CHAPTER 4

Looking to the future: challenges for scientists studying climate change and health

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Introduction

Chapter 3 describes ways in which climate change may affect human health and summarizes the findings of the Third Assessment Report of the IPCC (*1*). This chapter looks ahead and considers the challenges awaiting researchers who seek to advance knowledge of this area beyond what is contained in reports from the IPCC and other bodies. This begins with an outline of important ways in which climate change is different from other environmental health problems and explores the implications for researchers.

The biggest challenge is scale. Both the geographical spread of climate-related health problems and the much elongated time spans that often apply, are largely unfamiliar to public health researchers. Research on climate change typically is conducted on three time-scales:

1. relatively short periods between altered climate (expressed as weather) and the effects on health.
2. intermediate time periods that include recurring, inter-annual events like El Niño and La Niña.
3. longer intervals (decades or centuries) between the release of greenhouse gases and subsequent change in the climate. This category of research is most troublesome to standard epidemiological methods.

Researchers in the public health sciences are accustomed to studying geographically localized problems that have a relatively rapid onset and impact directly on human health. There are exceptions (e.g. the global spread of AIDS and tobacco-related diseases) but, typically, health problems (and control strategies) are defined by boundaries at a finer scale: neighbourhood, town or province. The standards that researchers bring to the evaluation of evidence frequently are born out of an experimental research tradition. In this vein the natural unit of observation tends to be the individual rather than the group and when thinking about causes the emphasis lies on specific agents acting downstream in the causal process.

Weather and climate variability do not fit well the conventional research model, partly because there is no easily identified unexposed control group and little variation in exposures between individuals in a geographical region. Consequently, studies of the effects on health of weather and climate variability need to use ecological designs (in which the study unit is a population). Following a period when population-based studies were somewhat out of favour, epidemi-

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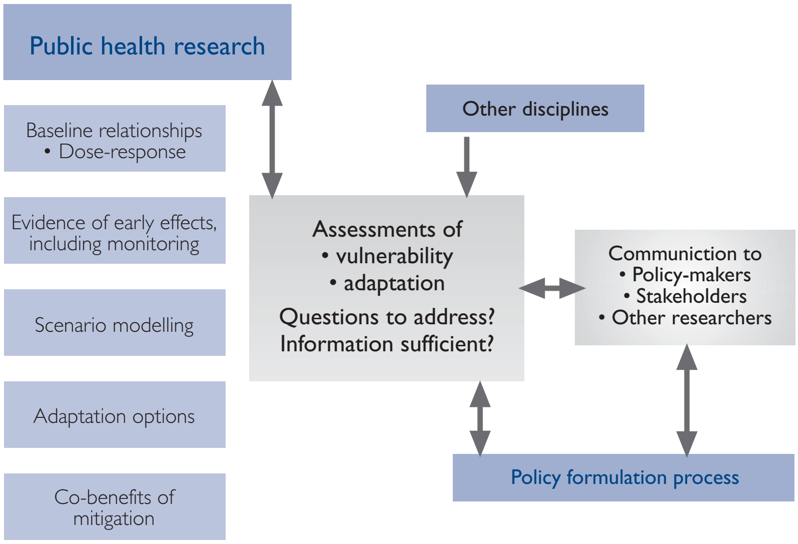
ologists are re-visiting their use and exploring ways in which evidence from ecological investigations can be combined with information collected at the individual level (*2*). While the exposure is common to a geographical area, there are frequently variations in coping capacity that cause considerable differences in outcomes. For example, excess mortality in the 1995 Chicago heatwave varied almost one hundred-fold between neighbourhoods as a result of factors such as housing quality and community cohesion (*3*).

Other important differences from traditional environmental exposures are the directness of the association between exposure and disease, and the degree to which interactions and feedbacks could occur. There are many pathways—some more direct than others—through which climate change could affect human health (see chapter 2): the effects of temperature extremes on health are direct, while the effects of changes in temperature and cloud cover on air pollution-related diseases involve several intermediate steps. Similarly, ecosystem change will be one mediator of the potential effects of changes in temperature and precipitation on vector-borne diseases. As another example, climate change may increase the amount of time taken for stratospheric ozone levels to return to pre-industrial concentrations. This delay could be decades or longer than expected under the Montreal Protocol (*1*). During this time, increased exposure to UV radiation is expected to continue to increase rates of skin cancer, cataracts and other diseases (see chapter 8).

Hypotheses of the effects of climate on health cannot be tested in experimental studies because climate cannot be assigned at the whim (random or otherwise) of the investigator. It may be possible to study some early effects using standard observational methods. However, the effects of future climate variability and change can be estimated only by analogue studies, using current weather or climate variability (such as El Niño events—chapter 5) that mimics in some way what might be expected under climate change, or by models. Such models cannot predict what will happen, but instead sketch out what would occur *if* certain conditions were fulfilled. Some—at least in theory—could assign probabilities, such as the chance of sea level rise along the coast of the United States of America over t he next 100 years. Ideally, models include scenarios of future societal, economic and technological conditions, since the impact of climate depends very heavily on these factors. It is important for these models to capture the effects of humans as an added stressor on the environment, and their ability to respond to change. Climate/health models should be informed but need not be constrained by historical data. For example, it is possible to construct a simulation model based upon assumed conditions and processes (e.g. with thresholds and non-linearities) different to those experienced historically.

