By Kim Knowlton, Miriam Rotkin-Ellman, Linda Geballe, Wendy Max, and Gina M. Solomon

Six Climate Change–Related Events In The United States Accounted For About $14 Billion In Lost Lives And Health Costs

ABSTRACT The future health costs associated with predicted climate change–related events such as hurricanes, heat waves, and floods are projected to be enormous. This article estimates the health costs associated with six climate change–related events that struck the United States between 2000 and 2009. The six case studies came from categories of climate change–related events projected to worsen with continued global warming—ozone pollution, heat waves, hurricanes, infectious disease outbreaks, river flooding, and wildfires. We estimate that the health costs exceeded $14 billion, with 95 percent due to the value of lives lost prematurely. Actual health care costs were an estimated $740 million. This reflects more than 760,000 encounters with the health care system. Our analysis provides scientists and policy makers with a methodology to use in estimating future health costs related to climate change and highlights the growing need for public health preparedness.

Kim Knowlton (kknowlton@nrdc.org) is a senior scientist in the Health and Environment Program at the Natural Resources Defense Council in New York City.

Miriam Rotkin-Ellman is a staff scientist in the Health and Environment Program at the Natural Resources Defense Council in San Francisco, California.

Linda Geballe is a student at Boalt Law School, at the University of California, Berkeley.

Wendy Max is a professor of health economics and codirector of the Institute for Health and Aging at the University of California, San Francisco.

Gina M. Solomon is an associate clinical professor of medicine at the University of California, San Francisco.

Climate change endangers public health. Rising atmospheric temperatures increase the frequency, intensity, duration, and geographic extent of heat waves, air pollution episodes, wildfires, activity of infectious disease vectors, rising sea levels, storms, extreme rainfall, and flooding.[1,2]

Prior studies have estimated future health costs related to climate change.[3–6] However, these figures are not specific enough to form the basis of health policy decisions. No US study has evaluated specific health outcomes associated with a set of events related to climate change.[7,8]

There is currently no well-accepted structure for quantifying the costs of the human health effects of climate change, in part because of the challenges of identifying comprehensive health impact data and a lack of consensus on health cost valuation methods. Some methods estimate health costs in monetary terms; others use physical units such as the number of lives saved or the number of cases of illness avoided. Another approach is to use indicators such as quality-adjusted life-years, a measure that incorporates both mortality and morbidity effects.[9]

Estimating the health costs of climate change is important for informing health policy decisions. Evaluating health-associated costs using a common method and then aggregating the costs can allow us to compare the various effects of climate change—once normalized, to account for geographic and other differences—with regard to magnitude or importance. Case studies can also help us gauge the progress of climate change–related health preparedness policies over time under different adaptation scenarios.[9] These scenarios present a range of possible regional climate effects, varying health vulnerabilities, and changing social and economic conditions that can help or hinder these policies' effectiveness.

The objective of this study was to provide a cost calculation of health effects associated with events related to climate change over the past

decade. Similar events can reasonably be expected to occur more frequently in the future.

Study Data And Methods

We focused on six major categories of climate-related events or episodes: ozone air pollution, heat waves, hurricanes, outbreaks of infectious disease, river flooding, and wildfires. These categories are well understood to be influenced by climate, they occurred in the United States during the past decade, and they are projected to increase in severity and frequency with future climate change.[10]

We searched the peer-reviewed journal literature and state and federal agency reports to identify an event or episode in each of these categories within the past decade for which quantitative data existed on morbidity and mortality. In cases where morbidity and mortality data from several events in the same category had been published, we selected one high-end, but not extreme, event.

The links between these individual episodes and climate change cannot be established definitively. Also, the relationship between climate change and health is complex and varies according to the type of event. However, these case studies represent the types of health impacts that are projected to worsen under climate change.

We calculated the mortality and morbidity for each event based on data reported in the published epidemiologic literature or by public health agencies, or we used extrapolations. These were based on values we inferred using ratios such as the number of hospitalizations to the number of visits to the emergency department and the number of hospitalizations to the number of outpatient visits, derived from the Medical Expenditure Panel Survey.[11] Morbidity costs reflect the expenses of hospitalization, emergency department visits, outpatient visits, and other medical services.

US OZONE AIR POLLUTION, 2000–02 Increasing atmospheric temperatures are projected to increase ozone pollution across many parts of the continental United States unless there are major reductions in precursor emissions.[12–14] Exposure to ozone pollution reduces lung function and inflames airways, leading to increased rates of emergency department visits, hospitalizations, and premature mortality—especially among people with respiratory illnesses, young children, and the elderly.[12]

Because of the national scale of ozone pollution, we based our analysis on a study by Bryan Hubbell and colleagues.[15] This is the most recent nationwide assessment of the health impact resulting from ozone levels that exceed national standards. It estimated the incidence of premature mortality, hospitalizations for respiratory problems, and asthma-related emergency department visits associated with ozone levels exceeding the eight-hour standard of eighty parts per billion for the years 2000–02. Consistent with the authors' data presentation, we averaged the results obtained by two different methods of estimating ozone concentration to produce an estimated annual incidence of the health impacts.

