Int J Biometeorol (2017) 61 (Suppl 1):S71–S80
DOI 10.1007/s00484-017-1406-1

IJB 60TH ANNIVERSARY (INVITED ONLY)

# The past and future in understanding the health risks of and responses to climate variability and change

Kristie L. Ebi[1] · Jeremy J. Hess[1,2]

Received: 25 May 2017 / Revised: 6 July 2017 / Accepted: 6 July 2017 / Published online: 21 July 2017


**Abstract** Climate change and health was established as a formal field of endeavor in the early 1990s, with the number of publications increasing since the mid-2000s. The key findings in assessment reports from the Intergovernmental Panel on Climate Change in 1995, 2001, 2007, and 2014 indicate the progress in understanding the magnitude and pattern of the health risks of a changing climate. The assessments maintained a similar structure, focusing on assessing the state of knowledge of individual climate-sensitive health outcomes, with confidence in the key findings tending to increase over time with greater understanding. The knowledge base is smaller than for other key sectors (e.g., agriculture) because of limited research investment in climate change and health. Vulnerability, adaptation, and capacity assessments can inform prioritization of the significant research gaps in understanding and managing the health risks of a changing climate; filling these research gaps would provide policy- and decision-makers with insights to increase short- and longer-term resilience in health and other sectors. Research needs include to understand how climate and development pathways could interact to alter health risks over time, better understand upstream drivers of climate-sensitive health outcomes, project aggregate health impacts to understand the breadth and depth of challenges that may need to be managed at geographic scales of interest, and project the time of emergence of changes in the geographic range and intensity of transmission of infectious diseases and other climate conditions. Engagement with other sectors is needed to ensure that their mitigation and adaptation activities also promote and protect health and take the health sector's needs into account. Making progress in these areas is critical for protecting the health of future populations.

**Keywords** Health · Climate variability · Climate change · Adaptation · Research needs

✉ Kristie L. Ebi
krisebi@uw.edu

Jeremy J. Hess
jjhess@uw.edu

[1] Center for Health and the Global Environment (CHanGE), University of Washington, Seattle, WA 98105, USA

[2] Departments of Medicine, Global Health, and Environmental and Occupational Health Sciences, Seattle, WA, USA

## Introduction

National and international organizations began serious consideration of the possible consequences for human and natural systems of increasing greenhouse gas emissions in the 1970s. For example, in 1970, the Massachusetts Institute of Technology convened a 1-month study of critical environmental problems, focusing on environmental issues whose cumulative effects on ecological systems would be so large and prevalent; they would have worldwide significance (SCEP 1970). The 50 study participants in that meeting were primarily concerned with the effects of pollution on humans through changes in climate, ocean ecology, and large terrestrial ecosystems. There was at the time no specific consideration of the possible impacts of climate change on human health and well-being.

Over the subsequent decades, accumulating evidence of the possible consequences of anthropogenic greenhouse gas emissions for the climate system led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The IPCC was founded to provide objective, scientific assessments of climate change, its potential consequences for human and natural systems, and adaptation and mitigation options to prepare for and manage resulting risks. Soon thereafter in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was established. The UNFCCC laid out its objective in Article 2 (UNFCCC 1992):

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.

Notably, the reasons for concern about dangerous anthropogenic interference with the climate system did not include health, water, or other critical sectors now viewed as central to understanding the challenges of climate change to individuals and societies (Oppenheimer et al. 2014). Few impacts of climate change had been observed at the time the UNFCCC was negotiated, so the negotiations assumed that impacts were unlikely to occur until later in the twenty-first century; this framing informed research until relatively recently.

The emergence of a new discipline can be dated by the publication of its first textbook (Kunh 1962). Climate change and health as a field was established by the publication in 1993 of "Planetary Overload" by Dr. A.J. McMichael (McMichael 1993). Dr. McMichael surveyed the emergence of population health hazards over past centuries, laying out the importance of maintaining the integrity of Earth's natural systems to support the health of human populations, and discussed a wide range of issues threatening those life support systems, including anthropogenic climate change. He outlined the basic threats of climate change for human health and well-being, framed the research and analysis that continues to this day, and put climate change within the context of other global environmental and development changes. He emphasized the importance of multidisciplinary, system-based approaches to understanding and managing the risks that will evolve and interact across spatial and temporal scales.

