# Environment and health: 2. Global climate change and health

*Review*

*Synthèse*

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Greenhouse gases, naturally present at low concentrations in the lower atmosphere, keep the Earth's mean surface temperature at around 15°C. Without this trapping of heat ("radiative forcing") the mean air temperature would be –18°C and the Earth would freeze. The mechanism of the greenhouse effect is illustrated in Fig. 1. The atmospheric concentrations of greenhouse gases have been increasing since the early industrial revolution, owing principally to humankind's rapidly increasing combustion of fossil fuels along with increases in deforestation, irrigated agriculture, animal husbandry and cement manufacture. Table 1 shows the most important anthropogenic greenhouse gases and the annual change in their concentrations.[1]

In 1997 and 1998 global temperatures reached their highest levels since record-keeping began last century; 9 of the 11 hottest years in the 20th century occurred within the last 10 years (Fig. 2).[2] The global mean surface temperature has increased by 0.4°C in the past 25 years, and climate scientists are becoming increasingly confident that the anticipated process of global warming has begun. Three studies indicating disproportionate mid-atmospheric warming,[3] disproportionate night-time and winter warming,[4] and increased variability[5] — consistent with projections — all led the Intergovernmental Panel on Climate Change, a major international scientific collaboration established in 1988 by the World Meteorological Organization and the United Nations Environment Program, to conclude that there has been a "discernible" human influence on the climate system.[1,6] More recent studies continue to find a dominance of greenhouse gases over solar and other influences.[7]

The Intergovernmental Panel on Climate Change has comprehensively reviewed the science of climate change and its potential impacts.[1,3] It foresees an increase of 1.0ºC–3.5ºC in the global mean temperature by the year 2100, with considerable regional variations. This assessment is derived from projections made by computer-based global climate models[1] that combine, through simultaneous equations within a 3-dimensional global grid, the atmospheric and oceanic processes that occur in response to increased greenhouse gases and the resulting rise in radiative forcing in the lower atmosphere.

Although the current generation of global climate models cannot forecast the precise spatial and temporal pattern of changes in climate means and variability with global warming,[1] extreme weather events such as drought, floods and storms may become more frequent and intense in the future. Indeed, with warming ocean surfaces[1] and the fact that each increase of 1°C in temperature enables the atmosphere to hold 6% more water vapour, the resulting intensification of the hydrological cycle corresponds to evidence in the United States and other nations of an increase in heavy rain events and prolonged droughts in 20th century.[5] There is evidence that El Niño events have increased in magnitude since the mid-1970s,[8] and climate change may alter the frequency and magnitude of the El Niño Southern Oscillation (ENSO) cycle.[9] Greater variability from norms may also indicate systemic instability of the climate regime,[10] increasing the potential for abrupt climate change.[11]

## Signals of climate change

Global warming is projected to increase both ambient temperatures and rainfall at high latitudes and high elevations.The migration of plants to higher altitudes has been documented on numerous peaks in the European Alps, Alaska, the Sierra



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Nevada (United States) and New Zealand.[12] These botanical trends, indicative of warming, have accompanied other physical changes such as the retreat of montane glaciers in Argentina, Peru, Alaska, Iceland, Norway, the Swiss Alps, Kenya, the Himalayas, Indonesia and New Zealand.[13] Since 1970 the lowest level at which freezing occurs has ascended about 150 m higher in mountains in tropical latitudes (from 30 N to 30 S latitude), which is equivalent to 1°C warming.[14]

Meanwhile, there have been reports that both insects and insect-borne diseases (including malaria and dengue fever) have been experienced at increasingly higher altitudes in Africa, Asia and Latin America.[15–17] Highland malaria is also reportedly increasing in Papua New Guinea and parts of sub-Saharan Africa.[18,19] A number of factors may be implicated, including deforestation, population movements and breakdown in public health, and it is not yet possible to attribute these increases to climatic change. However, a climatic influence is plausible, and the emerging pattern is compatible with the botanical and physical evidence of warming at high altitudes.[20]

