

Climate change: present and future risks to health, and necessary responses

■ A. J. McMichael¹ & E. Lindgren²

From the ¹National Centre for Epidemiology and Population Health, The Australian National University, Canberra, Australia, and ²Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden

Abstract. McMichael AJ, Lindgren E (The Australian National University, Canberra, Australia; and Karolinska Institute, Stockholm, Sweden). Climate change: present and future risks to health, and necessary responses (Review). *J Intern Med* 2011; **270**: 401–413.

Recent observed changes in Earth's climate, to which humans have contributed substantially, are affecting various health outcomes. These include altered distributions of some infectious disease vectors (ticks at high latitudes, malaria mosquitoes at high altitudes), and an uptrend in extreme weather events and associated deaths, injuries and other health outcomes.

Future climate change, if unchecked, will have increasing, mostly adverse, health impacts – both direct and indirect. Climate change will amplify health problems in vulnerable regions, influence infectious disease emergence, affect food yields and nutrition, increase risks of climate-related disasters and impair mental health. The health sector should assist society understand the risks to health and the needed responses.

Keywords: cardiovascular diseases, climate change, communicable diseases, health risks, injuries, malnutrition.

Introduction

The concept of human-induced 'global climate change' is both unfamiliar and complex. We have, therefore, not yet recognized the full extent of risks to human societies if climate change continues over coming decades, and perhaps well beyond.

Much of the public discussion of the consequences of climate change has focused on risks to economic conditions, vulnerable industries, physical property, environmental amenity and iconic ecosystems. These are very important social assets, but they are not as fundamentally important as are the health and survival of people. We build our societies to achieve security, amenity, economic gain, skill-sharing and ordered social relations. But these are not ends in themselves; rather, they are the means to enhancing well-being, health and survival. In most countries, the health sector has been slow to recognize the serious implications of climate change for population health and for the health care system. That partly reflects the misleading, individual-focused, model of 'health' and its causation. That model views individuals as free agents, responsible for their own actions, and therefore the primary arbiters of their own health. We are therefore less inclined to enquire how

a population's way of living and its collective environmental conditions influence rates and patterns of health and disease [1, 2]. Without that population perspective we cannot properly understand the health risks posed by climate change, as today's human-induced changes in the global climate, environment and ecosystems are occurring at unprecedented scales that impinge (often by disrupting systems and processes) on whole populations, present and future [3, 4].

Climatic conditions and weather patterns have many consequences for human physiology, health and survival. Some health impacts, as from extreme exposures such as heatwaves, occur directly. However, most climate-related health risks are mediated via the influences of climatic changes and shorter-term weather fluctuations on food yields, water flows, patterns of infectious diseases and the movement or displacement of groups and populations. When climatic conditions change over time, then we should expect changes in patterns of health risks and in population health profiles.

Most health impacts of climate change are likely to be adverse [5]. However, some health benefits will result in some regions – at least in the earlier stages of

climate change. For example, if winter in some temperate countries becomes milder then the usual seasonal excess of winter-time deaths from myocardial infarction and stroke should lessen. Elsewhere, hotter and drier conditions in some regions would reduce the numbers and survival rates of mosquitoes, and hence the risks of malaria and other mosquito-borne infectious diseases.

Climate change: update on recent science

Most of the world's climate scientists agree that emissions into the lower atmosphere of carbon dioxide and other greenhouse gases resulting from human activities are now contributing substantially to the ongoing warming of Earth's surface [6, 7]. This human-induced warming, superimposed on ongoing natural variations in climate, is now well evident in scientific observations. The extent and the particular pattern of warming cannot be explained by other natural factors (changes in solar activity, volcanic eruptions, aerosol pollutants).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stated, with over 90% certainty, that human activity has been the primary cause of the temperature rise since 1950. Specifically, the report stated that '*most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*' [6]. Of further relevance, 2010 has been reported as the hottest year, globally, in the instrumental record (i.e. since 1860) by the US-based Goddard Institute for Space Studies (NASA), the National Climatic Data Center (US National Oceanic and Atmospheric Administration), the Japanese Meteorological Agency and the UK Meteorology Office's Hadley Centre (Climatic Research Unit) (See also Fig. 1).

In considering 'climate change', the distinction between climate and weather is important. By statistical analogy, climate represents the 'mean' and weather represents the 'variation'. Weather varies from day to day. Climate differs across seasons and between regions; it also undulates from century to century. Hence, the clearest evidence of global climate change comes from considering the whole globe and observing changes from decade to decade.

Earth's average surface temperature has increased by approximately 0.8 °C over the last 130 years, see Fig. 1. This amount of warming is unusual relative to the range of average global temperatures over at least

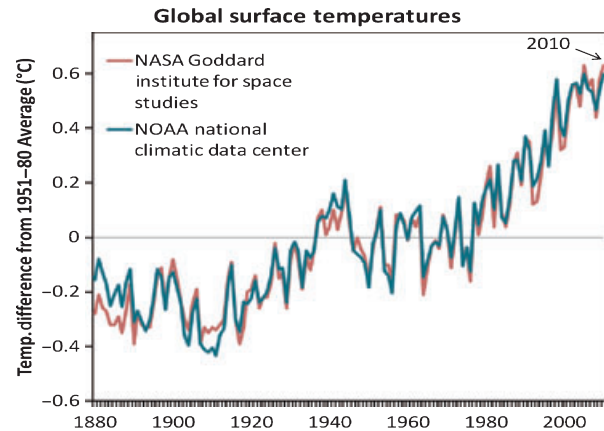


Fig. 1 Observed global surface temperatures 1880–2010. The figure shows temperature time-trends from two independent data sets (Source: Goddard Institute for Space Studies, NASA, 2011 [9]).

the last 1800 years. Based on a range of proxy measures of temperature, the global temperature over the past two decades has risen by around 0.5 °C above the apparent peak temperature of the mediaeval period [8, 9]. Further, from a geological perspective, the current warming is very rapid. The poles are warming three to four times faster than are the low latitudes [5]. Additional warming (approximately 0.6 °C) is already 'committed' within the slow-responding climate system. Further emissions in coming decades will lead to increasing, and potentially dangerous, climate change [3].

The warming of Earth's surface is manifested in various ways. This includes a significant temperature increase in the upper ocean, rising sea levels, diminishing Arctic sea ice, and shrinkage of most glaciers and snow cover [7, 10]. There are many published reports from all over the world of apparent effects of these climatic and environmental changes on plants (flowering, growth rates, changes in range) and animals (nesting breeding, feeding, migrating, etc.) [5, 7].

