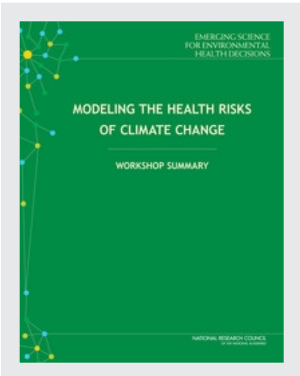

Modeling the Health Risks of Climate Change: Workshop Summary

DETAILS

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WORKSHOP SUMMARY

Kellyn Betts and Keegan Sawyer, Rapporteurs

Standing Committee on Emerging Science for Environmental Health Decisions
Board on Life Sciences
Division on Earth and Life Studies

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This workshop summary has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purposes of this review are to provide candid and critical comments that will assist the institution in making the published summary as sound as possible and to ensure that the summary meets institutional standards of objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following for their participation in the review of this summary:

Peter Berry, Health Canada
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Kim Knowlton, Natural Resources Defense Council
Benjamin Zaitchik, Johns Hopkins University

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse, nor did they see, the final draft of the workshop summary before its release. The review of the report was overseen by **Patrick Kinney** of Columbia University. Appointed by the National Academies, Dr. Kinney was responsible for making certain that an independent examination of the summary was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of the summary rests entirely with the authors and the National Research Council.

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INTRODUCTION AND OVERVIEW

> "The reason we are here is to be able to inform the kinds of decisions that have to be made both in terms of limiting the extent of climate change and in terms of protecting the vulnerable people who are going to be experiencing the risks."—John Balbus

Climate change poses risks to human health and well-being through shifting weather patterns, increases in frequency and intensity of heat waves and other extreme weather events, rising sea levels, ocean acidification, and other environmental effects. Those risks occur against a backdrop of changing socioeconomic conditions, medical technology, population demographics, environmental conditions, and other factors that are important in determining health. Models of health risks that reflect how health determinants and climate changes vary in time and space are needed so that we can inform adaptation efforts and reduce or prevent adverse health effects. Robust health risk models could also help to inform national and international discussions about climate policies and the economic consequences of action and inaction.

However, the development of models of health risks that result from climate change has been slow. Inherent uncertainty in what health and socioeconomic trends the future will bring, uncertainty about the links between climate-change events and health outcomes, and the variability and complexity of human health and disease are a few of the hurdles that health-risk modelers are endeavoring to overcome. Interest in resolving some of the challenges facing health effects modelers and health scientists led the National Research Council's Standing Committee on Emerging Science for Environmental Health Decisions (ESEH) to hold a workshop on November 3–4, 2014, in Washington, DC, to explore new approaches to modeling the human health risks of climate change. The workshop Statement of Task is provided in Appendix A.

Key topics addressed during the workshop included

- The state of development of health-risk models.
- Integrated systems-based approaches to health modeling.
- Approaches to generalizing and scaling up of health-risk models.
- Integration of health risks into models of aggregated impacts of climate change.

The workshop focused only on health risks of climate, not all potential health implications. Throughout the workshop, the discussions highlighted examples of current application of models, research gaps, lessons learned, and potential next steps to improve modeling of health risks associated with climate change.

GOALS

In his opening comments, John Balbus, the senior adviser for public health in the US National Institute of Environmental Health Sciences and a member of the workshop planning committee, emphasized that the workshop would be different from previous meetings of the ESEH committee. The committee "has been focusing on the basic science of environmental health, toxicology, and biology," he said. Balbus noted that the ESEH committee has been discussing the potential for a workshop on health effects of climate change for many years, and he applauded the committee for its vision in including the health effects of climate change as an important emerging topic in the scope of environmental health.

"The timing is perfect for this workshop," Balbus emphasized. The day before the workshop began, the Intergovernmental Panel on Climate Change[1] issued its starkest warning yet on global warming. In the preceding months, the World Health Organization (WHO) had held its first summit on climate change and health in advance of the UN Climate Summit, which in 2014 for the first time included a thematic session on climate change and health. More recently, WHO released a new assessment of the global burden of disease linked to climate change on the basis of cutting-edge approaches to estimation.[2]

Also during 2014, the US Department of Health and Human Services held its first climate-change briefing. In May 2014, the US Global Change Research Program's Third National Climate Assessment provided the first federal integrated effort to model health outcomes and exposures associated with a variety of events related to climate change, including increases in heat, air pollution, and populations of arthropod disease vectors (such as ticks and mosquitoes). A follow-up special report on climate and health that will quantify those health outcomes is being prepared.

Balbus outlined the goals of the workshop in light of the many interrelated national and international projects:

- Bring together different teams that are conducting climate-change modeling projects in different settings, and assess the state of the science.
- Think about questions that need to be answered to make decisions about how to protect human health and well-being. Do we have models to answer the questions? Do we have the information that we need to put mitigation, prevention, or adaptation measures into place to protect health in the setting of a changing climate?
- Brainstorm how to move forward. What partnerships are needed? What approaches do we want to look at? How will we get the best teams together to take us to the next level?

[1]An international, intergovernment body established by the UNUN Environment Programme and the World Health Organization to provide scientific views on the state of knowledge about climate change.
[2]http://www.who.int/globalchange/publications/quantitative-risk-assessment/en/

WORKSHOP OVERVIEW

On workshop day 1, Balbus welcomed participants and provided framing for the workshop. In the first session, summarizing the state of knowledge, Jan Semenza, of the European Centre for Disease Prevention and Control, described some of the current challenges associated with modeling and quantifying effects of climate change. Ben Zaitchik, of Johns Hopkins University, discussed emerging climate-change models, datasets, and applications. The opening session concluded with George Luber, of the US Centers for Disease Control and Prevention (CDC) who explained how models of health risks are being used to improve community preparedness.

The second session focused on the state of development of models of health risks that result from climate change; it was moderated by Linda Wennerberg, of the US National Aeronautics and Space Administration (NASA). Sari Kovats, of the London School of Hygiene and Tropical Medicine, provided an overview of the quantitative risk-assessment approach to modeling of the health effects of climate change. Michelle Bell, of Yale University, talked about climate and health effects of heat stress and air pollution. Juli Trtanj, of the US National Oceanic and Atmospheric Administration, told attendees about what is known on the subject of climate and waterborne diseases. Nick Ogden, of the Public Health Agency of Canada, described how modeling is and can be used to address our understanding of how vectorborne diseases are affected by climate change. All the speakers participated in a panel discussion on health-risk models. They were joined by Charles Benjamin Beard (Ben Beard), of CDC; Mary Hayden, of the University Corporation for Atmospheric Research; and Erin Lipp, of the University of Georgia.

The final session of day 1 focused on how systems approaches can be used to understand future vulnerabilities. The session was moderated by Gary Geernaert, of the US Department of Energy (DOE). Georges Benjamin, of the American Public Health Association, discussed a population-based approach to identifying climate-change effects. Joshua Elliott, of the University of Chicago and Argonne National Laboratory, told the audience how a systems approach has shed light on climate-change effects on agriculture and human health. Richard Jackson, of the University of California Los Angeles, discussed urbanization, climate change, and human health. All the speakers participated in a panel discussion on systems thinking and modeling of the health effects of climate change. They were joined by Molly Brown, of NASA), and Gregory Glass, of the University of Florida.

Workshop day 2 began with a session focused on incorporation of health risks into the aggregated impact of climate change. In addition to moderating the session, Kristie Ebi, of ClimAdapt, LLC, briefly recapitulated the presentations and discussions of the first day. Anthony Janetos, of Boston University, spoke about integration of climate-change impact models, including the state of the art and long-term goals. The session ended with a panel discussion on conceptual directions for research on integrating climate-change impact models, including Janetos, Kovats, Semenza, and Stéphane Hallegatte of the World Bank.

The final event of the workshop was a panel discussion on practical next steps to improve climate-change impact models. The panelists were Balbus; Anne Grambsch, of the US Environmental Protection Agency; Trtanj; Robert Vallario, of DOE; and Peter Berry, of Health Canada.

The workshop was attended by 65 persons, and another 81 joined via webcast. Workshop presentations and archived videos are available through the ESEH Web site.[3] The workshop agenda and a list of in-person workshop attendees can be found in Appendixes B and C, respectively.

ABOUT THIS REPORT

This report summarizes the presentations and discussions that took place during the workshop. It is organized by the major themes that emerged. Chapter 2 describes what we know about health effects of climate change, why models of health effects are needed, and the major hurdles that need to be overcome to develop robust models. Chapter 3 examines recent efforts to model health effects of climate change, including effects caused by changes in air quality, water quality, and arthropod disease vectors. It includes information about challenges to modeling of the effects and reasons for optimism. Chapter 4 discusses why and how to incorporate systems thinking into the modeling of the health effects of climate change. Chapter 5 summarizes ideas shared during the workshop for moving modeling efforts forward.

This publication is a factual summary of the presentations and discussions at the workshop written by rapporteurs. The views presented here are those of the individual workshop participants and do not necessarily represent all workshop participants, the organizing committee, or the National Research Council.

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[3]http://nas-sites.org/emergingscience /cchealthrisks/

2
HEALTH RISKS OF CLIMATE CHANGE: WHAT WE KNOW AND WHY WE MODEL

> "Any climate impact on health is mediated by other physical and environmental factors. There is no such thing as a direct climate impact."—Ben Zaitchik
>
> "It will help if we are clearer in our communications within and outside the health sector and if we talk about what we are modeling for. What are our goals? What are we trying to achieve?"—Kris Ebi

Throughout the workshop, speakers and panelists described a wide array of potential health risks of climate change and discussed why models of health risks are needed for public health and policy. Speakers focused in particular on health risks, like waterborne and vector-borne diseases, resulting from climate-induced changes in air quality, water quality, and temperature.

CLIMATE CHANGE AND HEALTH: WHAT DO WE KNOW?

