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Healthy people 2100: modeling population health impacts of climate change

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Abstract Quantitatively estimating the potential health impacts of climate change is facilitated by multi-determinant models that integrate micro- to macro-level exposures and processes that influence disease occurrence, including the public health responses, in order to identify regions and population groups that may be more vulnerable. Although progress has been made in constructing systems-based models, considerable work is required to address key issues of quantification of the climate-health associations and the factors that affect those associations; specification of model(s) appropriate to incorporate climate change, adaptation, and mitigation policies; incorporation of thresholds; incorporation of pathways of public health development; and quantification of uncertainties.

1 Introduction

Climate is one of multiple factors that influence the incidence and range of many health determinants and outcomes. The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report concluded that climate change is projected to increase threats to human health, particularly in lower-income populations, predominantly within tropical/subtropical countries (McMichael et al. 2001). Three broad categories of health impacts are associated with climatic conditions: impacts directly related to weather and climate variability; impacts resulting from environmental changes that occur in response to climate variability and change; and impacts resulting from consequences of climate-induced economic dislocation and environmental decline. The first two categories of climate-sensitive health determinants and outcomes include (1) changes in the frequency and intensity of thermal extremes and extreme weather events (i.e. floods and droughts) that directly affect population health, and (2) indirect impacts that occur through changes in the geographic range and intensity of

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transmission of infectious diseases and food- and waterborne diseases, and changes in the prevalence of adverse health outcomes associated with air pollutants and aeroallergens.

Ecosystem changes can facilitate the emergence and re-emergence of disease, even under current climatic conditions (National Research Council 2001). Climate change can further alter or disrupt natural systems, making it possible for diseases to spread or emerge in areas where they had been limited or had not existed, or for diseases to disappear by making areas less hospitable to the vector or the pathogen. The cause-and-effect chain from climate change to changing patterns of health determinants and outcomes is often extremely complex and includes factors such as wealth, distribution of income, status of the public health infrastructure, provision of medical care, and access to adequate nutrition, safe water, and sanitation. Therefore, the severity of future impacts will be determined by changes in climate as well as by concurrent changes in nonclimatic factors and by the adaptation measures implemented to reduce negative impacts.

Health models that can explore the range of potential impacts of a changing climate in the context of other drivers of population health are critical to better understand where, when, in what population group(s), and with what intensity climate variability and change could have negative health consequences. Identification of vulnerable populations and locations can be used by risk managers to facilitate the development and implementation of effective and efficient adaptation policies and measures to reduce projected negative impacts, and can be used by policymakers to identify mitigation targets and the possible health consequences of approaches to meet those targets. Policymakers also can use model results to “climate-proof” decisions, to better ensure that the interventions implemented will be resilient to changing weather patterns and trends.

Throughout this paper the term ‘model’ refers to parameterizations of exposure-response relationships, including key drivers of the outcome, to project how the burdens of climate-sensitive health determinants and outcomes could change under different assumptions of changes in climate, socioeconomic conditions, technology development, policy options, and other factors. Population health refers to the health of a population, measured by health status indicators; it is influenced by physical, biological, social, and economic factors in the environment, by personal health behavior, health care services, etc. (Last 2001). Risk is a term in everyday use that has different meanings in different contexts. Risk will be used to describe the combination of likelihood and consequences associated with an exposure or event.

Health researchers are typically reluctant to develop models because of the limited specification and quantification of relevant micro- to macro-level exposures and processes that influence disease occurrence, and because variables unique to a particular population or location could interact with these factors to affect model accuracy (Ebi and Gamble 2005). However, models facilitate understanding of what is known and what still needs to be understood of how systems actually function. In the context of climate change, models are critical for planning appropriate adaptation options to reduce the likelihood that climate-related changes will increase the burden of health determinants and outcomes. Continuing business as usual, ignoring the possible threats of climate change, could result in significant morbidity and mortality that could have been prevented with appropriate planning. Health is far behind other sectors in model development.

This special issue highlights some of the approaches that have been taken in model development. Campbell-Lendrum et al. use a comparative risk assessment approach to link exposure-response relationships for several climate-sensitive health determinants and outcomes with different climate scenarios to estimate future burdens, and to compare these with the burdens of air pollution-related health outcomes. Tol incorporates data on the current and projected future burden of malaria into an existing integrated assessment model to address the question of whether climate change-attributed malaria could have negative consequences for economic growth. Pitcher et al. report on the first phase of development of a model to predict life expectancy under different climate and socioeconomic scenarios. Kara et al. incorporate air pollution exposure-response relationships into an integrated assessment model to explore the health-related economic benefits of regulations.