## Health impacts

A change in world climate would have wide-ranging, mostly adverse, consequences for human health.[21,22] Most of the anticipated health impacts would entail increased rates of illnesses and death from familiar causes (Table 2). However, the assessment of future health outcomes refers to climatic-environmental conditions not previously encountered. Such conditions, particularly in conjunction with other global environmental changes now occurring (e.g., deforestation) may also increase the likelihood of unfamiliar health outcomes, including the emergence of "new" infectious disease agents.[23] The 1997/98 El Niño event brought surprises: Indonesia and Brazil experienced widespread respiratory illness due to haze from uncontrolled burning of tropical forests.[24] With Hurricane Mitch in Central America, in November 1998, deforested areas experienced increased flooding and landslides, the aftermath spawning "clusters" of water-, insect- and rodent-borne diseases (cholera, malaria, dengue fever and leptospirosis).[25]

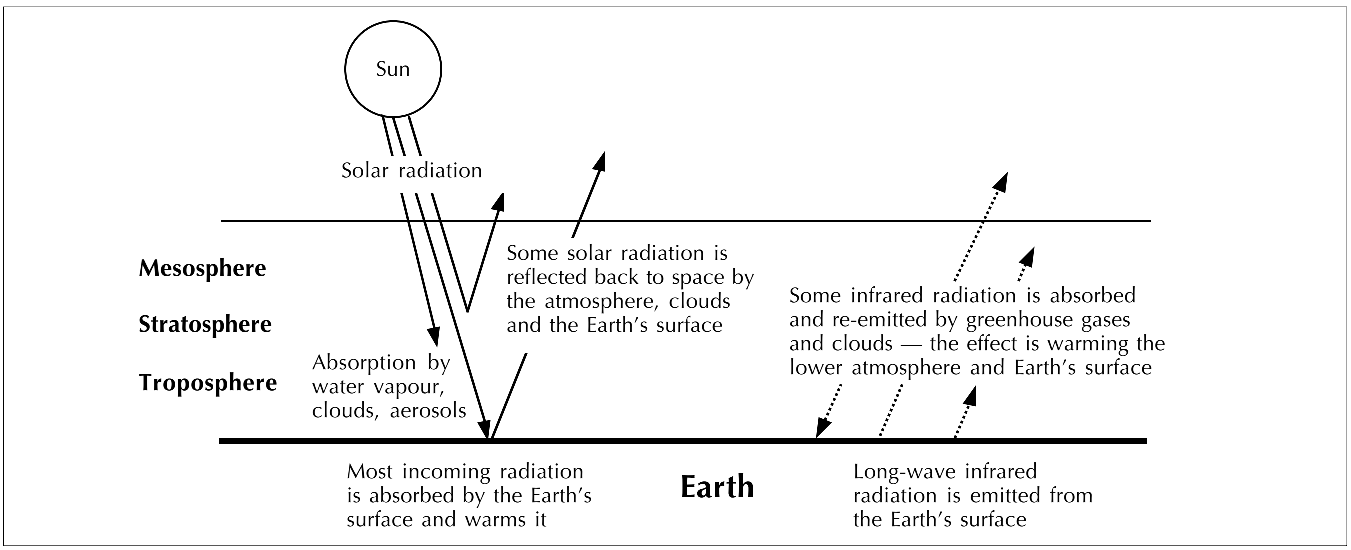


**Fig. 1: Mechanism of the greenhouse effect. Adapted from reference 2.**

**Table 1: Greenhouse gases influenced by human activities**

| Variable | $CO_2$ | $CH_4$ | $N_2O$ | CFC-11 | HCFC-22 | $CF_4$ |
|---|---|---|---|---|---|---|
| Pre-industrial concentration | 280 ppmv | 700 ppbv | 275 ppbv | 0 | 0 | 0 |
| Concentration in 1994 | 358 ppmv | 1720 ppbv | 312 ppbv‡ | 268 pptv‡ | 110 pptv | 72 pptv‡ |
| Annual rate of increase in concentration* | 1.5 ppmv (0.4%) | 10 ppbv (0.6%) | 0.8 ppbv (0.25%) | 0 pptv (0%) | 5 pptv (5%) | 1.2 pptv (2%) |
| Atmospheric lifetime,† yr | 50–200§ | 12¶ | 120 | 50 | 12 | 50 000 |