John Balbus, of the US National Institute of Environmental Health Sciences, described the main indicators of climate change and their connections to human health outcomes. The primary manifestations of a changing climate in the physical environment are "higher CO_2 concentrations, increasing high temperatures, rising sea levels, and increasing severity of some kinds of extreme weather phenomena, such as hurricanes", Balbus said. The pathways by which those climate-related changes affect human health are a complex mix of natural and human systems (Figure 2-1). For example, Balbus explained, higher temperatures may lead to the spread of the ranges of deer, mice, and ticks—"the ecologic causal chain that brings Lyme disease to humans". Severe storms, such as Superstorm Sandy and Hurricane Katrina, can overload the functionality of health-care systems, which in turn may have negative consequences in particular for the elderly and those who have chronic medical conditions.

Jan Semenza of the European Centre for Disease Prevention and Control, described data published in the 2013 Intergovernmental Panel on Climate Change[4] "Summary for Policymakers" that demonstrate increases in surface temperature and changing patterns of precipitation around the world. The reports observe that precipitation is increasing in northern latitudes and decreasing in southern latitudes. "Climate change is happening now," said Semenza, and the warming and precipitation trends are expected to continue. Semenza explained that the differences between wet and dry regions and between wet and dry seasons

[4]http://www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf

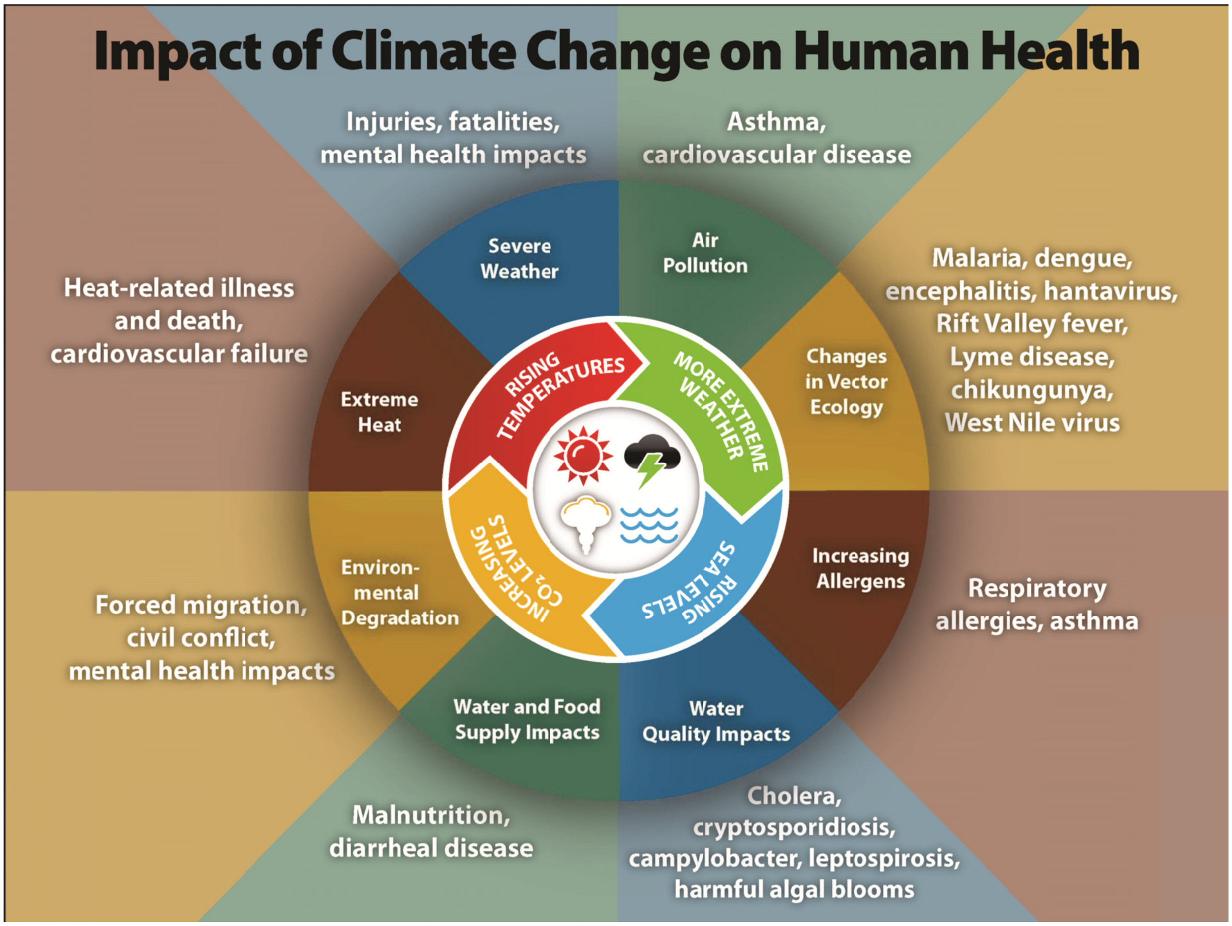

Figure 2-1 Illustration of the impact of climate change on human health

The inner circle represents the physical environment. The first ring represents the four primary manifestations of climate change in the physical environment (climate drivers): increasing carbon dioxide concentrations in the atmosphere (yellow), rising temperatures (red), rising sea levels (blue), and more extreme weather (green). The four climate drivers can act through natural and human systems to cause conditions listed in the second ring, such as changes in vector ecology, extreme heat, and changes in water and food supply. Surrounding the second ring are the types of health effects that may result from the conditions listed in the ring. Source: George Luber, workshop presentation, slide 21.

are expected to become greater later in this century. Among the health risks associated with a warmer and wetter climate include increased enterococcus and vibrio species[5] in coastal and marine waters, respectively; and greater geographic distribution and abundance of the mosquito species that caries West Nile Virus, noted Semenza.

George Luber of the US Centers for Disease Control and Prevention Climate and Health Program noted that the effects of global climate change will vary substantially by region. Some places are warming faster than others, and the percent of extreme temperature events

[5]Enterococcus is a genus of bacteria that can cause gastroenteritis ("stomach flu"). Vibrio is a genus of bacteria that can cause gastroenteritis, severe wound infections, and septicemia (blood poisoning).

(locations that experience above normal temperatures) has increased. "From a public-health standpoint, when it comes to weather what we really care about is the extremes," Luber said.

The increasing frequency of extreme weather events increases the likelihood of complex emergencies – "disasters within a disaster". Luber emphasized that complex emergencies occur at magnitudes greater than the norm, and may exceed the coping capacity of critical systems that are in place to protect health. They can involve multiple system failures, such as loss of telecommunication, egress and transportation, and electric power. Luber named Hurricane Katrina as an example of a complex emergency – 800,000 people were displaced, and thus the challenges accompanying lost livelihood and community impacted both New Orleans and the cities where citizens took up new residence. The combination of large-scale ecologic perturbations caused by climate change and by global trade and travel can lead to novel health threats, Luber said. The increasing spread of Lyme disease in association with the expanding range of suitable habitat for the deer and birds that serve as reservoirs for the black-legged ticks that are the vectors of the disease-causing bacteria is one example. The rising rate of ciguatera[6] poisoning from Gulf of Mexico fish that results from increases in sea temperature decreases in reef habitat related to oil-drilling platforms is another. A third example is the surge in West Nile fever in eastern Europe in 2010, Semenza said.

Effects of climate change on health and economics are already being documented throughout the world, said Anthony Janetos, director of Boston University's Frederick S. Pardee Center for the Study of the Longer-Range Future. "There hasn't been an overall assessment related to climate-change effects that I'm aware of that concludes that the risks of health effects in human populations will decrease," Janetos said. Rather, the climate-assessment literature concludes that risks to health from multiple pathways—including disease, heat stress, waterborne illnesses, recovery from events, and malnutrition—will increase.

The increases in temperatures throughout the world linked to climate change can affect both the abundance and the activity of animal vectors that can spread disease to humans, said Nick Ogden, senior research scientist in the Public Health Agency of Canada. Those vectors include mosquitoes, flies, ticks, fleas, and lice that reside mainly in wildlife. The potential spread of mosquitoes due to climate change is particularly a concern because they are the vectors for some of the most important global vectorborne diseases in humans such as malaria, dengue fever, and chikungunya.

Among tropical diseases, dengue has been spreading in the Americas over the last 50 years, and both the US and Canadian governments are monitoring recent cases of chikungunya. "We're now getting a lot of people coming back to Canada from the Caribbean with chikungunya," Ogden said. Many of them have the virus in their blood, and it is possible for one of them to be bitten by an Asian tiger mosquito, *Aedes albopictus*, which could then transmit both chikungunya and dengue fever within North America.

Canada is also monitoring the spread of Lyme disease across its borders. Migrating birds can easily transport the ticks that serve as vectors for the disease into Canada, Ogden commented. Over the last decade, the number of reported cases of Lyme disease in Canada has risen dramatically. The primary ways that climate change is affecting water systems are through sea-level rise and changes in the ocean's pH, changes in the water cycle itself, and

[6]A food-borne illness caused by eating fish whose flesh contains toxins originally produced by dinoflagellates (protists).

increases in extreme precipitation events. Juli Trtanj, of the US National Oceanic and Atmospheric Administration, spoke about research that is helping to capture the data needed to model how climate change may affect waterborne infectious diseases and water-related illnesses. It is a complicated issue that includes how runoff from urban and rural environments and infrastructure affects surface and groundwater sources of drinking water and coastal waters, she explained. That phenomenon is affected by temperature, nutrients in the water, changes in pH, salinity, and other biologic and chemical factors.

"Climate change will amplify existing health threats," emphasized Michelle Bell, of Yale University. For example, she explained, human exposure to tropospheric ozone is expected to increase substantially as a result of climate change. Many areas around the world already have a growing ozone problem that is due to the expansion of transportation and industry; and many people in the United States live in areas where tropospheric ozone concentrations exceed the US Environmental Protection Agency's health-based standard, she said. Increasing ozone concentrations in southern New York state are projected to raise the number of emergency-department visits due to asthma, Luber noted.

There will also be a marked increase in mortality due to multiple stressors and other effects on vulnerable populations, particularly in vulnerable locations. "The cumulative effect might be very great," Luber explained.

