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14 Climate and the spread of infectious diseases, present and future

Anthony J. McMichael

As the world continues to warm and climatic-environmental conditions change, various infectious diseases in humans will inevitably change their patterns of occurrence. The rate of transmission and the geographic and seasonal patterns of many infectious diseases are influenced by climate change. If we can better understand the climate-sensitive aspects of infection transmission, why and which populations vary in vulnerability, and the likely future occurrence of particular infections under climate change, then we can better inform the rationale for climate change 'mitigation' (abatement) and implement adaptive strategies to lessen the anticipated health risks.

Natural changes in climatic conditions on a decade-plus scale have been implicated as a major or contributory influence in many of the recorded outbreaks of epidemics in history — along with various concurrent (and perhaps interacting) influences from the social, economic and environmental realms. Examples include: the first two great pandemics of bubonic plague (in the the mid-6th and mid-14th centuries CE); the natural ebb and flow of malaria in northern Europe during the temperature fluctuations of around 1000–1850 CE; the epidemics that emerged during Europe's Great Famine in the second decade of the 14th century; the drought-related rodent-borne 'cocolitzli' epidemics in the post-conquest surviving Mexican populations in the mid-16th century; the outbreaks of typhus in Europe and eastern North America during the decade of extreme cold at the time of the massive Tambora volcanic eruption in the second decade of the 19th century — and perhaps the typhus epidemic that followed the climate-influenced Irish potato famine in the mid-19th century.

Many bacteria, viruses and protozoa proliferate more rapidly in warm water and food, while some proliferating infectious agents mature more quickly at higher temperatures within their vector insect. Many arthropod 'vectors' (mosquitoes, midges, ticks and others) breed and extend their range more readily in warm and humid conditions; and the numbers, density and movements of non-human vertebrate animal hosts for the pathogen are often affected by climatic factors. Patterns of rainfall, surface water and river flow are also important influences, e.g. for mosquito breeding sites, for black-fly breeding (the vector for West African 'river blindness') and for multiplication of the cholera and dysentery microbes in drinking water. Heavy rainfall and flooding can cause outbreaks of leptospirosis (from contact with *Leptospira* bacteria, excreted by rats, dogs and a diversity of other animal hosts), and drinking water can easily become contaminated by bacteria, viruses and agricultural wastes.

Human behaviour and biological susceptibility also vary seasonally and in response to changes in climatic conditions. Outdoors food consumption increases in summer-time, incurring greater risks of infectious gastroenteritis (e.g. *Salmonella* food poisoning); likewise recreational exposures to tick vectors during field and woodland outings. The human immune system is influenced by the level of solar ultraviolet exposure (immunosuppressive) where high levels of exposure over a period of time suppress the body's immune system, especially in the skin. Also climatic impairment of food yields and hence human nutritional status can weaken immune defences and predispose to infection.

Overall, the projected changes in global and regional climates over coming decades due to human influence on atmospheric composition would cause, predominantly, increases in disease incidence rates, seasonal range and geographic ranges. However, the *actual* changes due to climatic influences will be greatly conditioned by the many non-climatic factors that influence infectious disease occurrence. Further, the mix of impacts is expected to be very uneven and heterogeneous, and would include both increases and decreases in climate-related occurrence of specific infections. For example, some modelling studies indicate that warming and drying will be too great in some regions (such as Sahelian West Africa) to support the continued existence of mosquito populations. Indeed, if (as now looks increasingly plausible) average world temperatures this century were to rise by more than previously estimated, adding another 4–5ºC, the transmission of many vector-borne diseases would be curtailed.

Although outside the scope of this chapter, we should be aware that human wellbeing and health would be affected indirectly by climate change-related increases in various infectious diseases of crops, livestock and wild animals. In vulnerable populations, food supplies, livelihoods and nutritional health would be adversely affected by climate-related reductions in harvests and losses of livestock. For example, the recent northwards spread of the oft fatal midge-borne disease bluetongue virus in Europe poses a growing threat to cattle, goats, sheep and deer. During the first decade of this century the disease established itself in southern Europe and has now begun to spread into northern Europe. Considerable evidence links this spread to the background warming trend in Europe.

