible range in climate projections, climate scientists combine output from climate models run multiple times (e.g., under different scenarios of anthropogenic forcings, using different climate models, or with small variations in initial conditions). These techniques are used to address different sources of uncertainty in climate projections that climate scientists have recognized for more than a decade (30). However, although climate epidemiologists often consider different scenarios of anthropogenic forcings, other sources of uncertainty are only rarely addressed when projecting health impacts (31). When climate health projections fail to incorporate these, they risk presenting projection ranges that are too narrow or otherwise fail to adequately communicate potential variation.

For example, climate model uncertainty is usually incorporated in a very limited manner, if at all, in climate health projections. Many climate models exist and, given the same inputs (including emissions scenarios), provide different outputs (30, 31). This variation results from several factors, including differences in the models' physical processes, parameter values, and the numerical methods used to run the defined models computationally. One potential approach to exploring this uncertainty is by generating a range of projections through the use of output from ensembles of climate models, rather than output from a single model (20, 32, 33).

A few climate health projections have incorporated climate model uncertainty, but incorporating this uncertainty remains an area for potential growth in climate epidemiologic research (31). In 1 systematic review, researchers investigated projections of heat-related death and found that only 8 (22, 24, 34, 35) of 63 identified studies incorporated output from more than 10 climate models (31). By contrast, output is available from many climate models. The most recent CMIP collaboration, CMIP5, brought together 20 climate modeling groups, all of which contributed output from at least 1 model and several of which contributed output from multiple models (20). Furthermore, in future work, climate epidemiologists can consider not only incorporating climate outputs from larger model ensembles but also weighting multiple model outputs to account for similarities among some climate models (33, 36)—climate models are not independent, because the process of model refinement is iterative, based on shared previous models and using similar metrics of evaluation (33).

A second key source of uncertainty in climate projections results from internal climate variability, or climate "noise" (30, 37) that occurs across the climate system, including the state of oceans, sea ice, and soil moisture (38). Depending on the magnitude of this noise, climate exposures can be higher or lower on average during a period than would be expected over the long term for the location's climate. To account for internal climate variability in their projections, climate modelers use large, single-model ensembles in which the same climate model is run multiple times using the same emissions scenario, but under slightly different initial conditions (37). This creates an ensemble of projections in which the timing of the phases of lower-frequency elements of the climate system vary, so that the range of the projections characterizes uncertainty from internal climate variability. Only a few health projection studies have incorporated output from medium to large ensembles to help characterize uncertainty related to internal climate variability (39, 40), although projections that do not address this source of uncertainty likely present ranges that are too narrow.

Applying present-day exposure-response functions to future scenarios

For climate health projections, uncertainty is also introduced by uncertainty about the degree to which exposure-response functions, fit using present-day health and weather data, are applicable to the future (41–43). There are several reasons why these functions might change over time. First, communities can experience "unintentional adaptation," that is, change in ways that are not in direct response to a changing climate but that nonetheless alter their populations' vulnerability to climate-related exposures (41). For example, changes in health care systems, demographics, underlying population health, and building characteristics can affect a community's health response to climate-related events and exposures (31, 41).

There is, in fact, strong historic evidence that climate-related exposure-response functions change regionally or locally over time even without notable changes in climate (43). For example, researchers have investigated how the relationship between local temperature and mortality has changed at time scales of decades to a century (44–49). Most of these studies revealed a dampening of heat-related mortality risk over time, and some also found a decrease in the impact of cold on death. These changes coincided with an increasing prevalence of residential air conditioning and improvements in the diagnosis and treatment of chronic conditions that are particularly vulnerable to temperature changes, such as heart and lung diseases and mental illness (31, 41, 47).

There is also strong evidence that populations take direct measures in response to common climate exposures, resulting in local adaptation. For example, in a study of various locations across 12 countries, the relationship between heat and death was found to begin at higher temperatures in locations with warmer climates (50). In locations with frequent high temperatures, housing characteristics and behaviors that mitigate heat exposure may help protect the population (41). Studies have also revealed that vulnerability to heat is often lower at the end of the summer compared to the beginning of the summer (51), suggesting some short-term adaptation related to physical acclimatization.