The less than ideal fit between the problems and available study methods presents a challenge; this chapter describes some of the ways in which researchers are responding. Developments include new ways of estimating the impacts of future threats (such as scenario based assessments). Methods applied elsewhere to the study of complex non-linear systems are being translated to the health sphere (e.g. modelling of infectious disease). A more sophisticated approach to uncertainty assessment includes not only statistical sources of error (arising from sampling processes) but also the uncertainty that results from judgements that must be made to bridge knowledge gaps. Whereas in the past the variability in response between study units tended to be regarded as noise around the exposure-outcome signal, now this variability is seen as important in its own right. For example, to learn about possible mechanisms of adaptation to extreme

FIGURE 4.1 Tasks for public health science.



weather events, researchers in the United States have investigated the reasons for wide variations in the change in mortality for a given increase in daily temperature in cities (*4*).

The main tasks of public health science in assessing the potential health effects of climate variability and change (Figure 4.1) include:

- establishing baseline relationships between weather and health (introduced in chapter 2)
- seeking evidence for early effects of climate change (discussed in detail in chapter 10)
- developing scenario-based models (referred to in a number of chapters)
- evaluating adaptation options (discussed in detail in chapter 11)
- estimating the coincidental benefits and costs of mitigation and adaptation.

Consideration of the links between science and policy development must be incorporated in each of these steps. More precisely, the question is how science can best inform decision-makers in a timely and useful fashion.

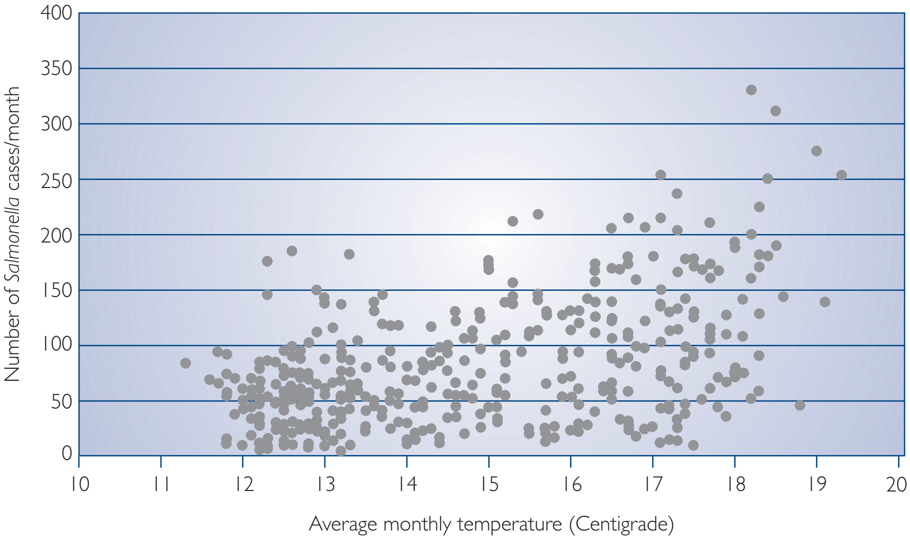
Tasks for public health scientists

Establishing baseline relationships

For centuries the relation between weather and health has attracted attention. However, interest in the topic has increased following the first signs that human activity may be influencing the world's climate. There are many unresolved questions about the sensitivity of particular health outcomes to weather, climate variability and climate-induced changes in environmental conditions critical to health. Yet a good deal is known about the effects of weather on aspects of human health, as shown in the following example.

The major pathogens responsible for acute gastroenteritis multiply more rapidly in warmer conditions so it would be expected that higher temperatures would be associated with greater risk of illness, all else being equal. This appears

FIGURE 4.2 Relationship between mean temperature and monthly reports of *Salmonella* cases in New Zealand.



to be the case: over the last 30 years the number of notifications of salmonella infections in New Zealand has been clearly related to the average temperature during the same month. (Figure 4.2).

To investigate the relation between ambient temperatures and the rate of enteric infections, Bentham and colleagues collected British data on all cases of food poisoning in a ten year period (1982–1991) (*5*). Statistical models of the relationship between the monthly incidence of food poisoning and temperatures were developed. The numbers of reported cases were compared with temperatures of both that and the previous month, on the basis of the known biology. An association was found with both temperature measures although the previous month showed the stronger effect. This suggests that temperature may act through effects on storage, preparation and hygiene close to the point of consumption. The even stronger relationship with the temperature of the previous month suggests the possible importance of conditions earlier in the food production process. It is important to emphasize that correlation is not causality; more work is needed to understand the mechanisms by which environmental change affects disease risk.