Research and practice on climate change and health continues to focus on (1) quantifying exposure-response relationships between weather, climate variability, and climate change and climate-sensitive health outcomes; (2) identifying the population groups and geographic regions particularly sensitive to changing weather patterns; (3) conducting detection and attribution studies of the extent to which climate change is observably altering the burdens of climate-sensitive health outcomes; (4) projecting how the magnitude and pattern of health risks could change under different climate and development scenarios; (5) developing guidance and tools for assessing risks, vulnerabilities, and capacities to identify baskets of adaptation options to prepare for and manage current and projected risks, including monitoring, evaluation, and learning to identify best practices and lessons learned for scaling up; and (6) promoting implementation of policies and technologies to reduce greenhouse gas emissions, including efforts to green the health sector and estimate the health cobenefits of mitigation actions by other sectors. There has been uneven progress in these topics, with more emphasis in quantifying exposure-response relationships, identifying vulnerable groups, and projecting risks over coming decades. Important topics repeatedly raised, but with limited research efforts, are the possible health risks of greenhouse gas mitigation and adaptation actions in other sectors, and how to most effectively promote cross-sectoral collaboration and coordination.

## Understanding in the 1990s of the health risks of climate change

Closely following the publication of Dr. McMichael's first book, the IPCC Second Assessment Report included for the first time a chapter on human health that detailed the state of knowledge (McMichael et al. 1995). Issues raised included the following:

- Overall, that climate change could have a multitude of serious, but underrecognized, risks to human health and well-being;
- The relative paucity of quantitative research on the possible health risks of a changing climate;
- Climate change can affect human health directly (e.g., mortality from heat waves and extreme weather and climate events) and indirectly (e.g., changes in the geographic range of vectorborne diseases);
- Potential impacts will likely change with additional climate change, and could be larger than most other environmental health risks;
- Changing weather patterns associated with climate change interact with population vulnerability to alter the risk of adverse health outcomes; and
- Impacts would likely be largest in low-income communities and countries where exposure and vulnerability are high and adaptive capacity relatively low.

Specific health outcomes considered were the following:

- Heat-related morbidity and mortality;
- Injuries, illnesses, and deaths associated with extreme weather and climate events;

- Increasing prevalence of a range of infectious diseases because of changes in their geographic range, seasonality, or transmission dynamics, with malaria as a key example;
- Undernutrition associated with increased food insecurity from changes in agricultural, animal, and fishery productivity;
- Respiratory diseases associated with increased concentrations of urban air pollutants, particularly ozone and particulates; and
- Adverse health outcomes arising from deterioration of social and economic circumstances, including conflict over dwindling environmental resources.

The chapter pointed out that climate-related changes in other sectors, such as reductions in food and water security, can have significant consequences for human health. The overall conclusion was that human health will primarily be adversely affected by climate change and its effects on Earth's natural systems.

Although the conclusions were drawn from a limited literature base, the IPCC Second Assessment Report identified the major health risks of a changing climate that continue to be the focus of national and international assessments. Subsequent publications provided greater understanding and quantification, but have not fundamentally altered the main conclusions, as discussed below. One exception is that the Second Assessment Report included discussion of the health risks of stratospheric ozone depletion; this topic was not covered in subsequent assessments. The Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments took up this issue.

The IPCC Second Assessment Report chapter on human health ended with a call for enhanced research and monitoring. Overarching research needs identified included developing and validating integrated mathematical models for projecting health risks; quantifying the influence of climatic factors on infectious diseases; and incorporating health-related measurements into global, regional, and local monitoring activities to detect early shifts in the burden of climate-sensitive health outcomes. Other needs included conducting research on heat waves, studying how the interplay between climatic impacts on forests and other ecosystems could affect the burden of vectorborne diseases, and examination of factors influencing vulnerability to climate change.

## International research progress in the last 20 years

Although the knowledge base is broadening and deepening, most of the key research gaps remain. The human health chapter in the IPCC Third Assessment Report (McMichael et al. 2001) laid out the basic categories of climate-sensitive health outcomes that were assessed in that and subsequent international assessment reports, including heat waves, extreme weather and climate events, air pollution, infectious diseases, food yields and nutrition, and social disruption, such as migration and civil conflict. New issues that arose over the years include occupational health, mental health, noncommunicable diseases, the health consequences of large-scale ecosystem collapse, and migration. These categories focus on assessing the state of knowledge within individual health outcomes, which is valuable, but risks are unlikely to arise individually. Communities and regions will increasingly face multiple risks simultaneously; further, these risks could interact, resulting in more complex challenges than projections of single health outcomes suggest.