CALIFORNIA HEAT WAVE, 2006 The frequency, duration, and intensity of heat waves—defined as more than two consecutive days of extreme heat—in the United States are projected to increase greatly by 2090.[16] During the 2006 California heat wave, daily maximum and minimum record high temperatures were exceeded throughout the state over a period of approximately two weeks.[17] Climate change projections for California suggest an increased frequency of this type of heat wave under various warming scenarios.[1,18]

Extreme heat increases stress on the heart, lungs, kidneys, and other organ systems. It is also linked to increased rates of emergency department visits, hospitalizations, and premature mortality.[19]

We estimated morbidity based on Kim Knowlton and colleagues' analysis of county-level hospitalizations and emergency department visits.[19] From this article we extracted the number of excess hospital admissions for those diagnostic categories in which a significant change in the rate of admissions (above the upper 95 percent confidence interval) was observed at the state level. The categories were electrolyte imbalance, acute renal failure, nephritis, and heat-related illnesses. A significant increase in all-cause emergency department visits was also reported, and we included the reported excess visits. Sumi Hoshiko and colleagues have provided an estimate of excess mortality from this event.[20]

FLORIDA HURRICANE SEASON, 2004 Climate change is projected to increase the rainfall and wind speeds associated with hurricanes.[1] We used the 2004 hurricane season in Florida—during which there were four major hurricanes in one month—as our case study because of the magnitude of the events, the size of the affected area, and the availability of health surveillance data. This cluster of severe storms is believed to be a harbinger of future hurricane intensity.[21] In fact, in 2005 Florida was hit by four more major storms.

Hurricane-associated winds and flooding can damage buildings and critical community infrastructure, causing drowning, injuries, popula-

tion displacement, and stress. They can also cause illnesses resulting from exposure to contaminated floodwater and carbon monoxide poisoning. Improper use of gas-powered generators is a major source of illness and death after a hurricane.[21,22]

Comprehensive mortality and morbidity surveillance data were not available, so we relied on mortality data from Patricia Ragan and colleagues;[21] reported hospital discharge data for Florida hospitalizations and emergency department visits resulting from carbon monoxide poisonings;[23] and psychological impacts based on a representative survey estimate from Ron Acierno and colleagues of affected adults meeting the criteria for hurricane-related post-traumatic stress disorder.[22] Because no reliable data on the use of health care for injuries related to these hurricanes were available, we did not include injuries in our analysis.

WEST NILE VIRUS OUTBREAK IN LOUISIANA, 2002 Global warming may extend the range and intensity of many infectious diseases because of changes in temperature, precipitation, and habitat.[1,24] West Nile virus is an example of a vectorborne disease that has recently emerged in the United States, linked to changing climatic conditions.[25] An infectious illness transmitted by mosquitoes, the virus can cause central nervous system symptoms ranging from fever to paralysis and requiring medical care, emergency services, or hospitalization. Sometimes it can be fatal.[26]

In 2002 a total of 4,156 cases of West Nile virus were reported in the United States, of which 329 were in Louisiana.[26] We examined the Louisiana outbreak because of the availability of hospitalization data. We excerpted case numbers and health care utilization from an article by Armineh Zohrabian and colleagues,[26] which reported mortality and hospitalization incidence reflecting the authors' extrapolation of available discharge data to all reported cases with central nervous system illnesses. In our study we extrapolated data on emergency department visits by applying the ratio of patients incurring emergency service charges to the total number of reported hospitalizations.

RED RIVER FLOODING IN NORTH DAKOTA, 2009 Climate change is projected to alter precipitation patterns, increase the frequency and intensity of major storm events, and increase the risk of floods throughout the United States—particularly in the Midwest and Northeast.[1] River flooding damages buildings and critical community infrastructure. It also causes drownings and other deaths, injuries, trauma, and stress.[1]

We obtained reported data on emergency department visits and mortality collected from March 23, 2009, to May 21, 2009, by state epidemiologists following the Red River flood in North Dakota (Lindsey VanderBusch, epidemiologist, North Dakota Department of Health, Division of Disease Control, personal communication, September 24, 2010). The flooding resulted from severe storms and near-record snow accumulation and rapid melting. Reported costs of infrastructure damage exceeded $68 million.[27]

SOUTHERN CALIFORNIA WILDFIRES, 2003 California is projected to experience climate changes that will result in a median increase in large fires of 21 percent between 2005 and 2034, and an increase of 84 percent between 2070 and 2099.[28] The 2003 fires in Southern California covered 736,597 acres and destroyed 3,631 structures, and the cost of responding to the fires was more than $3 billion. We chose to examine this event because of its magnitude and the availability of data on the health effects of increased smoke.[29]

Mortality data included reported deaths directly caused by the fire or by subsequent mudslides.[29] We inferred the number of deaths associated with smoke inhalation based on a ratio derived from the 2003 Healthcare Cost and Utilization Project[30] that we applied to hospitalization counts. Smoke-related morbidity was excerpted from a study by Ralph Delfino and colleagues[31] that determined excess hospital admissions in the affected counties for respiratory and cardiovascular problems. We included as admissions attributable to the wildfires those with a diagnosis of asthma or pneumonia because a significant association was observed between those conditions and the fires.