As climate change affects rates of famine and increases the likelihood of conflicts over scarce resources, it is also likely to undermine human health in other ways. Stéphane Hallegatte of the World Bank pointed out that there could be a huge effect on the dynamics of health worldwide. When people who have escaped from poverty fall back into it, the reason is related to health issues in 50–80% of the cases, he said. Famine and conflicts are also likely to decrease the capacity of developing countries to control the transmission of vectorborne diseases, Ogden said. Another route by which exotic vectorborne diseases can be transmitted throughout the world is migration of infected refugees who are fleeing the developing world because of war, famine, or pestilence, he said.

WHY MODEL THE HEALTH RISKS OF CLIMATE CHANGE?

Many efforts are under way to model the health risks of climate change. But why? A key argument for modeling is that health is likely to be important in inspiring people to take action on climate change, said Ben Zaitchik, of Johns Hopkins University. Nonetheless, What are our goals? What are we trying to achieve? asked Kristie Ebi, of ClimAdapt LLC. Ebi pointed out that there is broad confusion in the health sector about the goals of modeling the health risks posed by climate change. "The health sector needs a wide variety of models to achieve a wide diversity of purposes," Ebi stressed (Box 2-1). Scientists develop different models with different sets of assumptions because "we don't know what the future is going to look like," she said. Rather than wait until thresholds are crossed, models help scientists to "understand the thresholds before we have lots of cases of impact."

One use of models that many researchers are exploring is to inform *climate services* that enable people and institutions to make decisions about their actions, said Zaitchik. For example, satellite data on local soil-surface temperatures and moisture levels can be used to develop models of malaria risks. Zaitchik and colleagues have developed an application that funnels such information to local malaria clinics.

Box 2-1
Goals of Modeling Health Risks Posed by Climate Change

Ebi noted that models of health risks posed by climate change are needed to fulfill diverse purposes. She emphasized that modeling discussions should begin with communication about why a model is being developed or used. Ebi listed some of the purposes for which scientists are developing models:

- To understand exposure–response relationships, such as the health effects of heavy precipitation.
- To look into the future on the basis of what is known about current exposure–response relationships.
- To develop better early warning systems, which are not yet designed to address what may happen in a changing climate.
- To assess costs and benefits of health risks climate change or climate adaptation policies.

Modelers are grappling with improving the use of models for policy decisions by producing "deeply coupled" models that incorporate information about the climate, the physical environment, and human actions, Zaitchik said. Such models could be used to investigate whether, for example, the 2003 heat wave in Europe had an effect on European Union climate policy or whether Superstorm Sandy had an effect on US policy. A paradigm shift may be required to get to that point, he observed.

"We are talking about a lot of things when we talk about modeling the health effects of climate change," Balbus said. "We need to think in an integrated and holistic fashion about the total burden, but assessing it quantitatively will require considering some of the effects separately," he explained. For example, before modelers are able to develop complex, integrated, quantitative models, the effects of air pollution may need to be assessed separately from the effects of nutritional stresses related to effects on the agricultural system. Ultimately "many approaches need to be brought together and figured out in one place," he said.

Ebi cautioned against overinterpreting the numerical outputs of models. Rather, she said,"we are modeling for insights"—trying to understand how systems work and what may happen in a particular set of conditions. "We need to be more explicit that these are Bayesian experiments. We are gaining insights from models to inform what we do, how we go about things, and what needs to be done in terms of policies and budgets," she concluded.

3

MODELING HEALTH RISKS OF CLIMATE CHANGE: STATUS, HURDLES, AND OPPORTUNITIES

"What is the information we need from modeling? We need to know *where,* and we need to know *when* [effects occur]."—Nick Ogden

"How do you take all the disparate data from different sources, scales, and times and space and come up with something that people can use to make decisions?"—Gregory Glass

Many organizations are modeling the effects of climate change on local, regional, and global scales. Most models focus on a particular sector, such as agriculture, energy, or the economy. Fewer models exist for the human health sector. What does it take to model the health risks posed by climate change? Workshop speakers outlined the basic mechanics of and key considerations for developing useful models. Discussions focused on recent model developments for evaluating the health effects of climate-induced spread of vectorborne disease and other health risks of changes in water and air quality and temperature. Discussions also explored overcoming hurdles to improve modeling capabilities.

DEFINITIONS, MECHANICS, AND KEY CONSIDERATIONS

The models needed to understand climate change and its effects on human health are complex. How can the climate-change community—scientists, model developers, policy-makers, and other stakeholders—get a handle on the complexity? Ben Zaitchik, of Johns Hopkins University, outlined three factors that correspond to how the Intergovernmental Panel on Climate Change frames the issue: the physical environment, ecology ("natural processes"), and institutions. Those three factors mediate the relationships between changing climate conditions and human health outcomes. They also interact with one another. For example, climate change may result in increased rainfall (a component of the physical environment), and increased rainfall may support conditions for an increase in the population of a disease vector (ecology) in a country that lacks adequate institutionalized programs for vector control (institutions). Increased rainfall, increased number of disease vectors, and inadequate vector control all have effects on human health systems, such as medical practice and disaster response. Throughout the process of modeling, "we must think about humans," Zaitchik emphasized. Humans "modify our physical environment and are deeply involved in ecologic processes and institutions," he said. It takes many scientific disciplines and tools in addition to climate science to understand the interactions among the three factors and associated health outcomes, including hydrology, geography, ecology, agriculture, sociology, economics, biomedical science, and clinical medicine. When it comes to developing models, data to feed the models, and potential model applications, "we need developments in all those fields . . . to help us to understand climate," Zaitchik said.

What information is needed from models of climate-change effects? "We need to know *where*, and we need to know *when*" effects of climate change will occur, said Nick Ogden, a senior research scientist in the Public Health Agency of Canada. Ogden described four basic steps in developing and applying models of health risks due to climate change. First, we gather "our knowledge of current potential influences of climate and weather" on particular disease risks. Second, a model is used to "integrate the knowledge into abundance or presence and absence of diseases." Third, we use model outputs to "obtain a quantitative relationship between the climate and the . . . disease risk." Fourth, "we use this simple quantitative relationship or perhaps some more complex model to produce estimates of future risk." Ogden noted that models can be made to *predict* where an effect may occur, *forecast* effects in the near term, or *project* effects in the long term (Box 3-1). Model predictions, forecasts, and projections are used to help to decide and design "what we're going to do" about health risks posed by climate change and to "produce adaptation tools", Ogden explained.

Zaitchik noted that "in the climate-science world there is now a lot of talk about climate services," information that helps the health community to make decisions. The current framework for model development is top-down, beginning with climate and ending with health outcomes. Somehow, data on climate, physical environment, ecology, institutions, and human dynamics coalesce to "tell the health-system people what they're supposed to be doing." Zaitchik said that "a grand challenge" is to determine how decision-making needs of the health-system practitioners ought to drive model development from the bottom up. "We have this global framework for climate services that is fantastic," Zaitchik said, and the US National Oceanic and Atmospheric Administration (NOAA), the US Environmental Protection Agency (EPA), and many others are working on this problem. And yet, he asked, "how do we actually transform communities to think in this way and rebuild our tools to make [climate services] work?"

How modeling is approached depends heavily on the needs of the user, noted Sari Kovats, of the London School of Hygiene and Tropical Medicine. The priorities of local, state, regional, national, and federal governments are different, she stressed. Hence, Kovats, George Luber, of the US Centers for Disease Control and Prevention (CDC), and other workshop speakers emphasized that a critical component of any model is its scale. The methods and assumptions used in modeling depend on the scale, Kovats said. The scale determines what data are available to users of model outputs.

The temporal scales range from hours to multiple decades, Luber explained. On the spatial scale, there can be a city or international range. The policy planning horizons range from annual budgets to infrastructure meant to be in place for multiple decades. Anthony Janetos, director of Boston University's Frederick S. Pardee Center for the Study of the Longer-Range Future, said that there is generally a tradeoff between a model's spatial resolution and the period of time that it simulates. High-resolution climate models cannot be used for long-term simulations. Long-term simulations inevitably have lower spatial resolution than many climate-change scientists desire, he said.

How model outputs are interpreted also depends on their scale, Mary Hayden, of the National Center for Atmospheric Research (NCAR), pointed out. National and regional

Box 3-1
Definitions: Predictions, Forecasts, and Projections

Nick Ogden provided definitions that his research group uses to frame different types of climate-change model outputs:

Predictions tell where an effect is occurring

Forecasts tell where and when an effect is likely to occur in the next week or month. As models move toward smaller temporal and spatial scales, they incorporate larger numbers of elements and involve a greater degree of complexity.

Projections estimate where and when an effect is likely to occur in the next decade, decades, or century.

assessments are great, but they can mask communities that are living in marginal conditions. If the goal is to mitigate hazards and develop adaptation strategies, models need to be adjusted for "local ecology" information. "Local-level assessment ensures a more targeted intervention, response, and adaptation," Hayden explained.

INTEGRATING MODELS

In general, efforts to integrate climate-change models so that they can show the combined effects of different sectors are in their infancy. "We know that food and water interact, health interacts with many factors, and heat, urbanization, and air pollution all interact," Kovats explained. Several types of modeling are used to study those interactions: one-way modeling, one-way modeling that includes adaptation and institutional responses, and two-way modeling (Box 3-2).

There are many challenges in model integration. For example, food security is important, but many facets of how the US food system works are not captured by the way that we have interconnected our agriculture, climate, and economic models, said Molly Brown, of the National Aeronautics and Space Administration. Brown came to that conclusion as a result of putting together a report on food security for the US Global Change Research Program's recent National Climate Assessment.

Of the efforts toward intersectoral model integration, the furthest along are associated with combining modeling studies in different sectors, such as agriculture and hydrology, to explore interactions between sectors. The integrated-modeling community has been doing a lot of experiments with one-way modeling of effects, mostly physical and biologic effects, Janetos said. Studies on the effects of climate change rarely extend beyond physical and biologic effects to human health or economic consequences.

