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THE EFFECTS OF CHANGING WEATHER ON PUBLIC HEALTH

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■ **Abstract** Many diseases are influenced by weather conditions or display strong seasonality, suggestive of a possible climatic contribution. Projections of future climate change have, therefore, compelled health scientists to re-examine weather/disease relationships. There are three projected physical consequences of climate change: temperature rise, sea level rise, and extremes in the hydrologic cycle. This century, the Earth has warmed by about 0.5 degrees centigrade, and the mid-range estimates of future temperature change and sea level rise are 2.0 degrees centigrade and 49 centimeters, respectively, by the year 2100. Extreme weather variability associated with climate change may especially add an important new stress to developing nations that are already vulnerable as a result of environmental degradation, resource depletion, overpopulation, or location (e.g. low-lying coastal deltas). The regional impacts of climate change will vary widely depending on existing population vulnerability. Health outcomes of climate change can be grouped into those of: (a) direct physical consequences, e.g. heat mortality or drowning; (b) physical/chemical sequelae, e.g. atmospheric transport and formation of air pollutants; (c) physical/biological consequences, e.g. response of vector- and waterborne diseases, and food production; and (d) sociodemographic impacts, e.g. climate or environmentally induced migration or population dislocation. Better understanding of the linkages between climate variability as a determinant of disease will be important, among other key factors, in constructing predictive models to guide public health prevention.

INTRODUCTION

Environmental health concerns have traditionally focused on toxicological or infectious risks to human health from local factors. As we enter the next millennium, it is becoming ever more evident that disturbances of natural ecological systems pose

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new risks to health. During the past 2 decades, population growth and the spread of industrialization, which are unprecedented in human history, have resulted in accumulations of greenhouse gases in the atmosphere that are beginning to affect the world's climate.

Human interactions with each other as well as with other living creatures can have important effects on the health of all partners in the complex closed ecosystem of our planet (103). The ecological perspective on population health recognizes that the foundations of good long-term population health depend on the stability and functioning of ecological systems. As the scale of humankind's impact on biophysical systems rises, the extent of health impacts may grow to affect widely disparate populations. The field of public health will need to address the potential health risks posed by current and projected hazardous exposures stemming from climate change.

PREVAILING WEATHER IN THE CONTEXT OF GLOBAL ECOSYSTEM CHANGE AND HUMAN HEALTH

Climate and its effects on many natural processes are fundamental components that allow life to exist on Earth. The story of Noah reminds us of the awesome capacity of weather to affect human and animal life. Only those species protected from the ravaging waters by Noah's ark survived the flood (*Genesis,* chapter 6). Throughout history, disasters afflicting human populations, such as floods, famines, and plagues, have been reflections of local ecological disruptions, often the result of adverse weather conditions. During this century, environmentally related calamities, such as drought-induced famines of the Sahel, the spread of the cholera pandemic to Africa and Latin America, and the devastating damage of tropical storms in Bangladesh, highlight the critical ecological balance between humans, climate, infectious agents, and the environment. Today, several endangered regions around the globe have been identified where such life support systems as soil fertility and water supplies are threatened (82). For example, in Honduras, a fragile ecosystem has rendered the population increasingly vulnerable to changing climate, as reflected in the shifting pattern of insect vectors and infectious diseases (4).

Epidemiology has been a major contributing factor to successes in disease control in the past century, highlighted by achievements such as the global eradication of smallpox and the elimination of polio from the Western Hemisphere. These triumphs have their roots in the germ theory of the 1880s, which advocated control of specific infectious agents as opposed to collective sanitation or ecological stability as the itinerary of good health. More recent studies of epidemiological methodology have focused on the multiple risk factors for chronic noncommunicable diseases.

While lauding new insight into disease causation, epidemiologists have also identified the limitations of studying risk factor epidemiology alone to understand the determinants of population health, and these epidemiologists have advocated a social-ecological-systems perspective (178). This perspective can be traced to the classical Hippocratic doctrine of the importance of clean air, water, and food to individual health. In the 1800s, ideas by the practical sanitarians that good health was based on collective cleanliness shifted the focus from the individual to the population. In the 1950s and 1960s, the microbiologist Rene Dubos recognized that human health is subject to the biological stresses and challenges of a changing environment. He wrote: "... in an ever-changing world each period and each type of civilization will continue to have its burden of diseases created by the unavoidable failures of adaptation to the new environment" (40). Expanding on this idea, McMichael emphasized the concept of forecasting future health risks in relation to a changing environment (124).

Examinations of climate, ecosystem, and health connections suggest that climate change and variability may have significant and widely ranging impacts on human health. In 1988, the Intergovernmental Panel on Climate Change (IPCC), a multidisciplinary scientific body, was established by the World Meteorological Organization and the United Nations Environment Program to advise governments. Organized into three working groups, IPCC concentrates on (*a*) the climate system, (*b*) impacts and response options, and (*c*) economic and social dimensions. The IPCC released its second assessment report in 1995 (70), including an assessment of population health impacts. The IPCC's third assessment report will be completed in the year 2000. These integrated assessments illustrate that climate change will not affect any one sector in isolation, but will have simultaneous impacts on other biological and physical systems. Furthermore, these systems are interconnected, and changes in one sector (e.g. water, agriculture, or forestry) could affect another. To understand the human health implications of weather changes, it is thus efficacious to have some discussion of the observed and projected changes in climate and the climate system.

