Climate change and human health: present and future risks

Anthony J McMichael, Rosalie E Woodruff, Simon Hales

There is near unanimous scientific consensus that greenhouse gas emissions generated by human activity will change Earth's climate. The recent (globally averaged) warming by 0·5°C is partly attributable to such anthropogenic emissions. Climate change will affect human health in many ways—mostly adversely. Here, we summarise the epidemiological evidence of how climate variations and trends affect various health outcomes. We assess the little evidence there is that recent global warming has already affected some health outcomes. We review the published estimates of future health effects of climate change over coming decades. Research so far has mostly focused on thermal stress, extreme weather events, and infectious diseases, with some attention to estimates of future regional food yields and hunger prevalence. An emerging broader approach addresses a wider spectrum of health risks due to the social, demographic, and economic disruptions of climate change. Evidence and anticipation of adverse health effects will strengthen the case for pre-emptive policies, and will also guide priorities for planned adaptive strategies.

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National Centre for Epidemiology and Population Health, The Australian National University, Canberra 0200, Australia
(Prof A J McMichael PhD, R E Woodruff PhD); and University of Otago, Wellington School of Medicine and Health Sciences, Wellington, New Zealand
(S Hales PhD)

Correspondence to:
Professor A J McMichael
tony.mcmichael@anu.edu.au

There is near unanimous scientific consensus that the rising atmospheric concentration of greenhouse gases due to human actions will cause warming (and other climatic changes) at Earth's surface. The Intergovernmental Panel on Climate Change (IPCC), drawing on the published results of leading modelling groups around the world, forecasts an increase in world average temperature by 2100 within the range 1·4–5·8°C.[1] The increase will be greater at higher latitudes and over land. Global average annual rainfall will increase, although many mid latitude and lower latitude land regions will become drier, whereas elsewhere precipitation events (and flooding) could become more severe. Climate variability is expected to increase in a warmer world.

Climatological research over the past two decades makes clear that Earth's climate will change in response to atmospheric greenhouse gas accumulation. The unusually rapid temperature rise (0·5°C) since the mid-1970s is substantially attributable to this anthropogenic increase in greenhouse gases.[1,2] Various effects of this recent warming on non-human systems are apparent.[3–9] In view of greenhouse gas longevity and the climate system's inertia, climate change would continue for at least several decades even if radical international pre-emptive action were taken very soon.[1,10]

In the 1990s, climate change science relied on climate-system models with good atmospheric dynamics but simple representations of the ocean, land surface, sea ice, and sulphate aerosols, at coarse spatial resolution. Meanwhile, much has been learnt about how Earth's climate system responds to changes in natural and human generated effects: solar activity, volcanic eruptions, aerosols, ozone depletion, and greenhouse gas concentration. Today's global climate models are more comprehensive: they include more detailed representations of the ocean, land-surface, sea-ice, sulphate and non-sulphate aerosols, the carbon cycle, vegetation dynamics, and atmospheric chemistry, and at finer spatial resolution.[10] Recent understanding of how sea surface temperature affects the characteristics of tropical storms and cyclones, and how ocean subsurface temperatures, thermocline depths and thicknesses affect activity of the El Niño Southern Oscillation (ENSO) cycle, tropical cyclone intensification, and landfall prediction will further enrich modelling capacity.

Today's models have been well validated against the recorded data from past decades. Climate model projections, driven by anticipated future greenhouse gas and aerosol emissions, indicate that Earth will continue to warm, with associated increases in sea level and extreme weather events.

Modelling cannot be an exact science. There is debate about humankind's future trajectories for greenhouse gas emission. There are residual uncertainties about the sensitivity of the climate system to future atmospheric changes. The range in the forecast increase in world average temperature (1·4–5·8°C) by 2100 indicates both uncertainty about future greenhouse gas emissions and marginal differences in design of the several leading global climate models (UK, Germany, USA, etc). The spatial pattern of projected temperature and particularly rainfall changes also differ between models. Hence, estimates of climate changes over coming decades are indicative rather than predictive.[1] Note also that the uncertainty is symmetrical: underestimation of future climate change is as likely as overestimation. Longer term, the probability of exceeding critical thresholds—causing step-changes in climate, environment and related effects—will increase.[1,10]

A fundamental global environmental change, affecting physical systems and ecosystems, will affect human health in many ways. However, many details are debated. What health effects will occur? When will they

Search strategy and selection criteria

We used keyword combinations to search MEDLINE and Science Citation Index databases for articles published in all languages during the years 1995–2005, including the search terms "climate", "climate change", "health", "health effects", "dengue", "malaria", "heat", "heat waves", "time-series", "floods", "extreme weather", and "harmful algae".

take place? Will there be both beneficial and adverse effects?