Table 1 compares the key messages from the Third Assessment Report (TAR), Fourth Assessment Report (AR4), and Fifth Assessment Report (AR5) (McMichael et al. 2001; Confalonieri et al. 2007; Smith et al. 2014). The key findings cannot be directly compared because the summary statements were different in each assessment cycle, and because the guidance for assessing confidence in key findings, although similar, differed across the assessment cycles. Assessment of detection and attribution research appeared in the AR5.

Over the course of the assessments, confidence in the key findings with respect to heat-related morbidity and mortality increased, from high (TAR) to very high (AR5) confidence that heat waves will likely increase health risks, while the confidence in key findings for cold-related health outcomes decreased with greater understanding of the role of temperature in winter mortality. Because mortality is higher during winter months, an early assumption was that temperature was a key factor in winter mortality (Ebi and Mills 2013). However, further research questioned the basis for that assumption, resulting in lower confidence of how climate change could affect the magnitude of winter mortality. The issue of lost worker capacity and reduced labor productivity first appeared in the AR5.

The level of confidence in key findings about the health impacts of extreme weather and climate events decreased from the TAR to the AR4 with greater recognition of the socioeconomic and other factors that also are determinants of adverse health outcomes during and after extreme events. There was high confidence in the AR4 of the potential for climate change to increase the adverse health consequences of reduced air quality, including increased concentrations of ground-level ozone, particulate matter, and allergenic pollen species. The health risks of changes in air quality due to climate change did not rise to the level of a key finding in the AR5, perhaps because the research published between the AR4 and AR5 did not alter the key finding in the AR4.

Vectorborne diseases, particularly malaria and dengue, were the focus of key findings in all assessments, with the level of confidence changing over the assessment cycles as

**Table 1** Key findings from the IPCC Third Assessment Report (TAR), Fourth Assessment Report (AR4), and Fifth Assessment Report (AR5)

| Health outcome | TAR | Confidence | AR4 | Confidence | AR5 | Confidence |
|---|---|---|---|---|---|---|
| Heat-related morbidity and mortality | Heat waves will increase health risks, principally in older age groups and the urban poor | High | Climate change has increased heat wave-related deaths<br>Projected exposures will increase heat wave-related morbidity and mortality | Medium<br>High | Recent increase in temperatures increased the risk of heat-related illnesses and deaths<br>Greater risk of adverse health outcomes from projected increases in heat waves | Likely<br>Very high |
| Lost work capacity and reduced labor productivity | | | | | Continuing climate change will increase consequences<br>Under RCP 8.5, some parts of the world will experience high temperatures and high humidity that will compromise normal human activities | High<br>High confidence |
| Cold-related morbidity and mortality | Decrease in many temperate countries | High | Fewer deaths from cold | High | Modest reductions | Low confidence |
| Injuries, illnesses, and deaths from extreme events | Any regional increase in extremes could cause population displacement, adverse effects on food production and freshwater availability and quality, and increase the risks of infectious disease epidemics, particularly in developing countries | Very high | Projected changes in extreme events will increase adverse health outcomes | High | Greater risk of adverse health outcomes due to fires | Very high |
| Adverse health consequences of poor air quality | Climate change will cause some deterioration in air quality in many large urban areas | Medium to high | Climate change has altered the seasonal distribution of some allergenic pollen species<br>Changes in ground-level ozone will increase cardio-respiratory morbidity and mortality | High<br>High | | |
| Vectorborne diseases | In areas with limited or deteriorating public health infrastructure, and where temperatures are permissive of disease transmission, the geographic range of malaria, dengue, and leishmaniasis would extend<br>Higher temperatures in combination with conducive rainfall would prolong transmission seasons in some endemic locations<br>Reduction in transmission in some regions where rainfall is reduced or temperatures too high | Medium to high for higher altitudes and medium to low for higher latitudes<br>Medium to high<br>Low to medium | Climate change has altered the distribution of some vectors<br>Projected trends in exposures will continue to change the range of some infectious diseases<br>Mixed effects of climate change on the geographic range of malaria (expansions and reductions) and changes in the transmission season<br>Increase the number of people at risk of dengue | Medium<br>High<br>Very high<br>Low | Local changes in temperature and rainfall have altered the distribution of some disease vectors<br>Increased risks<br>Reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds | Medium<br>Medium<br>Medium |
| Other vectorborne diseases (e.g., mosquitoborne or tickborne encephalitis, Lyme disease) | Climate variability and change could affect transmission on the margins of current distributions | Medium to high | | | | |
| Diarrheal disease | | | Climate change will increase the burden | Medium | | |