MODELING: THE STATE OF THE SCIENCE

Scientists studying health effects of climate change are endeavoring to generate data that link environmental changes to health outcomes and then to incorporate the data into models of health risks posed by climate change. Three subjects that many scientists are focusing on are 1) disease vectors, 2) water quality, and 3) heat and air quality. The World Health Organization recently completed a quantitative risk assessment of climate change with respect to selected causes of death, the first assessment of its kind (Box 3-3).

Box 3-2
Three Types of Integrated Models

Anthony Janetos defined three types of integrated modeling studies that endeavor to represent all world regions and sectors—such as agriculture, hydrology, and economics—to explore their interactions. Such studies do not always include health effects.

One-way models include climate variables as additional drivers of both disease and nondisease pathways of health outcomes. These are classical climate-impact/risk studies and include many of the models discussed in the workshop.

One-way models that include adaptation and institutional response assume that the health systems and institutions of 20, 30, or 50 years from now will not be the same as today's. These models come closer to identifying actual health outcomes than simply assessing risk.

Two-way models include feedback from health outcomes and adaptation on the economy and on later consequences for both mitigation and future demographics. They offer the potential for "a complete integration of climate effects on health". The value of two-way modeling is its ability to provide a better understanding of how the health effects themselves interact with future demographics.

Disease Vectors and Health

Ogden described models that are used to understand the effects of climate change on vectorborne diseases. "Historically, climate has had a relatively small role in the variation in the geographic occurrence of vectors" because such human activities as habitat alteration, vector-eradication programs, and adaptation (such as the use of bed nets) were considered more important drivers, Ogden explained. However, he hypothesized that climate change will be especially important in developing countries because of their relative inability to control the spread of vectorborne diseases. Most modeling efforts related to climate change and vectorborne disease focus on estimating future occurrence or abundance of disease vectors; this requires knowledge about various factors involved in vectorborne-disease cycles, including vector biology, reservoir host dynamics, host infection and transmission dynamics, and land-use dynamics, Ogden said. The advantage of models developed thus far is that they are built on "unequivocal" data—"true observed field or laboratory relationships between climate and some important attributes of the vectors or the pathogens".

Simple mathematical models can be used for such science policy activities as country-level risk assessments or benefit–cost assessments. Simple models incorporate only one or two factors that have a known relationship between climate and a disease vector. Ogden and colleagues are using simple climatic indicators to project the distribution of the Asian tiger mosquito *(Aedes albopictus)* in Canada. The Asian tiger mosquito is a potential vector of chikungunya, an infectious disease typically found in the Caribbean. The number of infected travelers returning to Canada from the Caribbean is increasing because of the chikungunya epidemic in the Caribbean. Ogden compared two simple mathematical models that produced different outcomes. The model based on overwintering and annual mean temperature produced a map showing that the mosquito would not spread into Canada. The model based on temperatures in January and the summer and on annual rainfall produced a map showing that the mosquito could spread into Canada. "Much of the variation comes from the use of different indicators; this is one of the problems with simple models," Ogden said.

Complex simulation models are used when a decision-maker needs to account for many variables and detailed information. The more complex models can be used to address such

Box 3-3
World Health Organization Quantitative Risk Assessment of Climate Change with Respect to Selected Causes of Death, 2030s and 2050s

In fall 2014, the World Health Organization (WHO) published a report on the first quantitative assessment of the health effects of climate change on a global scale. The report was prepared by a multidisciplinary, multinational team. Workshop speaker Sari Kovats was one of the report's four editors. Kovats gave workshop participants a brief overview of the report objectives, approach, and model end points.

Objectives: The risk assessment was conducted in response to a WHO health-assembly mandate to update what is known about global health risks posed by climate change. No assessment of health effects of climate change had been conducted in over a decade.

Approach: The assessment looked at a "future world with and without climate change". The integrated modeling was conducted with one carbon dioxide emission scenario (A1b emissions trajectory), one world population projection out to the year 2100, and three economic-growth scenarios: high growth, base-case (middle) growth, and low growth. Model assumptions included some adaptation in response to climate change. Kovats explained that for all health categories except mortality due to coastal flooding, the models assumed general improvement in population health due to improvements in economic development. For flooding, the models assumed increased population vulnerability due to rapid urban development in coastal areas.

Model End Points: The risk assessment included annual projections of mortality from all causes and from six specific causes: heat (in people over 65 years old), coastal flooding, diarrheal disease, malaria, dengue, and undernutrition. Of particular interest was the distribution of mortality in different regions. The models were "all fitted with the best available observational global data",," Kovats said, although in the cases of heat and diarrhea outputs from statistical models based on locational data were included.

Kovats shared conclusions drawn both from the risk assessment and from the process of conducting it. An important message of the 2014 WHO risk assessment is that "even if you assume a lot of adaptation and high economic growth, the effects are still adverse," she said. In addition, "the effects are regionally focused"; for example, projected malaria-caused mortality is concentrated in eastern African countries. However, limitations need to be addressed. "We know that climate change will have more complex effects on health and on determinants of health" than the assessment includes, and "the uncertainties are large." Identifying uncertainties is useful because it helps us to "point to where research is needed", but Kovats cautioned that "we need to develop better methods to communicate and describe them."

programmatic activities as risk mapping to determine targets for disease surveillance or intervention strategies, identifying populations at risk, and predicting evolution of new pathogenic variants, Ogden said. He emphasized that complex simulation models are the only option for making dynamic projections of a vector's spread under different conditions. Ogden and his colleagues used a complex simulation model to assess Lyme disease emergence in Canada. The model was used to map projected distributions of blacklegged tick (*Ixodes scapularis*), the vector of Lyme disease, in 2020, 2050, and 2080. The risk map shows a "high risk" of spreading into most of eastern Canada. Ogden's group validated its findings with a prospective study. "Unfortunately, it's gone from a modeling exercise to a public-health issue," he said. He added that "systematic surveillance . . . in time and space" is needed to develop useful simulation models for other disease vectors.

Ogden noted that a weakness in modeling efforts is in the translation of projections of vector presence into cases of disease. "The ultimate goal is to correlate human risk with vector population densities and climatic variables so that we can project how climate change will affect disease risk," said Charles Benjamin Beard (Ben Beard), of CDC. To do that, "we need much more information on the distribution and abundance of vector populations, such as the blacklegged tick," he said. We also need local disease occurrence and information on the effects of temperature and precipitation on local vector populations. Beard emphasized the need "to continue to push the models to finer resolution" because public-health assessment and response are conducted at the local level.

Water Quality and Health

Juli Trtanj, of NOAA, discussed current efforts to develop models of climate-change effects on waterborne diseases and water-related illnesses. Waterborne diseases and water-related illnesses can arise through many pathways—exposures to bacteria or viruses in drinking water, to algal blooms in recreational water, to chemical contaminants in groundwater, and so on (Figure 3-1). The pathways are complex: the water cycle is combined with infrastructure, land use, and other biologic and physical factors. Trtanj explained that the reasons that the climate-change community is not farther along in developing coupled models is that neither the basic science underlying the water–health outcome pathways nor coupling of the factors involved is well understood. Trtanj indicated that although models of climate effects on sources of water contamination or on human exposure to water contamination are not yet advanced, such models are important stepping stones toward modeling health outcomes.

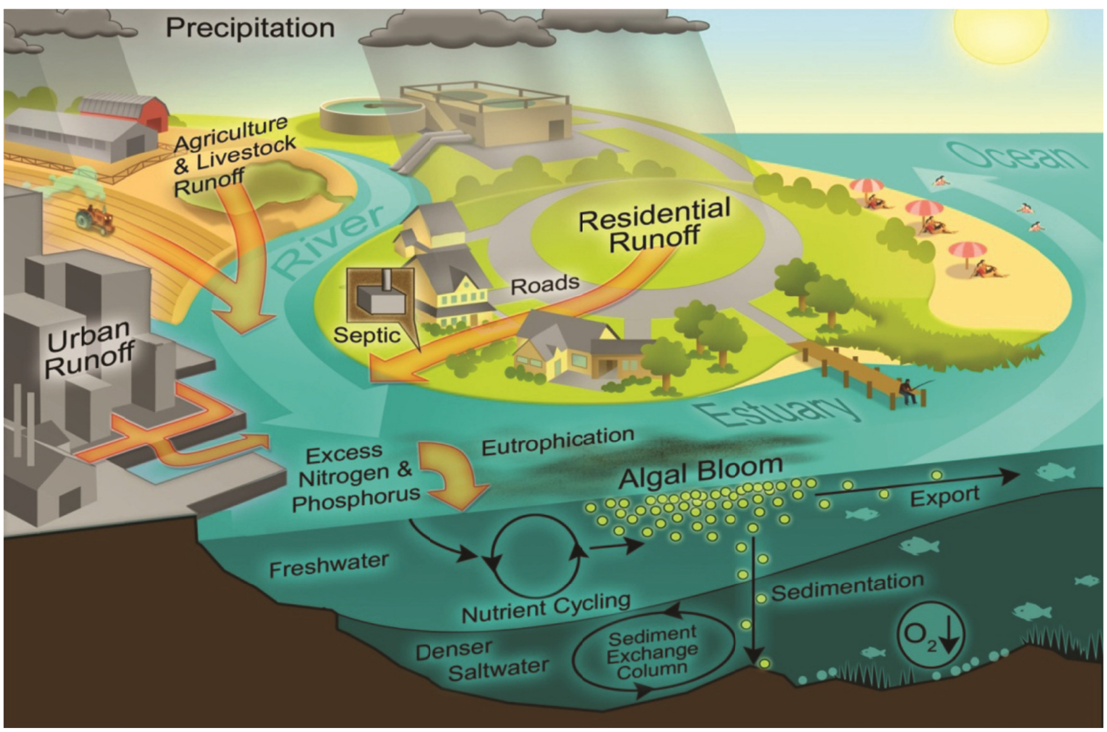

Figure 3-1 Waterborne-Disease Pathways, Freshwater–Marine Continuum

Julie Trtanj used this illustration to show the many factors in the pathway that links climate change to waterborne diseases and water-related illnesses. Such climate drivers as increasing ocean temperatures, ocean currents, and sea-level interact with exposure to contaminants from urban and rural environments or wildlife. Humans may be exposed to pathogens or other contaminants through drinking water and recreational or occupational water uses. Source: Juli Trtanj, workshop presentation, slide 3. Based on image originally created by Hans Paerl of the University of North Carolina, Chapel Hill for the US EPA.