If human-generated emissions of greenhouse gases continue to rise unchecked, Earth may warm by more than 4 °C by the end of the century. Some local temperature increases, especially at high latitudes, would be even higher. This would seriously affect the viability of many plant and animal species, as well as agricultural yields, freshwater availability, human health and physical built infrastructure. The current scientific consensus is that a rise greater than 2 °C

would move the planet, and ourselves, into 'dangerous' territory [3, 8]. The combined concentration of carbon dioxide (CO₂) and other greenhouse gases (methane, nitrous oxide, etc., measured as 'CO₂-equivalents') has increased substantially above preindustrial levels and has now reached a level of around 460 p.p.m. of CO₂-equivalents (to which CO₂ itself now contributes 393 p.p.m. – i.e. 40% above its preindustrial level of 280 p.p.m.). This already-existing level, if sustained over coming decades, would confer an estimated 50% probability of translating into a 2 °C rise by mid-century [6].

Assessing the significance of climate change

An important recent paper in the scientific journal *Nature* asked: How close are we to environmental safety limits on this planet, as we deplete and disrupt the Earth System? [3] Climate change was one of ten such domains of environmental concern. For three of those 10, (biodiversity loss, disruptions to the global nitrogen cycle and global climate change) the authors concluded that human actions have already caused more change than is safe for humanity's future.

Climate change can have impacts on human society and biology on its own. More often it acts jointly with other environmental changes, influencing processes such as the productivity of our food-producing systems, the breeding of mosquito populations or the functional integrity of ecosystems. Human-induced climate change is thus part of a *syndrome* of macroscopic environmental consequences of the unprecedented pressures that humans are now exerting on this planet. During last century, human numbers increased fourfold, combined with a threefold increase in average amount of energy used per person. The resultant order of magnitude increase in overall economic activity caused commensurate increases in stresses on the environment, including via the release of additional greenhouse gases into the atmosphere.

How worried should we be over a possible average global increase of 2–5 °C within the coming century – a range now widely regarded as possible, given current trends and plausible future human behaviours? In fact, both the size and the speed of change are cause for concern. It is instructive to compare those possible temperature rises with the timetable of Earth's gradual cooling over the last 35 million years. Very approximately, and recognizing some uncertainty in proxy measurements of paleotemperature, these are the equivalent time lapses as those higher temperatures prevailed [11]:

- 2 °C warmer than now 5 million years ago Arctic sea ice began forming;
- 3.5 °C warmer than now 10 million years ago West Antarctic ice sheet was forming;
- 5 °C warmer than now 15–25 million years ago East Antarctic ice sheet was forming.

How far do we dare to turn back the 'temperature clock'?

Health risks from climate change

Climate change is not just another discrete environmental health 'hazard'. It differs qualitatively from the very familiar category of locally acting, toxicological, environmental health hazards (such as pesticides, heavy metals, asbestos, ionizing radiation) (Fig. 2). Climate change is a complex phenomenon entailing altered conditions and processes that can alter the rates, ranges, seasonality and patterns of injury, disease and death. Except for some direct effects on health from increases in extreme weather conditions and events, it is not the climate itself that affects human health; rather, the health consequences result from the environmental, ecological and social impacts of a changing climate.

The most obvious health risks are from extreme events – especially heatwaves, storms, cyclones, fires and floods. In the medium to longer term, however, the wider spectrum of health consequences of climate change will encompass shifts in patterns of various infectious diseases, changes in regional food yields and nutritional quality, health consequences of diminished water flows in many

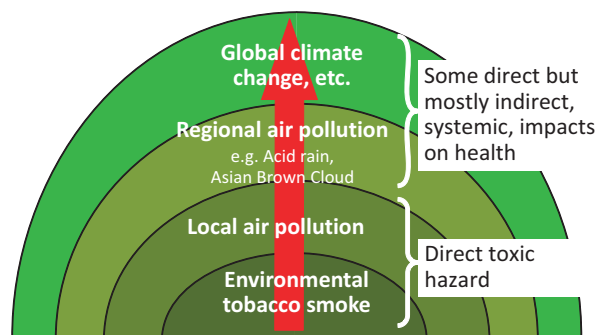


Fig. 2 Environmental health risks: Scale and type – from local direct-acting hazard to global system disruption.

regions, impacts on morale and mental health from environmental disruptions and threats and adverse consequences for remote (including many indigenous) communities because of adverse environmental changes.

The main categories of environmental disruption and changes that mediate the impacts of climate change are shown in Table 1, as are the main categories of health risks.

The research agenda: Estimating the health risks and impacts

To elucidate the health risks posed by climate change, present and future, three main categories of research (illustrated in Fig. 3) are needed:

- 1 Learning more about climate–health relationships by studying the impacts of recent variations and trends in climatic variables. This is ‘orthodox’ epidemiological research.

Table 1 *Climate change and human health: causal processes, paths and consequences. Changes in climate affect many biological, ecological and geophysical factors (e.g. water flows, sea level) and social conditions. These changes, via direct or indirect paths, then influence human well-being, health and survival. (Modified from: [61]: <http://www.thecommonwealth.org>)*

Causal processes and pathways that mediate the impacts of climate change include:

Changes in the range and extremes of ambient temperature (and associated air quality)

Frequency and intensity of weather disasters (floods, storms, fires)

Rainfall, temperature and soil moisture as determinants of crop yields and livestock and fisheries yields – and hence food supplies, food quality and human nutrition

Impacts of the above declines in food-system yield on social and economic well-being of farming and fishing families and communities

Rates of spread and multiplication of pathogens (i.e. viruses, bacteria and other microorganisms) and toxins (e.g. shellfish poisoning, mycotoxins, cyanobacteria)

Numbers, range and activity of vector species (e.g. mosquitoes, ticks, sandflies) that transmit some infectious diseases

Numbers, range and activity of non-human host species (e.g. rodents, bats) that naturally harbour (‘zoonotic’) infectious agents able to cause human infectious disease

Stocks/flows of water (rainfall catchment, glaciers/snowpacks, groundwater recharge)

Sea level (rise) and its consequences for local storm surges, water quality, fisheries, etc.

The likely resultant direct impacts include:

Consequences of extreme temperature episodes: deaths, hospitalizations (myocardial infarction, stroke, respiratory disorders, etc.)