This paper first discusses some issues relevant to model development, including quantification of the climate-health associations and the factors that affect those associations; specification of model(s) appropriate to incorporate climate change, adaptation, and mitigation policies, including consideration of scale issues; incorporation of thresholds; accounting for pathways of public health development; incorporation of adaptation, and discussion of uncertainties. The paper then finishes with ways forward in model development and concluding remarks.

2 Model specification and development

2.1 Quantification of exposure-response relationships

The increasing need to estimate the geographic range and magnitude of the health impacts of climate change has encouraged the quantification of associations between weather variables and health outcomes both to explain current relationships and to identify and project regions and population subgroups that may be more vulnerable to climate variability and change. This expanding literature base presents an opportunity for more, and more detailed, models of climate/health relationships.

A number of factors make quantification of weather-health exposure-response relationships challenging. Although public health has considerable experience dealing with exposures to hazardous agents where a defined exposure causes a specific adverse health outcome in identifiable exposed populations, weather has only recently been considered a potentially hazardous exposure that needs to be evaluated in its own right (Bernard and Ebi 2001). Isolating the role of weather in disease patterns is difficult because most climate-sensitive health determinants and outcomes have many causal factors, with the causal chains neither linear nor direct, sometimes with a lag between the exposure and response, and with a number of factors influencing whether an adverse health outcome occurs. Although the entire population is exposed to weather, climate variability, and climate change, the risk associated with a particular exposure varies within the population due to intrinsic and extrinsic vulnerabilities. For example, poverty, under-nutrition, water storage practices, substandard housing, lack of access to safe water and sanitation, certain land use practices, and other factors can combine with climatic conditions to favor vector-breeding and promote the spread of some infectious diseases. Further, exposures are changing over time with changing weather patterns.

Most exposure-response relationships have been based on exposure defined in terms of mean weather variables. However, projections of increased climate variability (Folland et al. 2001) suggest that health models need to extrapolate beyond the current exposure-response relationships to weather conditions and extreme events to which populations are not currently accustomed (Beniston 2004; Meehl and Tebaldi 2004). There is extensive literature discussing approaches to low-dose extrapolation to predict possible health impacts of exposures to occupational and environmental hazards. Whereas low dose extrapolation is bounded at no exposure and no response, increasing climate variability suggests the need for high-dose extrapolation. Different statistical approaches may be needed to estimate the shape of exposure-response relationships outside the upper range of current exposure data. Such approaches will further understanding of the limits of current models, as well as spatial and temporal analogs.

Model development requires more than quantification of exposure-response relationships. Assuming the model will be used to project possible future health impacts, the exposure-response relationship needs to be quantified in ways that allow linkage with, at a minimum, climate and socioeconomic models. The critical factors associated with the outcome need to be understood sufficiently for incorporation into the model; this includes considering the extent to which other factors (or alternative explanations) could explain an association between weather/climate and a health outcome, and whether the factors to be included in the model are consistent with what is known about the health outcome. In many cases, model development will be constrained by our incomplete understanding of disease mechanisms. For many climate-sensitive health outcomes, there is limited knowledge of the relationships among weather, other drivers of the health outcome, and the health outcome. For example, Chan et al. (1999) developed an integrated assessment framework for climate change and infectious diseases, and conducted a literature review to determine data availability. Of the 16 linkages in this simple model, data were available for only three, primarily because the other linkages were multi-disciplinary questions that had received insufficient research attention.

The issues of which factors need to be understood and in what detail are sources of the controversy for modeling malaria. Using biological and statistical approaches, several groups have modeled the current distribution of malaria, with the greatest focus on *Plasmodium falciparum* malaria (e.g. Martens et al. 1999, Rogers and Randolph 2000, Tanser et al. 2003, World Health Organization 2002). One limitation of current malaria models is that they rarely include key drivers besides climatic factors, such as land use change, drug resistance, and economic and technological development, and no model includes all these factors. Appropriate consideration of these factors and how they interact is important when trying to project plausible possible future changes in the geographic range and incidence of malaria. Projecting likely locations where malaria may retract or spread with changing weather conditions within the next few decades (in order to decide where surveillance programs may best be placed, for example) may require a different model than projecting likely burdens of endemic and epidemic malaria under specific climatic changes.