Note: $CO_2$ = carbon dioxide, $CH_4$ = methane, $N_2O$ = nitrous oxide, CFC-11 = chlorofluorocarbon-11, HCFC-22 = hydrochlorofluorocarbon-22, $CF_4$ = carbon tetrafluoride, ppmv = parts per million per volume, ppbv = parts per billion per volume, pptv = parts per trillion per volume.
*The rates for $CO_2$, $CH_4$ and $N_2O$ are based on data for the decade beginning 1984; the rates for the other gases are based on data for recent years (1990s).
†Average time spent by a gas in the atmosphere after it has been emitted.
‡Estimated from 1992/93 data.
§No single lifetime for $CO_2$ can be defined because of the different rates of uptake by different sink processes. Sinks are systems such as forests and oceans that can take up greenhouse gases.
¶Adjusted to take into account the indirect effect of methane on its own lifetime. CFCs also deplete ozone in the stratosphere and are now controlled by the Montreal Protocol. HCFCs have been temporarily permitted as substitutes for CFCs but are also potent greenhouse gases.
Adapted from Houghton JT et al.[1]

The potential health impacts of global warming can be broadly classified as direct or indirect (Table 2). The former category refers to the direct impact of extremes in local weather conditions. Epidemiological studies and public health data have identified how thermal stresses (including heat waves) and weather disasters can result in serious illness, injuries and death. Estimating the consequences of indirect effects poses more of a challenge because those impacts typically result from changes in complex processes. They include alterations in the transmission of vector-borne infectious diseases, alterations in water quality and quantity, and changes in the productivity of agroecosystems,[26] with the potential for displacement of vulnerable populations as a result of local declines in food supply or sea level rise.[2,6]

The range of likely health impacts can be assessed, in part, by studying the consequences of local climatic variability, including short-term trends. One useful, although limited, analogue of future climatic change is the ENSO cycle, which affects temperature, precipitation and extreme events (e.g., storms) in many parts of the world. The ENSO cycle influences, often strongly, the incidence of various infectious diseases in many parts of the world: malaria in northeastern Pakistan, Sri Lanka, Colombia and Venezuela, Murray Valley encephalitis and epidemic polyarthritis (Ross River virus) in Australia and dengue fever in the South Pacific.[27–32] Historical analyses showed that the risk of a malaria epidemic increased 5-fold in the semi-arid Punjab during the year following an El Niño and 4-fold in southwestern Sri Lanka during the El Niño year. El Niño events are also strongly associated with the numbers of people affected globally by natural disasters, particularly droughts, that cause major harm to human health.[33] A recent review has documented a range of health impacts that may be affected by the ENSO cycle.[34]

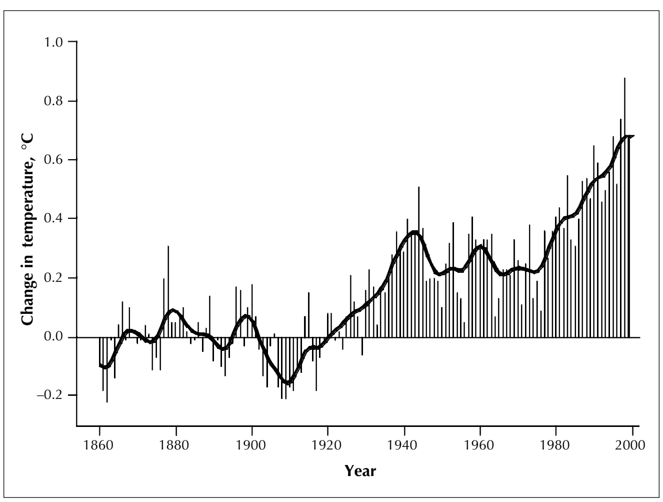


**Fig. 2: Changes in global surface air temperatures from 1860 to July 1999. Annual means (bars) and trends (line) relative to that at the end of the last century. Reprinted with permission from the Hadley Centre for Climate Prediction and Research, UK Meteorological Office.[2]**

Thermal extremes provide a clearly relevant form of climatic variation for study, as global warming is projected to increase the frequency of heat waves and decrease the frequency of winter cold spells. Modelling based on previous studies of mortality associated with heat waves in specified urban populations in the United States has indicated that the rate of deaths related to heat waves might increase substantially by the year 2050, particularly if little acclimatization to warmer weather occurs.[35] A study of 10 Canadian cities suggested that, in the case of Montreal for example, heat-related deaths would increase from 70 per annum to 240–1140 in an "average" summer in 2050 without acclimatization.[36] The investigators suggested that some acclimatization of populations might occur in Montreal and Toronto but probably not in Ottawa. Because the conversion of nitrogen oxide to ground-level ozone (smog) is temperature-dependent, a projected 5-fold increase in the number of hot days with temperatures above 30°C could lead to increases in the number of days with concentrations of ground-level ozone considered to be a risk to health for sensitive individuals.[37] The association between mortality and temperature is J-shaped in many countries. The rela-