Trtanj discussed a few case studies that used modeling on a regional scale to demonstrate "where we are" with modeling. One study looked at how projected increases in storms that result in sewage overflows may affect drinking water in the Great Lakes. "We already know that we are expecting an increased incidence of precipitation events because of climate change, and 67% of waterborne-disease outbreaks are preceded by precipitation events," Trtanj said. In the Great Lakes, she explained, intense rainfall taxes the wastewater-treatment infrastructure. Researchers developed a model that projected future increases in rainfall. The result was that future rainfall would exceed the amounts planned for by wastewater managers. The rainfall output of the regional precipitation model was then used as an input for an "infrastructure model" of "how much water is going to be coming through the pipes." The bottom line is that the model predicted that sewage overflows will increase by 20%, Trtanj said.

Trtanj and Jan Semenza, of the European Centre for Disease Prevention and Control, also described models for investigating climate-change effects on water temperature in relation to the potential for outbreaks of *Vibrio* species, bacteria that occur naturally in coastal waters. Vibrio can cause gastrointestinal-tract illnesses and wound infections and are responsible for 95% of seafood-related deaths in the United States. "If your doctor is not prepared for wound infection in the emergency room, you might well lose your limb," Trtanj emphasized. Although there are not many cases of vibrio infection, there is a shift in the range of the bacteria in coastal waters, she said. Semenza was involved in an effort to predict the likelihood of vibrio infection in the Baltic Sea. *V. vulnifucus* starts to bloom when sea temperatures exceed 15°C and salinity is low. The research team used geospatial tools to monitor surface temperature and salinity to predict the likelihood of the occurrence of vibrio infection. They developed the Vibrio Risk Model. Semenza also investigated the relationship between West Nile fever (WNF), which is driven by the presence of infected birds, and climate's influence on water temperatures in southeastern Europe. After analyzing the factors involved in a major outbreak in 2010, he and colleagues put together a multivariate model that included water temperature, the presence or absence of wetlands, and the presence of the virus in the previous year. The model successfully predicted the incidence of WNF in 2014.

Trtanj summarized the status of models of climate-change effects on waterborne diseases and water-related illnesses as mostly qualitative but quantitative when data are available; mostly regional, subregional, or local but not global; and mostly statistical although more dynamic, mechanistic models are needed. It will be important to incorporate "risk windows" for waterborne diseases into the models; it is necessary to factor in the habitat suitability and period that would be associated with changes in risk, said Erin Lipp, of the University of Georgia College of Public Health. Current models are able to link climate-induced changes to environmental exposures but have not linked them to health outcomes, and they do not include social variables, Trtanj said. She stressed that "gaps abound" and added that "we have to have the fortitude as agencies and scientists to figure out what we need to do, and do it," even with the knowledge that advances will be neither inexpensive nor fast.

Heat, Air Quality, and Health

It is "critically important" to understand how environmental stressors, such as air quality, affect human health today if we are to understand what happens to the relationship in a changing climate, stressed Michelle Bell, of Yale University. Research has demonstrated that human exposure to tropospheric ozone causes "increased risk of hospital admissions, premature mortality, increases in such respiratory symptoms as coughing and wheezing, reduced lung function, and other conditions." More than 100 million people in the United States live in areas that exceed the US EPA's health-based ozone standard, she said. Climate change may affect tropospheric ozone through multiple pathways, including changing precipitation patterns, changing wind speed and direction, and increased temperature. "Higher temperature means higher ozone," Bell said. She explained that higher average temperatures increase the speed of chemical reactions for ozone formation and increase emissions of natural ozone precursors.

Bell described a study that her group published that used global climate, air quality, and meteorologic modeling to investigate how climate change could affect summer ozone concentrations in 50 eastern US cities. The goal was to "isolate the effect of climate on health", so they modeled ozone emissions if we experienced the projected climate of 2050 today. For this study, estimates of what ozone emission magnitudes, technology, or population would be like in 2050 were not needed. "All the cities showed either a negligible difference or an increase in ozone," she said. In particular, she said, the models showed increases of 12% or more in cities in the upper Midwest, including Ohio, Michigan, Indiana, and Illinois. Uncertainty of regional effects was somewhat high; the overall models projected that the number of days with unhealthy ozone concentrations would increase.

Bell told the audience about an exercise that used different models and climate scenarios to investigate how heat waves linked to climate change might affect mortality in Chicago in 2081–2100. The models accounted for changes in population. All the models and scenarios showed an increase in mortality. "The biggest uncertainty was associated with the choice of climate-change model," Bell said.

Hayden pointed out that NCAR has developed a risk map of heat-related mortality at the census-block level for the city of Houston. The map is based on outputs of a hierarchic model in which spatially varied coefficients are based on death counts, numerical-model weather simulations, and census and parcel data, Hayden said. The risk maps produced from the model outputs help researchers to understand differential vulnerability. "We have learned that an increase in heat-stress nights will increase mortality and that extreme heat disproportionately affects the elderly, those who are socially isolated, those of low income, blacks, and people who use public transportation."

The model also is able to look at each census block and determine what demographic factors contribute to risk at that level. A publicly available map enables users to find the nearest cooling centers, such as the closest community centers, pools, or Walmart store. The map shows how far away cooling centers are and the centers' hours of operation. And it gives users access to CDC's tips for cooling oneself immediately, Hayden said. "We think that these maps are an important step toward including drivers of vulnerability on multiple scales. They connect people with where they are, and they increase the ability of communities and stakeholders to develop a program to mitigate risk," she said.

HURDLES

The climate-assessment literature tends to be extremely cautious about projecting health outcomes. Most studies are couched in terms of risk in part because whether adaptation is included is highly variable in the underlying literature, Janetos said.

It is difficult to link changes in climate with public-health outcomes because of the large variance in data and the low signal-to-noise ratio, Semenza said. Another challenge is dealing with multifactorial disease patterns that involve complex interactions with different drivers and teasing out the contributions of the different drivers. A third difficulty involves attributing individual climate events to health outcomes, he said. "Any climate-related effect on health is mediated by other physical and environmental factors. There is no such thing as a direct climate effect," Zaitchik emphasized; for example, the built environment plays an important role. There is extreme heterogeneity in rural and urban environments with regard to exposure to heat and air quality, Luber said. "Even within an urban environment, there is great variability in a census block; even the side of the street can affect exposures," he said.

Further complicating the challenge is the need to factor in what the Intergovernmental Panel on Climate Change calls "natural mediators", such as the ecologic and biologic processes associated with the pathogens that cause infectious disease and with allergens, Luber said.

Brown, who was involved in the US Global Change Research Program's recent National Climate Assessment, pointed out that many agricultural models do not include pests and disease and therefore could be optimistic in their projections of agricultural output in 2050 and 2100. "Such secondary effects may be enormous, especially in light of the acceleration of organism changes that we are trying to prevent with genetic engineering."

No surveillance system attempts to link effects of climatic events to real outcomes, Semenza said. Many health effects are institutionally mediated, Luber added, pointing out as an example that climate change does not directly cause famine.

Public-health leaders often lack knowledge about climate change or shy away from the issue because it is not seen as a winnable battle, observed Richard Jackson, of the University of California, Los Angeles.

Systems modelers do not necessarily have the same objectives as stakeholders, said Gary Geernaert, of the US Department of Energy. Even among the world's top modelers of the health risks posed by climate change, it is not always clear what questions the models are being produced to answer, said Kristie Ebi, an independent consultant with ClimAdapt, LLC.

That all adds up to a massively interdisciplinary problem, Zaitchik said. It is easier to model exposures and risks than health outcomes, he commented.

Furthermore, many data have been collected on the possible health effects of climate change, but not many have been collected in a desirable way, Ogden said.

An important issue related to collecting data is privacy concerns, said John Balbus, the senior adviser for public health in the National Institute of Environmental Health Sciences. "Are there ways to aggregate to ameliorate that issue?" he asked.

Georges Benjamin, of the American Public Health Association, raised the potential value of insurance claims data. Peter Berry, of Health Canada, pointed out that his agency has been trying to improve its links with the urban-planning community.

Models addressing climate change and health can leverage many existing data, said Anne Grambsch, of EPA. They include data on disasters, such as air pollution, and health data and research data focused on temperature sensitivity. Many models control for weather, she pointed out.

Databases contain many types of data, but it is important to understand the implications of how they were collected, Beard said. We need not only to put data into a model but work with people who understand the data. For example, in the United States, cases of disease are recorded by county of residence, not by where people might have been exposed to disease agents. Thus, if a case of a disease is related to travel, that is not captured, he said.

OPPORTUNITIES

The availability of new satellite data and of expanded data services and low-cost sensors is improving our ability to model the physical environment, Zaitchik said. NASA's Global Precipitation Measurement Mission, on a satellite launched in February 2014, is "game-changing", he said. It provides more data on global precipitation than its predecessors gathered and at a much higher resolution, less than 10 km, with multiple passes each day. A satellite scheduled to launch in January 2015 will collect unprecedented information on soil moisture throughout the world with better resolution and the ability to "see through" vegetation to collect information that cannot be collected now. And NASA's Giovanni data services are making satellite data more accessible than they were previously, he added.

Now that researchers have access to more than 35 years of satellite data, they can capture decadal-scale variability related to local environmental characteristics in a way that can reveal something about climate change, Zaitchik pointed out. The open-data policy that most institutions have adopted gives scientists better information to use in analyzing how the climate is changing.