2.2 Issues with model specification

Models are attempts to reduce complex situations to key parameters that can be used to describe the current range and incidence of health determinants and outcomes, and to project how health burdens might change when one or more of the parameters is changed. Some of the challenges in specifying climate/health models include considering scale issues, aggregating different outcomes with different exposure-response relationships (including appropriate approaches for extrapolation of relationships from one population to another), and incorporating increasing climate variability.

It is a challenge to effectively incorporate interactions across scales, including geographic and temporal, into models. Population health is affected by a number of modifying and/or interacting factors with feedback mechanisms that operate at different scales, from community (e.g. whether or not there is an effective early warning system for heat waves) to individual levels (e.g. whether or not an individual spends adequate time in cooled environments during a heat wave) (Ebi and Gamble 2005). Because climate change will be experienced at local scales, local actions, such as land use changes that contribute to heating or cooling of the environment (e.g. urban heat islands), can amplify or ameliorate larger scale climate forces. In addition, although by definition measurements of the impact of climate change entails identifying effects relative to "exposures" above a baseline, the baseline itself has been changing. Further, the baseline burden of climate-sensitive health determinants and outcomes is changing due to factors unrelated to climate, such as the increasing number of older adults at risk for heat-related morbidity and mortality.

Another concern in model development is that few studies of the associations between weather and climate-sensitive health outcomes have been conducted across a wide range of geographic regions (Campbell-Lendrum et al. 2003). For example, the Global Burden of Disease study analyzed the potential impact of climate change on diarrheal disease; exposure-response relationships were available only from studies in Peru and Fiji (McMichael et al. 2004; Checkley et al. 2000; Singh et al. 2001). These locations include only a limited range of climate and climate variation; different relationships may exist at higher or lower temperatures. Regional and global models based on the extrapolation of relationships from a limited number of areas raises questions of the validity and applicability of model projections for other regions.

Until recently, most models developed for climate-sensitive health determinants and outcomes provided global or large regional estimates of changes in risk associated with climate change. Increased resolution and downscaling of climate models have resulted in the development of finer scale models that can be linked with health exposure-response relationships to project increases in disease risk at scales appropriate for decision-makers. For example, models of the potential air pollution-related health effects of climate change for several regions in the United States were recently published (Knowlton et al. 2004; Patz et al. 2004). These models linked city or region-specific ozone exposure-response relationships with changes in ozone concentrations projected under the Special Report on Emission Scenarios (SRES) A2 scenario. All models projected increases in ozone-related hospital admissions and/or mortality by mid-century.

In the most comprehensive analysis, McMichael et al. (2004) used a comparative risk assessment approach as part of the Global Burden of Disease study to project the total health burden attributed to climate change between 2000 and 2030 and how much of this burden could be avoided by stabilizing greenhouse gas emissions. Health outcomes were analyzed by region to better understand where current and projected future burdens are highest and the outcomes that contribute to the largest share of the total burden. The Global Burden of Disease study assessed more than two-dozen other risk factors, allowing the comparison of the climate-related health burden with the burden associated with other important risk factors for population health, such as outdoor air pollution and cigarette smoking. Limitations of this approach include the limited number of quantitative models to estimate the likely impacts of climate change on health, the limited geographic range of many of the models, the fact that not all of the models directly estimate the incidence or prevalence of the outcomes, the limited number of demographic, socioeconomic, and climatic scenarios analyzed, and the crude and indirect adjustments for the effects of other factors, such as poverty, that can influence vulnerability.

The health outcomes included in the analysis were chosen based on sensitivity to climate variation, predicted future importance, and availability of quantitative global models (or feasibility of constructing them) (McMichael et al. 2004). Specific health outcomes included were episodes of diarrheal disease, cases of *Plasmodium falciparum* malaria, fatal unintentional injuries in coastal floods and inland floods/landslides, and non-availability of recommended daily calorie intake (as an indicator for the prevalence of malnutrition). In the year 2000, climate change was estimated to have caused the loss of over 150,000 lives (0.3% of worldwide deaths) and 5,500,000 Disability Adjusted Life Years Lost (DALYs) (0.4%), with malnutrition accounting for approximately 50% of deaths and DALYs (Ezzati et al. 2002; McMichael et al. 2004). These estimates relate to a period when exposures to climate change were very limited, suggesting that future studies may find larger health burdens due to climate change.