Publications about relations between (natural) variation in meteorological variables, especially temperature, and health effects is extensive, encompassing several decades. Many papers have been published, for example, on the association of heat waves with mortality excesses. Much of this empirical evidence is uncontentious, and rather than reviewing it comprehensively, we have cited representative examples of research published in mainstream journals. Publications estimating, via modelling and extrapolation, how climate change will affect population health in future are much less extensive. They also entail several controversies (including debate over the relative effects of climatic versus social, economic, and topographic conditions on vector-borne infectious disease transmission). We cite representative reports to illustrate the main contending points of view. There is little empirical research exploring whether climate change over the past three decades has affected health, and the few papers attributing some particular recent health changes to climate change are debated. We have attempted to represent those debates fairly. Finally, little research has been done on the indirect pathways that link climate change to resultant social, economic, and demographic disruptions and their knock-on health effects. We comment on these because they are important, despite the sparse research.

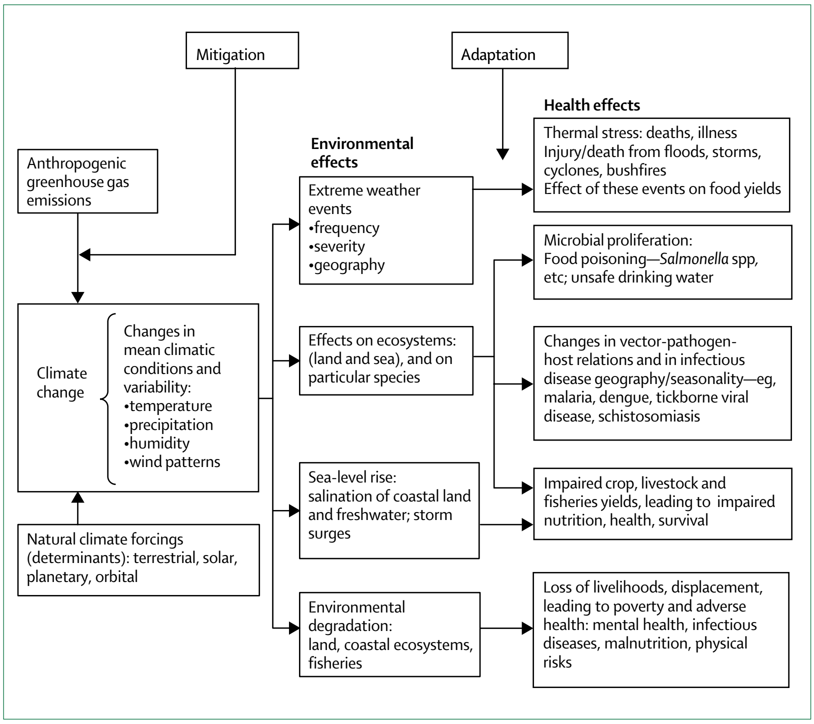

Figure 1: **Schematic summary of main pathways by which climate change affects population health**
Mitigation refers to true primary prevention (reducing greenhouse gas emissions). Adaptation (a form of late primary prevention) entails interventions to lessen adverse health effects.

There are several limitations to the available information. First, most empirical climate-health studies and most national assessments of health risks from future climate change have been done in high-income countries. Second, the estimation of future health trends and effects is necessarily subject to various uncertainties. Hence, our review inevitably differs from a more conventional review of published empirical biomedical evidence.

Figure 1 summarises the main pathways by which climate change can affect population health. The several main climatic-environmental manifestations of climate change are shown in the central section. The right-hand boxes, from top to bottom, entail an increase in complexity of causal process and, therefore, in the likelihood that health effects will be deferred or protracted. Most of the diverse anticipated health consequences are adverse, but some would be beneficial. Milder winters would reduce the normal seasonal peak mortality in winter in some temperate developed countries, and warming or drying in already hot regions would reduce the viability of mosquitoes (table).

The climate-health relationships that are the easiest to define and study are those in relation to heatwaves, the physical hazards of floods, storms, and fires, and various infectious diseases (especially those that are vector-borne). Other important climatic risks to health, from changes in regional food yields, disruption of fisheries, loss of livelihoods, and population displacement (because of sea-level rise, water shortages, etc) are less easy to study than these factors and their causal processes and effects are less easily quantified.

Climate variations and health

Before the prospect of anthropogenic climate change emerged, epidemiologists were not greatly interested in climate-health relations. Modern epidemiology has focused mainly on studying risk factors for non-communicable diseases in individuals, not populations. Meanwhile, there have been occasional studies examining deaths due to heatwaves, some epidemiological studies of air pollution incorporating temperature as a covariate, and a continuation of the longer standing research interest in meteorological effects on microbes, vectors, and infectious disease transmission. Overall, the health risks of climate-related thermal stress, floods, and infectious diseases have been the most amenable to conventional epidemiological studies.