Deaths, injuries and poisonings owing to extreme weather events/disasters (other than heatwaves)

Respiratory disorders owing to increased concentrations of ground-level ozone and other climate-affected air pollutants:

Increased concentrations of certain allergens (pollen, spores, moulds) as causes of asthma and allergic disorders

The likely resultant indirect and more diffuse impacts include:

Delayed health impacts of extreme events/disasters: food shortages, epidemics, mental health disorders, etc.

Nutritional (especially child developmental) consequences of declines in:

Agricultural food yields, causing lowered nutritional quality

Seafood harvests owing to changes in ocean temperature, currents and acidity

Infectious disease owing to altered water flows and/or increases in temperatures leading to contamination of food and water; also, health risks from water shortages (affecting hygiene and sanitation)

Indirect health impacts of changes in ecosystems or species that mediate zoonotic or vector-borne infectious diseases (malaria, dengue fever, hantaviruses, leishmaniasis, Lyme disease, schistosomiasis, Henipah virus, etc.)

Health consequences, including mental health disorders, of loss of rural livelihoods, property loss, displacement and conflict (over dwindling natural resources)

- 2** Seeking evidence of any actual changes in rates, ranges or other aspects of health outcomes that are known or suspected to be sensitive to climate.

As a supplement to Category 2, the proportion of the current rate, or population health burden, of Disease X that is attributable to climate change can be estimated. This requires good quantitative risk-function information from Category 1 research listed above. This approach was used in a major, pioneering, assessment coordinated by WHO (Geneva), to assess, for the year 2000, the proportions of undernutrition, malaria, diarrhoeal disease, deaths and injuries from flooding and health impacts of temperature extremes that were reasonably attributable to the small amount of climate change that had already occurred [12]. Approximately 160 000 deaths were deemed attributable, and nearly all of these (155 000) were owing to amplifications of the first four of those causes, occurring almost entirely in low-income and middle-income countries.

More generally, it is now becoming standardized practice for national governments to conduct assessments of risks to the health of their population from climate change, using several such methods and approaches [13].

- 3** Modelling (or otherwise estimating) the future health risks, in specified populations or regions, owing to plausible scenarios of climate change. These geo-gridded scenarios are generated by climate science modellers, using global, regional or more localized, integrated, climate models.

Category 1

Epidemiologists have, until recently, had little interest in the climate as an influence on human health (although some of the better-quality studies on the health impacts of air pollution have included ambient temperature as a confounding factor). Much 'catch-up' empirical research is therefore now being performed, studying the relationship between recent past variations in local climatic conditions and rates of various health outcomes.

Category 2

Identifying population health changes that can reasonably be attributed to recent, slowly evolving, climate change is a complex task. In these early stages of human-induced climate change, therefore, there is limited evidence of *changes* in climate actually affecting health outcomes. The task is compounded by the fact that most health outcomes in humans are influenced by multiple factors, and, further, that the human species is buffered (by housing, infrastructure, trade, water engineering, food aid and other social factors) against many of the immediate (and not yet severe) risks arising from climate change. Hence, wealthier, well-governed and geographically lower-risk societies may notice little adversity during the initial stages. Meanwhile, however, vulnerable populations elsewhere are already being affected.

There is, nevertheless, suggestive evidence of some health changes occurring that are reasonably attributable to the recent climate change [14]. This

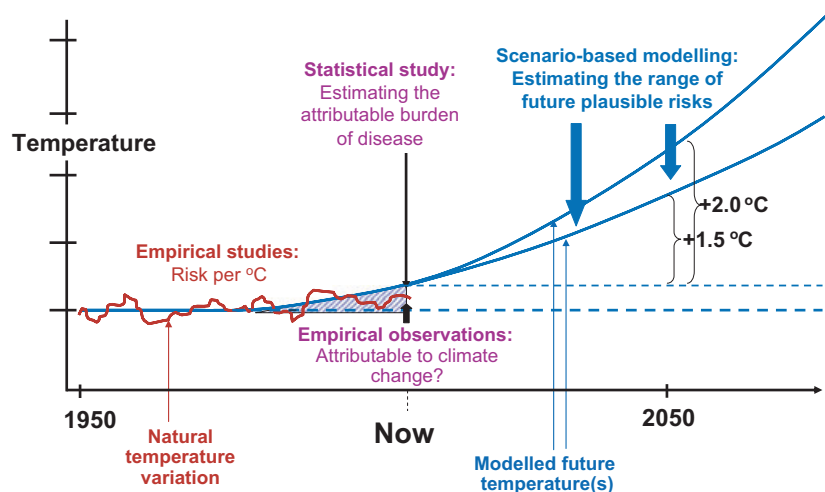


Fig. 3 Schematic representation of four categories of research needed to identify, quantify and forecast the impacts of climate change on health. This encompasses empirical studies of the past and present, and modelling studies of the future.

includes reports of: (i) an uptrend over recent decades in deaths, injuries and other adverse health impacts from cyclones, storms, wild fires and flooding; (ii) an increase in annual deaths from heatwaves in several countries; (iii) shifts in the range and seasonality of some climate-sensitive infectious diseases; (iv) adverse mental health consequences in farming communities affected by drying; and (v) impairment of food yields (and hence the risk of malnutrition-related child development) in some already food-insecure populations.

Category 3

The unusually long-term, and continually escalating, character of climate change as an 'environmental exposure' means that research attention must also be focused on the future. With increasing knowledge of the determinants of local climatic conditions, and with heightened computing power, increasingly high resolution projections of future temperature and rainfall are becoming possible. The empirical knowledge from Category 1, above, can then be applied to estimating how those local scenarios of climate change would affect the risks of particular health outcomes in future. How will the maps of malaria and dengue fever change in future, region by region, as local temperatures rise, rainfall alters, and humidity changes – taking into account, also, the regional population's vulnerability? How will staple food yield be affected by climate change and by more (or less) frequent weather disasters, and how will this affect the levels of nutrition, starvation and child deaths?

Direct health impacts

Extreme weather events

Regional weather patterns are anticipated to become more variable, more unstable, as global warming proceeds [6]. Extreme events may become more intense, and perhaps more frequent. However, this future trend in climate variability is technically not yet easy to model at a regional scale. The climate system is inherently chaotic in its short-term behaviour, and most extreme weather events are determined by the interactive combination of several geophysical components of the climate system.