A change in climate can influence the intermixing of wild species and hence the exchange of their habitual infectious agents. In association with recent warming in North America, for example, elk and white-tailed deer have extended their ranges north and their habitual infections have subsequently spread to previously unexposed musk ox and caribou.

Climatic influences and causal complexity

This topic of 'causation' of infectious disease is complex, spanning social, environmental and ecological factors. Unlike the simpler relationship between, say, extreme heatwaves and rates of death, many climate–disease relationships are multi-stage and multi-faceted. Bubonic plague (which causes thousands of cases in several dozen locations around the world each year) is a good example. The (simplified) causal chain includes:

> auspicious climatic conditions → more local vegetation → expansion of wild infected (underground-burrowing) natural-host rodents → increased number of infected rodent-resident fleas → weather disruption (floods, droughts, etc.) of rodents' wellbeing → displacement from burrows → contact with human-cohabiting rats → infected rats → infected fleas abandon dying rats → fleas infect humans

Some climate-affected vector-borne infections (VBDs), such as dengue and malaria, have simpler human–vector–human transmission pathways. Human to human transmission is even simpler. In general, as the complexities of ecological and transmission processes increase, so the role of climatic–environmental conditions become relatively more important, increasing as one moves from human to human ('contagion', including immediate airborne passage); to human to human via environmental (water, food, soil) contamination; to human to human via an infected vector organism (the 'vector-borne infections', or VBDs); and then to zoonotic infections (infections transmitted from animals to humans) of humans arising from animal sources (with or without an intervening vector). To illustrate from the two ends of that mode-of-transmission axis: sexually transmitted diseases (STDs) are not directly climate-related while malaria transmission occurs much more readily in warm and humid settings and tick-borne infections (Lyme disease, tick-borne encephalitis, etc.) are amplified by warmer conditions that allow expansion of the habitats of ticks and their natural mammal hosts.

A basic question arises in relation to the possible impacts of climate change on various infectious diseases in humans. That is: how sensitive is Infectious Disease X to a change in climatic conditions? Three subsidiary questions are: Which aspects of climate most affect that disease? Is there evidence, yet, of any changes in occurrence of that disease that are reasonably attributable to climate change? Do we know enough about the nature of the climate–disease relationship to apply that knowledge to projections of climate change in order to foresee the *potential* changes in future patterns of occurrence of disease X?

In broad terms, the existing bank of knowledge of relationships between changes in climatic conditions and changes in rates and ranges of particular infectious diseases differs greatly between diseases and regions of the world. Some diseases, such as malaria — which during the period 1850–1950 was of huge significance in Africa and South Asia as a barrier to European exploration, trade, imperial ambition and colonial health — attracted intensive study that elucidated how biological aspects of the transmission process (e.g. mosquito breeding, survival and biting rates, and rates of maturation of the malaria pathogen inside the mosquito) were affected by temperature, rainfall, humidity and other factors.

In the past two decades, cholera has attracted similar attention in diverse settings in relation to temperature influences on coastal and estuarine algal blooms with consequent proliferation of the symbiotic cholera vibrio and its spread via infected seafood. Historical fluctuations in cholera have been examined in relation to extremes of flooding and drought in southern India; and variations in incidence rates in relation to short-term temperature fluctuation that show a clear positive relationship with cholera in countries where the disease is endemic.

Many infectious diseases, vector-borne and other, are now the subject of intensified research, to learn more about the specific ways in which climatic factors influence stages of the transmission process (see Figure 14.1). Exploring these often complex causal relations is interesting research in its own right. However, under today's unusual conditions of ongoing and projected human-caused climate change, the research takes on a much greater significance. It is important for planning and decision-making at many levels, including the ultimate decisions about the need for international action to curb climate change, to assess whether some infectious diseases are already changing in response to climate change, and to estimate the likely changes in infection risks in a world with a different climate.