Extreme weather events

Extreme weather events include periods of very high temperature, torrential rains and flooding, droughts, and storms. Over time, regional populations adapt to the local prevailing climate via physiological, behavioural, and cultural and technological responses. However, extreme events often stress populations beyond those adaptation limits. Understanding the health risks from

	Adverse effect	Beneficial effect	References	
			Climate variability	Climate change
Temperature extremes (more very hot days, possibly fewer very cold days)	More daily deaths and disease events—primarily due to more very hot days	Reduced winter deaths and disease events in (at least some) temperate countries	11–13, 14, 15–18, 19–29	30–36
Floods	More injuries, deaths and other sequelae (infectious disease, mental health disorders)		37–44	2, 34, 45–47
Aero-allergen production	Increased allergic disorders (hay fever, asthma) due to longer pollen season	Reduced exposure to aero-allergens in some regions due to lesser production or shorter season of pollen circulation	48	
Food-poisoning (diarrhoeal disease)	Greater risks at higher temperature (especially salmonellosis)		40, 49–55	34
Water-borne infection	Cholera risk might be amplified by coastal/estuarine water warming, local flooding	Less risk where (heavy) rainfall diminishes	40, 56–61	62–64
Vector-borne infections	Mosquito-borne infections tend to increase with warming and certain changes in rainfall patterns: heightened transmission. Likewise tick-borne infections, although via more complex ecological changes	Mosquito reproduction and survival could be impaired by altered rainfall and surface water and by excessive heat: reduced transmission. Similar determinants may apply to ticks, snails and other vectors.	65–76	34, 60, 77–95
Regional crop yields	Reductions in many low-latitude and low-rainfall regions	Increases in currently too-cold regions (might not be sustained with continuing climate change)		34, 96, 97
Fisheries	Declines or shifts in local fisheries: protein shortages (in poor populations). Possible increased contamination	Latitudinal shifts of fisheries, with ocean warming, may benefit new host populations		98–100
Sea-level rise	Health consequences of population displacement, lost livelihood, exposure to coastal storm surges and floods. Salinisation of freshwater and coastal soil.			101

***Table:* Main known and probable health hazards of climate variability and climate change**

these events is important because the future frequency and intensity of extreme events is expected to change as both climatic means and variability change.[1]

Thermal stress

Populations typically display an optimum temperature at which the (daily or weekly) death rate is lowest. Mortality rates rise at temperatures outside this comfort zone.[11] Figure 2 shows a typical U-shaped relation. The trough represents the comfort zone; the steeper (right-side) arm of each line shows the mortality increase at hot temperatures, and the shallower (left-side) arm of each line shows the increase with colder temperatures.

The temperature-mortality relation varies greatly by latitude and climatic zone. People in hotter cities are more affected by colder temperatures, and people in colder cities are more affected by warmer temperatures.[11,12] Regions where housing provides poor protection against cold have higher excess winter mortality than expected for that location.[13] In the UK and some other northern high-latitude countries, seasonal death rates and illness events are higher in winter than in summer.[14–18,30,102,103] There, the role of cold temperature itself, beyond the role of seasonal infectious agents (influenza in elderly people[104] and respiratory syncytial virus in infants[105]) and seasonal haematological changes,[102] remains unresolved.

Most epidemiological studies of extreme temperatures have been done in Europe and North America. These studies have shown a positive association between heatwaves and mortality, with elderly people (who have diminished physiological capacity for thermoregulation),[19,20] especially women,[21–23] being the most affected. Other research indicates that mentally ill people,[106] children,[24,107] and others in thermally stressful occupations or with pre-existing illness are also vulnerable. The striking mortality excess (about 30 000 deaths) during the extreme heatwave of August, 2003, in Europe,[25] especially France,[26] attests to the lethality of such events. The actual burden of life-years lost depends on the proportion of those deaths that is due to short-term mortality displacement in people otherwise likely to have died within the next 1–2 months. In the USA this proportion is around 30–40%.[108]

Most heatwave deaths occur in people with pre-existing cardiovascular disease (heart attack and stroke) or chronic respiratory diseases. People living in urban environments are at greater risk than those in non-urban regions.[27] Thermally inefficient housing[28] and the so-called urban heat island effect (whereby inner urban environments, with high thermal mass and low ventilation, absorb and retain heat) amplify and extend the rise in temperatures (especially overnight).[20] In 2003 in Paris[26] many nursing homes and other assisted-living and retirement communities were not air-conditioned, and elderly residents might not have been promptly moved to air-conditioned shelters and rehydrated with fluids.