HEALTH COSTS Although cost estimates for some climate-related events are available, the use of varying health valuation methods makes it difficult to compare or aggregate costs. We therefore implemented a consistent calculation across all six case studies based on standard measures of health effects and costs.

We based mortality costs on the "value of a statistical life" approach, as recommended for economic research by the Environmental Protection Agency. We used a value of $7.9 million in 2008 dollars, which is the central value from a range of studies.[32] We calculated morbidity costs using an incidence-based "cost of illness" approach that included total medical costs and the value of lost work productivity. This approach is generally considered to yield a conservative estimate of the true cost of disease.[9,15,33] Health costs are reported in 2008 dollars, using the Consumer Price Index[34] to adjust past health costs.

We used data from the Healthcare Cost and

Utilization Project[30] to derive average length-of-stay and medical costs for hospitalizations. We used the Medical Expenditure Panel Survey's[35] average cost per emergency department visit, annual out-of-pocket expenses for hospitalized patients, and outpatient expenses by diagnostic condition category. We estimated lost work productivity from hospital stays based on the usual median weekly earnings of full-time employees as reported by the Bureau of Labor Statistics.[34]

We used the Healthcare Cost and Utilization Project web tool[36] to convert reported charges to costs. The tool uses cost-to-charge ratios based on national and state hospital accounting reports. When the Healthcare Cost and Utilization Project did not perform the conversion, we applied a constant cost-to-charge ratio of 0.65.[37] We divided weekly earnings by five to arrive at a daily wage, which we multiplied by the average length-of-stay for hospital admissions for each particular illness, according to primary diagnosis. More details about our calculation methods are available in the online Appendix.[38]

In a health cost study such as this one, there are multiple data sources and assumptions on which it is possible to base an analysis. Variability is introduced depending on which illnesses are considered, which direct costs are included, and how costs are inferred. Therefore, where the literature presented a range of data options, we conducted sensitivity analyses that included estimates of variability. Details on the sensitivity analyses for the case studies can be found in the online Appendix,[38] and results from the sensitivity analyses are discussed below.

LIMITATIONS The precision and accuracy of our cost estimates are limited by biases and assumptions in the underlying epidemiological studies we relied on, the extrapolations we used to create a more uniform data set, and our health cost valuation methods. Comprehensive surveillance data were missing for some of the morbidity and mortality associated with our case studies.

Most notably, our analysis of hospitalizations and emergency department visits resulting from the 2004 hurricane season in Florida was restricted to those uses of health services associated with carbon monoxide poisoning. Other health effects of hurricanes are documented in the literature, including increased emergency department visits and an overall injury rate of 4.6 percent in adults—equivalent to approximately 340,000 injuries in Florida. However, we were unable to find or calculate a quantitative assessment of hospitalizations and emergency department visits.[22,39,40]

The lack of comprehensive health data could lead to underestimates. But inferring health care use based on the Medical Expenditure Panel Survey disease categories and assigning average costs to climate-related health outcomes could, in some cases, result in overestimates.

Study Results

The six case studies resulted in 1,689 premature deaths, 8,992 hospitalizations, 21,113 emergency department visits, and 734,398 outpatient visits (Exhibit 1). The estimated associated health costs were more than $14 billion (Exhibit 2). Note that this multibillion-dollar price tag is from health costs alone. It does not include the costs of other types of damage, such as damage to buildings and infrastructure.

Because of the high costs associated with the loss of human life, premature mortality makes up approximately 95 percent of the estimated total cost. On a case study–specific basis, the mortality percentage ranged from 78 percent for the floods to 97 percent for the heat wave. However, only a small portion of the people affected died, and they used only a small portion of the health care services in our case studies. We estimated a health care cost of more than $740 million to address illnesses and injuries from the six events we analyzed. This reflects more than 760,000 encounters with the health care system.

The total health costs associated with ozone pollution ($6.5 billion) and the heat wave ($5.4 billion), dominated the analysis (Exhibit 2). The high costs were partially driven by the events' wide geographic scope and their large associated mortality. However, when normalized to the respective regional populations, the cost of the 2009 North Dakota flooding was also large, at $145,495 per 1,000 people—close to the cost of the 2006 California heat wave, which was $148,792 per 1,000 people. In contrast, the cost of the ozone pollution event was $22,705 per 1,000 people.

SENSITIVITY ANALYSES Because of the limitations in the relevant data, we evaluated the variability in health impacts for the ozone air pollution, hurricane, infectious disease outbreak, and wildfire case studies. In aggregate, the sensitivity analyses, accounting for variability in estimated health effects as well as in health valuation methods, resulted in an adjustment to the total cost for the case studies—$14.1 billion (Exhibit 2)—ranging from −$9.6 billion to +$25.6 billion, or a range of $4.5–39.7 billion. The results for the individual case components of the sensitivity analysis, which were analyzed separately, are presented below.