Are climate-related changes yet evident?

A recurring difficulty in attributing changes in the occurrence of infectious diseases in human populations to recent climate change is that human diseases nearly always have a complex configuration of causal factors. There is, as epidemiologists say, much background noise that must be allowed for in data analysis in order to discern a valid signal. That situation differs greatly from observations of sea-ice melting, which can only be due to the warming of sea-surface water and/or surface-level atmosphere. Likewise, if spring arrives earlier and butterflies migrate poleward earlier, that is a fairly clear indicator that the climate has varied, if not changed. But if malaria moves up the slopes of the highlands in eastern Africa, that could be due to warming, or to non-climatic influences, such as land-clearing, altered agricultural practice, greater mobility of human populations, cessation of mosquito control programmes and so on. For at least that reason there is as yet no agreed generally accepted sentinel case of a climate change-induced change in the occurrence of infectious disease.

Malaria

Malaria, the world's most serious and widespread vector-borne infection, remains a major scourge, especially in sub-Saharan Africa and South Asia. Approximately 200 million cases are reported annually, causing around 700,000 deaths, mostly from cerebral (falciparum) malaria. Concerted international efforts and the ongoing background increase in social-economic development have brought an overall reduction in these numbers over recent decades. Might climate change slow, or even reverse, this trend?

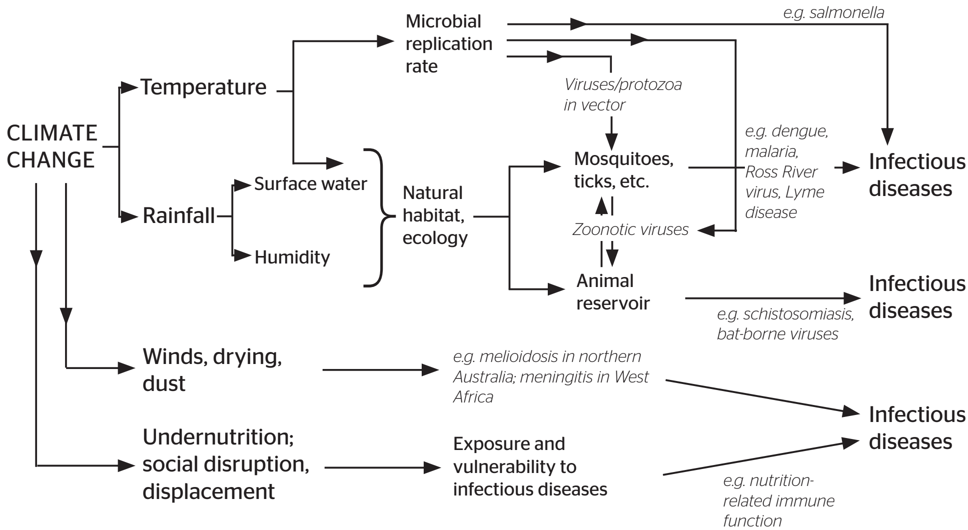

Fig 14.1 Schematic diagram of the main pathways by which climate change and its several key manifestations can influence the occurrence of different types of infectious diseases.
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Malaria outbreaks have been reported in several highland regions in East Africa, in association with local decadal rises in temperature. The evidence that inter-decadal temperature trends have influenced changes in malaria incidence in that region has become increasingly strong, although those temperature trends may not have been the major cause of changes in malaria incidence. Findings have been inconsistent and debate persists, including over the most appropriate way of handling time-series meteorological data.

The modelling of likely future climate-related changes in the global and regional mapping of malaria has often been criticised as over-estimating future risks — particularly by not allowing adequately for the non-climate determinants of malaria occurrence. One recent study, using a mid-level climate change scenario, estimated that if the climate changes while current economic growth rates do not, then around 62% of a world population of 8.5 billion in 2050 would face malaria risk, whereas if economic growth rates increase strongly and equitably and climate does not change, that at-risk figure drops to around 20%. If changes occur on both fronts the at-risk proportion of population increases a little to 23%.