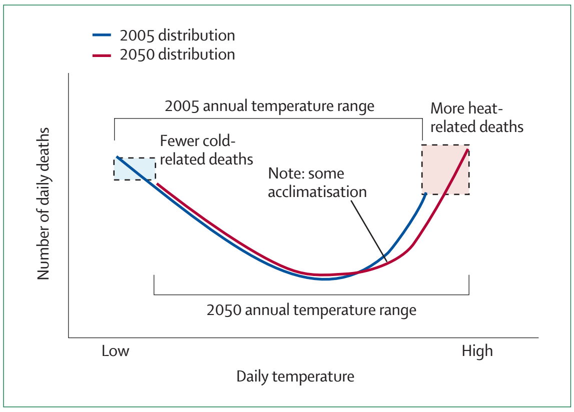

Figure 2: **Schematic representation of how an increase in average annual temperature would affect annual total of temperature-related deaths, by shifting distribution of daily temperatures to the right**
Additional heat-related deaths in summer would outweigh the extra winter deaths averted (as may happen in some northern European countries). Average daily temperature range in temperate countries would be about 5–30°C.

Physiological and behavioural adaptations can reduce heatwave morbidity and mortality,[20] as can changes in public health preparedness.[109] An overall drop in mortality associated with heatwaves across a recent three-decade period in 28 US cities[29] shows that weather-mortality relations can change over time. This decline indicates that adaptations to climate change (air conditioning, improved health care, and public awareness—along with changes in underlying health status) can reduce risks. Even so, under extreme conditions an increase in deaths can arise in cities that are accustomed to heatwaves and have high levels of prevention awareness and air conditioning.[110]

Floods

Floods are low-probability, high-impact events that overwhelm physical infrastructure, human resilience, and social organisation. From 1992 to 2001, there were 2257 reported disasters due to droughts or famines, extreme temperature, floods, forest/scrub fires, cyclones, and windstorms. The most frequent natural weather disaster was flooding (43%), killing almost 100 000 people and affecting over 1·2 billion people.[37]

Floods result from the interaction of rainfall, surface run-off, evaporation, wind, sea level, and local topography. In inland areas, flood regimens vary substantially depending on catchment size, topography, and climate.[111] Where people live close to rivers, natural flows have usually been modified to avoid floods (eg, by constructing levees, dikes, and dams). Water management practices, urbanisation, intensified land use, and forestry can substantially alter the risks of floods.[38,39,45,111,112] The trend in high-income countries for people to move to the coast, along with the world's topographic profile of deltas and coral atolls, means that many settlements and much arable land are at increasing risk from flooding due to rise of sea level.[46]

Floods have recently tended to intensify, and this trend could increase with climate change.[3,47] The ENSO cycle determines inter-annual variability in temperature and in rainfall, and the likelihood of flooding, storms, and droughts in many regions.[113] It is a major part of the world's pre-eminent source of climate variability: the Pacific Ocean and its several regional climatic oscillations. It has a far-reaching, quasi-periodic, westward-extending effect every 3–6 years. Some health consequences arise during or soon after the flooding (such as injuries, communicable diseases,[40] or exposure to toxic pollutants[41]), whereas others (malnutrition[42] and mental health disorders[43,44]) occur later. Excessive rainfall facilitates entry of human sewage and animal wastes into waterways and drinking water supplies, potentiating water-borne diseases.[56–59] Globally, disaster effects are greatest for droughts (and associated famines) because of their regional extent.[114]

Infectious diseases

Transmission of infectious disease is determined by many factors, including extrinsic social, economic, climatic, and ecological conditions,[115] and intrinsic human immunity (analytic methods that differentiate extrinsic and intrinsic influences are now evolving[116]). Many infectious agents, vector organisms, non-human reservoir species, and rate of pathogen replication are sensitive to climatic conditions.[60,61] Both salmonella and cholera bacteria, for example, proliferate more rapidly at higher temperatures, salmonella in animal gut and food, cholera in water. In regions where low temperature, low rainfall, or absence of vector habitat restrict transmission of vector-borne disease, climatic changes could tip the ecological balance and trigger epidemics. Epidemics can also result from climate-related migration of reservoir hosts or human populations.[117]

In many recent studies investigators have examined the relation between short-term climatic variation and occurrence of infectious disease—especially vector-borne disease. Studies in south Asia and South America (Venezuela and Columbia) have documented the association of malaria outbreaks with the ENSO cycle.[65–68] In the Asia-Pacific region, El Niño and La Niña events seem to have affected the occurrence of dengue fever outbreaks.[69–71] Similarly, inter-annual (especially ENSO-related) variations in climatic and environmental conditions in Australia affect outbreaks of Ross River virus disease.[72,73,118]

Many of these associations between infectious diseases and El Niño events have a plausible climatic explanation. High temperatures in particular affect vector and pathogen. The effect of rainfall is more complex. For example, in tropical and subtropical regions with crowding and poverty, heavy rainfall and flooding may trigger outbreaks of diarrhoea, whereas very high rainfall can reduce mosquito populations by flushing larvae from their habitat in pooled water.