Weather disasters, such as the major cyclones that have struck vulnerable coastal populations of Bangladesh, Myanmar, the Philippines and Vietnam in recent years, cause many injuries and deaths and damage crops, livestock and housing. The year 2010

was not only one of the two hottest years in the 150-year instrumental (thermometer) record; it was also a year of extreme weather events. Severe weather disasters occurred in North America, much of Europe, and in the greater Eurasian region encompassing Russia, Pakistan, China and Southeast Asia. In that Eurasian region, the combination and scale of flooding (Pakistan and China), landslides (China), extreme heatwaves (Russia, China, Vietnam) and wild fires (Russia) during mid-2010 was, literally, extraordinary. In European Russia, an excess of 54 000 deaths is estimated to have occurred during July–August 2010 owing to the combination of heat and smoke (Boris Revich, personal communication).

In many regions, the increase in population size and density will force people, in particular in low-income countries, to relocate – often into areas where the tempo of extreme weather events will be increasing.

Temperature extremes

Temperature extremes that exceed physiological coping capacity also affect bodily functioning, mood and behaviour. This usually happens at temperatures above 30 °C (the exact 'threshold temperature' depends on the prevailing climate and population acclimatization) and is modulated by humidity, wind movement and heat radiation. This has particular relevance to segments of the workforce exposed to extremes of ambient temperature – more specifically, exposure to extreme heat stress that can cause dehydration, organ damage, fatigue and risk-prone behaviour [15, 16].

Heatwaves kill people, primarily by causing myocardial infarction, strokes, respiratory failure and heat stroke. The August 2003 heatwave in Western Europe caused an estimated 40 000–50 000 deaths, especially in older persons and people in any age group with lung disorders and cardiovascular diseases [17, 18]. Populations differ widely in the shape of their temperature-mortality risk function. In temperate countries, there is typically an unsymmetrical U-shaped curve – with a steeper right-hand side (at high temperatures), and a shallower left-hand side (at colder temperatures) [19].

In some countries, warmer winters may reduce the number of temperature-related deaths and other health events, as exposure to extremes of cold recedes. However, this would not apply in populations that currently do not exhibit an upturn in risk of death at colder daily temperatures – such as the

population of Delhi, India [20]. Meanwhile, it has not been easy to quantify the relative health losses from greater heat extremes and health gains from lessened cold extremes, particularly because there is no directly corresponding, acute, 'cold-wave' equivalent of a heatwave. Many of the excess deaths that occur in winter-time relative to other seasons (e.g. in the UK) appear to be related to influenza epidemics and seasonal changes in living conditions.

Sea-level rise

The annual rate of sea-level rise has increased over the past two decades, relative to preceding decades [21–23], largely because of an upturn in the contribution of ice-sheet melting, in addition to thermal expansion [22, 24]. Recent estimates indicate that as the rate of ice-sheet melting (currently approximately 3 mm per year) increases, a rise of one metre or more could occur by the end of this century [23].

Sea-level rise poses direct and indirect risks to health and jeopardizes social stability. It is therefore a crucial issue for many low-lying small island states in the Pacific and Indian Oceans, the Caribbean, and elsewhere, and for low-lying (continental) coastal populations and river delta regions. A one-metre rise would inundate an area of Bangladesh currently inhabited by around 40% of its total population. It would displace more than 20 million people along the vulnerable coastal regions of Bangladesh, Egypt and Nigeria – without allowance for future population growth [7, 25].

The direct risks include the physical hazards from coastal inundation, more extensive episodes of flooding, and increasingly severe storm surges (especially at times of high tide). Damage to coastal infrastructure (roads, housing and sanitation systems) would all pose direct risks to health.

The indirect risks to health include the salination of freshwater supplies (a particular problem for many small islands) [26], the loss of productive farm land and changes in breeding habitats for coastal-dwelling mosquitoes. Sea-level rise is already endangering food yields, freshwater supplies and physical safety in several low-lying small island states [27, 28].

Air quality

Higher temperatures also affect the formation, dispersal and (less certainly) the biological impact of various air pollutants. Ozone, a major urban air

pollutant, forms more readily from air pollutant precursors from car exhausts ('volatile organic compounds') at higher temperatures. Much of the huge mortality excess caused by the August 2003 heatwave in Western Europe may have been due to the coexistent high levels of ozone in and around some of the big cities – high levels that, indeed, may themselves have been partly attributable to the unusually high temperatures potentiating ozone formation [29, 30].

The range, volume and seasonality of pollens and spores ('aeroallergens') are also affected by temperature, rainfall and humidity. Associated increases in incidence of hay fever and asthma have been reported in some urban populations [31].

Indirect pathways

The word 'indirect' spans a range of different types of complex, multi-stepped, diffuse or deferred causal paths.

Droughts, predicted to become more frequent and severe in many (especially subtropical) regions under climate change, offer a good illustration. Droughts cause hunger, starvation, displacement and misery; farming jobs are lost, rates of depression increase, as do suicide rates, especially in farmers. The extent of the resultant social and psychological distress is influenced by the 'resilience' of the community, reflecting the level of social capital available to confer flexibility and coping capacities [32].

Water insecurity

Water and food are essential to health and survival. Water scarcity impairs domestic and communal hygiene, reduces farm yields and can increase water-borne infectious diseases (cholera, other diarrhoeal organisms, cryptosporidium, etc.). In more extreme situations, water scarcity readily becomes a cause of tension and open conflict, with inevitable adverse health consequences.

Climate change will exacerbate water insecurity in many regions. In Africa, where 300 million people are already water insecure, climate change is likely to greatly increase this number. Increased water insecurity is particularly likely in the world's subtropical regions, including the Sahel and southern Africa, northern India, southern Spain and Italy, southern Australia and mid-latitude South America. Concerns are also rising in regions such as Bangladesh, Myanmar

and the Mekong River basin and delta, where Himalayan glacier loss is beginning to affect flows, and where inter-country tensions loom because of the likely upstream damming and diversion of major river flows.

Food insecurity

Food insecurity remains widespread. The Food and Agricultural organization [33] estimates that in 2009, over one billion people were undernourished. This number has increased by around one-fifth since the late 1990s. Food production systems in many regions are coming under multiple stresses – from water shortage, soil exhaustion, biodiversity losses (which can affect pollination, control of pest species and soil nutrients) and climate change. The direct effects of higher temperature and reduced soil moisture are well known to affect photosynthesis. Studies from the International Rice Research Institute in the Philippines show that a 1 °C rise in night-time temperature can reduce rice yields by 10% [34].