Populations, however, rarely completely adapt to heat, and some risk remains even in communities with hot climates and at the end of summer (50–52). Furthermore, although some climate-related exposures (e.g., high temperatures) have increased in past decades, larger changes are expected over the coming century. It is unclear the degree to which adaptation or efforts to reduce vulnerability can mitigate the effect of increasing temperatures on human health, and this, therefore, is a key source of uncertainty in climate health projections (43). For example, projections of the impact of climate-related changes in the patterns in vector-borne disease could be substantially influenced by the introduction of new or improved measures for mosquito control (11). Similarly, the degree to which more frequent exposures to extreme heat in the future will exacerbate mental health conditions depends on whether medications will be developed that can treat these conditions without impeding thermoregulation, as many current medications do (9).

Given the limited scientific information on adaptation to climate-related exposures, many climate health projections assume no adaptation or other change in vulnerability (41). For example, in a large international study, researchers projected temperature-related death under climate change in more than 20 countries but considered only scenarios in which present-day exposure-response functions remain identical into the future (53). Some studies, however, have explored how adaptation or other changes in vulnerability may introduce uncertainty in health projections. Changes in heat vulnerability across the 20th century in New York City, New York, were measured in a study and then extrapolated in a continuing pattern into future years (22). Adaptation scenarios have been incorporated in other studies by elevating the point at which mortality risk begins to increase with rising temperatures (i.e., the minimum mortality temperature) or by decreasing the slope of the temperature-health relationship (54–56). Still others have used information gathered from other cities with climates that are similar to the expected future climate in the city of interest, either through the use of single analogue cities (57, 58) or with more complex models that incorporate data from cities with a variety of climates (40, 59).

Climate epidemiologists have not settled on a single method for addressing the potential for adaptation in climate change-related health projections (41, 42, 52). They have, however, determined that this choice strongly influences projections (22, 40, 42). For instance, in 1 study, authors found greater uncertainty in projections of heat-wave death impacts related to the selected adaptation scenario than to internal climate variability, emissions scenarios, or population-change scenarios (40). To better understand and reduce this source of uncertainty in health projections, it is critical to better understand how societal changes affect vulnerability to climate-related exposures. The degree to which decreasing vulnerability to heat over recent decades is related to increasing prevalence of air conditioning has been investigated in some studies (47), whereas demographic factors, including age and sex, that help explain variability in temperature vulnerability across individuals and locations have been investigated in other studies (60). Still others have explored changes in heat vulnerability based on timing of heat exposures in the summer months (51). Understanding the society-level factors that influence adaptation and vulnerability can also help inform policies and actions to reduce vulnerability, as evidenced through recent studies investigating the effectiveness of heat action plans and warning systems (28, 61, 62).

OPPORTUNITIES ARISING FROM ONGOING ADVANCES IN CLIMATE SCIENCE

Climate attribution studies

In climate attribution studies, researchers investigate recently observed climate-related exposures to determine the degree to which they are linked to climate change (1, 63). By integrating epidemiologic results with results from this developing field, climate epidemiologists could help identify, communicate, and mitigate the health impacts of climate change that are already underway, by quantifying how climate change-attributable characteristics of extreme events or exposures affect health (64). The focus of most attribution studies to date has been on weather conditions and events, rather than the downstream impact of these exposures to ecosystems or humans. However, some researchers have explored climate attribution for barrier reef bleaching, marine resources, and ecosystem productivity (65), and a handful of climate attribution studies have been conducted for health outcomes (66), including an investigation of death in England and Wales during and after the 2003 heat wave (67).

The climate science required for such studies has advanced rapidly in recent years, and various methods of attribution analysis have been developed (63). One is similar to the epidemiologic concept of attributable fractions, estimating the fraction of attributable risk. This fraction of attributable risk compares the probability of observed weather conditions or events under climate models run with versus without anthropogenic forcings driving climate change. A fraction of attributable risk of 1 indicates that the observed event would not have been possible without climate change (65), and in the latest of a series of special issues on climate attribution studies, 3 studies estimated fractions of attributable risk of 1 for weather conditions, including heat extremes, observed in 2016 (68–70).

A second approach to attribution analysis starts with the assumption that the atmospheric circulation that caused the event occurred. Using this method, researcher then explore how climate change modified the subsequent characteristics of the event, through its influence on elements of the thermodynamic state like sea surface temperature and sea level (63). As an example, this approach was used to explore how climate change modified Superstorm Sandy in 2012 (71). In this study (71), researchers found that climate change, by increasing the sea surface temperature, likely led to more intense wind and precipitation during the storm. These characteristics, in turn, may have exacerbated the storm's impacts on human health, which included observed increases in hospitalizations (72), cardiovascular events (73), and mental health outcomes (74).