The increased availability of sensors facilitates collection of local data, which in turn can add greater spatial resolution to models, Zaitchik continued Many of the sensors are small and inexpensive enough to be placed almost anywhere. The ability of cell phones both to act as sensors and to share data via crowd-sourcing allows interested citizens to get involved in data collection. Technologies for assimilating all the data collected by the satellites and sensors are also improving, he said.

Scientists' increasing use of geographic information systems and information from remote sensing allows modelers to incorporate potentially useful data from such sources as weather stations, habitat maps, and digital elevation models, Ogden said.

New datasets on human mobility are also helping climate modelers. Those data, often captured by mobile phones, enable models to factor in "the human side of the ecology" in addition to the environmental ecology, Zaitchik said. An emerging field is coupled analysis that combines information about human population dynamics with such information as parasite population dynamics. Zaitchik said that he is working on a coupled analysis of how human and mosquito dynamics in the Amazon can affect malaria rates.

It is clear that diverse approaches are needed to model the health risks posed by climate change, Ebi summarized. Models can help to provide insight into exposure–response relationships, including how the relationships may change. They can also serve as early-warning systems, she said. And some can help to identify prices and benefit–cost relationships in association with climate variability and long-term change. "We do not know what the future will look like, so models have different sets of assumptions. As we move forward, we will need various models with various assumptions to address the questions that policy-makers will ask us," she said.

4

APPLYING SYSTEMS THINKING TO UNDERSTAND FUTURE VULNERABILITIES

"Clearly, the idea of a systems approach is to capture the full impact of climate change; right now, we are capturing snippets."—Georges Benjamin

"Modeling to understand systems at any level is essentially the same as asking whether we understand the systems well enough to make projections, predictions, or forecasts."—Anthony Janetos

Systems thinking is not yet widespread in modeling efforts although the climate-change community is increasingly acknowledging its importance. Workshop speakers discussed definitions of systems thinking and how it might be used to advance models of health risks posed by climate change, drawing lessons from modeling efforts in agriculture and other sectors.

SYSTEMS THINKING: DEFINITIONS AND IMPORTANCE

Why is systems thinking important for developing models of the health risks posed by climate change? Before answering that question, Georges Benjamin, of the American Public Health Association, offered definitions of *systems thinking* and *health system* (Box 4-1).[7] "Systems thinking is an approach to thinking about how things interact with one another," he said. The systems view of how we study health, climate, or anything intermediary is that "the components are interdependent," noted Gary Geernaert, of the US Department of Energy (DOE). The interdependent components of a health system include medical infrastructure and resources, medical and public-health staff, and mechanisms to facilitate access to care, Benjamin explained. The challenge is to determine the extent of interdependence, Geernaert said; "if you are building models, some components are more interdependent than others, and our challenge is to figure out how to reflect the interdependence appropriately and come up with robust conclusions."

Systems thinking is particularly relevant in the context of extreme weather-related events, Benjamin said. "We build our health systems for just-in-time management for the mean; we cannot afford to build for extremes." But robust medical infrastructure is critical for response in the aftermath of a disaster. To illustrate that point, Benjamin described the medical and public-health challenges posed by the EF5 tornado that hit Moore, Oklahoma, in 2013. The

[7]World Health Organization. 2005. What is a Health System? http://www.who.int/features/qa/28/en/

Box 4-1
Definitions: Systems Thinking and Health System

Georges Benjamin offered the following definitions of *systems thinking* and *health system* to workshop attendees:

> Systems thinking: An approach that gives one an understanding of a system by examining the linkages and interactions between the various components that make up the entirety of the system.
>
> Health system: The total of all the organizations and resources whose primary purpose is to improve health. A health system needs staff, funds, information, supplies, transport, communication, and overall guidance and direction. And it needs to provide services that are responsive and financially fair while treating people decently.

tornado leveled the town and heavily damaged the Moore Medical Center. Effects on the health system included infrastructure loss, relocation of medical staff away from Moore, and reduction in access to medical care. He emphasized that what happens to employees or access to medical care after such disasters is often not accounted for in models. "And we often do not include human behavior in our models," Benjamin said. For example, the Hurricane Katrina disaster in 2005 showed that people often will not leave their pets. In addition, there is often an enormous mental-health effect on both the people who have suffered losses and the officials who are trying to manage the disaster, Benjamin said. "We talk about direct effects, but we do not talk about these tail events."

We need to build models that address cascading system failures and secondary and tertiary effects, said Molly Brown, of the National Aeronautics and Space Administration. An analysis conducted in the wake of Superstorm Sandy showed that what most affected "human welfare and public health were all the aspects that we never thought of and that are not in the models, such as generators below sea level and unexpected cascading power outages," Brown said.

Systems thinking can enable us to prepare for climate change, Brown suggested. In the last 5 years, a massive transformation related to food crops and infrastructure has been going on in some African countries. What citizens want is for new crops and new infrastructure to be tolerant to climate change "so that they don't have to retrofit everything 20 years from now," she said.

When thinking about climate-change effects, we need to include both regional change and local change and their interactions with trade, food movement, effects on water systems, and how systems will adapt, said Robert Vallario, of DOE. "Understanding such complex systems and their potential evolution is not deterministic modeling. We are exploring thresholds, tipping points, and sensitivities in the context of science-based and quantitative approaches," he said.

INCORPORATING SYSTEMS THINKING INTO MODELS

The kinds of models that apply systems thinking involve what Anthony Janetos, director of Boston University's Frederick S. Pardee Center for the Study of the Longer-Range Future, referred to as two-way models (see Box 3-2). Such models can include adaptation and institutional response and therefore come closest to identifying health outcomes. Two-way

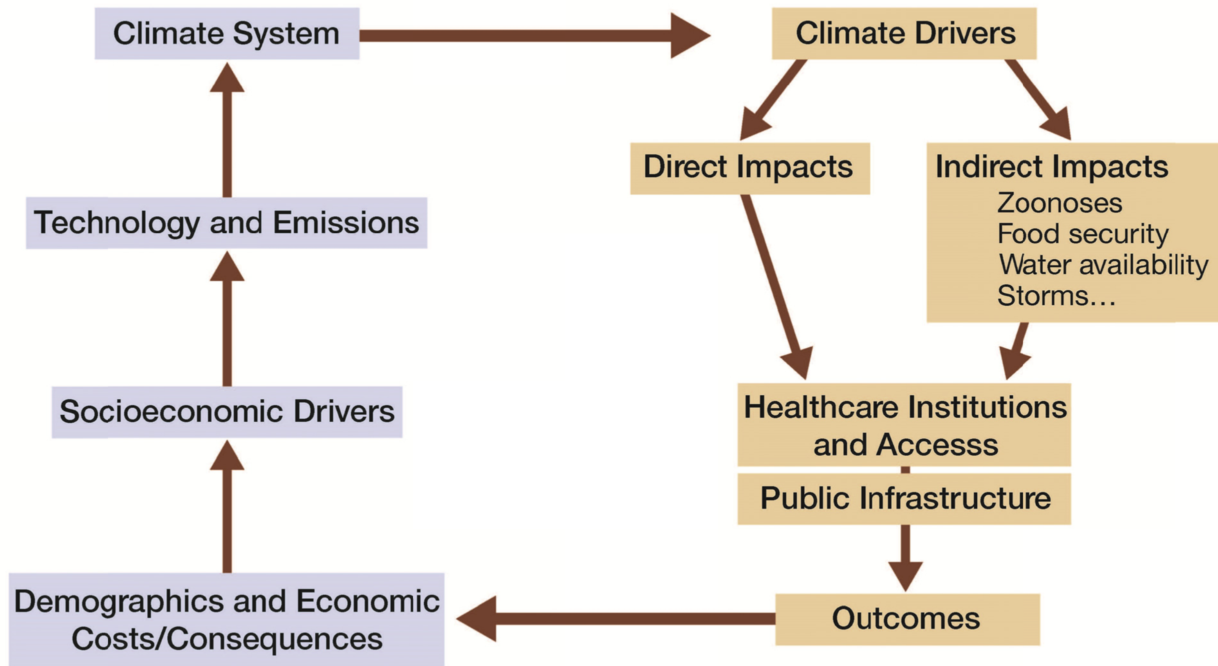

Figure 4-1 Health outcomes from a systems perspective

Janetos told workshop attendees that even the simplest diagram that he could think of to reflect health outcomes of climate change is complex. He emphasized that no study has yet modeled the entire system and that "any component could be expanded into its own system diagram." Source: Janetos Slide 21.

models can account for feedback loops in health outcomes, adaptation of the economy, and later consequences for both mitigation and demographics (Figure 4-1).

"The complexity of the system is partly a function of what we choose to model and what level we want to try to grapple with," Janetos said. "One big question that we have to confront is the degree to which we want to think about health effects in a systems context. Do we want to think of them as part of an overall climate–demography system, or do we want to think of them as a sector that has its own forcings, behavioral responses, and interventions that we could model?"

"Modeling to understand systems at any level is essentially asking whether we understand the systems well enough to make projections, predictions, or forecasts," Janetos said. Building models so that they have those capabilities is difficult. Efforts to factor in such components as human adaptation and mitigation efforts are complicated by the reality that although much evidence suggests that adaptation will occur, little clarifies when or at what level it will occur, said Sari Kovats, of the Faculty of Public Health and Policy of the London School of Hygiene and Tropical Medicine.

The models may not necessarily be best created via the conventional "top-down" approach, said Anne Grambsch, of the US Environmental Protection Agency. "We tend to think of systems as things that we design from the top down, but systems also can emerge from data and observations," she said. She added that systems thinking can reveal values that may emerge from comparing tradeoffs. That raises the question of how to collect and structure such data so that they can tell us something useful, she said; "It is not so much how we use systems to identify cascading failures as it is how cascading failures tell us how distantly things are connected."

Gregory Glass, of the University of Florida, noted that incorporating systems thinking into models of health risks posed by climate change will ideally not only improve our understanding of health outcomes but help us to identify "where our weaknesses and gaps are."

Context matters, Brown emphasized. "The world has a distribution of the haves and the have nots, the resilient and the less resilient, and the least vulnerable and the most vulnerable." More modeling outcomes need to be put into that context "so that we can ensure that safety nets are appropriate," she said.