Nevertheless, the modelling of likely future health risks is important for at least two reasons. First, while we cannot *know* what patterns of development and geopolitical and economic strife will ensue over the next half-century, it is useful to at least estimate how intrinsically environmentally risky the world might become under climate change conditions. An example is the high-resolution modelling of future (falciparum) malaria risk distribution in Zimbabwe carried out for years 2000, 2025 and 2050. This showed previously unsuitable areas with dense human populations (especially the capital and second cities, in the highlands) becoming suitable for malaria transmission by mid-century. This type of modelling provides an indication of what extra programmes of surveillance and control might be needed in future, and the resultant likely future cost of 'holding the line' against the threatened large increase in total population at risk in Zimbabwe.

Second, modelling methods can, and will, be improved as it becomes feasible to downscale to more detailed local regions — and to take account of the impact of warming on the relatively sensitive altitude factor in highland regions; temperatures decline by around 1°C for every 600 metres ascent. Two-dimensional mapping studies unavoidably smooth out topographical variations in altitude and thus miss the likely and quite marked change in the ascent of malaria risk (and its intensification at lower altitudes) with warming.

Dengue

Dengue, a mosquito-borne viral infection that is currently largely confined to tropical and subtropical regions, causes approximately 80 million cases annually, and around 25,000 deaths. The disease shows a strong seasonal variation in Southeast Asia. There is some, though not consistent, evidence of an association of dengue with spatial and temporal variations in climate, including observations that both heavy rainfall and drought can increase dengue transmission. Recent research in New Caledonia (in the Pacific) using 40 years of data on meteorology and dengue occurrence found that most of the fluctuations in the disease were explained by the positive association with the combination of temperature and humidity.

The main dengue vector, *Aedes aegypti*, has adapted well to urban environments, and can breed opportunistically in very small pools of water (e.g. flowerpots and old tyres). Both rainfall patterns (breeding) and humidity (biting rates and survival) influence the size and longevity of the mosquito population. Dengue's other mosquito vector, *Aedes albopictus* (the 'Asian tiger mosquito'), has been spreading into many regions of the world over past decades, in large part reflecting long-distance maritime trading and increased movements of people, including military contingents. In the past decade there have been reports of this mosquito entering Italy, Spain and southeastern Europe. Might this have been facilitated by the gradually warmer conditions?

An ongoing World Health Organization (WHO)-based study has modelled the future risk of dengue under climate change conditions (based on the IPCC's mid-range A1B emissions scenario). Averaging the results from three different global climate models, each run forward to 2050, yielded an estimate of 4.86 billion people living in areas at risk of dengue in 2050 — an increase of 6.1% (280 million people) over the number that would have been expected without climate change. However, inclusion of projected growth in GDP, as index for development, reduced that extra 280 million by a little over 40% (to 120 million).

Tick-borne infectious diseases

Tick-borne diseases such as Lyme disease (borreliosis) and tick-borne encephalitis (TBE) are a major health problem in northern and central Europe (both diseases) and in northeast USA and southeast Canada (Lyme disease). Tick phenology, numbers, range and activity are influenced by climatic factors, particularly temperature. Studies in Canada show northward (and some westward) spread of the tick *Ixodes ricinus*, the vector for Lyme disease (borreliosis), associated with recent warming trends. The annual incidence of Lyme disease in southern Sweden is positively associated with mild winters and warm humid summers.

TBE was first identified in Sweden in the 1950s and the annual number of reported cases has increased ever since — overall by around six- to eight-fold. Northward extension of the tick vector's range was reported in several earlier papers, associating it with increasingly warm winters during the 1980s and 1990s. While no other factor apparently explained this extension, the complex ecology and epidemiology of tick-borne diseases has spawned ongoing debate as to how much climatic factors are involved. Some research points to socio-economic factors as the main cause of the recent increase in TBE rates in central and eastern Europe. A continuing flaw in this debate is the polarized 'either/or' argument, when 'both' is the much more likely answer.