Increased notifications of (non-specific) food poisoning in the UK[49,50] and of diarrhoeal diseases in Peru and Fiji[51,59] have accompanied short-term increases in temperature. Further, strong linear associations have been noted between temperature and notifications of salmonellosis in European countries[52] and Australia,[53] and a weak seasonal relation exists for campylobacter.[54,55]

Are any health effects of climate change detectable?

Since global temperatures have risen noticeably over the past three decades (see introduction), some health outcomes are likely to already have been affected. However, there is nothing distinctive about the actual types of health outcomes due to longer-term climate change, versus shorter-term natural variation. Hence, the detection of health effects due to climate change is at this early stage difficult. However, if changes in various health outcomes occur, each plausibly due to the preceding climate change, then pattern-recognition can be used—as was recently used for assessment of non-human effects of recent climate change.[119]

The complexity of some causal pathways makes attribution difficult. Recent climate change might have contributed (via changes in temperature, rainfall, soil moisture, and pest and disease activity) to altered food yields in some regions.[96] In food-insecure populations this alteration may already be contributing to malnutrition. Subsistence hunting and fishing have been much harmed by recent climate changes in Alaska, through stresses on fish and wildlife driven by warming of air and sea, sea ice retreat, and ecosystem shifts.[98]

Some actions taken in response to the advent of climate change also entail health risks. Sea level (figure 1) has risen moderately in recent decades, and population relocation from some of the lowest-lying Pacific islands is starting to take place.[101] Such displacement often increases nutritional, physical, infectious disease, and mental health risks.

Extreme events

The number of people adversely affected by El Niño-related weather events over three recent decades, worldwide, appears to have increased greatly.[120] Systematic studies of trends over time in the effects of extreme events on human populations are needed to clarify this situation. One manifestation of global warming over the past 50 years is an increased duration of heatwaves in Alaska, Canada, central and eastern Europe, Siberia, and central Australia (data for South America and Africa are unavailable).[121] Although no one extreme event can be attributed solely to climate change, the probability of a particular event occurring under modified climatic conditions can be estimated. Recent studies have shown that the record-breaking 2003 European summer heatwave was consistent with climate-change modelling[31,32] and substantially attributable to human-induced warming.[33]

Rainfall seems to have become more variable globally, and the frequency of intense rainfall has increased in some areas.[1] However, evidence that climate change has affected the frequency or magnitude of river floods is inconsistent.[81,122,123] Globally there has been a substantial increase in the risk of great floods (ie, in river basins larger than 200 000 km^2 and at levels greater than 100 years) over the past century.[47] At this stage, therefore, to attribute changes in flood-related health effects to climate change is difficult.

Infectious diseases

Several recent reports have shown that climate change might be affecting some infectious diseases—although no one study is conclusive. Tick-borne (viral) encephalitis in Sweden has reportedly increased in response to a succession of warmer winters over the past two decades,[77,78] although this interpretation is contested.[79] The geographic range of ticks that transmit Lyme borreliosis and viral encephalitis has extended northwards in Sweden[78] and increased in altitude in the Czech Republic.[124] These extensions have accompanied recent trends in climate.[78,125]

Changes in the intensity (amplitude) of the El Niño cycle since 1975, and more recently its frequency—both probably manifestations of climate change—have been accompanied by a strengthening of the relation between that cycle and cholera outbreaks in Bangladesh.[62] The cholera vibrio naturally harbours within coastal and estuarine marine algae and copepods, whose proliferation is affected by sea-surface temperature and other environmental factors.[63] Evidence of marine ecosystem changes linked to climate trends[126] indicates that climate change is amplifying harmful algal blooms.[64,127]

There is some, though inconclusive, evidence of increases in malaria in the eastern African highlands in association with local warming. Several investigators have documented an increase in highland malaria in recent decades,[80–82] including in association with local warming trends.[83,128] Although two other studies showed no statistically significant trends in climate in those same regions,[84,85] the medium-resolution climate data used[129] were not well suited to research at this smaller geographical scale.[130]

Within the climate range that limits the transmission rate and geographic bounds of infectious disease, many other social, economic, behavioural, and environmental factors also affect disease occurrence. For example, many environmental factors affect malaria incidence, including altitude,[131] topography,[132] environmental disturbance,[74] short-term climate variability,[75] ENSO,[76,114] and longer-term climate trends.[130] To make a quantitative attribution of change in incidence to any single factor is therefore difficult.