The projected relative risks attributable to climate change in 2030 vary by health outcome and region, and are largely negative, with the majority of the projected health burden due to increases in diarrheal disease and malnutrition, primarily in low-income populations already experiencing a large burden of disease (McMichael et al. 2004). Absolute health burdens depend on assumptions of population growth, future baseline disease incidence, and the extent of adaptation. Warmer winter temperatures are projected to result in a small proportional decrease in cardiovascular and respiratory disease mortality attributable to climate extremes in tropical regions, with a slightly larger benefit in temperate regions. The relative risk for diarrhea in 2030 in low-income countries is projected to be between 1.0 and 1.1 under unmitigated emissions, compared with baseline climate. Countries with an annual GDP of $6,000 or more are assumed to have no additional risk of diarrhea. The projected impacts of malnutrition vary from a large increase (relative risk=1.1–1.3) in the World Health Organization (WHO) region SEAR-D (Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Maldives, Myanmar, Nepal) to no change or a small decrease (relative risk=0.99–1.0) in WHO region WPR-B (Cambodia, China, Cook Islands, Fiji, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Micronesia, Mongolia, Nauru, Niue, Palau, Papua New Guinea, Philippines, Republic of Korea, Samoa, Solomon Islands, Tonga, Tuvulu, Vanuatu, Vietnam). Developed countries are assumed to suffer no climate change-related malnutrition impacts. Coastal flooding is projected to result in a large proportional increase in risk under unmitigated emissions; however, this is applied to a very low burden of adverse health outcomes. The projected increase in relative risk of coastal flooding is equally high in high- and low-income countries. Large changes are projected in the risk of *falciparum* malaria in countries at the edge of the current distribution, with relative changes much smaller in areas that are currently highly endemic for malaria.

A single approach or model will be inadequate to address the questions that decision-makers will ask concerning the issues of vulnerability, adaptation, and mitigation. The existence of a diversity of models and scenarios ensures that appropriate tools will be available to address the questions that will arise. Recent developments in synthesizing scientific knowledge of the drivers of climate-sensitive health outcomes into models that aid visualization of the potential impacts of climate variability and change include models that project the potential future health impacts of climate change, for example (Van Lieshout et al. 2004; Campbell-Lendrum et al. 2003); project the implications for economic activity of changes in the intensity and range of diseases (for example, Tol, this volume); and models that describe how population health may evolve (for example, Pitcher et al., this volume).

2.3 Incorporation of thresholds

Thresholds are defined to identify accepted or tolerable levels of health outcomes associated with an exposure. Thresholds can be viewed as the exposure concentration at which the health burden associated with exposure becomes unacceptable. Knowledge of the factors that determine the health burden in a population, and how those factors interact, facilitates the identification of thresholds, and, thus, the assessment of risk. The choice of a threshold is often based on social acceptance of a particular risk (Jones et al. 2004). Identification of thresholds is relatively easy for non-continuous events such as floods and tropical storms. In high-income countries, the population expects that these events will result in no or at most a handful of deaths. Setting thresholds for continuous distributions is more difficult; it requires deciding how much disease is acceptable. A threshold above zero means that it is acceptable that a specified percentage of a population will contract a particular disease and perhaps die. Different populations may accept different thresholds of risk, as in the case of some occupational and environmental exposure limits.

Establishing thresholds for climate-sensitive health outcomes can be approached from the perspective of the exposure or response (Jones et al. 2004). These approaches are not mutually exclusive, but there are situations where one perspective will dominate.

An example of an exposure threshold is the influence of temperature and precipitation on malaria transmission. Climate is a primary determinant of whether the conditions in a particular location are suitable for stable *Plasmodium falciparum* malaria transmission (Craig et al. 1999; MARA/ARMA 1998). Changes in precipitation or temperature may result in conditions during the season of transmission that are conducive to increased or decreased parasite and vector populations, or may lengthen or shorten the period of time that mosquitoes or parasites can survive. Small changes in precipitation or temperature may cause previously inhospitable altitudes or ecosystems to become conducive to transmission by rendering hospitable higher altitudes that were formerly too cold or desert fringes that previously were too dry for mosquito populations to develop. Based on experience, the degree of change in weather variables that has been associated with increased disease transmission can be used to establish an exposure threshold. This threshold can be used to model future malaria risk, assuming limited change in land use, vector control, parasite drug resistance, access to medical care, and other factors.