The challenges faced by researchers investigating base-line relationships are similar to those faced in public health sciences generally. They include difficulties with accurately measuring outcomes, obtaining meaningful assessments of the exposure and dealing with large numbers of potential confounding factors. In the case of the studies reported here, month-by-month variations in notifications of infectious disease are not likely to be due to reporting artefact. Changes in the accuracy of diagnosis and completeness of reporting are a greater concern when long-term time trends are analysed.

Seeking evidence for early health effects of climate change

The changes in the world's climate in the past 50 years or so are remarkable when compared with patterns over the past 10 000 years. The rate of change of atmospheric concentrations of greenhouse gases is outside human experience and recently the rise in average temperatures has exceeded what is considered the bounds of natural variability (chapter 2). It would seem reasonable therefore to look for evidence of early health effects of climate change: changes in health outcomes that become apparent soon after the onset of climate change. The Intergovernmental Panel on Climate Change (chapter 3) considered the following lines of evidence:

- observed variations in disease incidence and range in association with short term climate variability;
- long-term disease trends and the factors that may be responsible;
- projections based on first principle relations between temperature and the development of disease;
- empirical disease models based on the current geographical distribution of climate-sensitive diseases.

There are many studies of physical and biological systems reporting a variety of phenomena linked to long-term, decade-scale change in temperature and rainfall. These include events such as permafrost melting, ice sheets breaking up and glaciers retreating. Biological changes associated with climate alteration include lengthening of growing seasons, earlier flowering, changes in egg laying and poleward shift in distribution of a number of insects (*6*). In one example of this kind of work (and showing climate change to have positive as well as negative effects) Nicholls charted changes in Australian wheat yields from 1952 to 1996 (*7*). Over this period the average yield increased from 1.1 to almost 1.6 tonnes per hectare. In the same years the diurnal temperature range fell by almost 0.5 °C, largely as a consequence of warmer overnight temperatures (relevant because wheat is sensitive to frost). Several techniques were used to attempt to control for non-climatic influences such as changes in crop types and land use patterns. Especially persuasive was the strong correlation between year-to-year variation in temperature range and wheat yield. On the basis of these data Nicholls estimates that climate trends in the second half of the twentieth century (including natural and human-induced climate change) were responsible for 30–50% of the observed increase in wheat yields.

There are few reports of the effects of climate change on human health to match the range of observations on physical and ecological effects. Lindgren has reported geographical changes in tick-borne encephalitis in Sweden that match shifts in both the vector and long-term climate. She observed also a northward extension of the tick population following a trend of warmer winters (*8*). In Africa some investigators have reported changes in the occurrence of malaria (including rising altitude limits) that they think unlikely to be due to changes in land-use patterns, increasing drug resistance or diminishing effectiveness of health services (*9*). A good deal has been written about associations of weather and health, but apart from the examples given here there are few studies documenting effects that might be attributed to year on year change in climate.

Why the relative paucity of evidence of early health impacts? Our species is not immune to changes in climate—there are plenty of studies reporting acute effects of extreme weather such as heatwaves, floods and storms, and short-term variations in climate such as El Niño (*10*, *11*). Less work is being done in this area than in the natural sciences—that is, the denominator (all climate/health research) is smaller. More importantly, research on free-living human populations includes a layer of complexity that does not apply to investigators working with butterflies, ticks or wheat. Not only are there non-climatic confounding factors but also there is the phenomenon of social adaptation. Humans are unrivalled in their capacity to adapt to changing environmental circumstances. European butterflies have no choice but to head north when it heats up; humans have many coping strategies at their disposal from planting shade trees, changing hours of work or making use of cooler times of the day, to installing air-conditioning.

Time trends in disaster losses show how effectively humans can protect themselves against climate. In the United States in the 1900s, hurricane damages in constant dollar terms increased from about US$ 5 billion in the 1930s to more than US$ 30 billion in the 1990s. This increase was due principally to massively increased exposure to financial losses (resulting from new settlements on flood plains and in coastal regions) rather than any change in the frequency or severity of storms. Over the same period the number of deaths due to hurricanes was reduced ten-fold. In the United States the effect of improved communications, early warning systems, transport, building standards and other elements of civil defence has been to insulate the population to a large extent from the effects of climate extremes (*12*).

The challenge for public health scientists is to pick the settings, populations and health outcomes where there is the best chance of firstly, detecting changes and secondly, attributing some portion of these to climate change. This means seeking research opportunities where the necessary information can be found: because climate change spreads over decades, time series data on outcomes and confounders over a similar period are required. From first principles, impacts are likely to be seen most clearly where the exposure-outcome gradient is steepest and adaptive capacity weakest. Attribution is most straightforward when there are few competing explanations for observed associations and when these links can be clearly specified.