**Table 1** (continued)

| Health outcome | TAR | Confidence | AR4 | Confidence | AR5 | Confidence |
|---|---|---|---|---|---|---|
| Foodborne and waterborne diseases | | | | | Local changes in temperature and rainfall have altered the distribution of some diseases<br>Increased risks with projected climate change | Medium<br>Very high |
| Ciguatera and shellfish poisoning | Increase in incidence | Low | | | | |
| Undernutrition | Number of undernourished will increase in developing countries | Medium | | | Local changes in temperature and rainfall have reduce food production for some vulnerable populations<br>Increased risk of undernutrition from diminished food production in poor regions<br>Geographic shifts in food production with projected climate change | Medium<br>High<br>Medium |
| Socioeconomic dislocation and population displacement | Health impacts of any increase would be substantial | High | | | | |
| Adverse health risks in low-income countries | | | Impacts will be highest | | Health impacts will be reduced but not eliminated in populations that benefit from rapid and economic development, particularly among the poorest and least health groups | Very high |
| Vulnerable populations | | | Urban poor, elderly, children, traditional societies, subsistence farmers, coastal population | High | Most effective measures to reduce vulnerability are programs that implement and improve basic public health measures | Very high |
| Adaptation | There are a range of options to lessen any impacts | | Even high-income countries are not well prepared for extremes | High | | |

*Source*: McMichael et al. (2001), Confalonieri et al. (2007), and Smith et al. (2014)

new information became available and with increased understanding of the other drivers of the geographic range, seasonality, and transmission of dynamics of these diseases. There was no consistent trend in the level of confidence. The AR5 concluded that there was medium confidence of increased risks when considering how other factors could affect disease transmission dynamics. The AR4 had a key finding on diarrheal disease, with the AR5 providing a more comprehensive assessment of foodborne and waterborne diseases, concluding that there was medium confidence in observed impacts from recent climate change and very high confidence in future risks.

Undernutrition did not have a key finding in the AR4, while the AR5 provided three key findings on observed impacts of changing temperature and precipitation on food production (medium confidence), increases in projected health risks in poor regions (high confidence), and projected geographic shifts in food production (medium confidence). The AR4 and AR5 assessments had key findings on the distribution of vulnerable populations and the magnitude of impacts, concluding that low-income countries would experience an increase in the size of vulnerable populations and greater impacts.

The IPCC assessments were based on a growing body of research into the associations between adverse health outcomes and weather, climate variability, and climate change. Verner et al. (2016) tracked the number of publications on climate change and health between 1990 and 2014 based on two scientific databases and the IPCC reports. The number of publications started from a very low base in 1990, slowly increased until around 2006, and then increased exponentially to 2014, with 6079 citations in PubMed and 17,395 in Science Direct in that year. These numbers support the extent of key findings in the IPCC assessments, with greater understanding and nuance as the numbers of publications increase. Approximately two thirds of the publications were carried out in high-income countries, predominantly in North America and Europe. Figure 1 shows the climate change and health publications by health impact from PubMed over 1990–2014 (Verner et al. 2016). Some major risks, particularly undernutrition, were decidedly understudied. A caveat on the strength of the literature was provided in a review of publications from 2000 to 2010; nearly 43% of publications were not original research, but comments, editorials, letters, or reviews (Hosking and Campbell-Lendrum 2012).

Although the increasing trend in number of climate and health publications is very positive, Vernier et al. (2016) found that the growth in climate and health was less than half of that for other climate-sensitive sectors. A key factor has been limited research funding by traditional sponsors of biomedical research, including foundations. In the USA, the National Institutes of Health commit 0.025% of their annual research budget to climate change and health (Ebi et al. 2016a). The European Union Seventh Framework Programme committed 0.08% of the total budget to climate change and health. In Australia, less than 0.1% of health funding has been allocated to climate change and health (Green et al. 2017). The limited research investment means that research is not providing timely and useful information to policy- and decision-makers on the magnitude and pattern of risks, or of options to prepare for and manage the challenges of a changing climate.