There are several types of response thresholds. There are exposures that have linear associations with population health outcomes, where any amount of exposure may convey some risk, such as certain foodborne diseases (Kovats et al. 2004). There are exposures that exhibit J-shaped relationships with health outcomes, where either too little or too much exposure is detrimental to health, such as atmospheric concentrations of oxygen. There also are exposures that have threshold relationships with health outcomes, such as the number of organisms (the dose) required to develop a case of diarrheal disease, where low levels of exposure are not associated with increased morbidity and mortality. Thresholds also depend on other factors, such as the presence of malnutrition in the case of some diarrheal diseases (Scrimshaw 2003).

Identifying response thresholds can be complex when exposure-response relationships have a continuous distribution (Yohe and Ebi 2005). For example, ambient temperature is associated with all-cause mortality, with most regions showing a J-shaped pattern. There usually is a narrow range of temperatures at which mortality is lowest, with increasing rates on either side of the minimum. It is not clear from these distributions what should be the point that separates acceptable from unacceptable mortality. Historically, meteorological organizations or national weather services set a temperature above which they declared a heat event (Kalkstein et al. 1996). Because humidity and others factors also determine which weather patterns are associated with increased morbidity and mortality in a community, some heat event early warning systems are based on the association between daily mortality and synoptic air masses; a threshold is set based on the number of daily deaths that can be discernable above the background rate (Kalkstein et al. 1996).

Another example of a threshold is the summer 2003 heatwave in Europe. The temperatures were much higher than the population had experienced in at least 50 years

(Beniston 2004). Prior to the heatwave, only Lisbon, Portugal had implemented a heat health early warning system. Because the system was based on known relationships between mortality and weather patterns that did not include the extremes experienced during the 2003 heatwave, the extent of the resulting mortality would have been difficult to predict (Kalkstein, personal communication, 2004). Models should consider the health consequences of climate variability increasing beyond historic ranges.

Few models address changes in climate variance, the increasing rate of climate change, or surprises that could result from large non-linear changes. By definition, surprises are not known in advance. However, models need to incorporate the possibility of increasing variance and non-linear changes occurring at random points in time, in part to estimate whether such changes could cross thresholds for the geographic range and incidence of climate-sensitive health outcomes.

2.4 Pathways of public health development

Population health and adaptive capacity vary dramatically over time and space, with recent examples of both improvements (e.g. China) and deterioration (e.g. the former Soviet Union) in public health. Approaches to understanding how public health might evolve include developing models that extrapolate current trends into the future and using scenarios to describe possible social, economic, demographic, and ecological dynamics for future health pathways. Health-specific scenarios have not been developed that describe the health transitions that occurred since the mid-nineteenth century and that model pathways for future health transitions. The concept of the health transition incorporates both the demographic transition that describes the change from high fertility and mortality rates in low-income countries to low fertility and mortality rates in higher-income countries, and the epidemiologic transition that describes the changes in morbidity and mortality patterns (from infectious to chronic diseases) as the demographic and socioeconomic structures change within a population (Omran 1998; Martens 2002). Incorporating health transitions into scenarios could lead to more plausible visions of future population health.

Traditionally, three stages have been identified in the health transition: the age of pestilence and famine, the age of receding pandemics, and the age of chronic diseases (Omran 1998). High levels of fertility and low life expectancy are characteristics of the age of pestilence and famine. Infectious diseases are the primary causes of death, food and safe water supplies are inadequate, there is limited access to health care and education, and there is insufficient social and economic capital to develop infrastructure and gain access to technology (such as vaccines). Many low-income countries are in this stage.

The age of receding pandemics is characterized by somewhat lower mortality rates and increased life expectancy, primarily from increased access to safe water and adequate nutrition, leading to a reduction in the prevalence of infectious diseases (Omran 1998). High-income countries entered this stage in the middle of the nineteenth century. Countries with economies in transition are currently in this stage.

The age of chronic diseases is characterized by improvements in the medical care and social determinants that influence health (Martens 2002). Chronic diseases are the dominant causes of death due to continued improvements in social circumstances and economic growth; this is accompanied with further increases in life expectancy. Literary rates are high and fertility rates low.