▸ OZONE AIR POLLUTION: Given the limitations in the article by Hubbell and colleagues,[15] our base-case analysis of the costs of air pollution

EXHIBIT 1

Total Health Impact Assessment, By Case Study Event

Climate-related health stressor	Health endpoint[a]				
	Premature death	Hospitalization	Emergency department visit	Outpatient visit[b]	Estimated number of people exposed[c]
Ozone air pollution	795	4,150	485[d]	365,468	287,803,914
Heat wave	655	1,620	16,166	152,095	35,979,208
Hurricane	144	2,197	2,633	160,387	17,375,259
Infectious disease outbreak	24	204	135	5,767	4,466,068
River flooding	2	43	263	3,076	139,918
Wildfires	69	778	1,431	47,605	20,078,194
Total	1,689	8,992	21,113	734,398	—[e]

SOURCE Authors' analysis of data sources listed in the online Appendix (see Note 38 in text). [a]Number of incidents reported or extrapolated from data in case studies. [b]Includes outpatient visits, home health visits, and incidents when medicine was prescribed. [c]Census Bureau population in case study event area. [d]Related to asthma only. [e]Exposed population is not totaled because it is specific to one type of event.

included only asthma-related emergency department visits rather than those visits related to all respiratory illnesses. Inferring the number of all respiratory-related emergency department visits from the hospitalization data that Hubbell and colleagues reported resulted in a substantial increase—8,459 visits altogether, instead of 485 visits for asthma alone. The cost would be $5.6 million—eighteen times greater than the cost of the visits for asthma.

When these inferred emergency department visits were included, the total morbidity costs associated with high levels of ozone was approximately $259 million, or 2.1 percent higher than in the base-case scenario.

The base case used the then-current ozone standard of eighty parts per billion from Hubbell and colleagues.[15] However, the Environmental Protection Agency has since proposed to reduce the health-based standard to sixty parts per billion.[41] A sensitivity analysis using sixty parts per billion resulted in a mortality rate of 0.0056 per 1,000 people and associated costs of $44,000 per 1,000 people. These numbers are twice as high as those calculated using the base case.

Applying these rates to the total population estimated to live in a county where the air quality would exceed the lower threshold,[41] we estimated a potential cost associated with premature mortality from current levels of ozone pollution

EXHIBIT 2

Total Health Impact Cost Assessment, By Case Study Event

Climate-related health stressor	Health endpoint				Total health cost ($ thousands)	Normalized cost per 1,000 people ($)[b]
	Premature death ($ thousands)	Hospitalization ($ thousands)	Emergency department visit ($ thousands)	Outpatient visit ($ thousands)[a]		
Ozone air pollution	6,280,500	36,212	314	217,616	6,534,642	22,705
Heat wave	5,174,500	28,435	14,110	136,380	5,353,425	148,792
Hurricane	1,137,600	18,321	4,365	232,547	1,392,833	80,162
Infectious disease outbreak	189,600	12,935	104	4,808	207,447	46,449
River flooding	15,800	839	232	3,486	20,357	145,495
Wildfires	545,100	9,952	1,050	22,538	578,640	28,819
Total	13,343,100	106,693	20,175	617,376	14,087,344	—[c]

SOURCE Authors' analysis. **NOTE** All dollar amounts are thousands of 2008 US dollars except for normalized costs, which are 2008 US dollars. [a]Includes costs of outpatient visits, home health visits, and other incidents when medicine was prescribed. [b]Census Bureau population in case study event area. [c]Exposed population is not totaled because it is specific to one type of event.

at $8.046 billion—an increase of 28.1 percent compared to the base case.

▶ HURRICANES AND MENTAL HEALTH: Broader health care utilization—such as increases in primary care and doctor visits not related to mental health but associated with anxiety disorders, including post-traumatic stress disorder—were included in a study by Paul Greenberg and colleagues[42] but were not used in our base-case analysis of hurricanes' health costs. Including the additional costs increased the cost of hurricane-related post-traumatic stress disorder to $312 million. This exceeded the $255 million in costs in the base-case analysis, which included only hospitalizations, emergency department visits, and associated outpatient health care use. Including the additional costs resulted in a total health cost estimate for this event of $1.5 billion—an increase of 4.1 percent over the base-case scenario.

▶ INFECTIOUS DISEASE: Our base-case scenario for infectious disease excluded emergency department visits that did not result in hospitalization. To include a more comprehensive assessment of such visits, we applied an emergency department utilization rate—based on the Medical Expenditure Panel Survey condition category of infectious diseases—to the hospitalization rate reported by Zohrabian and colleagues.[26] This estimate more than doubled the number of emergency department visits reported in the original article,[26] giving a total of 378 visits. Their cost was estimated at $290,000, increasing the total health cost to $210 million—an increase of 1.2 percent over our base-case estimate.

▶ WILDFIRE: Adding the 95 percent confidence interval from the literature to the average estimates of the effect of wildfire smoke on respiratory health resulted in asthma and pneumonia hospitalization incidences of 314 (95% confidence interval: 49.5, 571.7) and 464 (95% confidence interval: 55.3, 865.9), respectively.[31] The total estimated cost of these hospitalizations was $10 million, and the upper and lower bound 95 percent confidence interval cost estimates were $1.3 million and $18.4 million.