With such conditions in mind, what are the best bets for studies of early effects? Vector-borne diseases may be relatively sensitive indicators because transmission involves intermediate organisms, such as mosquitoes, open to environmental influences. Intestinal infections (food poisoning) show very strong seasonal patterns (suggesting a powerful effect of climate variability) and have been routinely reported for many years (although the data are known to be incomplete). Deaths, injuries and illnesses caused by extreme events (such as heatwaves, cold spells, floods and storms) satisfy the condition of few competing explanations, but in many populations it may be difficult to distinguish the climate change signal from much stronger mitigating effects of social and economic development.

Developing scenario-based models (future effects)

With climate change, researchers are attempting to quantify future effects of future weather exposures and, more fundamentally, trying to understand and delineate the magnitude of future risks. The risks arise from a wide range of diseases and injuries, some readily quantified (e.g. deaths due to storms and floods) others more difficult to capture statistically (the health consequences of food insecurity). Whether the potential for climate-related disease is translated into actual occurrence of death and illness depends on both how quickly the climate changes and how successfully humans adapt to new conditions. Interacting exposures may make it difficult to forecast dose-response relations from historical data: a study of 29 European cities found the effect of particulate air pollution on daily mortality was almost three times stronger in the warmest cities than in the coldest (*13*). This suggests that at least some part of the effects of rising temperatures will be dependent on future trends in urban air pollution. Multidisciplinary research is required to make progress in this field: modelling changes in future socioeconomic status and examination of its implications for susceptibility will require health scientists, economists and experts from other disciplines to work together.

One response to this challenge has been the development of integrated assessments, a term that has been variously defined. Under one definition, "integrated assessment is an interdisciplinary process of combining, interpreting, and communicating knowledge from diverse scientific disciplines in such a way that the whole set of cause-effect interactions of a problem can be evaluated from a synoptic perspective with two characteristics: it should have added value compared to single disciplinary oriented assessment; and it should provide useful information to decision-makers" (*14*). The essential points in this definition are synthesis (combining information from more than one discipline) and application to decision-making. The integration may be horizontal (between disciplines) or vertical (bringing together assessments at different levels of complexity within the one discipline). An example of the former is an assessment of the impact of climate change on the prevalence of hunger, which was based on climate forecasts, plant science, demographic scenarios and economic models of food trade (*15*). A vertical assessment is exemplified by the work done by UV researchers to estimate impacts of stratospheric ozone depletion on skin cancer rates (*16*). Such approaches have proven useful in evaluating potential impacts of climate change other than effects on human health, and are beginning to be applied to a range of climate change and health issues (*17*). The goal of integrated assessment is to provide insights that cannot be gained from traditional, single disciplinary research (see chapter 12 discussion about prioritization of research agenda). An example of integrative assessment is the inclusion of pathogen transmission dynamics; contextual elements such as changing land use; and demographic forces such as population movement into an evaluation of the potential impacts of climate change on infectious diseases (*17*). Integrated assessment also allows evaluation of how feedback mechanisms and adaptation measures could change the system response. As with any type of risk assessment, the choices about which variables to include (or exclude) may make a big difference to the conclusions.

Modelling is one of several methods employed to conduct an integrated assessment. An array of component models of varying degrees of complexity (from simpler parametric to more detailed process-oriented models) is developed, each with mathematical representations of cause-effect relationships. These are linked to show the interrelationships and feedback mechanisms among the key components. The resulting framework aids the identification and prioritization of scientific uncertainties. Sensitivity analyses can be conducted to understand better the sensitivity of the system to changes in each relationship (*17*). Although modelling is useful for risk categorization, it can imply more precision than is appropriate where full data are absent, and relevant available data may be excluded or overemphasized. In addition, the technical limitations of the model might defeat the ultimate value of the analysis (*18*).

If integrated models are to advance understanding of phenomena such as climate change, they must simulate to some degree the interrelationships and feedbacks that occur in complex systems. If the results are to be widely accepted and applied, these models must be congruent with the points of view and understandings of those who are ultimately the users of the information. Studies indicate that integrated assessments are more likely to be accepted when they incorporate a variety of methods (demonstrating that similar answers are obtained via different routes), include multiple objectives (since users are likely to be concerned with a range of outcomes) and when the users receive immediate feedback on the implications of changing key parameters (*19*, *20*).

Evaluating adaptation options

Adaptation means taking steps to reduce the potential damage that occurs when the environment changes. As a policy option this approach has a number of attractions. First, it offers opportunities for win-win strategies (building adaptive capacity to risks under current conditions may be beneficial, regardless of future climate change). Second, it recognises that—to some extent—the world is committed to climate change. Even if immediate substantial reductions were made in greenhouse emissions, over the next 50 years the planet would continue to warm and sea levels continue to rise for hundreds of years due to the time it takes for basic global systems to reach a new equilibrium.