Although descriptive of historic patterns, health transitions in developing countries are not following these three distinct stages in a predominantly linear sequence because the socio-economic-political conditions that prevailed when developed countries were developing were different than what currently developing countries experience. In fact, many currently developing countries could be described as being simultaneously in an age of pestilence and an age of chronic disease (Martens 2002). Public health infrastructures and medical care communities are struggling to deal with the double burden of infectious and chronic diseases, trying to reduce epidemics at the same time as trying to reduce the health effects of high levels of air pollution and other environmental exposures. Poor health is one factor hampering economic growth (Sachs 2001). In addition, population health and economic growth are increasingly affected by conditions that transcend national borders and political jurisdictions, such as macroeconomic policies associated with international financial institutions, global trade agreements, water shortage, pollution that crosses borders, etc. (Labonte and Spiegel 2003). These global issues could affect the health transition in complex and non-linear ways.

Several visions have been proposed for the next stages in the health transition, including an age of emerging infectious diseases, an age of medical technology, and an age of sustained health (Olsansky and Ault 1986; Olsansky et al. 1998; Martens 2002). An age of emerging infectious diseases could result from the re-emergence of infectious diseases that are currently controlled through public health efforts along with the simultaneous emergence of new infectious diseases. The likely consequences could include increasing rates of infectious diseases in both high- and low-income countries, with falling life expectancies and economic productivity. Travel and trade, microbiological resistance, human behavior, breakdowns in health systems, and increased pressure on the environment would facilitate this health transition (Barrett et al. 1998). A number of worldwide events and trends support this possibility, such as malaria parasites becoming increasing drug resistant, HIV/AIDS lowering life expectancy in several African countries, the mosquito-borne disease West Nile virus crossing the Atlantic, severe acute respiratory syndrome (SARS) quickly moving worldwide via travelers, etc.

An age of medical technology could result from increased economic growth and improvements in technology, offsetting health risks caused by changes in lifestyle and the environment (Martens 2002). An age of sustained health could result from investments in social and medical services leading to a reduction in lifestyle-related health outcomes, with the elimination of most environmentally related infectious diseases. Either of these health transitions could lead to increasing life expectancy, which would have consequences not only for medical care and other services, but also for sectors from water to energy consumption.

Another possible pathway for future population health is a decrease in life expectancy and economic productivity due to an increased burden of lifestyle-related health outcomes in both high- and low-income countries. A number of current trends suggest that this health transition may be underway, including projections for the burden of HIV/AIDS in many low-income countries and the burden of obesity (Mokdad et al. 1999, 2001) and other lifestyle-related health outcomes in most countries. For example, the United Nations Population Division's 2002 Revision projected a more serious and prolonged impact of the HIV/AIDS epidemic in the most affected countries than previous revisions (United Nations Population Division 2002). Under the medium population growth variant, the 2002 Revision projected a lower population in 2050 than did the 2000 Revision: 8.9 billion instead of 9.3 billion. About half of the 0.4 billion difference resulted from an increase in the number of projected deaths, the majority from the higher projected levels of HIV/AIDS and the remainder from a reduction in the number of projected births, mostly due to lower expected future fertility levels. Over the current decade, the number of excess deaths because of AIDS among the 53 most affected countries is estimated at 46 million, with that figure projected to increase to 278 million by 2050.

One issue with modeling possible future pathways based on past health transitions is that some of the key drivers for development, such as access to safe water and sanitation, sufficient agricultural production, or an adequate public health infrastructure, may take more effort to solve in low-income countries than they did for high-income countries because the factors constraining development may not be of the same relative magnitude. Most high-income countries are not constrained by the amount of available water; however, solving the problem of access to safe water in some low-income countries will be more difficult, requiring more and different investment. Further, high-income countries experienced fairly clear transitions; however, this paradigm does not appear to apply to low-income countries, (World Health Organization 2004).

Health models have yet to incorporate mixed trends of increasing and decreasing health burdens. As shown in Pitcher et al. (in this volume), a relatively simple model including literacy, access to simple medical care, and access to safe water and sanitation (along with an indicator for Sub-Saharan Africa) explains national-level life expectancy. Plausible assumptions for trends in each of these factors could be used to develop a model of country-level health transitions. For access to safe water, these assumptions should consider how other factors, such as climate and land use change, could affect future availability.