HEALTH COST VALUATION METHODS Using established ratios to extrapolate our baseline cost-of-illness analysis to incorporate broader costs that are better captured using a "willingness to pay" approach, we estimated health costs in the range of $14.4–15.5 billion, or an increase of 2.9–10.7 percent, compared to our baseline. Using the range of published "value of a statistical life" estimates ($0.9–21.1 million) and our base-case estimate of mortality incidence, we estimated mortality costs of $1.5–35.6 billion, equal to 11–270 percent of the base-case analysis, respectively.

Estimates of the health-associated costs of climate change have been largely absent from public policy discussions.

Discussion

QUANTIFYING THE HEALTH COSTS OF CLIMATE CHANGE For policy makers concerned about climate change, the consistent valuation of its consequences is an important problem. Estimates of the health-associated costs of climate change have been largely absent from both the scientific literature and public policy discussions. This article represents a first attempt to synthesize health data from the literature on events related to climate change and to develop a uniform method of quantifying their health costs. These health costs alone—more than $14 billion across the six case studies—combined with the current and projected frequencies of these events may assist policy makers as they consider the potential benefits of policies to prepare Americans and their communities for the health effects of climate change.

The case studies included in our analysis varied in duration and geographic scale, which made it difficult to extrapolate their costs for the time period we examined and for the future. For example, the infectious disease case study reflected a statewide tally of cases for an entire year, while the wildfire case study represented a one-month period in Southern California. Surveillance data relevant to health were available to track the annual number of cases of West Nile virus in each state.[43] In contrast, the Hazards and Vulnerability Research Institute tracked wildfires according to damage assessments per county.[44]

Additional research is needed to evaluate the degree to which other big wildfires—eighty-five occurred nationwide between 2000 and 2009—may have health costs of a magnitude comparable to those of our case study. It was beyond the scope of this study to quantify annualized

Our analysis illustrates the economic health burden of climate-related hazards.

costs for these events over the past decade or to extrapolate future costs, although this study could provide a basis for such estimates.

Future projections suggest a potentially large health and financial burden associated with climate-related events such as those evaluated here. For example, heat waves occurred on average approximately three times per year in California during the past decade. A heat wave the length of the period evaluated for the 2006 California case study has occurred less than once a century. One study simulating extreme heat events under climate change scenarios suggests that the extreme temperatures of the 2006 heat wave could become an annual event by the late twenty-first century.[45]

We examined other projections for increased frequency of events, including a 58–128 percent increase in the annual number of large wildfires in California by 2085 and a 10–25 percent increase in summer ground-level ozone concentrations in the northeastern United States by 2090 when compared to the 1990s, under higher emissions scenarios.[13,28]

Some portion of the health costs of these events could be avoided through adaptation policies. These policies would help human, natural, or economic systems adjust in response to actual or expected climate change effects to limit the potential damage or harm. For example, expanded programs for surveillance and control of insect vectors could help reduce the number of West Nile virus cases. Municipal and workplace warning systems for heat waves are effective in reducing heat-related illness and death.[46] Reductions in ozone precursors reduce illness and death related to air pollution, as well as associated costs. Another study—of a sample of grants to mitigate hazard losses[47]—has demonstrated that the benefits of reducing climate-related hazards are considerable and outweigh the costs by a factor of 5.0:1 for flooding and 3.9:1 for wind.

The projection of morbidity and mortality into the future, including the consideration of adaptive capacity to reduce health costs, is relevant to the policy discussion. However, it is outside the scope of this article.

ADDITIONAL COSTS The calculations in this study were based on the availability of data on climate-related health stressors and available health valuation tools. The case studies represent a subset of climate-related morbidity and mortality and associated costs. Other climate-related health concerns include waterborne illnesses, such as cryptosporidiosis;[48] plant pollen allergies exacerbated by rising carbon dioxide concentrations;[49] increased rates of foodborne illnesses; and the long-term health effects associated with population displacement after storms.[1]

Climate-related health stressor events also have the potential to cause chronic disease. However, we did not include chronic health effects in this study because of data limitations and the incomplete scientific understanding of this relationship.

Furthermore, we did not include lost leisure time, days when activity is restricted, lost school days for children, and lost work and leisure time for those who instead must visit or care for patients. Nor did we include other social costs that cannot be easily monetized, such as the increased health and financial inequality that is predicted because climate change will disproportionately affect low-income communities; and the pain and suffering caused by extreme events.[50] These are important areas for future cost research on the health effects of climate change, and their omission here suggests that our analysis underestimates the future health costs that could result from climate change.