The reason why some systems cope better than others when stressed has attracted the interest of researchers in many disciplines. Geneticists have been intrigued by the particular sensitivity of some populations to introduced infections, and some have proposed that variability (in genotypes) might be an important protective factor (*21*). Ecologists have explored the attributes of ecosystems that are relatively robust under pressure. Complexity or interconnectedness and diversity are two elements that appear to enhance adaptability. Diverse plant communities, for example, are more effective than simple communities in fixing atmospheric carbon (*22*) and more stable in the face of severe environmental stress such as drought (*23*). The distribution of risk also is important. Amory Lovins has described a resilient energy system as "one that has many relatively small dispersed elements, each having a low cost of failure. These substitutable components are interconnected, not at a central hub but by many short, robust links" (*24*). This is analogous to the system of veins that distributes nutrients through the leaves of a tree, or the electronic links that make up the Internet. It might be a model for secure food supplies or robust global health care.

Public health researchers have applied many of these ideas when investigating why some populations are more vulnerable than others to disease and injury. Studies of disaster preparedness have emphasized the importance of diverse community networks, both formal and informal (*25*). Populations dependent on a few staple foods are at greater risk of famine than those with a variety of foods (*26*). Studies of historical climate-related disasters have shown that political structures and economic arrangements are very important in modifying the effect of droughts and other extreme events on health outcomes (*27).*

When applied to climate change, vulnerability may be defined as the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change including variability and extremes. Components include the:

- extent to which health, or the natural or social systems on which health outcomes depend, are sensitive to changes in weather and climate (i.e.

TABLE 4.1 Examples of factors affecting vulnerability.

Level	Influence on vulnerability	Description
Individual	Disease status	Those with pre-existing cardiovascular disease, for example, may be more vulnerable to direct effects such as heatwaves
	Socioeconomic factors	Poor in general are more vulnerable
	Demographic factors	Elderly are more vulnerable to heatwaves, infants to diarrhoeal diseases
Community	Integrity of water and sanitation systems and their capacity to resist extreme events	
	Local food supplies and distribution systems	
	Access to information	Lack of early warnings of extreme events
	Local disease vector distribution and control programmes	
Geographical	Exposure to extreme events	Influence of El Niño cycle or occurrence of extreme weather events more common in some parts of the world
	Altitude	Low-lying coastal populations more vulnerable to the effects of sea level rise
	Proximity to high-risk disease areas	Populations bordering current distributions of vector-borne disease may be particularly vulnerable to changes in distribution
	Rurality	Rural residents often have less access to adequate health care; urban residents more vulnerable to air pollution and heat island effects
	Ecological integrity	Environmentally degraded and deforested areas more vulnerable to extreme weather events.

Source: reproduced from reference 1.

exposure-response relationship—drinking water contamination associated with heavy rainfall);

- exposure to the weather or climate-related hazard (includes character, magnitude and rate of climate variation);
- adaptive capacity—the ability of institutions, systems and individuals to adjust to potential damages, take advantage of opportunities, or cope with the consequences (for example: watershed protection policies, or effective public warning systems for boil-water alerts and beach closings) (*1*).

Individual, community and geographical factors all contribute to capacity to adapt to change in climate (Table 4.1). These include the level of material resources, effectiveness of governance and civil institutions, quality of public health infrastructure, access to relevant local information on extreme weather threats, many other socioeconomic factors, and pre-existing level of disease (*28*).

Scheraga and Grambsch propose several principles for policy-makers considering options for adaptation (*29*). First, the principle of heterogeneity: the effects of climate change will vary by region, between different demographic groups and over time. This means that adaptive responses need to be specific to a particular setting. Second, the effects of climate change will not occur in isolation from other social and environmental stressors so adaptation must take account of coincidental factors such as population growth and environmental degradation. Third, the costs and effectiveness of adaptive options must be weighed when setting priorities (current efforts to cope with climate variability may provide a guide to this). Lastly, it is important to bear in mind that attempts at adaptation can do more harm than good: poorly designed coastal defences may increase vulnerability to storms and tidal surges if they engender a false sense of security and promote settlement in marginal coastal areas.

Estimating ancillary benefits and costs

Decisions on climate change are driven largely by the anticipated consequences in the medium and long-term future. However, steps taken to reduce emissions of greenhouse gas (mitigation) or to lessen the impact of climate change on health (adaptation) may have immediate effects. A greater emphasis on public transport at the expense of personal motor vehicles may not only reduce emissions of CO_2, but also improve public health in the short-term by reducing air pollution and traffic accidents. The magnitude and timing of ancillary costs and benefits are very important for policy-makers. Political decision-making occurs within a short time horizon but the costs of climate change actions often must be borne before there is any discernible effect on climate or the health consequences. As a result, it may be helpful to include outcomes that can be attributed to climate change interventions and occur soon after the introduction of such interventions. Such changes may be positive or negative. Policies that restrict access to motor cars but do not ensure the availability of alternative forms of transport, might do more harm than good in health terms (for example, making it more difficult for people to get to health care facilities).