Modelling studies have consistently projected that overall, climate change will negatively affect global food yields [35]. The impacts, however, will occur unevenly: Some temperate regions may benefit, whilst countries in the tropics and subtropics, where both warming and reduced rainfall are projected, are at greatest risk of yield reductions. In many low-income countries, the livelihoods, well-being and health of smallholder and subsistence farmers are particularly threatened [36]. Many studies indicate that South Asia is likely to experience declines in total cereal grain yields of the order of 10–20% by later this century [37].

As ocean temperatures rise, various fish populations are anticipated to move to higher latitudes. Such shifts will affect supplies of dietary protein, and livelihoods, in much of coastal Africa, many small island states, and large Asian river deltas. Ocean fisheries provide over 2.6 billion people with one-fifth of their protein intake.

Many model-based estimates are likely to be conservative. They are unable to take account of the episodic, perhaps ‘surprise’, climate-related events that will cause great damage to yields and harvests. Climatic conditions also affect the likelihood of damage by pests and pathogens to crops and livestock. The recent northwards extension of the blue-tongue virus from its base in Southern Europe, in association with

warming over the past decade, poses an economically catastrophic threat to cattle and sheep populations in Europe [38] – and to many farming families and agricultural workers.

Translating projections of climate-related harvest deficits into an estimation of the burden of disease and functional impairment (including intellectual development in children) from undernutrition is a complex and inexact task. Further, countries differ greatly in the extent to which climatic conditions determine food availability, relative to nonclimate factors such as social policies relating to local food access.

Infectious diseases

Many infectious diseases are sensitive to climatic conditions, see Fig. 4. Temperature, rainfall and humidity variously affect the replication, maturation and viability of the pathogen, the vector organism (where applicable), and the range and abundance of any reservoir or intermediate animal species. For example, disease-transmitting insects are ‘cold-blooded’ and thus very sensitive to temperature. They are also easily desiccated if conditions become too dry.

Many microorganisms multiply more rapidly in food and in nutrient-loaded water in warmer conditions. Studies in several countries, including the UK, Australia and Canada, have shown that the incidence of salmonella food poisoning varies positively in relation to short-term (e.g. weekly) temperature variation. Changes in rainfall patterns affect river flows, flooding, sanitary conditions and the spread of various

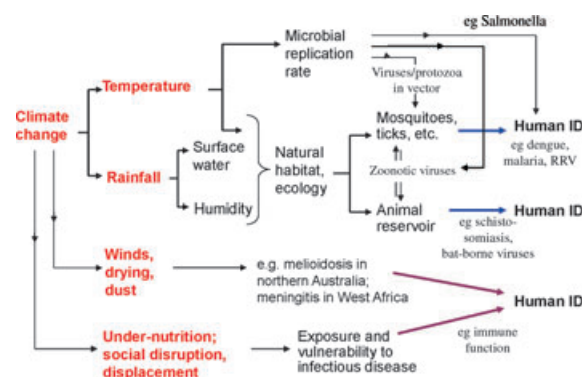


Fig. 4 Climatic influences on infectious disease (ID) occurrence: multiple pathways, varying complexity.

diarrhoeal diseases, including cholera. A reasonable expectation is that, with continued warming, the range and incidence of food-borne and water-borne infections will tend to increase – as was apparently foreshadowed by the recent emergence of coastal seafood contamination with *Vibrio parahaemolyticus* around the northern coast of Alaska when the summer temperature of coastal water, having gradually increased over the preceding decade, reached a critical temperature [39].

Zoonotic (animal-derived) infections are transmitted by air, food, water or vector organism (e.g. mosquitoes, fleas and ticks). Climate change can affect zoonotic infections in two main ways, by influencing: (i) the geographic range or abundance of animal reservoirs or insect vectors or (ii) the length of transmission cycles. Meanwhile, by affecting human mobility or the long-distance viability of vector organisms or animal reservoirs (e.g. by sea or air), climate change may also enable the introduction and establishment of ‘novel’ infectious diseases in new regions.

Modelling studies show that under projected climate change conditions, the range of tick-borne Lyme disease is likely to increase substantially in Canada [40] and in Europe [41]. In Canada, where temperature determines the northern limit of the ixodic tick populations, research indicates that tick abundance may extend a further 200 km northwards by the year 2020. Similar modelling has projected a northern extension of schistosomiasis zone (for which water snails are the intermediate host), in response to warming over the coming half century [42]. Biomathematical modelling of the (nonlinear) dynamics of vector-borne disease transmission shows that a small temperature rise can substantially heighten transmission probability. Hence, where malaria has recently increased alongside warming, as in parts of eastern Africa – or as with tick-borne encephalitis in the Russian Arctic – a reasonable inference is that the climate trend partly explains the observed increase [43, 44].

Many zoonotic infections are also influenced by climate-related changes in either density or movement of the ‘reservoir’ animal species. Examples include: West Nile Fever (Europe, USA and Canada: birds as reservoir), Rift Valley Fever (Africa: cattle), Ross River Virus (Australia: kangaroos), tick-borne encephalitis (Europe: mouse) and, perhaps, Nipah Virus (Malaysia: from displaced forest bats, to battery-farmed pigs, and thence to human handlers).

Some vector-borne infections appear to have undergone a recent increase in their geographic range in association with regional warming and altered length of seasons. This includes malaria in some eastern African highlands [45], tick-borne encephalitis and Lyme disease at higher altitudes in Czech Republic [46] and the spread of ixodic ticks to higher latitudes in Sweden [47].

Social disruption and population displacement

Climate change will displace many people and communities, as local food yields falter, as freshwater supplies decline, as coastal inundation occurs and as the regional tempo of extreme weather events changes. This increase in human movement – both deliberative migration and involuntary refugee flows – will occur within States and across international borders [5, 48]. Estimates of the likely numbers of persons displaced by climate change vary, with projected numbers typically approximating several hundred million by 2050 [48]. In 2008, the UN High Commissioner for Refugees projected that climate change will be a major contributor, over coming decades, to the anticipated overall surge in human displacement.

Many poor urban communities are situated in parts of cities that are at high risk of climate change impacts – from floods, storms and landslides. Further, much of the climate change-related displacement will occur in developing regions where public health resources are inadequate [48, 49]. Hence, rural people migrating into these settings may face heightened environmental and, hence, health threats.