Can current effects be estimated, if not yet directly observed? The current burden of disease attributable to climate change has been estimated by WHO as part of the Global Burden of Disease (2000) project, a comprehensive standardised risk assessment exercise that underwent critical review.[133] The estimation of the attributable burden was a statistical exercise that entailed three steps: (i) estimation of the baseline average annual disease burden in 1961–90; (ii) specification (from published work) of the increase in disease risk per unit increase in temperature or other climate variable; and (iii) estimation, by geographic region, of the current and future global distributions of population health effects of the change in climate. The extent of climate change (relative to the 1961–90 average climate) by the year 2000 is estimated to have caused in that year around 160 000 deaths worldwide and the loss of 5 500 000 disability-adjusted life-years (from malaria, malnutrition, diarrhoeal disease, heatwaves, and floods).[34]

This exercise was conservative in several respects, including being limited to quantifiable health outcomes. Nevertheless, is it reasonable to attribute a proportion of global deaths from malaria, malnutrition, or other such outcomes in 2000, to the global warming that has taken place since around 1975? The fact that equivalent estimations are routinely made for other such relationships involving a disease with known multivariate causation—eg, the proportion of all stroke deaths in 2000 attributable to hypertension[134]—suggests that, in principle, wherever a well documented exposure-effect relation exists, the incremental change in health outcome can legitimately be estimated for an incremental exposure (eg, temperature).

A more specific question is, can we attribute to climate change some fraction of the health effect associated with a particular climatic event that itself is partly attributable to climate change? For example, the probability of occurrence of the severe European heatwave of 2003 was estimated to have been doubled by the underlying warming trend largely induced by human activities.[33] Simple arithmetic therefore suggests that half the excess heat was due to that warming. Thus we could infer that approximately half of excess deaths during the 2003 heatwave were due to that underlying anthropogenic contribution.

Estimates of future health effects

Climate change will have many effects on health over the coming decades (figure 1). In view of the residual uncertainties in modelling, how the climate system will respond to future higher levels of greenhouse gases, and uncertainties over how societies will develop economically, technologically, and demographically, formal predictions of future health effects cannot be made. The appropriate task is to make estimations, for future modelled climate situations, of the consequent health effects.[136]

This estimation can be done in three contexts: (i) in classic experimental fashion, holding constant all other non-climate factors likely to affect future health; (ii) incorporating such factors acting independently into a multivariate model, to estimate net changes in population health burden; (iii) also incorporating effect-modifying factors, especially those due to adaptive responses. Not surprisingly, much of the initial modelling research has been of type (i) above. Published work consists of both reports of specific modelling studies and of systematic assessments done over the past decade by national governments (eg, UK, Australia, USA, Portugal, Norway, Japan) and, recently, by WHO as part of its global burden of disease (2000) assessment.[135]

Extreme events

The early modelling of the effect of extreme events assumed that climate change would act mainly by shifting the mean values of temperature and other meteorological variables. Little attention was paid to the possibility of altered climate variability.[136] Recently however, there have been gains in the modelling of how climatic variability will also change in future. One such study, for example, has estimated that major cities in Europe and northern USA will have substantial rises in both frequency and duration of severe heatwaves by 2090.[32] The importance of considering changes in variability is illustrated in figure 3: small changes in temperature variability, along with a shift in mean temperature, can greatly increase the frequency of extreme heat. Similar reasoning applies to other meteorological variables. Because populations in high-income countries are predicted to age substantially over coming decades (the proportion aged over 60 years increasing from 19% to 32% by 2050),[137] and with a trend towards urbanisation in all countries (projected to increase from 45% in 1995 to 61% by 2030),[138] a greater proportion of people in all countries will be at risk from heat extremes in future, even without substantial climate change.[139] In Australia, for a medium-emissions climate change setting in 2050, the annual number of deaths attributable to excess heat in capital city populations is expected to increase by 50% to 1650 (assuming no change in population size and profile).[35]

Conversely, the mortality risk from cold weather is expected to decline in northern latitudes.[36] Currently, physiological and behavioural acclimatisation probably explains the gradient in the low-temperature threshold for increasing mortality, apparent from northern to southern Europe.[12] But whether populations can offset temperature-related changes in mortality risks by acclimatisation (eg, through changes in building design[12]) is uncertain.