Schistosomiasis in China and Africa

The water-borne infection schistosomiasis, caused by the (tiny worm-like) helminth *Schistosoma japonicum* and with water snails as intermediate host, has long been a public health scourge in China and several neighbouring countries. In Africa, the disease (with two different species of *Schistosoma*) is also a continuing and great burden. In China, the main reservoir species is water buffalo in rural settings which excrete the pathogen into water. Schistosomiasis has been greatly curbed by the national control programme originating in the 1950s. Now, however, regional climate change, especially warming, is expected to extend the distribution of the intermediary water snail host northwards, putting many additional millions of people at risk of schistosomiasis. The northern boundary of snail habitat is limited by the mid-winter 'freezing zone' where temperatures fall below 0°C. That geographic limit is projected to shift further north with climate change — having already shifted over the past four decades in association with a regional warming trend of over 1°C. Modelling studies of schistosomiasis (*S. mansoni*) in sub-Saharan Africa project increases in regional burdens and severity of the disease as temperatures rise in coming decades, although little overall change in prevalence because, as temperatures increase above 30°C, survival of the water snails and the water-borne intermediate form of the parasite declines.

Infections transmitted by microbially contaminated food and water

Gastroenteritis (diarrhoeal disease) is caused by diverse micro-organisms. This unglamorous disease category accounts for a huge proportion of the global burden of disease due to climate-sensitive infections. Increasing rates of gastrointestinal ('enteric') illness have been observed in many populations in association with increasing temperature. Two major enteric pathogens, *Salmonella* and *Campylobacter*, show a clear seasonal variation, with highest infection rates in warmer months, which probably reflects both temperature stimulation of microbial proliferation in food and water and seasonal changes in human behaviours (food storage, food choices, eating sites, etc.). Enterovirus infections also typically peak in summer and autumn months, although rotavirus peaks in winter and is a major cause of child diarrhoeal disease.

Increases in rainfall and in surface water also influence the occurrence of enteric infections. Rates of *Salmonella* infection of various commercial crops (e.g. lettuce) increase under both flooding and drought conditions. After heavy rainfall events the concentration of enteric viruses tends to increase in drinking water and recreational water. In Arctic communities permafrost melting can cause local flooding that disrupts sewage disposal, leading to contamination of drinking water sources.

One major category of food-borne and water-borne enteric infections results from ingestion of *Vibrio* bacteria. These vibrios belong to a genus of marine organisms, some of which are human pathogens, most notably *V. cholerae*, the pathogen that causes cholera. The versatile cholera vibrio can be transmitted not only by sea water and seafood, but also by fresh water, whereas *V. parahaemolyticus*, *vulnificus* and *alginolyticus* are transmitted to humans only in sea water and shellfish. Risk of infection is influenced by temperature, in particular, and by rainfall, flooding and sea-level rise.

Recent expansions of the marine range of these human-infecting vibrios have been reported. *V. parahaemolyticus* has spread north into Alaskan coastal waters and along the southern Pacific coasts of Peru and Chile — in each case strongly correlated with unusually warm coastal waters. This spread of vibrio populations has been associated with increases in human infection. The recent proliferation of *Vibrio* species in the Baltic Sea has been linked with the warming of that water body over preceding decades. A warming of approximately 0.7°C per decade over the past 30 years has been accompanied by an increase in *Vibrio* infections in northern Europe, particularly around the Baltic coast. Around the Alaskan coast, an outbreak of seafood (oysters) contamination with *V. parahaemolyticus* bacteria occurred in cruise ships in 2004, when the summer temperature of coastal water, having warmed over the preceding decade, reached a critical temperature that allowed the vibrio (apparently for the first time) to survive and multiply throughout the summer months.