Displacement typically entails increased risks to health from undernutrition, infectious diseases, conflict situations, mental health problems – and from changes in health-related behaviours such as alcohol consumption, tobacco smoking and transactional sex [50]. Indeed, the mental health consequences of these social and cultural disruptions, and of associated perceptions of future threats, pose a substantial and growing risk to health. Children, in particular, are likely to be at increased risks to mental health, emotional development and physical health and safety from impacts of climate change, including extreme weather events [51]. In the wake of Hurricane Floyd in North Carolina, in 1999, the incidence of child abuse within families rose, in association with increased parental stress and reduced social support. Elsewhere, following a hurricane in the USA, there was a fivefold increase in the

rate of inflicted head injury in children aged <2 years [52].

Risk management: adaptive strategies

Climate change mitigation (i.e. the reduction in greenhouse gas concentrations in the atmosphere) is, necessarily, the first-order task for governments. However, as climate change is already occurring and further change is already 'locked in', as previously described, adaptive strategies are required to protect against increasing risks to health.

Some adaptation will occur spontaneously (for example, gradual physiological adjustment to living at higher temperature), but most adaptation must be explicitly planned (deliberate). Examples of planned adaptation include early-warning systems for extreme weather events, physical protection against such events, improved 'surge capacity' (disaster preparedness) of health and emergency sectors, enhanced infectious disease surveillance, vaccination programs, greater crop diversity (including selected climate-resistant cultivars), stronger social networks and the enhancement of community resilience.

A key component of adaptation, particularly in many lower-income countries, will be to reinforce public health capacity and action. Wherever the preexisting disease rates, such as child diarrhoea, are already high, a further multiplicative increase in rates, owing to climate change, would significantly add to the disease burden. However, by lowering the background rates in advance, much of the threatened absolute increase owing to climate change can be averted. This remains a major challenge because substantial differences persist in material and social conditions

and, hence, in health status and life expectancy between subgroups and regions [53]. Many health inequalities are at risk of being exacerbated by the environmental and social consequences of climate change [54].

Many adaptive strategies to protect health will require coordinated inter-sectoral action, often extending well beyond the capacity of the health sector. Meanwhile, the health sector must also adapt its own capacities and priorities – such as widening the geographic range of infectious disease surveillance programs. In many settings, institutions (hospitals, ambulance services, etc.) will need greater capacity to respond to the impacts of extreme weather disasters. Primary health carers will have an important educational and supportive role to play, both for communities and families.

Adaptive strategies should address three important considerations: (i) immediate cost-effectiveness; (ii) longer-term protection from the 'climate-proofing' of settlements, institutions and societies; and (iii) equity. That third consideration underscores the central issue of 'vulnerability'.

Differences in vulnerability

Vulnerability to the impacts of climate change is a function of, first, location and associated level of external climatic exposure, and, secondly, the status, conditions and adaptive capacity of the exposed population.

The brunt of adverse health impacts of climate change – at least in its earlier stages – will mostly be borne by low-income and geographically vulnerable

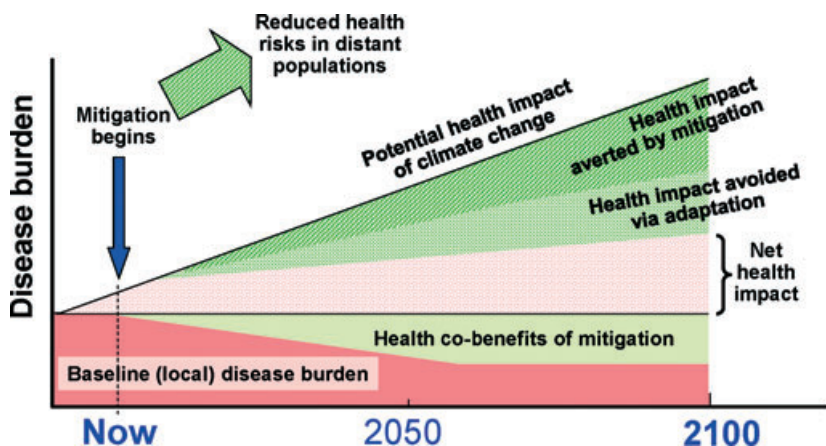


Fig. 5 Reducing the health impacts of climate change via primary (mitigation) and secondary (adaptation) prevention. Note, too, the 'bonus' health co-benefits that can accrue to local populations that undertake community-wide mitigation actions.

populations [50]. Bangladesh is illustrative: its high vulnerability reflects the nation's widespread poverty and food insecurity, a large and densely settled population, high existing rates of 'tropical' infectious diseases, a large coastal population exposed to cyclones and storm surges, and, increasingly, changes to major river water flows from heightened torrential monsoon downpours, melting Himalayan glaciers, and threats of damming by China and India.

Meanwhile, populations in higher-income countries also display gradients in vulnerability. In the USA, for example, the physical and mental health impacts of the severe heatwave in Chicago in 1995 [55] and Hurricane Katrina in New Orleans in 2005 differed markedly amongst ethnic and socio-economic groups [56].

Mitigation: A special opportunity for influence by the health sector

The preceding text has explored the risks to global health from climate change. From the health sector's perspective, the primary prevention task is, as stated, to arrest human-induced climate change (Fig. 5). Here lies a particular opportunity for the health sector to reinforce society's commitment to undertake mitigation action – by promoting the *positive* message that many mitigation strategies will also yield additional, near-term, health gains to any local population that takes such action.

The following are examples of 'co-benefits' to human health from local mitigation strategies that reduce atmospheric greenhouse gas concentrations:

- A reduction in fossil fuel combustion (e.g. from power generation, traffic and other sources) will improve urban air quality and thus decrease respiratory and cardiovascular diseases [57].
- Reduced use of wood burning and other biomass for indoor cooking (commonly used in rural India, China and parts of Latin America) will improve indoor air quality and health amongst women and children.
- Increased use of public transport, cycling and walking will increase physical activity, reduce obesity and stimulate social contacts [57].
- In high-income countries, where the average daily intake of red meat exceeds dietary needs, a reduction in meat consumption – especially meat from cattle, sheep and other ruminants that produce much enteric methane, with its much greater

warming effect than carbon dioxide – would confer both human health and local environmental gains [58].

- Reforestation projects would help to restore dietary diversity in some regions, as well as medicinal substances and other health-related materials [59].