The costs estimated in this article were related to selected health outcomes and events. For comparison, the costs associated with asthma among US children have recently been estimated at $2.2 billion annually, whereas the total costs of key environmental diseases in children have been estimated at $76.6 billion.[51]

We did not examine the potential health benefits of climate change. However, at least one study suggests that the US population is fully acclimatized to cold temperatures but not to heat. This indicates that decreases in cold weather are not likely to result in parallel decreases in deaths related to the cold.[52]

Previous researchers have not used case studies to evaluate the US health costs of specific events related to climate change. However, two of the studies we relied on included some evaluation of costs.[15,26] Despite some differences in methodology, our average morbidity costs per case were fairly consistent with the results in those studies. However, the differences in total

costs between our analysis and those of Zohrabian and colleagues[26] are appreciable, largely because the latter bases mortality costs on the "lost productivity" approach, rather than the "value of a statistical life" approach.

Conclusion

Our analysis illustrates the economic health burden of climate-related hazards and the potential implications for health and costs if global warming continues unchecked and communities are not prepared for its effects. A better understanding of the range of economic impacts of climate change on health risks could help prioritize preparedness efforts to reduce vulnerability, costs, and losses. In turn, that would improve the US population's ability to withstand the effects of climate change. ∎

NOTES

1 US Global Change Research Program. Global climate change impacts in the United States: a state of knowledge report. New York (NY): Cambridge University Press; 2009.
2 Sheffield PE, Landrigan PJ. Global climate change and children's health: threats and strategies for prevention. Environ Health Perspect. 2010;119(3):291–8.
3 Ebi KL. Adaptation costs for climate change–related cases of diarrhoeal disease, malnutrition, and malaria in 2030. Global Health. 2008;4:9.
4 Ruth M, Coelho D, Karetnikov D. The US economic impacts of climate change and the costs of inaction [Internet]. College Park (MD): University of Maryland, Center for Integrative Environmental Research; 2007 Oct [cited 2011 Sep 30]. Available for download from: http://www.cier.umd.edu/climateadaptation/
5 Center for Health and the Global Environment. Climate change futures: health, ecological, and economic dimensions. Boston (MA): Harvard Medical School; 2005.
6 Tol RSJ. The economic effects of climate change. J Econ Perspect. 2009;23(2):29–51.
7 Bosello F, Roson R, Tol RSJ. Economy-wide estimates of the implications of climate change: human health. Ecol Econ. 2006;58(3):579–91.
8 Markandya A, Chiabai A. Valuing climate change impacts on human health: empirical evidence from the literature. Int J Environ Res Public Health. 2009;6(2):759–86.
9 Sussman FG, Cropper ML, Galbraith H, Godschalk D, Loomis J, Luber G, et al. Effects of global change on human welfare. In: Gamble JL, editor. Analyses of the effects of global change on human health and welfare and human systems. Washington (DC): Environmental Protection Agency; 2008 Sep. (US Climate Change Science Program Synthesis and Assessment Product No. 4.6). p. 111–68.
10 Interagency Working Group on Climate Change and Health. A human health perspective on climate change: a report outlining the research needs on the human health effects of climate change [Internet]. Research Triangle Park (NC): National Institute of Environmental Health Sciences; 2010 Apr [cited 2011 Sep 30]. Available from: http://www.niehs.nih.gov/health/docs/climatereport2010.pdf
11 Agency for Healthcare Research and Quality, Medical Expenditure Panel Survey. Household Component summary tables [Internet]. Rockville (MD): AHRQ; [cited 2011 Oct 12]. Available from: http://www.meps.ahrq.gov/mepsweb/data_stats/quick_tables_search.jsp?component=1&subcomponent=0
12 Bell ML, McDermott A, Zeger SL, Samet JM, Dominici F. Ozone and short-term mortality in 95 US urban communities, 1987–2000. JAMA. 2004;292:2372–8.
13 Jacob DJ, Winner DA Effect of climate change on air quality. Atmos Environ. 2009;43:51–63.
14 Weaver CP, Liang X-Z, Zhu J, Adams PJ, Amar P, Avise J, et al. A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. Bull Am Meteorol Soc. 2009; 90:1843–63.
15 Hubbell BJ, Hallberg A, McCubbin DR, Post E. Health-related benefits of attaining the 8-hr ozone standard. Environ Health Perspect. 2005;113(1):73–82.
16 Meehl GA, Tebaldi C. More intense, more frequent, and longer lasting heat waves in the 21st century. Science. 2004;305:994–7.
17 Kozlowski D, Edwards LM. An analysis and summary of the July 2006 record-breaking heat wave across the state of California [Internet]. Reno (NV): Western Regional Climate Center; 2007 Feb 27 [cited 2011 Sep 30]. (Western Region Technical Attachment No. 07-05). Available from: http://www.wrh.noaa.gov/wrh/07TAs/ta0705.pdf
18 Miller NL, Hayhoe K, Jin J, Auffhammer M. Climate, extreme heat, and electricity demand in California. J Appl Meteorol Clim. 2008;47(6):1834–44.
19 Knowlton K, Rotkin-Ellman M, King G, Margolis HG, Smith D, Solomon G, et al. The 2006 California heat wave: impacts on hospitalizations and emergency department visits. Environ Health Perspect. 2009;117:61–7.
20 Hoshiko S, English P, Smith D, Trent R. A simple method for estimating excess mortality due to heat waves, as applied to the 2006 California heat wave. Int J Public Health. 2010;55(2):133–7.
21 Ragan P, Schulte J, Nelson SJ, Jones KT. Mortality surveillance: 2004 to 2005 Florida hurricane-related deaths. Am J Foren Med Pathol. 2008;29(2):148–53.
22 Acierno R, Ruggiero KJ, Galea S, Resnick HS, Koenen K, Roitzsch J, et al. Psychological sequelae resulting from the 2004 Florida hurricanes: implications for postdisaster intervention. Am J Pub Health. 2007;97(Suppl 1):S103–8.
23 Sniffen JC, Copper TW, Johnson D, Blackmore C, Patel P, Hardar-Morano L, et al. Carbon monoxide poisoning from hurricane-associated use of portable generators—

Florida, 2004. MMWR. 2005; 54(28):697–700.