**Table 2: Mediating processes and direct and indirect potential effects on health of changes in temperature and weather**

| Mediating process | Health outcome |
|---|---|
| **Direct effects** | |
| Exposure to thermal extremes | Changed rates of illness and death related to heat and cold |
| Changed frequency or intensity of other extreme weather events | Deaths, injuries, psychological disorders; damage to public health infrastructure |
| **Indirect effects** | |
| Disturbances of ecological systems: | |
| Effect on range and activity of vectors and infective parasites | Changes in geographical ranges and incidence of vector-borne disease |
| Changed local ecology of water-borne and food-borne infective agents | Changed incidence of diarrheal and other infectious diseases |
| Changed food productivity (especially crops) through changes in climate and associated pests and diseases | Malnutrition and hunger, and consequent impairment of child growth and development |
| Sea level rise with population displacement and damage to infrastructure | Increased risk of infectious disease, psychological disorders |
| Biological impact of air pollution changes (including pollens and spores) | Asthma and allergies; other acute and chronic respiratory disorders and deaths |
| Social, economic, and demographic dislocation through effects on economy, infrastructure, and resource supply | Wide range of public health consequences: mental health and nutritional impairment, infectious diseases, civil strife |

*Reprinted from McMichael and Haines,[22] with permission from BMJ Publishing Group.

tion between increased mortality and low temperatures is more complex than that with high temperatures, thus the degree to which cold-related deaths in temperate countries may decline with global warming is unresolved. Excess winter mortality is higher in some countries with temperate climates (e.g., the United Kingdom) than in those with very cold winters, probably because of fuel poverty and inadequate housing and winter clothing.[38,39] Although much of the winter excess in mortality is due to increases in cardiovascular events, some may be due to viral infections arising from increased crowding during winter.[40]

In addition, disproportionate warming at high latitudes, at high altitudes, during winter and at night time could produce disproportionate impacts. Canada, for example, could experience a greater relative increase in heat waves and conditions conducive to outbreaks of vector-borne infectious diseases than nations at lower latitudes. In Canada, malaria disappeared at the end of the 19th century, although in 1998 cases of locally transmitted malaria were reported in Toronto.[24] However, although increased temperatures may result in conditions suitable for the reintroduction of malaria, the existence of effective public health programs will be the main determinant of the existence and extent of such infections. Many of the encephalitides in North America, including St. Louis and La Crosse encephalitis and western, eastern and Venezuelan equine encephalomyelitis, are transmitted by mosquitoes. Although the mosquito lifespan tends to diminish if temperatures rise excessively, viral maturation rates increase with temperature, within the viable ranges of the mosquitoes and pathogens. It has been suggested that, as a result of climate change, there could be a northward shift in western equine and St. Louis encephalitis, with the disappearance of the former in southern endemic regions.[41]

## Modelling the effects of climate change

Complex, integrated mathematical models are used to estimate the likely effects of climate change on vector-borne diseases. These highly aggregated models are in the early stages of development and do not take into account local environmental and ecological circumstances.[42] Nevertheless, they are useful for forecasting the broad direction and potential magnitude of future change.

Such models project substantial increases in the transmission of malaria and dengue fever worldwide and a decrease in the transmissibility of schistosomiasis because of excessive warming of water and some regional drying.[43–45] Conditions conducive to malaria transmission, for example, are expected to increase from a doubling of atmospheric carbon dioxide. The majority of computer projections indicate some increase in malaria transmissibility in response to standard scenarios of climate change. The actual changes in the incidence of malaria and dengue fever would, of course, depend on many factors, including future patterns of social development, land use and urban growth, and the effectiveness of preventive measures such as vector control and vaccination.

The growth of algae in surface waters, estuaries and coastal waters is sensitive to temperature.[46,47] About 40 of the 5000 species of marine phytoplankton (algae) can produce biotoxins, which may reach human consumers through shellfish. Warmer sea temperatures can encourage a shift in species composition of algae toward the more toxic dinoflagellates.[48] Upsurges of toxic phytoplankton blooms in Asia are strongly correlated with the ENSO cycle.[49]

It is also apparent that algal blooms potentiate the transmission of cholera. Electron microscopy has shown that algae and the zooplankton that feed upon them provide a natural refuge for *Vibrio cholerae*, where, under normal conditions, the bacteria exist in a nonculturable, dormant state. An increase in sea surface temperature, along with high nutrient levels (eutrophication) that stimulate algal growth and deplete oxygen, can activate the blooms and vibrios. Sea surface temperature in the Bay of Bengal is correlated with algal blooms and outbreaks of cholera in Bangladesh.[50] Climate variability and change may thus influence the introduction of cholera into coastal populations. *V. cholerae* occur in the Gulf of Mexico and along the east coast of North America.