Conclusion

Over the past 150 years, the harnessing of fossil fuel energy and major technological advances in industry and agriculture have yielded great (albeit unevenly shared) gains in population health. Now, though, the wider environmental consequences of those intensified and expanded economic activities are beginning to jeopardize the natural environmental foundations of human population health. Human-induced climate change is a major, and clear, example. The topic is of great importance because, if human-induced climate change continues for long, there will inevitably be many, predominantly adverse, consequences for human health.

Research on health risks posed by climate change is relatively new, and research concepts, strategies and methods are rapidly evolving. There are still many information gaps to fill, ranging from basic understanding of relationships between various climate factors and health to complex assessments of ongoing impacts and scenario-based modelling of future changes in risks. Cross-linkages are evolving between disciplines to enable research that better elucidates the consequences of climate change.

As the understanding of climate change impacts on the environment, human societies and human biology increases, it becomes clearer that the risks to human well-being, health and survival are the real 'bottom line' issue. Nearly all of the other adverse impacts of climate change (food yields, water flows, sea-level rise, infrastructural damage, etc.) will converge on human biological well-being. The health sector therefore has an opportunity to engage in the arresting of this potentially great, emerging, source of risk to human health [60]. This includes promoting research, educating health personnel, informing both public and policy-makers about present and future risks and the preventive actions needed and contributing to overall mitigation effort by working to lower the 'carbon footprint' of the health care system.

Conflict of interest statement

No conflicts of interest to declare.

References

- Rose G. Sick individuals and sick populations. *Int J Epidemiol* 2001; **30**: 427–32. discussion 433–4.
- McMichael AJ. Prisoners of the proximate: loosening the constraints on epidemiology in an age of change. *Am J Epidemiol* 1999; **149**: 887–97.
- Rockström J, Steffen W, Noone K *et al*. A safe operating space for humanity. *Nature* 2009; **461**: 472–5.
- Steffen W, Grinewald J, Crutzen P, McNeill J. The Anthropocene: conceptual and historical perspectives. *Philos Trans R Soc Lond B Biol Sci* 2011; **369**: 842–67.
- Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Parry ML, Canzani OP, Palutikof JP *et al*, eds. Cambridge, New York: Cambridge University Press, 2007.
- Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon S, Qin D, Manning M *et al*, eds. Cambridge, UK and New York, NY: Cambridge University Press, 2007.
- Richardson K, Steffen W, Liverman D (eds). *Climate Change: Global Risks, Challenges and Decisions*. Cambridge: Cambridge University Press, 2011.
- US National Research Council of the National Academies. *Surface Temperature Reconstructions for the Last 2,000 Years*. Washington, DC: The National Academy Press, 2006.
- NASA [homepage on the Internet]. Goddard Institute for Space Studies-GISS [updated 18 Jan 2011; cited 31 March 2011]. *Surface Temperature Analysis (GISTEMP)*. Available at: <http://data.giss.nasa.gov/gistemp/2008/>; <http://www.giss.nasa.gov/research/news/20110113/>.
- Pritchard HD, Arthern RJ, Vaughan DG, Edwards LA. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature* 2009; **461**: 971–5.
- Hansen J, Sato M, Kharecha P *et al*. Target atmospheric CO₂: where should humanity aim? *Open Atmos Sci J* 2008; **2**: 217–31.
- McMichael A, Campbell-Lendrum DH, Kovats RS *et al*. Global climate change. In: Majid E, Lopez AD, Rodgers AA, Murray CJL, eds *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*. Geneva, Switzerland: World Health Organisation, 2004; 1543–650.
- Lindgren E, Ebi K. *Climate Change and Communicable Diseases in the EU Member States. Handbook for National Vulnerability, Impact and Adaptation Assessments*. ECDC Technical Document. Stockholm, Sweden: European Centre for Disease Prevention and Control, 2010.
- McMichael AJ, Bertollini R. Risks to human health, present and future. In: Richardson K, Steffen W, Liverman D, eds *Climate Change: Global Risks, Challenges and Decisions*. Cambridge: Cambridge University Press, 2011; 114–6.
- Kjellström T. Climate change, direct heat exposure, health and well-being in low and middle income countries. *Glob Health Action* [serial on the internet] 2009 [cited 31 March 2011]. Available at: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2780846/>
- Kjellström T, Kovats RS, Lloyd SJ *et al*. The direct impact of climate change on regional labor productivity. *Arch Environ Occup Health* 2009; **64**: 217–27.
- Robine JM, Cheung SL, Le Roy S *et al*. Death toll exceeded 70000 in Europe during the summer of 2003. *C R Biol* 2008; **331**: 171–8.
- Fouillet A, Rey G, Laurent F *et al*. Excess mortality related to the August 2003 heat wave in France. *Int Arch Occup Environ Health* 2006; **80**: 16–24.
- McMichael AJ, Woodruff R, Hales S. Climate change and human health: present and future risks. *Lancet* 2006; **367**: 859–69.
- McMichael AJ, Wilkinson P, Kovats SR *et al*. International study of temperature, heat and urban mortality: the 'ISOTHURM' project. *Int J Epidemiol* 2008; **37**: 1121–32.
- Rahmstorf S, Cazenave A, Church JA *et al*. Recent climate observations compared to projections. *Science* 2007; **316**: 709.
- Domingues CM, Church JA, White NJ *et al*. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 2009; **453**: 1090–3.
- Church JA, White NJ. Sea-level rise from the late 19th to the early 21st century. *Surv Geophys* [serial on the internet] 2011 [cited 16 April 2011]. Available at: <http://www.springerlink.com/content/h2575k28311g5146/>
- Rignot E, Velicogna I, van den Broeke MR *et al*. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys Res Lett* 2011; **38**: L05503.
- Allison NL, Bindoff RA, Bindenschadler PM *et al*. *The Copenhagen Diagnosis: Updating the World on the Latest Climate Science*. Sydney, Australia: The University of New South Wales, Climate Change Research Centre (CCRC), 2009.
- White I, Falkland T, Metutera T *et al*. Climatic and human influences on groundwater in low atolls. *Vadose Zone J* 2007; **6**: 581–90.
- Perch-Nielsen SL, Bättig MB, Imboden D. Exploring the link between climate change and migration. *Clim Change* 2008; **4**: 375–93.
- Kelman I. Island security and disaster diplomacy in the context of climate change. *Les Cahiers de la Sécurité* 2006; **63**: 61–94.
- Dear K, Ranmuthugala G, Kjellström T *et al*. Effects of temperature and ozone on daily mortality during the August 2003 heat wave in France. *Arch Environ Occup Health* 2005; **60**: 205–12.
- Kinney PL. Climate change, air quality, and human health. *Am J Prev Med* 2008; **35**: 459–67.
- Beggs PJ, Bambrick HJ. Is the global rise of asthma an early impact of anthropogenic climate change? *Environ Health Perspect* 2005; **113**: 915–9.
- Berry HL, Bowen K, Kjellström T. Climate change and mental health: a causal pathways framework. *Int J Public Health* 2010; **55**: 123–32.
- Food and Agricultural Organization. *The State of Food Insecurity in the World, 2009*. Rome, Italy: FAO, 2010.
- Peng S, Huang J, Sheehy JE *et al*. Rice yields decline with higher night temperature from global warming. *PNAS* 2004; **101**: 9971–5.
- Nelson GC, Rosegrant MW, Koo J *et al*. *Climate Change: Impact on Agriculture and Costs of Adaptation*. Washington, DC: International Food Policy Research Institute (IFPRI), 2009.
- Morton JF. The impact of climate change on smallholder and subsistence agriculture. *PNAS* 2007; **104**: 19680–5.