The accurate estimation of future deaths from floods and storms is impeded by the absence of empirically documented exposure-response relations. Further, the typical spatial scale of global climate models—even at the country level—is still too coarse for reliable projections of precipitation.[45] Unless current deficiencies in watershed protection, infrastructure, and storm drainage systems are remedied, the risk of water-borne contamination events will probably increase.[40]

Infectious diseases

Climate change will affect the potential incidence, seasonal transmission, and geographic range of various vector-borne diseases. These diseases would include malaria, dengue fever, and yellow fever (all mosquito-borne), various types of viral encephalitis, schistosomiasis (water-snails), leishmaniasis (sand-flies: South America and Mediterranean coast), Lyme disease (ticks), and onchocerciasis (West African river blindness, spread by black flies).[86]

The formal modelling of the effects of climate change on vector-borne diseases has focused on malaria and dengue fever. Modelling of dengue fever is conceptually simpler than for malaria. Whereas malaria entails two main pathogen variants (falciparum and vivax) and relies on several dozen regionally dominant mosquito species, dengue fever transmission depends principally on one mosquito vector, *Aedes aegyptii*. Both statistical and biologically based (mathematical) models have been used to assess how a specified change in temperature and rainfall pattern would affect the potential for transmission of these and other vector-borne diseases.

Various research groups have published estimates of how climate change will affect future transmission of malaria.[87–93] Biologically based models of climate-malaria futures depend on the documented mathematical relation between temperature and transmission, including a simple threshold for the effect of rainfall. Empirical statistical models can account for interactions between temperature and rainfall effects, but are affected by the uncertainty of modelled projections of future rainfall.[92] Several models project a small geographical expansion of potential malaria transmission in the next few decades,[88,90] with some estimating more substantial changes later this century.[90,91,93] In several studies that have modelled seasonal changes in transmission researchers estimate a substantial extension—such as a 16–28% increase in person-months of exposure to malaria in Africa by 2100.[89]

Three research groups have estimated how climate change will affect dengue fever. Early models were biologically based, driven mainly by the known effect of temperature on virus replication within the mosquito. Warmer temperatures (up to a threshold) shorten the time for mosquitoes to become infectious, increasing the probability of transmission.[94] Studies with both biologically based[94] and statistical models[95] project substantial increases in the population at risk of dengue (eg, figure 4).

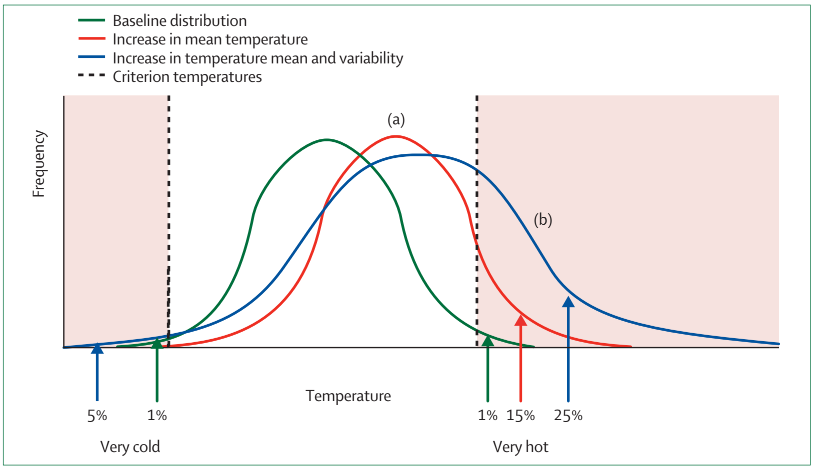

Figure 3: **The effect of increases in (a) mean temperature, and (b) temperature mean and variability, on frequency of extreme temperature days**

Arrows designate the area-under-the-curve, beyond the criterion temperatures for very cold and very hot. Percentages are approximate only.

Such modelling excludes many (often unforeseeable) non-climate aspects of the future world. Nevertheless, estimation of how the intrinsic probability of disease transmission would alter in response to climate change alone is informative—and accords with classic experimental science (see type (i) in Estimates of future health effects). Whether the change in disease transmission actually occurs also depends on non-climate factors; presence of vector and pathogen is prerequisite, as is vector access to non-immune people. The transmission of such diseases is also much affected by socioeconomic conditions and by the robustness of public health defences.[91,140,141] For example, case surveillance and treatment in fringe areas, management of deforestation and surface water, and effective mosquito control programmes would tend to offset the increased risk due to climate change, whereas universally-funded bed-net campaigns would reduce infection rates. Future modelling will benefit by incorporation of those non-climate contextual changes that are reasonably foreseeable.