Other indirect climate-related risks of infectious disease

There are, of course, many indirect pathways by which climate change influences infectious diseases, including some that entail several 'widening ripple' steps. For example, the clearing of forests in Southeast Asia and their replacement by palm oil plantations, done in part for the production of biofuels as replacement for greenhouse-gas generating fossil fuels, contributes to the displacement of forest-dwelling fruit bats. Colonies of bats, with their many naturally occurring viruses, often then relocate to commercial and residential areas where other fruit supplies exist. This type of process has contributed to the emergence from bat sources of Nipah virus and Hendra virus diseases in humans in that part of the world.

Increased international migration and refugee flows may introduce infection from countries with endemic vector-borne infections to settings where the vector organism but not the actual infectious agent is present. This is currently the case for mosquito-transmitted dengue fever in Australia.

Conclusion

When considered together, the observations of recent range extensions of various temperature-sensitive infectious diseases or their vectors indicate that global warming is beginning to influence these patterns of distribution and occurrence. Key examples include the following: malaria transmission zones have apparently extended to higher altitude in western Kenya, the mid-winter northernmost survival boundary of schistosomiasis-related water snail has extended further north in eastern China, various *Vibrio* species have extended their range at higher latitudes in the oceans in association with warming water and increases in on-shore vibrio-related gastrointestinal infections, the geographic range of tick-borne encephalitis has expanded northwards in Sweden and the ixodic tick that transmits Lyme disease (borreliosis) has extended north in eastern Canada.

It is important to note, too, that climate changes can influence infectious disease occurrence via both biological and social pathways. Warming can amplify the proliferation of bacteria, vector organisms and host animal species, and may also influence social behaviours such as outdoors eating and recreational exposure to vector species (mosquitoes, ticks, etc.) Similarly, cooling can influence biological factors in disease transmission, for example, by slowing the proliferation of bacteria, vector organisms and host animal species, and can foster infection outbreaks via social disturbances due to hunger-related unrest, mobility, crowding and displacement.

There is still much to learn about the ecological, social and biological processes by which changes in climatic conditions affect rates and ranges of infectious diseases. Much of that new knowledge must be sought at regional and even local levels, to take account of the subtle differences in interplay among these various sources of influence and the several stages in the transmission process. Meanwhile, there is urgent need to gain a surer sense of the main types of changes in risks of infectious diseases under projected climate change, and of the populations, groups and settings of greatest vulnerability, in order to understand our societies' likely future circumstances, and, hence, to anticipate the emergence of changes in risk of infectious disease occurrence, and to plan and take pre-emptive adaptive actions to reduce those risks.

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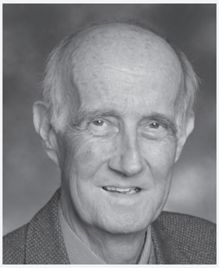
Professor Emeritus of Population Health
Australian National University
Canberra, Australia
Email: tony.mcmichael@anu.edu.au



Anthony J McMichael

Tony (AJ) McMichael, medical graduate and epidemiologist, is Professor Emeritus of Population Health at the Australian National University. During 2001–2012 he headed the research programme on the health risks of climate and environmental change, present and future. He is an elected member of the US National Academies of Science, Associate Fellow of Chatham House (London, programme on Global Health Security), and Honorary Professor of Climate Change and Health at the University of Copenhagen. Since 1993 he has contributed substantively to the sequence of scientific assessments by the UN's Intergovernmental Panel on Climate Change (IPCC). He is a frequent advisor to the World Health Organization on climate change risks to human health. He chairs an international expert group for the Tropical Diseases Research Program on the interactions between environment, climate, agriculture and poverty in the emergence of infectious diseases. Tony McMichael has published several hundred peer-reviewed papers, many book chapters, and authored three books (Cambridge University Press and Penguin). He is currently struggling to complete an historical analysis of climate change and human health, provisionally titled 'When Climates Change: Famines, Fevers and Fates of Populations'.