- 37 Fischer G, Shah M, Tubiello FN, van Velhuizen H. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Philos Trans R Soc Lond B Biol Sci* 2005; **360**: 2067–83.
- 38 Purse BV, Mellor PS, Rogers DJ *et al*. Climate change and the recent emergence of bluetongue in Europe. *Nat Rev Microbiol* 2005; **3**: 171–81.
- 39 McLaughlin JB, DePaola A, Bopp CA *et al*. Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *N Engl J Med* 2005; **353**: 1463–70.
- 40 Ogden NH, Maarouf A, Barker IK *et al*. Climate change and the potential for range expansion of the Lyme disease vector *Ixodes scapularis* in Canada. *Int J Parasitol* 2006; **36**: 63–70.
- 41 Jaenson TGT, Lindgren E. The range of *Ixodes ricinus* and the risk of Lyme borreliosis will increase northwards when the vegetation period becomes longer. *Ticks Tick Borne Dis* 2011; **2**: 44–9.
- 42 Zhou X-N, Yang G-J, Yang K *et al*. Potential impact of climate change on Schistosomiasis transmission in China. *Am J Trop Med Hyg* 2008; **78**: 188–94.
- 43 Pascual M, Ahumada JA, Chaves LF *et al*. Malaria resurgence in the East African highlands: temperature trends revisited. *Proc Natl Acad Sci* 2006; **103**: 5829–34.
- 44 Revich B, Kharkova T, Kvasha Y *et al*. *Climate Change Impact on Public Health in the Russian Arctic*. Moscow, Russia: United Nations in the Russian Federation, 2008.
- 45 Omumbo JA, Lyon B, Waweru SM *et al*. Raised temperatures over the Kericho tea estates: revisiting the climate in the East African highlands malaria debate. *Malar J* 2011; **10**: 12.
- 46 Daniel M, Materna J, Honig V *et al*. Vertical distribution of the tick *Ixodes ricinus* and tick-borne pathogens in the northern Moravian mountains correlated with climate warming (Jeseniky Mts., Czech Republic). *Cent Eur J Public Health* 2009; **17**: 139–45.
- 47 Lindgren E, Tälleklint L, Polfeldt T. Impact of climatic change on the northern latitude limit and population density of the disease-transmitting European tick *Ixodes ricinus*. *Environ Health Perspect* 2000; **108**: 119–23.
- 48 McMichael AJ, McMichael CE, Berry H, Bowen K. Climate change, displacement and health: risks and responses. In: McAdam J, ed. *Climate Change and Population Displacement: Multidisciplinary Perspectives*. London: Hart Publishing, 2010; 191–219.
- 49 Carballo M, Smith CB, Pettersson K. Health challenges. *Forced Migr Rev* 2008; **31**: 32–3.
- 50 McMichael AJ, Friel S, Nyong T, Corvalan C. Global environmental change and health: impacts, inequalities, and the health sector. *BMJ* 2008; **336**: 191–4.
- 51 Strazdins L, Friel S, McMichael AJ *et al*. Climate change and children's health: likely futures, new inequities? *Int J Public Health* 2011; **2**: 493–500.
- 52 Fritze J, Blashki GA, Burke S, Wiseman J. Hope, despair and transformation: climate change and the promotion of mental health and well-being. *Int J Ment Health Syst* 2008; **2**: 13.
- 53 Marmot M, Friel S, Bell R *et al*. The Commission on Social Determinants of Health. Closing the gap in a generation: health equity through action on the social determinants of health. *Lancet* 2008; **372**: 1661–9.
- 54 Friel S, Dangour AD, Garnett T *et al*. Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *Lancet* 2009; **374**: 2016–25.
- 55 Semenza JC, Rubin CH, Falter KH *et al*. Heat-related deaths during the July 1995 heat wave in Chicago. *N Engl J Med* 1996; **335**: 84–90.
- 56 Elliot JR, Pais J. Race, class, and Hurricane Katrina: social differences in human responses to disaster. *Soc Sci Res* 2006; **35**: 295–321.
- 57 Friel S, Bowen K, Campbell-Lendrum D *et al*. Climate change, noncommunicable diseases, and development: the relationships and common policy opportunities. *Annu Rev Public Health* 2011; **32**: 133–47.
- 58 McMichael AJ, Powles J, Butler CD, Uauy R. Food, livestock production, energy, climate change and health. *Lancet* 2007; **370**: 1253–63.
- 59 Sala OE, Meyerson LA, Parmesan C. *Biodiversity Change and Human Health. From Ecosystem Services to Spread of Disease*. Washington, DC: Island Press, 2008.
- 60 Pencheon D. Health services and climate change: what can be done? *J Health Serv Res Policy* 2009; **14**: 2–4.
- 61 McMichael AJ. Climate change and human health. Commonwealth Health Ministers' Update, 2009. London Commonwealth Secretariat, 2009; 12–21. ISBN No: 978-0-85092-872-3. <http://publications.thecommonwealth.org/commonwealth-health-ministers-update-2009-717-p.aspx>, Accessed June 29, 2011.

Correspondence: Anthony J. McMichael, MBBS, PhD, National Centre for Epidemiology and Population Health, The Australian National University, Canberra, ACT 0200, Australia.
(fax: +61-2-61255608; e-mail: tony.mcmichael@anu.edu.au) ■