2.5 Incorporation of adaptation

Adaptation is a critical factor determining the actual health impacts experienced by a population. The determinants of adaptive capacity include the range of available options, the availability of the human, social, institutional, and financial capital needed to implement the options, the capacity of decision-makers to manage information, and the political will to implement the options (Smit et al. 2001). Individuals, communities, and regional and national agencies and organizations will need to adapt, with the measures implemented influenced by factors such as who is expected to take action; the current burden of climate-sensitive health determinants and outcomes; the effectiveness of current interventions to protect the population from weather- and climate-related hazards; projections of where, when, how, and with what intensity the burden of outcome could change as the climate changes (including changes in climate variability); the feasibility of implementing additional cost-effective interventions; other stressors that could increase or decrease resilience to impacts; and the social, economic, and political context within which interventions are implemented (Yohe and Ebi 2005).

Increasing recognition of the importance of adaptation by policymakers stresses the need to develop adaptation models. Modeling adaptation will be at least as complex as developing systems-based models of the key drivers of climate-sensitive health determinants and outcomes. Wealth, distribution of income, status of the public health infrastructure, provision of medical care, access to safe water and sanitation, and other factors influence both the range and incidence of health outcomes and the capacity to adapt. In order to better project the magnitude and distribution of climate change-related health impacts, it is important to develop realistic assumptions about how adaptation and mitigation will change over time.

One categorization of adaptation options is into interventions designed to increase the ability to cope with present-day climate risks, and interventions that are needed to cope with projected climate change-related health impacts, while maintaining or improving current public health standards. This is an artificial categorization based not on differences in the measures actually implemented, but on the motivations behind the changes in strategies, policies, and measures. Because the climate-sensitive health determinants and outcomes projected to increase with climate change are problems today, national and community-level public health efforts to control these health outcomes will need to be revised, reoriented, and/or expanded just to maintain current levels of disease control. Coping with projected climate change impacts may require implementation of interventions from other countries/regions to address changes in the geographic range of diseases, development of new interventions to address health threats, and other actions.

Limited attempts have been made to model adaptation. Adaptation could be modeled as decreasing health burdens based on actual trends or realistic assumptions; sensitivity analyses should be conducted for a range of decreasing disease burdens, such as 10%, 20%, etc. This was the approach taken by the Global Burden of Disease study (McMichael et al. 2004). Another modeling approach has been to use expert judgment to estimate how much adaptation could reduce health burdens (e.g. Van Lieshout et al. 2004).

Appropriately modeling adaptation includes modeling the measures currently in place that affect vulnerability (e.g. the adaptation baseline); modeling the policies and measures that could be implemented (along with an estimate of effectiveness); modeling adaptive capacity; and modeling the consequences, including co-benefits, of mitigation policies at appropriate scales. Further, models need to take into account that many possible measures for adapting to climate change are outside the health sector in areas such as sanitation and safe water supply, education, agriculture, trade, tourism, transport, development, and housing.

2.6 Discussion of uncertainties

Developing models of future risks involves combining epidemiologic knowledge about the climatic and non-climatic risk factors for the health outcomes with projections for these risk factors, including a description of key uncertainties (McMichael et al. 2001). Uncertainties in projections of the magnitude, timing, and nature of future changes in the climate system, socioeconomic development, and future potential health consequences of climate change lead to a need to estimate the impacts of a range of possible climate scenarios on health. There are multiple sources of uncertainty in developing models, including whether the appropriate model structure was chosen, whether the key processes incorporated into the models are well understood and described, how underlying variables will change over time (i.e. the rate, speed, and regional extent of climate change; changes in economic development, technology, etc.), how populations in different regions will respond to climate change, and the effectiveness of mitigation and adaptation strategies, policies, and measures (McCarthy et al. 2001; Kovats et al. 2003).

The basic question is how well is it known that climate change is likely to affect the range or incidence of a particular health outcome. There is extensive literature on uncertainty in climate models. Because impacts are specific to a time, place, and disease context, and because much remains to be learned about exposure-response relationships, there will be varying degrees of confidence in statements about impacts on local and regional scales, and these statements will depend on assumptions about development, specific adaptations, and adaptive capacity. For example, models could project with high confidence that in some regions malaria has the potential to extend its range along the edges of its current distribution, but there will be less confidence in other regions. There will be higher confidence about the potential impacts of flooding in regions where climate models suggest that extreme precipitation events are projected to increase, yet other regions may experience rare flooding events with severe consequences. Trying to make one overarching statement about a particular health outcome across regions will result in a weaker statement than if statements are more specific to regions or vulnerable groups.