Issues apparently contributing to the mismatch between the political interest in protecting population health in a changing climate and the extent of the research investment include that research funders framing research on global environmental change and health from the narrow medical model view of health with traditional public health approaches, and the health sector viewing climate change as an environmental problem that is the responsibility of other sectors (McMichael 1993). Another issue is that many health researchers and funders concerned with potentially climate-sensitive health outcomes and concerns (such as chronic diseases, health system development, indigenous health) still do not see the links with climate and climate change. Together, these issues result in biomedical research continuing to prioritize reductionist, top-down perspectives that focus on proximate, individual-level risk factors that, while successful over the last century in reducing the burdens of infectious diseases, are insufficient to protect health in a world facing significant environmental changes (McMichael 1993; Ebi et al. 2016a). While comprehensive comparative risk assessment methods that incorporate upstream drivers of health outcomes such as development, education, and fertility, like the Global Burden of Disease, account for some relevant dynamics, additional approaches are needed to incorporate changes in environmental drivers and hazards more specifically. Risk-centered, system-based approaches, such as those promoted by biometeorology, are needed to understand how population health can be affected by and can affect social, economic, and environmental systems, including their interactions over coming decades. Vulnerability, adaptation, and capacity assessments can provide valuable information for prioritizing research to support the needs of local to national jurisdictions to inform effective and efficient adaptation planning (WHO 2012). These assessments frame, focus, and translate knowledge for decision-makers to use.

## Areas where research progress is needed

Research advances over the past 20 years have begun to fill in some knowledge gaps, providing limited quantifications of the magnitude and pattern of the current and projected health risks of climate change, at least for major infectious diseases (e.g., malaria and dengue), respiratory and cardiovascular outcomes associated with reduced air quality, and adverse health outcomes of temperature extremes and other extreme weather

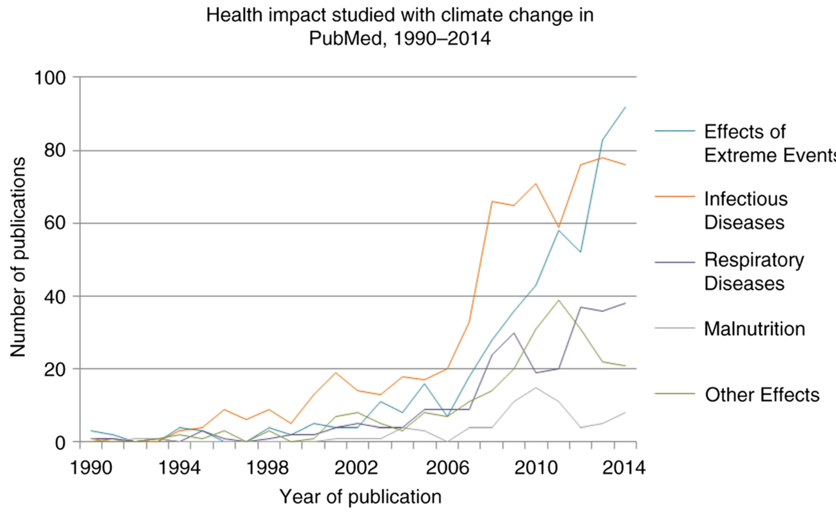


**Fig. 1** Climate change and health publications by health impact, PubMed 1990–2014 (Verner et al. 2016)

and climate events. Further understanding is needed of exposure-response relationships for these climate-sensitive health outcomes to inform actions to prepare for and manage health risks in the context of iterative risk management approaches that explicitly incorporate climate change (Ebi 2011; Hess et al. 2012; Hess and Ebi 2016). Doing so is critically important to protect population health in a changing climate, but insufficient. As climate change continues, attention is needed to understand not just the burden of climate-sensitive health outcomes but also the other issues that will confront future societies, the range of risk management options, and the interactions between environmental changes, risk management activities, development, and health. A partial list includes the following:

- Interactions between climate and development pathways and impacts on vulnerability and adaptive capacity in the health sector. Until recently, most projections of the health risks of climate change include limited consideration of the vulnerabilities and capacities of possible future societies. Age and economic growth are the variables most commonly included, but these do not adequately describe the multiple factors that will affect the magnitude and pattern of future health risks under different development pathways (Smith et al. 2014). Moreover, these variables do not capture variability across societies related to investment in risk reduction, risk sharing, and risk transfer mechanisms in health and other sectors (Ebi 2014). Better understanding of these interactions will inform prioritization of actions to, for example, increase access to safe water and improved sanitation in the context of changes in weather patterns and development pathways.
- Better understanding of the nexus between food, water, and energy security and population health. This is more than providing more robust and detailed projections of the extent of undernutrition as crop yields change and the micronutrient content of foods shift. Food security also includes production, transport, processing, and consumption. Research, including modeling, is needed to explore at local to national scales the implications for health of shifts in food, water, and energy security over time, including the implications for livability of regions and for migration and conflict. Very limited research has attempted to quantify the risks of food security in high-income countries, although populations in these countries will likely be affected. Food production and water resources are intertwined, with climate change affecting the availability and quality of both. Changes, for example, in the Asian monsoon, could significantly affect health, livelihoods, and development. Health research into these issues is very limited. Future populations will be poorly prepared without understanding how these large-scale changes could affect the burdens of climate-sensitive health outcomes, including but not limited to undernutrition and diarrheal disease.
- Research is needed to increase understanding of the upstream drivers of climate-sensitive health outcomes, to inform actions to protect and promote population health. As elegantly shown by Semenza et al. (2016), the top five upstream drivers of 116 infectious disease threats in Europe between July 2008 and December 2013 were (in order) travel and tourism, food and water quality, natural environment, global trade, and climate. A hierarchical cluster analysis indicated that travel and tourism were different from the other drivers. The analysis also indicated that some segments, such as climate and natural environment, and migration and social inequality, were more related to each other than to the other drivers. Sociodemographic and public health system factors were less frequent drivers of outbreaks. These results highlight