24 Gage KL, Burkot TR, Eisen RJ, Hayes EB. Climate and vectorborne diseases. Am J Prev Med. 2008; 35(5):436–50.

25 Soverow JE, Wellenius GA, Fosman DN, Mittleman MA. Infectious disease in a warming world: how weather influenced West Nile virus in the United States (2001–2005). Environ Health Perspect. 2009;117:1049–52.

26 Zohrabian A, Meltzer MI, Ratard R, Billah K, Molinari N, Roy K, et al. West Nile virus economic impact, Louisiana, 2002. Emerg Infect Diseases. 2004;10(10):1736–44.

27 Richards S. North Dakota statewide flooding expenses top $68 million. Forum of Fargo-Moorhead. 2009 Jun 22.

28 Westerling AL, Bryant BP, Preisler HK, Hidalgo HG, Das T, Shrestha SR. Climate change, growth, and California wildfire. Sacramento (CA): California Climate Change Center; 2009 Mar. (Draft Paper No. CEC-500-2009-046-D).

29 Governor's Office of Emergency Services. 2003 Southern California fires after action report. Mather (CA): The Office; 2004.

30 Agency for Healthcare Research and Quality. Healthcare Cost and Utilization Project [home page on the Internet]. Rockville (MD): AHRQ; [cited 2011 Sep 30]. Available from: http://www.ahrq.gov/data/hcup/

31 Delfino RJ, Brummel S, Wu J, Stern H, Ostro B, Lispett M, et al. The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. Occup Environ Med. 2009; 66(3):189–97.

32 Environmental Protection Agency, National Center for Environmental Economics. Valuing mortality risk reductions for environmental policy. Presentation to: EPA's Science Advisory Board Environmental Economics Advisory Committee; 2010 Dec 10. (Draft White Paper).

33 Drummond MF, Sculper MJ, Torrance GW, O'Brien BJ, Stoddart GL. Methods for the economic evaluation of health care programmes. 3rd ed. Oxford: Oxford University Press; 2005.

34 Department of Labor, Bureau of Labor Statistics. Consumer Price Index [Internet]. Washington (DC): BLS; 2010 [cited 2011 Sep 30]. Available from: http://www.bls.gov/cpi/data.htm

35 Agency for Healthcare Research and Quality, Medical Expenditure Panel Survey. MEPS HC-118D: 2008 hospital inpatient stays [Internet]. Rockville (MD): AHRQ; 2010 Sep [cited 2011 Oct 12]. Available from: http://meps.ahrq.gov/mepsweb/data_stats/download_data/pufs/h118d/h118ddoc.shtml

36 Agency for Healthcare Research and Quality. Databases and related tools from the Healthcare Cost and Utilization Project (HCUP) [Internet]. Rockville (MD): AHRQ; [revised 2011 Mar; cited 2011 Oct 12]. (Fact Sheet). Available from: http://www.ahrq.gov/data/hcup/datahcup.pdf

37 Nigrovic LE, Chiang VW. Cost analysis of enteroviral polymerase chain reaction in infants with fever and cerebrospinal fluid pleocytosis. Arch Pediatr Adoloesc Med. 2000; 154(8):817–21.

38 To access the Appendix, click on the Appendix link in the box to the right of the article online.

39 Bailey MA, Glover R, Huang Y. Epidemiologic assessment of the impact of four hurricanes—Florida, 2004. MMWR. 2005;54(28):693–7.

40 Platz E, Cooper HP, Silvestri S, Siebert CF. The impact of a series of hurricanes on the visits to two central Florida emergency departments. J Emerg Med. 2007;33(1):39–46.

41 Environmental Protection Agency, Office of Air Quality Planning and Standards. Review of the national ambient air quality standards for ozone: policy assessment of scientific and technical information. Washington (DC): EPA; 2007. Appendix 6-A, p. 6A-1.

42 Greenberg PE, Sisitsky T, Kessler RC, Finkelstein SN, Berndt ER, Davidson JR, et al. The economic burden of anxiety disorders in the 1990s. J Clin Psychiatry. 1999;60(7):427–35.