Joshua Elliott, of the University of Chicago's Center for Robust Decision Making on Climate and Energy Policy (RDCEP), cautioned that developing a "supermodel" of the whole Earth may be unproductive. He suggested that a better approach may be to think of a sector, such as agriculture, as a "system within a system" and try to understand it and its interactions with other systems.

One way to find out how to create pathways to desirable end points is the approach used in economic models, Brown said. If you define the end point that you want to reach, you can run simulations to find ways to reach it. An example shared by Geernaert was "no blackouts by 2050". He urged attendees to think of examples that were more health-focused in an appropriate timeframe. To identify those kinds of end points, it is important to get people to think about the different outcomes that they are willing to accept, Glass said.

Janetos suggested that the health goals in the Millennium Development Goals[8] could serve as end points in models for assessing the health effects of climate change. He also noted that "forward" modeling may not always be needed to understand how to target interventions. "We might do well to turn the problem around, ask about the degree to which we understand parts of the system that determine vulnerability and sensitivity, and then model the degree to which an intervention could have an effect." Only then, he suggested, does it make sense to ask whether a change in climate would make the intervention beneficial or not.

Kovats suggested there is value in thinking about health as both a result and a driver in the context of poverty eradication and sustainable development. She and Stéphane Hallegatte, of the World Bank, suggested that it will be important to make sure that investments take into consideration adaptation. To improve disaster-risk mapping, more attention is needed on the social side, Kovats added; for example, projections of poverty and of where people will live are critical.

Elliott discussed the results of a recent model-intercomparison project to illustrate the complexity involved in comparing results from one or two sectors. The study included data from more than 40 models. Groups in four sectors collaborated to compare the results of their models with regard to climate effects, including health. The comparison suggested a strong

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[8]Global, time-bound, quantified targets for addressing extreme poverty in its many dimensions—income, hunger, disease, lack of adequate shelter, and exclusion—while promoting sex equality, education, and environmental sustainability. For more information, visit http://www.un.org/millenniumgoals/.

likelihood that a tropical region's ability to produce maize and wheat would be adversely affected by rising CO_2 concentrations, Elliott said; there is less model agreement with respect to rice and soy, which may be favorably affected.

The project included an ensemble of 11 global hydrologic models run with the same set of climate scenarios as the crop models. The researchers combined the results of the global crop and hydrologic models to analyze the potential of irrigation as both an adaptation mechanism and a measure of climate change. They found that water limitations caused by reduced runoff and hydrologic limits resulted in a decrease in food production of 8–24% compared with today's agricultural production even when increases in plant productivity associated with increased atmospheric concentrations of CO_2 were included. The decreases were much larger in scenarios that did not include increased plant productivity in the presence of increased CO_2.

When the modelers included freshwater limitations implied by the hydrologic models and the reduction in runoff, their simulation suggested that 20–60 million hectares of irrigated cropland would have to be converted to being only rain-fed by the end of the century. That implies a further decrease in food production, Elliott said.

The US Centers for Disease Control and Prevention (CDC) Climate and Health Program created a model to help cities and states to prepare for health effects of climate change. Building Resilience Against Climate Effects (BRACE) uses the principles of adaptive management, which encompasses loop learning and feeding what is learned back into the system, said George Luber, CDC's associate director for climate-change programs. "We forecast the climate effects for a region and couple them with the existing vulnerabilities of the location," he said. On the basis of population dynamics and projected increases or decreases in heat, precipitation, drought, and so on, the model enables researchers to assess vulnerabilities.

The National Science Foundation is funding a project to investigate how an approach known as agent-based modeling can help researchers to understand how the experience of living through multiple disaster scenarios involving multiple system failures may affect human behavior on both the institutional and individual levels, said Benjamin Zaitchik, of Johns Hopkins University. The models are designed to be capable of investigating both engineering interventions to harden infrastructure and effects on human health. They are intended to investigate such questions as how many intensive heat waves are required to prompt institutions to change urban infrastructure to reduce the effects of the heat waves.

A Web site run by RDCEP includes access to programs that allow anyone to run simulations that show the effects of global climate change, Elliott said. The WebDice model runs simulations that project how such actions as carbon taxes, climate treaties, and "optimized policies" may affect global warming. It is based on a widely used integrated-assessment model of the economics of climate change called DICE, which was invented at Yale University in 2007. "We have added many features and assumptions and have enabled people to tweak assumptions to see what kinds of effects they have," Elliott explained.

5
MOVING FORWARD

What are the next steps by which researchers can focus their work in modeling of health risks posed by climate change? Speakers and panelist offered a variety of answers to that question, including thoughts on model complexity and context, new paradigms, time scales, decision-making needs, and communication.

COMPLEXITY, CONTEXT, AND FUTURE SCENARIOS

"We expect complexity; it's not remarkable," said Kristie Ebi, of ClimAdapt, LLC. Health systems and disease transmission are complicated, so the question is what to do with the complexity in modeling, she stated. Modelers need to address complexity both by defining the task at hand and by acknowledging climate change in the context of other drivers of health outcomes, noted Anthony Janetos, of Boston University's Frederick S. Pardee Center for the Study of the Longer-Range Future. Janetos explained that many factors may be more important than climate change and variability in determining health outcomes. Thus, it is important to know that climate change "may have the capacity to influence only one or a few of the factors in important ways but not all of them," he added. As an example, Jan Semenza, of the European Centre for Disease Prevention and Control, described a "thought experiment" that he published in 2011[9] in which he and colleagues identified three broad classes of drivers that are involved in unexpected infectious-disease outbreaks and pandemics (such as SARS and avian influenza): globalization and environmental change, social and demographic change, and public-health systems. He developed plausible scenarios that linked each of those drivers with a health outcome and then compared the results with what happened in real outbreak events. The comparison was "much more complicated than expected" and underlined the idea that when it comes to health, climate change should be considered within the broader context of other health drivers, Semenza said.

One health driver that should be accounted for in models of health risks posed by climate change is urbanization, Ebi said. Unplanned urban environments can exacerbate health risks. For example, the *Aedes* mosquito that carries dengue is now found "in places it shouldn't be because it likes to overwinter in sewers and is transported around the world in used tires," she explained. Models for dengue are growing in their ability to look at weather measures, "but we are not looking at urbanization although we know that it is important." She stressed that including future scenarios of urbanization in models is an important next step.

Sari Kovats, of the Faculty of Public Health and Policy of the London School of Hygiene and Tropical Medicine, noted that integrated assessment models are good at quantifying effects on gross domestic product but that there is a big gap when it comes to quantifying

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[9]Jonathan E. Suk and Jan C. Semenza. 2011. Future Infectious Disease Threats to Europe. American Journal of Public Health. 1010(11):2068-2079.

nonmarket effects. She suggested that adding health cobenefits to integrated assessment models may be easy to achieve in the short term because there are solid data to draw on; for example, the health risks posed by air pollution are well documented.

John Balbus, of the US National Institute of Environmental Health Sciences, emphasized that predictive modeling that includes social factors should also be developed. "We cannot be relevant without being based on demography and on a solid understanding of what is happening in populations and socioeconomics," he said.

SHIFTING THE PARADIGMS

There is a large and robust health-modeling community, but the people in the community generally do not focus on ecologic drivers, Balbus noted. Complicating the issue is that the health community tends to be reactive and look backward and not to think so much about what may happen in the future, he said. "That mindset has to be changed," he stressed. Ebi asked, How do we proceed with inadequate information? She said that the use of modeling to design surveillance programs to make it possible to avoid projected health effects of climate change will constitute an important paradigm change for the health community.

Janetos recommended a three-pronged approach. First, integrated modeling at a high level can help researchers to understand long-term trends and the evolution of climate–health linkages over several decades and in the developing world, he said. Second, systems modeling at a more detailed level can shed light on specific cases and perhaps help in assessing the value of particular interventions. Third, empirical research and modeling can help researchers to understand where sensitivities arise and the best methods for reducing vulnerability.

Along the way, everyone will benefit by embracing "getting things wrong", said Anne Grambsch, of the US Environmental Protection Agency (EPA). "In the first work that we do, we are going to be wrong," she said, pointing out that EPA's BenMAP model for estimating the health and economic effects associated with air quality got things wrong at first. "It is when you are wrong that you actually make progress," she continued.

RELEVANCE TO DECISION-MAKERS

Ebi noted that policy-makers "do not want to know what is happening about heat or diarrheal disease". The type of question that they want an answer for is, What will happen in sub-Saharan Africa as water resources decline, crop yields fall, temperatures increases, and diarrheal disease and malnutrition increase? The "health outcome-by-outcome, region-by-region, and country-by-country" approach to modeling is not useful to many decision-makers. Stéphane Hallegatte, of the World Bank, agreed, providing example of the types of questions that the World Bank is exploring in its work on climate change and poverty (Box 5-1).

Janetos works with mayors on short-term and long-term planning for climate change. He pointed out that a mayor's job is "to protect lives, livelihoods, and property". Mayors are not necessarily concerned with understanding the scientific complexity of systems; they need a more broad-scale view of how climate change may affect their cities and people. The lack of a broad-scale view may be causing a "systematic underestimate of how big a problem climate change is," Janetos said.

Box 5-1
Interactions Between Climate Change and Poverty: Some Policy Questions

To illustrate the types of questions that decision-makers are asking about climate change and health, Stéphane Hallegatte described the World Bank's activities regarding interactions between health and poverty. The World Bank has a target to reduce extreme poverty drastically by 2030. That means that fewer than 3% of the world's population would be in extreme poverty in 15 years. The effect of climate change on the effort, however, is a subject of investigation to inform planning. Some questions about efforts to model the health risks posed by climate change:

- Can health effects of climate change influence whether the 2030 target is reached?
- Do approaches to eradicating poverty need to change in light of climate change?
- If the 2030 target is reached, would that avoid or mitigate health effects of climate change?
- If the 2030 target is not reached, would future efforts to eradcate poverty become more complex as the health effects of climate change materialize?