the importance of fostering multisectoral collaboration to prevent infectious disease threats. Modeling the linkages between and among these drivers and infectious disease outbreaks can provide insights into monitoring, including developing early warning systems, to prevent outbreaks turning into public health emergencies.

- Thresholds and the time of emergence of climate-sensitive health outcomes. Growing scholarship into the health risks of climate variability and change is informing research on thresholds and the time of emergence or re-emergence of, particularly, infectious diseases. This research can be used to improve public health monitoring and preparedness to manage disease outbreaks. For example, an outbreak of gastroenteritis associated with *Vibrio parahaemolyticus* in Alaskan oysters in 2004 occurred when the mean daily water temperatures exceeded 15.0 °C for an extended period (McLaughlin et al. 2005). The year 2004 was the first year when water temperatures in July and August at the implicated shellfish farm did not fall below 15.0 °C, the theorized threshold for replication of *V. parahaemolyticus*. Between 1997 and 2004, mean water temperatures during summer months increased 0.21 °C per year. This outbreak extended the northern range of this illness in the western USA by 1000 km. Similarly, *Vibrio* cases in the Baltic Sea region between 1977 and 2010 increased in correlation with temperature increases, with more reported infections in years with greater warming, following a negative binomial distribution; for every 1 °C increase in the maximum annual sea surface temperature, the number of observed cases increased nearly twofold (Baker-Austin et al. 2013). These examples highlight the need for greater understanding of when diseases could emerge, taking into consideration when vectors could move into new geographic regions, the time for the vector and the pathogen to become established (and not require regular reintroduction), and when environmental conditions could be conducive for transmission. Advance warning can provide health systems with time to prepare, if they have the capacity to use these warnings.
- Projections of the health risks of climate change focused on how the geographic range, seasonality, and/or burden of health outcomes could change with changing weather patterns. Further, these projections are needed at a scale appropriate for the decisions being taken. While these projections are critical to understand, for example, how the number of heat-related illnesses and deaths could increase with warmer temperatures and more heat waves, departments and ministries of health in a region will need to prepare for and respond to the aggregate impacts across a range of health and other issues, such as increases in ground-level ozone concentrations, injuries from possible increases in interpersonal violence, possible increases in foodborne and waterborne diseases with warmer temperatures, and impacts on transportation of railway lines during heat waves, among others. Similarly, ministries of health need joint projections of how malaria, undernutrition, and diarrheal disease could change over coming decades, to have more informed insights into changing risks, taking into consideration how development choices could reduce the burdens of climate-sensitive health outcomes even as climate change alters environmental conditions in ways that could facilitate increased burdens.
- Climate change could affect the functioning and effectiveness of health systems through several pathways (Paterson et al. 2014). Changes in the magnitude and pattern of climate-sensitive health outcomes will alter demands for health care, and extreme weather and climate events can impact infrastructure, such as flooding or storm surges affecting access to and the operations of facilities. Sea level rise is very likely to imperil certain facilities later in this century. Health care facilities are critical infrastructure during an extreme event, so keeping them open and effectively functioning is vital to recovery and response efforts. Better understanding of the range of possible risks and how they could be most efficiently managed is needed.
- Health adaptation is ramping up, with increasing interest by departments and ministries of health in identifying, implementing, monitoring, and evaluating options to prepare for a changing climate (e.g., Araos et al. 2016; Ebi and Otmani del Barrio 2017; Marinucci et al. 2014). One key goal of adaptation is to develop climate-resilient health systems that have the resources, flexibility, skills, and tools needed to effectively prepare for a changing climate (WHO 2015). However, an implicit assumption is that climate change will proceed along a smooth trajectory of projections; that is, there will be a relatively steady change in global or regional mean surface temperature with associated changes in precipitation and other variables. However, analyses by Jones and Ricketts (2016) indicate that changes are more likely to be nonlinear, proceeding in a series of step changes with periods of relatively stable weather variables followed by sudden shifts (step changes). Not considering how to prepare for these uneven patterns into adaptation planning can lead to inefficient adaptation that underestimates the magnitude, pattern, and timing of risks (Ebi et al. 2016b).
- Efficacy of potential climate change adaptations in the health and other sectors. In large part, climate change presents familiar challenges to public health, but the timing, magnitude, and location of these challenges are shifting (Frumkin et al. 2008), and in many cases, the risk associated with these worsening hazards is increasing, in some cases dramatically. More effective, comprehensive, appropriately timed, and iteratively managed interventions are required (Ebi 2011; Hess et al. 2012), yet the evidence base related to intervention efficacy—from early warning