43 Centers for Disease Control and Prevention. West Nile virus: statistics, surveillance, and control archive [Internet]. Atlanta (GA): CDC; [last modified 2011 Jun 22; cited 2011 Oct 3]. Available from: http://www.cdc.gov/ncidod/dvbid/westnile/surv&control_archive.htm

44 Hazards and Vulnerability Research Institute. SHELDUS: Spatial Hazard Events and Losses Database for the United States [home page on the Internet]. Columbia (SC): University of South Carolina; [last updated 2011 May 18; cited 2011 Oct 3]. Available from: http://www.sheldus.org

45 Mastrandrea MD, Tebaldi C, Snyder CP, Schneider SH. Current and future impacts of extreme events in California. Sacramento (CA): California Climate Change Center; 2009. (Paper No. CEC-500-2009-026-F).

46 Ebi KL, Teisberg TJ, Kalkstein LS, Robinson L, Weiher RF. Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–98. Bull Am Meteorol Soc. 2004;85(8):1067–72.

47 Rose A, Porter K, Dash N, Bouabid J, Huyck C, Whitehead JC, et al. Benefit-cost analysis of FEMA hazard mitigation grants. Nat Hazards Rev. 2007;8(4):97–111.

48 Thomas KM, Charron DF, Waltner-Toews D, Schuster C, Maarouf AR, Holt JD. A role of high impact weather events in waterborne disease outbreaks in Canada, 1975–2001. Intl J Environ Health Res. 2006;16(3):167–80.

49 Ziska LH, Epstein PR, Rogers CA. Climate change, aerobiology, and public health in the Northeast United States. Mitig Adapt Strat Global Change. 2008;13:607–13.

50 Morello-Frosch R, Pastor M, Sadd J, Shonkoff SB. The climate gap: inequalities in how climate change hurts Americans and how to close the gap [Internet]. Los Angeles (CA): University of Southern California; 2009 [cited 2011 Oct 12]. Available from: http://dornsife.usc.edu/pere/documents/The_Climate_Gap_Full_Report_FINAL.pdf

51 Trasande L, Liu Y. Reducing the staggering costs of environmental disease in children, estimated at $76.6 billion in 2008. Health Aff (Millwood). 2011;30(5):863–70.

52 Medina-Ramon M, Schwartz J. Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. Occup Environ Med. 2007;64(12):827–33.

ABOUT THE AUTHORS: KIM KNOWLTON, MIRIAM ROTKIN-ELLMAN, LINDA GEBALLE, WENDY MAX & GINA M. SOLOMON

Kim Knowlton is senior scientist with the Health and Environment Program at the Natural Resources Defense Council.

In this month's *Health Affairs*, Kim Knowlton and coauthors report on their estimate of the health care costs associated with six climate change–related events sustained in the United States between 2000 and 2009. The authors estimated that the health care costs exceeded $14 billion, of which 95 percent was attributed to the value of lives lost prematurely.

In all of the attention to the impact of climate change, establishing the cost in terms of health care has been largely missing, observes Knowlton, senior scientist with the Health and Environment Program at the Natural Resources Defense Council. "In no way are we trying to downplay the human pain and suffering, but economics often drives policy and, yes, even health policy," she says. The unique contribution of the paper by her and her colleagues is that it offers a method of estimating those costs, she adds.

In addition to her position at the Natural Resources Defense Council, Knowlton is assistant clinical professor of environmental health sciences at the Mailman School of Public Health at Columbia University and chair of the Global Climate Change and Health Topic Committee in the Environment Section of the American Public Health Association. Her research includes heat- and ozone-related mortality and illness, and climate change's effects on aeroallergens. Knowlton holds a master's degree in environmental and occupational health sciences from Hunter College and received her doctorate in public health from Columbia University.

Miriam Rotkin-Ellman is a staff scientist with the Health and Environment Program, Natural Resources Defense Council.

Miriam Rotkin-Ellman is a staff scientist with the Natural Resources Defense Council's Health and Environment Program. She is involved with researching the links between global warming and health, reducing air pollution from industrial sources, and protecting communities from pesticides and other toxins. Her research includes analysis of morbidity associated with the 2006 California heat wave and community vulnerability to climate change–related health threats. Rotkin-Ellman earned her master of public health degree in environmental health sciences from the University of California, Berkeley.

Linda Geballe is a candidate for a juris doctor degree at the University of California, Berkeley.

Linda Geballe is a juris doctorate candidate at the University of California, Berkeley, School of Law. She has a master's degree in environmental management with a concentration in environmental economics from Yale University.

Wendy Max is a professor of health economics at the University of California, San Francisco.

Wendy Max is a professor of health economics and codirector of the Institute for Health and Aging at the University of California, San Francisco. Her research has focused on modeling the economic impact of illness and disease. She earned her doctorate in economics from the University of Colorado, Boulder.

Gina M. Solomon is an associate clinical professor of medicine at the University of California, San Francisco.

Gina Solomon is a senior scientist at the Natural Resources Defense Council and an associate clinical professor of medicine at the University of California, San Francisco, where she is also the director of the Occupational and Environmental Medicine Residency Program. Her work has included more than forty scientific papers, book chapters, and reports on environmental and occupational health issues.

She earned her master of public health degree from the Harvard School of Public Health and her medical degree from Yale. She did postgraduate training in internal medicine, public health, and occupational and environmental medicine at Harvard.