To extend the methodology of climate attribution to encompass health impacts, climate epidemiologists will need to adapt and develop models and methods (65, 66), including methods for causal inference (75, 76). For certain exposures and health outcomes, relevant epidemiologic models are already well developed. For example, exposure-response functions for the temperature-death relationship have been fit in many locations worldwide. By comparison, little scientific evidence exists for many other climate-related exposures and health outcomes, representing a significant opportunity for climate epidemiology researchers.

Subseasonal to seasonal forecasts

Climate projections provide reasonable estimates of the climate in future decades and centuries but are unable to forecast expected conditions on specific days or seasons. Numerical weather prediction, conversely, aims to forecast conditions at a specific time, but with a lead time of only about 2 weeks (77). Research on subseasonal to seasonal (S2S) forecasting is working toward providing forecasts with longer lead times (weeks to months) by integrating contributions from the weather and climate research communities (77). Such S2S forecasts offer the promise of advancing forecasts of climate-related exposures in the coming weeks or months, including changing risks of heat waves, cold spells, wildfires, floods, and tropical cyclones (77).

By increasing lead time, S2S forecasts could provide critical information for public health management and planning for climate-related exposures. As the science behind S2S forecasting advances, there will be an increasingly important role for epidemiologists who can pair these forecasts with epidemiologic models to forecast changing risks for weather-related health impacts. Some public health warning systems are already being developed at the S2S forecast timescale (4), including early warning systems for malaria in Botswana (78) and dengue fever in Singapore (79) and Ecuador (80).

Decadal climate predictions

Within a given period, a location's weather is influenced not only by climate but also by the phase of lower-frequency phenomena in the climate system, including oceanic, land surface, and sea ice conditions. Most climate health projections use multidecadal output, which captures changes in these lower-frequency phenomena, but with projected phases that fail to align with when we should actually expect specific phases (81). Therefore, these projections should be given with a wider range (e.g., through the use of large ensembles) to accommodate this internal climate variability than if the timing of the phases were known.

Decadal predictions seek to tighten climate projections for the near future by reducing uncertainty related to these phases—although the timings of lower-frequency phenomena may not be forecastable in longer-term projections, it may be possible to forecast them with some skill in the shorter term (i.e., up to 30 years). Climate epidemiologists, in turn, may be able to build on these decadal predictions to tighten shorter-term projections of climate-related health impacts. As with S2S forecasts, there are several planning and preparation activities that operate at a timescale relevant to decadal predictions (82–84). For example, some water management decisions require a lead time of years to decades (85, 86).

Decadal predictions initialize the climate model using data on the observed state of the climate in the recent past (82), integrating techniques from climate modeling and numerical weather forecasting. The science of decadal climate predictions is still under development; in CMIP5, decadal predictions were included only to help inform other developments within the climate science community rather than as outputs ready for operational use (20, 82). However, as the science of decadal predictions continues to develop, climate epidemiologists will have a role to play in near-term decadal predictions of health impacts of climate change.

CONCLUSIONS

Climate change is expected to pose critical threats to human health. Past human activities have already committed the world to a certain level of climate change in the next few decades, regardless of the policies enforced to mitigate climate change now or later in the century (3). Climate epidemiology will play a powerful role in understanding, planning for, and preventing some of these health impacts. Key opportunities exist in climate epidemiology to better understand and communicate potential variation in climate health projections. Such work will be critical for informing policymakers of the potential health-related impacts of climate change—indeed, the synthesis report of the Fifth Assessment of the Intergovernmental Panel on Climate Change highlights that "an integral feature of their reports is the communication of the strengths and uncertainties in scientific understanding underlying assessment findings" (1). Furthermore, rapid developments in climate science are creating several new opportunities for climate epidemiology. Although projections of the potential health impacts of climate change late into the 21st century can shape national and international policy decisions for climate change mitigation, shorter-term projections may be particularly helpful for more localized planning, including at regional and municipal scales. At these scales, epidemiologic work that builds on shorter-term climate-related outputs—including climate attribution studies, S2S forecasts, and decadal predictions—could help inform scientists about conditions that already exist or anticipate and prepare for conditions likely to exist soon. To realize these opportunities, epidemiologists will need to work closely with climate scientists, public health practitioners, and disaster management specialists to combine epidemiologic models with climate-related outputs in a way that best informs public health preparations for coming changes in climate-related exposures.

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