systems to home energy assistance programs to building disaster resilience in health systems, to name just a few examples—is in many cases lacking (Hosking and Campbell-Lendrum 2012). This limits the ability of the health sector and its partners to determine which interventions should be prioritized as the climate changes.

- Strategies for communicating with the public, policymakers, and other stakeholders regarding climate change and health. The health frame has been found to resonate with the public for promoting mitigation, in particular (van der Linden et al. 2015). Additional research is needed to clarify strategies for communicating about the health risks of climate change and adaptation priorities in the health sector.
- Finally, climate change is only one of several global environmental changes underway. Understanding the potential health implications of the interactions among climate change, biodiversity loss, population change, and changes in the nitrogen cycle, for example, is needed to inform effective and efficient approaches to achieving the Sustainable Development Goals. Health officials and researchers need to be engaged with adaptation and mitigation decision-making and implementation in other sectors, to maximize health co-benefits and to reduce possible health harms from poorly designed or implemented measures.

The benefits of reducing greenhouse gas emissions from health care and quantifying the health co-benefits of mitigation policies and technologies are growing areas of research and practice whose importance will increase as countries work to implement their Nationally Determined Contributions under the Paris Agreement.

## Discussion

Dr. McMichael established the health risks of a changing climate in the mid-1990s, with subsequent research verifying that the first principles he laid out were correct: that warmer temperatures, changing precipitation patterns, ocean acidification, and sea level rise will have adverse consequences for injuries, illnesses, and deaths from a range of climate-sensitive health outcomes, depending on the extent to which health systems are prepared to manage those risks and on the reductions of greenhouse gas emissions to reduce risks later in the century. As research is filling in this basic outline of the climate-sensitive health outcomes that could be affected by a changing climate, new issues are arising where system-based, transdisciplinary approaches are needed to understand the magnitude and pattern of future challenges to population health. The knowledge gained from vulnerability, adaptation, and capacity assessments can be used to prioritize public health adaptation efforts to identify those with the greatest potential for increasing short- and longer-term resilience. With increasing investment in adaptation and mitigation in other sectors, a growing need is for engagement of health researchers and practitioners in those decision-making processes to ensure that population health is protected. Biometeorology, with its inherent interdisciplinary approaches, can help provide insights to ensure that policy-makers have the knowledge and tools to protect and promote population health even as the climate, and associated risks, continues to change. Doing so requires increased research investment for understanding the complex and interacting challenges of this century, and of the options to prepare for and manage these risks.

## References


Araos M, Austin SE, Berrang-Ford L, Ford JD (2016) Public health adaptation to climate change in large cities: a global baseline. Int J Health Serv 46:53–78

Baker-Austin C, Trinanes JA, Taylor NG, Hartnell R, Siitonen A, Martinez-Urtaza J (2013) Emerging *Vibrio* risk at high latitudes in response to ocean warming. Nat Clim Chang 3:73–77

Confalonieri U, Menne B, Akhtar R, Ebi KL, Hauengue M, Kovats RS, Revich B, Woodward A (2007) Human health. Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 391–431

Ebi K (2011) Climate change and health risks: assessing and responding to them through 'adaptive management'. Health Aff (Millwood) 30(5):924–930

Ebi KL (2014) Health in the new scenarios for climate change research. Int J Environ Res Public Health 11:30–46. doi:10.3390/ijerph100x000x

Ebi KL, Mills D (2013) Winter mortality in a warming climate: a reassessment. WIRES Clim Change 2013. doi:10.1002/wcc.211

Ebi KL, Otmani del Barrio M. (2017) Lessons learned on health adaptation to climate variability and change: experiences across low- and middle-income countries. Environ Health Perspect in press