To illustrate this point: improving energy efficiency and increasing the use of low pollution energy sources would not only reduce greenhouse emissions, but also improve air quality for much of the world's population. An analysis was carried out to estimate the local health benefits of adopting greenhouse mitigation policies in four major cities (Santiago, São Paulo, Mexico City and New York) (*30*). In this study it was assumed that climate mitigation policies would lead to a 10% reduction in levels of fine particles and ozone in urban areas. Upper and lower bounds of particle-related mortality were estimated, as were a number of other health impacts (hospital admissions, asthma attacks, lost workdays due to acute illness). The conclusion of the study was that "policies aimed at mitigating greenhouse gas emissions can provide a broad range of more immediate air pollution benefits to public health".

In general terms, the challenge for researchers is to conceive study designs that capture information on coincidental benefits (and costs). Co-benefits apply not only to measures that reduce greenhouse gases but also to adaptation policies. These may yield co-benefits in the form of reductions of other (non-climate-related) environmental problems. They may also provide co-benefits in the form of reductions in greenhouse gases.

Informing policy

How can research into the effects of climate change contribute most usefully to policy? Early risk assessment/risk management models describe a linear, unidirectional process in which science precedes (and is remote from) issues of values, trade-offs and ethics (*31*). However, close examination of what happens in practice shows that it is difficult to draw a clear distinction between scientific risk assessment and social risk management. Two examples in the literature are a study of the health effects of acid rain (*32*) and Conrad Brunk's analysis of three assessments of the pesticide, Alachlor. In his case study Brunk pointed out numerous decision points where the risk assessors' values were paramount (*33*). It was differences in these value-driven choices (such as whether to assume "adhering to best practice" or "plausible real behaviour" exposure scenarios) that explained the three orders of magnitude difference between the risks calculated by Monsanto and Health and Welfare Canada, not disagreements over scientific methods or the basic data.

The titles of recent United States' National Research Council (NRC) publications on risk reflect the shift in thinking that has occurred away from the linear objective science—subjective policy model. "Science and judgement" (*34*), was followed by "Informing decisions in a democratic society" (*35*), and "Towards environmental justice" (*36*). Scientific assessments are not remote technical exercises, they are part of the messy, problematic and negotiated world of social decision-making. The NRC report "The science of regional and global change: putting knowledge to work," states:

> *"Assessment and policy analysis are essential to understand the overall impact of changes in human behavior and natural processes, to link research agendas with decision needs, and to monitor the results of policy actions. Effective assessment aims to integrate the concepts, methods, and results of the physical, biological, and social sciences into a decision support framework" (37).*

There are important implications in accepting such a view. One is that scientific assessments should not assume a common understanding of the problem faced, let alone a single view of the solution. Scheraga and Furlow argue that for an assessment to be informative, the assessors must know the particular issues and questions of interest to stakeholders (e.g. public health officials) (*38*). Stakeholders should be engaged from the outset of the assessment process and involved in the analytical process throughout the assessment. Openness and inclusiveness enable different participants to bring a diversity of views and information that may benefit the assessment process: including all interested parties makes the assessment process more transparent and credible. Another writer has argued that an important part of scientists' work is to try to achieve "widespread agreement on what questions are being asked, why they are important, what counts as answers to them and what the social use of these answers might be" (*32*). Aron puts it this way: "the process of integrated assessment must grapple with questions of values up front" (*19*). Without this clarity, policy-makers may find it difficult to interpret insights from assessments and may struggle to appreciate the reasons for disagreement between different researchers.

The purpose of assessment is to inform decision-makers, *not* to make policy choices. The ways in which information is presented may strongly affect subsequent choices, but scientists cannot determine what is the best policy choice. Determining what is best is a societal decision, involving societal values. The next section examines the interplay of values and scientific assessment in relation to climate change, and other factors that contribute to uncertainty.

Recognizing and responding to uncertainty

The effect of climate change on human health depends on a sequence of events that produces a "cascade of uncertainty" (*39*). There is no doubt that human activity has altered the composition of Earth's atmosphere. The resultant effects on the world's climate are less certain but, as already noted, most of the warming that has occurred in the last 50 years probably is human-induced (*1*). It is more difficult to forecast what will happen in the future—complicating factors include future trends in greenhouse emissions, biophysical feedback forces and threshold phenomena in the climate system that by their very nature are difficult to anticipate. Impacts on human health will depend not only on the nature and rate of climate change at the local level, but also on the ability of ecological systems to buffer climate variability. Yet as discussed in chapter 12, assessments can provide insights even if predictions cannot be made, conducting bounding exercises to estimate the potential magnitude of particular impacts and the importance of their effects.

Sources of uncertainty can be examined by taking as a particular case study the relation between climate change and mosquito-borne diseases (discussed in more detail in chapter 6). Mosquito-borne diseases are a major cause of human ill-health worldwide—each year there are hundreds of millions of cases of malaria and dengue, the two most common infections transmitted in this way. New and emerging infections also are a potential threat, as shown by the surprisingly rapid spread of West Nile virus in North America.