Other health effects

Beyond the specific and quantifiable risks to health are indirect and knock-on health effects due to the social, economic, and political disruptions of climate change, including effects on regional food yields and water supplies. Modelling of climate change effects on cereal grain yields indicates a future world of regional winners and losers, with a 5–10% increase in the global number of underfed people.[97] The conflicts and the migrant and refugee flows likely to result from these wider-ranging effects would, typically, increase infectious diseases, malnutrition, mental health problems, and injury and violent death. Future assessments of the health effects of climate change should attempt order-of-magnitude estimates of these more diffuse risks to health.

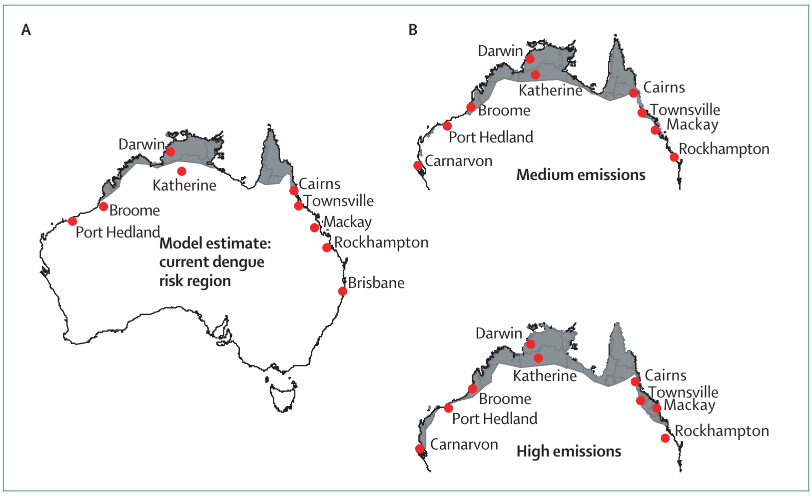

Figure 4: **Modelled estimates of the current (A) and future (2050) (B) geographic regions (shaded areas) suitable for maintenance of the dengue vector *Ae aegyptii* in Australia**
Model based on baseline (1961–90) estimates of water vapour pressure estimates for current climate and for future climate, in settings of medium and high global emissions of greenhouse gases.[35]

The wider ramifications of climate change for health are well illustrated by a recent study of how ocean warming around the Faroe Islands will facilitate the methylation of (pollutant) mercury and its subsequent uptake by fish. Concentrations in cod and pilot whales would increase by an estimated 3–5% for a 1°C rise in water temperature.[99] Eating methyl-mercury-contaminated fish impairs fetal-infant neurocognitive development.[142] Further, ocean warming is already beginning to cause geographic shifts in fisheries.[100] Climate change might also alter the timing and duration of pollen and spore seasons and the geographic range of these aeroallergens, affecting allergic disorders such as hay fever and asthma.[48]

The advent of changes in global climate signals that we are now living beyond Earth's capacity to absorb a major waste product: anthropogenic greenhouse gases. The resultant risks to health (and other environmental and societal outcomes) are anticipated to compound over time as climate change—along with other large-scale environmental and social changes—continues.

Research on climate, climate change, and health has focused largely on thermal stress, other extreme weather events, and infectious diseases. The wider spectrum of health risks should now be given more attention. With the adaptability of human culture, many communities will be able to buffer themselves (at least temporarily) against some of the effects of climate change. Buffering capacity, though, varies greatly between regions and communities, indicating differences in geography, technological resources, governance, and wealth.[143] Research to characterise vulnerable groups is needed.

Knowledge of vulnerability allows an informed approach to development and evaluation of adaptive strategies to lessen those health risks. Although details[144] are beyond our scope here, it is noteworthy that governments are now paying increasing attention to adaptation options. Researchers must engage, too, with the formulation, evaluation, and economic costing of adaptive strategies. Beyond structural, technological, procedural, and behavioural adaptations by at-risk communities are larger-scale technical possibilities—such as applying satellite data and computer modelling to natural disaster forecasting, and geographic information system modelling of the effect of changes in rainfall and vegetation on specific infectious diseases. Other generalised strategies include protection from coastal storm surges, improved sentinel case surveillance for infectious diseases, development of crops resistant to drought and disease, and most importantly, the fostering of renewable energy sources.

Conclusion

Research into the existence, future likelihood, and magnitude of health consequences of climate change represents an important input to international and national policy debates. Recognition of widespread health risks should widen these debates beyond the already important considerations of economic disruption, risks to infrastructure, loss of amenity, and threatened species. The evidence and anticipation of adverse health effects will indicate priorities for planned adaptive strategies, and crucially, will strengthen the case for pre-emptive policies. It will help us understand better the real meaning of sustainability.

Conflict of interest statement
All the authors have been or are involved in the scientific review activities of the Intergovernmental Panel on Climate Change (IPCC).

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