Ebi KL, Semenza JC, Rocklov J (2016a) Current medical research frameworks are insufficient to address the health risks of global environmental change. Environ Health. doi:10.1186/s12940-016-0183-3

Ebi KL, Ziska LH, Yohe GW (2016b) The shape of impacts to come: lessons and opportunities for adaptation from uneven increases in global and regional temperatures. Clim Chang. doi:10.1007/s10584-016-1816-9

Frumkin H, Hess J, Luber G, Malilay J, McGeehin M (2008) The public health response to climate change. Am J Pub Health 98:435–445

Green D, Pitman A, Barnett A, Kaldor J, Doherty P, Stanley F (2017) Advancing Australia's role in climate change and health research. Nat Clim Chang. 7:103–106

Hess JJ, Ebi KL (2016) Iterative management of heat early warning systems in a changing climate. Ann N Y Acad Sci 1382(1):21–30

Hess JJ, McDowell JZ, Luber G (2012) Integrating climate change adaptation into public health practice: using adaptive management to increase adaptive capacity and build resilience. Environ Health Perspect 120:171–179

Hosking J, Campbell-Lendrum D (2012) How well does climate change and health research meet the demands of policymakers? A scoping review. Environ Health Perspect 120:1076–1082

Jones RN, Ricketts JH (2016) Reconciling the signal and noise of atmospheric warming on decadal timescales. Earth Syst Dyn Discuss. doi:10.5194/esd-2016035,2016

Kunh, T. (1962) The structure of scientific revolutions. University of Chicago Press

Marinucci GD, Luber G, Uejio CK, Saha S, Hess JJ (2014) Building resilience against climate effects—a novel framework to facilitate climate readiness in public health agencies. Int J Environ Res Public Health 11:6433–6458

McLaughlin JB, DePaola A, Bopp CA, Martinek KA, Napolilli NP, Allision CG, Murray SL, Thompson EC, Bird MM, Middaugh JP (2005) Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. New Engl J Med 353:1463–1470

McMichael, A J. (1993) Planetary overload: global environmental change and the health of the human species. Cambridge University Press

McMichael AJ, Ando M, Carcavallo R, Epstein P, Haines A, Jendritzky G, Kalkstein L, Odongo R, Patz J, Piver W (1995) Human population health. In: Watson RT, Zinyowera MC, Moss RH (eds) Climate change 1995: the IPCC Second Assessment Report. Cambridge University Press, Cambridge, pp 562–584

McMichael A, Githeko A, Akhtar R, Carcavallo R, Gubler D, Haines A, Kovats RS, Martens P, Patz J, Sasaki A (2001) Human health. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University press, Cambridge, pp 453–485

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi (2014) Emergent risks and key vulnerabilities. In: Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 1039–1099

Paterson J, Berry P, Ebi KL, Varangu L (2014) Health care facilities resilient to climate change impacts. Int J Environ Res Public Health 11:13097–13116

SCEP/Study of Critical Environmental Problems (1970) Man's impact on the global environment: assessment and recommendations for action. MIT Press, Cambridge available at http://mitpress.mit.edu/books/mans-impact-global-environment

Semenza JC, Lindgren E, Balkanyi L, Espinosa L, Almqvist MS, Penttinen P et al (2016) Determinants and drivers of infectious disease threat events in Europe. Emerg Infect Dis 22:581–589

Smith KR, Woodward A, Campbell-Lendrum C, Chadee DD, Honda Y, Liu Q, et al. (2014) Human health: impacts, adaptation, and co-benefits. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE (eds) Climate change 2014: Impacts, adaptation, and vulnerability. Part a: Global and sectoral aspects. Contribution of working group ii to the fifth assessment report of the intergovernmental panel on climate change. In: Fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, United Kingdom

United Nations Framework Convention on Climate Change, Document FCCC/INFORMAL/84, GE.05–62220 (E) 200705 (1992), available at http://unfccc.int/essential_background/convention/items/2627.php, last accessed 10 April 2017

van der Linden S, Maibach E, Leiserowitz A (2015) Improving public engagement with climate change: five "best practice" insights from psychological science. Perspect Psychol Sci 10(6):758–763

Verner G, Shutte S, Knop J, Sankoh O, Sauerborn R (2016) Health in climate change research from 1990 to 2014: positive trend, but still underperforming. Glob Health Action 9:30723. doi:10.3402/gha.v9.30723

WHO (World Health Organization (2012) Protecting health from climate change: vulnerability and adaptation assessment. Geneva, 72 pp.

WHO (World Health Organization) (2015) Operational framework for building climate resilient health systems. Geneva, 56 pp