Mosquitoes cannot regulate their internal temperatures and therefore are exquisitely sensitive to external temperatures and moisture levels. Specifically, temperature influences the size of vector populations (via rates of growth and reproduction), infectivity (resulting from the effects on mosquito longevity and pathogen incubation) and geographical range. As a result, any comprehensive global study of the impacts of climate change must include possible effects on the global pattern of malaria, dengue and other mosquito-borne diseases. Climate change will be associated with changes in temperature, precipitation and possibly soil moisture, all factors that may affect disease prevalence. Yet mosquitoes are not only temperature dependent they are also very adaptable: these insects can adjust to adverse temperature and moisture by exploiting microenvironments such as containers and drains (and as a result can over-winter in places that are theoretically too cold for mosquitoes). Many other factors are important in transmission dynamics. For example, dengue fever is greatly influenced by house structure, human behaviour and general socioeconomic conditions. This is illustrated very well by the marked difference in the incidence of the disease above and below the United States–Mexico border: in the period 1980–1996, 43 cases were recorded in Texas compared to 50 333 in the three contiguous border states in Mexico (*40*).

There are few instances in which effects of long-term climate change on human health have been observed directly. Where there have been substantial changes in rates of mosquito-borne disease in recent times, there is little evidence that climate has played a major part (*41*, *42*). This means that assessments of the impact of future climate change rely on expert judgement, informed by analogue studies, deduction from basic principles and modelling of health outcomes related to climate inputs.

The IPCC's Third Assessment Report concluded that rising temperatures and changing rainfall would have mixed effects on the potential for infections such as malaria and dengue worldwide (chapter 3). It reported that in areas with limited public health resources, warming in conjunction with adequate rainfall would likely cause certain mosquito-borne infections to move to higher altitudes (medium to high confidence) and higher latitudes (medium to low confidence). The IPCC concluded also that transmission seasons would be extended in some endemic locations (medium to high confidence).

There are other views than those of the IPCC. Some argue that simple climate change models provide no useful information about future disease rates because factors other than climate are bound to be more important (*43*, *44*). Others conclude that there is sufficient evidence that global warming already is extending the geographical range of significant mosquito-borne diseases (*45*).

Why should scientific assessments that agree largely on evidence and methods come to rather different conclusions? One possible explanation is that the assessments are attempting to answer different questions. For example, the IPCC conclusion is couched explicitly in terms of disease potential (what would happen *if* certain conditions were to apply). Others, such as Reiter, have focused more strongly on predictions of actual disease incidence (not what *might*, but what *will* happen) (*43*).

The "what might happen" view is more wide-ranging, consistent with the position that science has a legitimate function in tackling "what if?" questions. According to this position, one objective of climate change research is not to propose testable long-range hypotheses rather to provide indicative forecasts to guide pre-emptive policy-making. Strictly speaking, no scientific study (not even the most tightly controlled experiment) can predict the consequences of a particular course of action and all research operates in the realm of what might happen. What is more, extrapolations from the research environment to the real world setting inevitably are hedged by conditions: it may not be explicit, but the conclusion always takes the form "*if* the setting in the laboratory was to be replicated, *then* the following outcomes would be expected . . ."

This is not to suggest that there should be only one way of carrying out climate research. One useful approach is the traditional hypothesis testing approach. Another is the "what if?" analysis—useful for risk management decisions as well as contributing to weight-of-evidence arguments. Both approaches have value but they may lead to different types of insights and information.

Assessments of climate change impacts are based, necessarily, on assumptions about the state of a future world. Any summary statement about the likely effects of a changed climate assumes a certain level of susceptibility, whether the status quo or what might be predicted from current trends, formal modelling, scenario analyses, or a worst-case scenario. An optimistic scenario would be a configuration of high disease control capacity and low population susceptibility (as a result of socioeconomic improvements, for example). Another assessment might include a range of possible futures, some of which are more disease-prone, such as settings in which public health services deteriorate, economic productivity declines and social order unravels.

Scale may be another factor that contributes to differences between scientists, adding to uncertainty for policy-makers. Factors that produce the most noticeable changes over a short time may not be the same as those that cause long-term changes in disease rates. Similar considerations apply to spatial distributions: malaria has been pantropical for centuries, essentially a function of climate. As noted already, recent retreats and advances of the disease are not due primarily to climate, but on a global scale they are movements on the margins. McMichael has applied this idea to the pool of disease, emphasizing the difference between factors that agitate the surface (short-term, localized variations) and the conditions that determine the depth of the pool (*46*). The latter class of causes also has been described as the driving force of disease incidence (*47*). The relative importance of different causes will depend partly on the scale that is chosen: what time and space-defining windows should be applied depend on the problem in hand.

An investigation of an outbreak of disease will naturally focus on the causes of short-term and localized variations in incidence, but an assessment of long-term future trends in disease is more likely to capture influences that occur upstream in the sequence of causes. If applying the outbreak frame of reference, then climate change is invisible because it is too big to fit into the study picture. This does not mean that climate change is irrelevant, rather that other approaches, on larger scales, are needed to comprehend this particular problem.