"Public health is a local matter, so the response [to health effects of climate change] needs to be a local response," said Benjamin Beard, of the US Centers for Disease Control and Prevention. "We need better predictions at the local level." Some municipalities, such as Los Angeles, are investing in training to help their public-health employees to understand the effects of climate change projected in their areas, said Richard Jackson, of the University of California, Los Angeles. He has been involved in efforts to train public-health officials in Los Angeles about facets of climate change, including vulnerable populations and adaptation management. Balbus noted, however, that information relevant to policy-makers will come from research on both local and global scales. "Many decisions that we make are at the local level, but many decision-making processes, such as benefit–cost analysis, require aggregation and integration that are large-scale," he said. Both local and global are important.

A compelling case showing the value to policy-makers of incorporating more health into climate-change modeling would go a long way toward helping researchers to obtain funding for these efforts, Balbus said. Making the case for a long-term preventive strategy is daunting, he said, given that institutions may not be around as long as the timeframe that needs to be considered.

The Canadians' success in engaging decision-makers, as described by Peter Berry, of Health Canada, is a reason for optimism. "I think we have been successful in changing the level of knowledge of public-health decision-makers" compared with 10 years ago, he said. He credits the institutional mechanisms that his country has put into place to link the various groups that can support model development and the generation of data.

MODEL COMPARABILITY

One challenge is that modeling "has been very ad hoc," Kovats noted. "No one has brought the community together to think about model parameters for a coordinated activity or how to network better among modeling communities," she observed. However, Janetos cautioned that because modeling of health risks posed by climate change is in a nascent stage, model-comparability studies may yield results that are not understandable. Ebi disagreed: she suggested that a coordinated project with a common set of measures, such as time scale, or a variety of scenarios could be useful. Hallegatte noted that careful consideration needs to be given to goals of comparability studies and to the types of models to include. He stressed that diversity of models is useful and that restricting some models to a specific set of measures could restrict innovation. "Comparability works for some things but not everything—and only when a field has reached a level of maturity," he stated.

COMMUNICATON

Balbus concluded that the workshop had made it clear that there are many pathways and communities and that the models needed by different constituencies are at different stages. "We are trying to change the paradigm of how we model risk to apply a systems approach . . . to bring in new teams and new ways of thinking." The overall picture is heterogeneous and at times confusing, he stressed.

"Everyone is saying that if you want to raise the interest of policy-makers and decision-makers, you need to focus on the time between now and 2030, but we need to fight hard to say that there are messages for the 2080s and even beyond that matter for today's decisions," Hallegate argued. Ebi added that 2100 seems far away to some but that "children and grandchildren born now will see the consequences of actions we are taking."

Institutions might not be around over the timeframes that we are discussing, let alone the people in current political offices, Balbus noted. In addition to building models of health risks posed by climate change, the scientific community needs to work at building a long-term preventive mindset among decision-makers, he concluded.

APPENDIX A
STATEMENT OF TASK

An ad hoc committee will organize and convene a public meeting on modeling the health risks of climate change and emerging scientific approaches to enhance model robustness. Meeting discussions will explore the state-of-development of a range of health risk models (for health impacts of heat stress and air pollution, vector-borne disease, water-born infectious disease, etc.); new data on and approaches to incorporate future scenarios of exposure-response and human system vulnerabilities (e.g. in infrastructure, food or water delivery systems, etc.); and approaches to integrate health risks into models of aggregated impact of climate change.

APPENDIX B
WORKSHOP AGENDA

Monday, November 3, 8:30am – 5:00pm

SESSION 1 Human health risks of climate change: State-of-Knowledge

Moderator: John Balbus, National Institute of Environmental Health Sciences (NIEHS)

8:30 Welcome and Opening Remarks – Helmut Zarbl, Robert Wood Johnson Medical School & John Balbus, NIEHS

8:45 Where We Are: Hurdles and Opportunities – Jan Semenza, European Centre for Disease Control and Prevention (ECDC)

9:15 Emerging models, datasets, and applications – Benjamin Zaitchik, Johns Hopkins University

9:45 Using health risk models to improve community preparedness – George Luber, Centers for Disease Control (CDC)

10:15 Break

SESSION 2: Health Risk Models of Climate Change: State-of-Development

Moderator: Linda Wennerberg, National Aeronautics and Space Administration

10:30 Quantitative Risk Assessment Approach to Modeling the Health Impacts of Climate Change – Sari Kovats, London School of Hygiene & Tropical Medicine (LSHTM)

11:00 Climate and health effects of heat stress and air pollution— Michelle Bell, Yale University

11:30 Climate and water-borne infectious diseases – Juli Trtanj, National Oceanic and Atmospheric Administration

11:30 Climate and vector-borne diseases – Nick Ogden, Public Health Agency of Canada

12:30 Lunch on your own

1:15 Panel Discussion on Health Risk Models – Limitations and Opportunities

Discussants: Charles Benjamin Beard, CDC, Mary Hayden, University Corporation for Atmospheric Research, Erin Lipp, University of Georgia , Session 2 Speakers

SESSION 3: Human Systems-based Approaches to Understanding Future Vulnerabilities

Moderator: Gary Geernaert, Department of Energy (DOE)

2:15 Systems Thinking in Health: A Population Based Approach to Climate Change Impact– Georges Benjamin, American Public Health Association

2:45 Systems Approach to Climate Change, Agriculture, and Human Health – Joshua Elliott, University of Chicago and Argonne National Laboratory

3:15 Urbanization, Climate Change, and Human Health – Richard Jackson, University of California, Los Angeles

3:45 Break

4:00 Panel Discussion on Systems Thinking and Modeling the Health Impacts of Climate Change

Discussants: Molly Brown, NASA, Gregory Glass, University of Florida, Session 3 Speakers

Tuesday, November 3, 8:30am – 12:00pm

Session 4: Incorporating Health Risks into the Aggregated Impact of Climate Change

Moderator: Kristie Ebi. ClimAdapt LLC

8:30 Welcome and Opening Remarks – Kristie Ebi, ClimAdapt LLC

8:50 Integrating climate change impact models: where we are and where we need to go – Anthony Janetos, Boston University

9:20 Panel Discussion on Conceptual Directions for Research on Integrating Climate Change Impact Models

Discussants: Stéphane Hallegatte,World Bank, Anthony Janetos, Boston University, Sari Kovats, LSHTM, Jan Semenza, ECDC

10:15 Break

10:30 Panel Discussion on Practical Next Steps toward Improving Climate Change Impact Models

Discussants: John Balbus, NIEHS, Peter Berry, Health Canada, Ann Grambsch , Environmental Protection Agency, Juli Trtanj, NOAA, Robert Vallario, DOE

11:45 Closing Comments – John Balbus, NIEHS

12:00 pm Adjourn Workshop

APPENDIX C
WORKSHOP ATTENDEES

Valerie Adams, US Department of Defense

Linnea Availone, US National Science Foundation

John Balbus, US National Instituted of Environmental Health Sciences

Charles Benjamin Beard, US Centers for Disease Control and Prevention

Georges Benjamin, American Public Health Association

Robert Benson, US Environmental Protection Agency

Michelle Bell, Yale University

Peter Berry, Health Canada

Ashely, Bieniek-Tobasco, George Washington University

Laura Bonzanigo, World Bank

Timony Bouley, World Bank

Ross Bowling, US National Institute of Environmental Health Sciences

Molly Brown, US National Aeronautics and Space Administration

Duarte Costa, University of Exeter

George Daston, Proctor and Gamble

Richard Denison, Environmental Defense Fund

Caroline Dilworth, US National Institute of Environmental Health Sciences

Kristie Ebi, University of Washington

Joshua Elliot, University of Chicago

Lauren Everett, US National Academy of Sciences

Josh Gardenier, retired

Turkan Gardenier, Pragmatica Corp.

Gerald Geernaert, US Department of Energy

Sarah Gerould, US Geological Survey

Gregory Glass, University of Florida

Anne Grambsch, US Environmental Protection Agency

Gubraiel Ghusai, affiliation unknown

Stéphane Hallegate, World Bank

Mary Hayden, University Corporation for Atmospheric Research

Jawed Hameedi, US Department of Commerce

Eric Hooker, Tetra Tech Inc.

Vito Ilacqua, US Environmental Protection Agency

Anthony Janetos, Boston University

Hans Kaper, Georgetown University

Sari Kovats, London School of Hygiene and Tropical Medicine

Jennifer Lincoln, US National Institute on Occupational Safety and Health

Erin Lipp, University of Georgia

Germaine Louis, US National Institutes of Health

George Luber, US Centers for Disease Control and Prevention

Stephen Marcus, US National Institutes of Health

Suril Mehta, US Environmental Protection Agency

WB Meino-Zorento, unknown affiliation

Jonathan Mellor, Yale University

Ana Navas-Acien, Johns Hopkins School of Medicine

Nick Ogden, Public Health Agency of Canada

Gerald Poje, Society for Occupational and Environmental Health

Craig Postelwaite, US Department of Defense

William Rom, US Environmental Protection Agency

Crystal Romeo, University of Maryland

Sara Ruth, US National Science Foundation

Laura Sappelsa, Analytic Services Inc.

Jan Semenza, European Centre for Disease Control and Prevention

Keegan Sawyer, US National Academy of Sciences

Marilee Shelton-Davenport, US National Academy of Sciences

Mark Shimamoto, US Global Change Research Program

Lauren Soni, US National Academy of Sciences

Amanda Staudt, US National Academy of Sciences

WA Toscano, University of Minnesota

Juli Trtanj, US National Oceanic and Atmospheric Administration

Joyce Tsuji, Exponent

Robert Vallario, US Department of Energy

Linda Wennerberg, US National Aeronautics and Space Administration

Wenying Wu, Johns Hopkins University

Helmut Zarbl, Robert Wood Johnson Medical School

Ben Zaitchik, Johns Hopkins University

Lauren Zeise, California Environmental Protection Agency

Lewis Ziska, US Department of Agriculture