3 Ways forward and conclusions

Significant challenges are posed by the fact that the health impacts of climate variability and change can be direct, indirect, multiple, and simultaneous. Although the complex causal structure and the uncertainties associated with future projections of relevant climatic and non-climatic factors pose severe constraints on the accuracy with which future health impacts can be assessed, policymakers, decision-makers, resource managers, negotiators, and other stakeholders need to understand the boundaries of where, when, and how extensively climate change could affect future health burdens at the spatial and temporal scales of interest. For example, signatories to the United Nations Framework Convention on Climate Change regularly submit national communications that summarize their vulnerability to climate change and the options available to reduce projected future impacts. Non-Annex 1 countries (primarily low-income countries) are beginning their Second National Communications and many would like to include health among the sectors they consider. Agriculture, water, and coastal zones have well-developed (and multiple) models that project country-level impacts based on input from general circulation models and socioeconomic and demographic scenarios (such as the SRES, Nakicenovic et al. 2000). The health sector has no current models to aid countries better understand how climate change could affect population health. Much can be achieved using qualitative approaches, but models would enhance standardization and comparisons of results over a range of geographic and temporal scales. Models also could be used in national assessments and other assessment processes.

There are a number of limitations to model development. One is that the limited reliable epidemiologic data on the current relationships between climatic factors and health outcomes, especially in low-income countries, hampers the projection of future health risks. Hitz and Smith (2004) summarized the general shape of the damage function that describes the presumed benefits or avoided damages of reducing atmospheric concentrations of greenhouse gases and concluded that the literature is insufficient to form other than the most rudimentary conclusions about potential health impacts. The published studies were not consistent along critical dimensions, including how endpoints were categorized, or in demographic and socioeconomic assumptions, scenarios, and time slices analyzed. In addition, limited validation of published exposure-response relationships decreases confidence in projections of health impacts.

The level of interacting and confounding factors associated with health outcomes makes developing health models challenging. One lesson learned from the controversy over modeling the relationship between climatic factors and malaria is that models need to incorporate the critical drivers of the health outcome. Climate is one factor that affects the geographic range and incidence of climate-sensitive health outcomes. Social vulnerability, access to health care, land-use, drug resistance, and other factors affect the current burden of malaria. Models should incorporate, at least, relationships based on expert judgment to begin development of systems-based models (Chan et al. 1999). In addition, research is needed to model climate change impacts through to health burdens rather than to intermediate indicators, such as populations at risk.

Underlying these limitations is the lack of sufficient funding, which is partially due to the limited interdisciplinary approaches of many funding agencies and institutions (Chan et al. 1999). Health-focused funding sources support studies to define and further understand exposure-response relationships, but there has been limited interest in integrating other factors, such as land use change, that can affect disease transmission dynamics. Besides limiting understanding of the complex system that affects health outcomes, another consequence has been that there are insufficient numbers of students trained in multidisciplinary approaches to carry this research forward.

Despite these and other challenges to developing models to project the potential health impacts of climate change, there is cause for optimism. Scientific interest is increasing in model development, as evidenced by the papers in this volume and other recent publications. There are a number of opportunities for rapid advancement in health models. The WHO Global Burden of Disease study (McMichael et al. 2004) could provide a starting point for model development, augmented by exposure-response relationships (for both climate and contextual determinants) described in recent research. Attention should be paid to demographic changes and to disease trends that can influence population vulnerability, such as the increasing obesity trends in the United States that may increase vulnerability to heat waves. In addition, national and international health models could incorporate a range of climatic and socioeconomic simulations, allowing the users to choose future scenarios consistent with current climatic trends and plausible development expectations.

Model development should consider not only what scientists know about the climate-health relationship, but also what stakeholders need to know for effective decision-making (Scheraga et al. 2003). Ideally, model development should be an iterative process involving scientists and policymakers to ensure that modeling results will address the needs of decision-makers and contribute to the body of scientific knowledge. One example of how scientists and decision-makers have worked together is the development of heat event early warning systems that use information on physiological responses to high ambient temperature and on populations at increased risk during a heat event to create systems designed to reduce morbidity and mortality (Kalkstein et al. 1996).

Multiple climate-health models are needed to address the questions of interest to current and future stakeholders. Although there are constraints to model development, failing to invest in such development violates one of the goals of public health – to minimize current and future burdens of climate-sensitive health determinants and outcomes.

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