General issues concerning uncertainty

The IPCC raises the question (without giving an answer) of whether "science for policy" is different from "science itself". Researchers concerned with producing science for the purpose of informing decision-makers have additional challenges. They need to consider the specific questions asked by particular decision-makers and the time frame in which the questions must be answered. Their research must focus on answering those questions—as best they can—in a timely fashion. They also must characterize all relevant uncertainties and the implications of these for the decisions under consideration. Whether or not the science is able to inform policy, decisions *will* be made under uncertainty. Fundamentally, an informed decision is preferred to an uninformed decision. Are there ways of retaining quantitative estimates, but tempering them with a full description of uncertainty bounds? Possible approaches included in the IPCC report are standardized graphical displays (*1*) and verbal summaries of confidence categories.

The approach taken depends on the information needs of the decision-makers (e.g. public health officials), how the information most usefully can be conveyed to them and the questions they want answered by the assessors. The issue is not so much whether there are different kinds of science or different standards of proof. Really it is a question of the types of methods that exist to inform decision-makers who must make decisions despite the existence of uncertainties. An alternative, perhaps more constructive and useful approach, would be to ask the question: "What would one have to believe is true for the following to happen?" By asking this, there is no judgment on the relative likelihood of an outcome. Rather, the decision-maker is provided with insights into the necessary conditions for an outcome to occur and can then decide the likelihood of those conditions for the particular situation being addressed—and the level of risk.

Studies of perceptions of risk show that values and social positions have an important bearing on the way individuals view environmental hazards (*48*). For this reason it is important to engage stakeholders in the problem formulation phase of an assessment process (to help shape the questions that will be the focus of the assessment), the assessment itself and communication of the results.

Van Asselt and Rotmans liken risk assessment to a group of hikers crossing an unfamiliar landscape (*49*). Although the hikers start together and face the same terrain, it would not be surprising if they choose different routes and, as a result, come to different destinations. The choices made along the way (to cross a dangerous river or take a lengthy diversion, follow footpaths or forge new routes, continue when the weather is threatening or take shelter) depend on past experiences, preferences, interests and preconceptions about the nature of the land ahead.

In a similar manner, no one begins an assessment of the effects of climate change with a completely open mind. Scientists bring to the task expectations, attitudes and values that influence the questions asked, help to make sense of the data and inevitably, shape the meaning given to results. Important dimensions of difference include presumptions about nature (which might be viewed as capricious, benign, forgiving, fragile or any combination of these qualities), the limits of human capacities and priorities given to core values (such as equity and individual liberties). Even between disciplines there may be major differences. A survey of experts in the field found that natural scientists' estimates of the total damage caused by climate change tended to be much greater than those of economists. It was suggested "economists know little about the intricate web of natural ecosystems, whereas scientists know equally little about the incredible adaptability of human economies" (*50*). This is why it is so important to engage different disciplines in the assessment process—and have them converse with one another.

Do multi-disciplinary assessments such as those carried out by the IPCC, underestimate uncertainty? In theory, they might. Collaborations like the IPCC have important strengths: no one discipline holds all the knowledge required to deal with complex environmental problems like climate change. Multi-disciplinary assessments may capture more uncertainties because one discipline may identify matters never thought of by another discipline. For example, an ecologist might identify health outcome sensitive considerations that a public health expert would not. This might increase, not decrease, uncertainties. Conversely, a group with many disciplines may find it more difficult to provide a complete account of uncertainties than is possible when all the authors speak the same technical language. Contingencies tend to be overlooked when scientific debates move from specialized forums to public settings and a similar process has been observed with scientific panels in the past. Wynne states: "Doubts and uncertainties of core specialists are diminished by the overlaps and interpenetrations with adjacent disciplines . . . the net result is a more secure collective belief in the policy knowledge, or the technology, than one might have obtained from any of the separate contributing disciplines" (*51*).

Conclusions

Researchers seek to understand ways in which weather and climate may affect human health and (where they exist) to estimate the size, timing, and character of such effects. For public health scientists and officials the primary goal is to prevent any increases in disease associated with changing weather and climate, while recognizing that the scarce resources available to the public health community may have to be diverted to other higher-priority public health problems. Both scientists and policy-makers are interested in the magnitude of potential effects and their distribution—which regions and which populations most likely will be affected? Why? When? How can vulnerability be reduced and adaptive capacity increased?

The research community has provided some answers to these important questions (including those summarized by the IPCC) but still there is much to be done. It is not just that understanding of the science is never complete. In this instance policy choices will need to be made before all relevant scientific information is available. It would be convenient if a decision on re-setting the global thermostat could be delayed until the health costs and benefits of a warmer world were known. However, climate systems cannot be turned on and off like an air conditioning unit. The considerable lag period between greenhouse emissions and climate impacts, and the large inertia in the climate system's response to perturbations, means that policy-makers must make decisions many years before the full effects are apparent. This means extra pressures on researchers to provide robust scientific advice on climate change and health, as early as possible.

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