Heavy rainfall may cause outbreaks of cryptosporidiosis,[51] which causes severe diarrhea in children and can cause death in immunocompromised individuals.

Rodent populations are also influenced by climate anomalies. Prolonged droughts deplete rodent predators (owls, snakes and coyotes), whereas rains provide new food supplies. These dynamics apparently contributed to the 1993 outbreak of hantavirus pulmonary syndrome in the southwestern United States[52,53] and may have contributed to recent outbreaks of that disease in Argentina, Bolivia, Chile, Canada and Paraguay.[54–56]

Lyme disease is also important in North America. Large deer populations (with few predators) and warm winters allowing overwintering of tick populations at higher latitudes[37,57] could increase the range of the disease.

Climate change could also affect food production, with declines concentrated in low-latitude regions, where food insecurity often already exists,[26,58] including Africa, the Middle East and India. There is a range of estimates of the risk of hunger reflecting different assumptions about future population growth, international trade and adaptive agricultural technology. Such estimates, however, do not include the likely additional influence of extreme weather events[58] or of increases in agricultural pests and pathogens.[61]

Accelerated rise in sea level would have a variety of health impacts. The Intergovernmental Panel on Climate Change has forecasted a rise of about 40 cm by 2100.[1] With unmitigated emissions of greenhouse gases by 2080, the number of people flooded annually would increase from 13 million to 94 million: 60% in South Asia and 20% in Southeast Asia.[2] Populations on low-lying islands such as the Maldives, the Marshall Islands, Kiribati and Tonga, and in the deltaic regions of parts of Africa and the United States, would also be vulnerable to accelerated rises in sea level and associated increases in storm surges. Salination of coastal farmlands and of freshwater aquifers would cause economic disruption, population displacement and additional adverse health consequences. In Canada, much of the coast of Prince Edward Island is highly erodable, and shorefront buildings may be threatened along the Gulf of St. Lawrence. Rises in sea level and increased storm surges along the tundra coast of Alaska and Canada are likely to cause erosion and flooding.[60] The Arctic and the Antarctic are, in general, likely to be particularly vulnerable to climate change, resulting, for example, in substantial loss of sea ice and changes in species composition, with implications for indigenous communities following traditional lifestyles. In addition, loss of ice cover will alter the Earth's albedo (reflectivity), thus increasing heat absorption and contributing to climate change.

## Conclusion

Industrialized nations produce most of the world's greenhouse gas emissions. Even if these nations achieve the limited reductions agreed to at the 1997 Kyoto Climate Change Convention, global carbon dioxide emissions are likely to increase substantially, with increasing contributions from countries such as China, India and other developing nations.[61] Developing countries, in order to protect their own development prospects, will therefore need substantial incentives to cut emissions, including the transfer of nonpolluting renewable energy and energy-efficient technologies. Reducing fossil fuel combustion will also have substantial direct health benefits, such as preventing many thousands of air-pollution–induced deaths annually worldwide from both indoor and outdoor sources.[62,63]

Some degree of global warming now seems certain. Thus, adaptations to climate change will be required, such as housing designs that enhance summer-time cooling, the "greening" of inner cities, the strengthening of coastal buffers and improved control of vector-borne and water-borne diseases. Health-indicator monitoring and disease surveillance should be integrated into the 3 nascent global observing systems for world climate, oceans and terrestrial systems.[64] Multidisciplinary research into the identification, understanding and modelling of health impacts needs support, as do intergovernmental and interagency collaborations to develop health early warning systems that can facilitate timely, environmentally friendly public health interventions.[25,34]

Recognizing the wide-ranging potential consequences of climate change for our health and well-being can greatly strengthen the international rationale for reducing greenhouse gas emissions. Although there is much that is unavoidably complex and uncertain about these large-scale risks to human population health, the case for health professionals urging a health-protecting, precautionary approach that will have multiple health benefits remains clear.[65]

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