WEATHER AND CLIMATE

Weather

Weather refers to short-term fluctuations in the atmosphere (hours to days), as opposed to long-term, or climatic changes. Weather is often identified and studied in terms of brightness, cloudiness, humidity, precipitation, temperature, visibility, and wind. Atmospheric variations occur as weather systems develop from atmospheric instabilities. However, characteristics of weather systems are determined mainly by chaotic dynamics and, therefore, lack predictability beyond several days.

Climate

Climate is usually defined as average weather over a period of time (years) and in a particular geographic region. Climate descriptions and quantitative measures include statistical information on various climate variables. Owing to the longer time scales involved, these may include information on climate variability and extreme events. Climate involves variations in interactions between different components of the climate system, the atmosphere, the oceans, sea ice, and the land and its features. The atmosphere is said to be coupled to the biosphere and the ocean. Forests, part of the biosphere over land, are described as carbon sinks, because they remove CO_2 from the atmosphere for photosynthesis. The ocean also acts as a sink, but for heat, stored in its deep layers.

Changes in any of the climate system components, whether from internal or external forcing, can cause the climate to vary. Changes in components external to the climate system may result from natural events like volcanoes or from human activities, such as increases in greenhouse gases, changes in atmospheric aerosol content, or extensive and sustained deforestation activities (thereby destroying important carbon sinks). Of all components, the atmospheric circulation is mainly responsible for regional changes in climatic variables such as wind, temperature, and precipitation, whether in the normal range or the extremes.

INCREASING CONCERNS ABOUT CLIMATE CHANGE AND THEIR POSSIBLE IMPACTS ON PUBLIC HEALTH

Observed Trends

Climate change, whether caused by natural variability or human activity, depends on the overall energy budget of the planet—the balance between incoming (solar) short-wave radiation and outgoing long-wave radiation (Figure 1). Since preindustrial times (approximately the mid-1800s), changes in atmospheric composition of CO_2, CH_4, and N_2O have far exceeded any changes that occurred in the preceding 10,000 years. Historical levels of these greenhouse gases are known from analysis of air trapped in bubbles in ice cores from Antarctica (44, 62). Increases in greenhouse gas concentrations have led to positive radiative forcing by absorbing and re-emitting infrared radiation toward the lower atmosphere and Earth's surface (Figure 1). This perturbation to the energy balance between the Earth and atmosphere tends to cause warming and produce other climatic changes. The concentration of CO_2, the major greenhouse gas, for example, has risen by almost 30%, from $\sim$280 ppm by volume (ppmv) in the late 18th century to 358 ppmv in 1994 (168).

Analyses of observations of surface temperature from around the globe show that there has been a mean warming of 0.3°C–0.6°C over the past 100 years (147; Figure 2). Changes in precipitation, climate variability, and extremes differ between geographical regions, and global patterns are not readily apparent (147). On a regional scale, however, some trends are beginning to emerge. For example, Karl et al described an increased percentage of rainfall in extreme 1-day events over the United States (79–81). On average for the continental United States, the frequency of heat waves has increased over the past 40 years (48). Although not usually considered a climatic variable, global mean sea level is estimated to have risen 10–25 cm over the past 100 years (190).

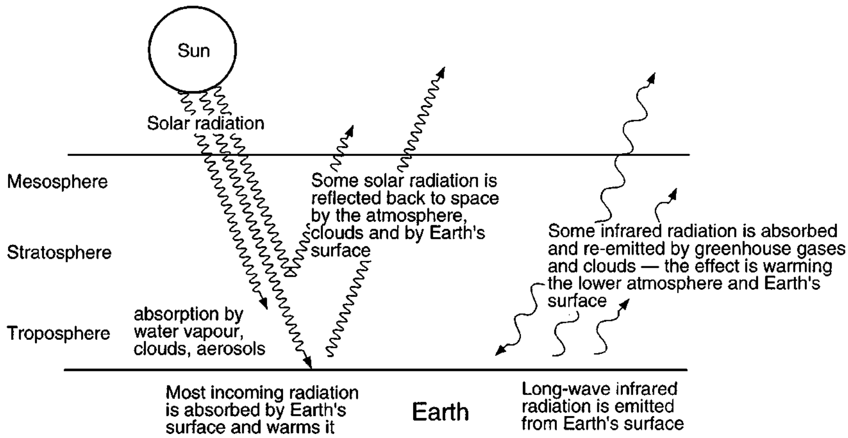

Figure 1 Components of the Earth's radiation and energy balance. Incoming solar radiation is partially reflected by clouds, the atmosphere, and Earth's surface. The remainder is absorbed by clouds, water vapor, aerosols, and finally Earth's surface. Some of this heat is returned to the atmosphere as evapotranspiration or is reradiated as thermal infrared radiation. Some of the infrared fraction of this radiation is absorbed by greenhouse gases in the atmosphere and emitted both back into space and toward the Earth's surface, producing the greenhouse effect. The greenhouse gases include carbon dioxide, methane, ozone, nitrous oxide, halogenated compounds (e.g. chlorocarbons, fluorocarbons, and bromocarbons), and water vapor. For partitioning of the global mean energy budget and values of its components, see Kiehl & Trenberth (90). (Reprinted with permission from reference 69.)

Human Influence on Climate Change

Until recently, changes in climate occurred solely through natural processes, associated, for example, with changes in the output of the sun or slow changes in ocean circulation. Today, human activities are implicated in the observed climate change. The IPCC second assessment report states that "the balance of evidence suggests a discernible human influence on global climate" (70). Fossil-fuel (coal, oil, and gas) combustion has been a major contributor to the concentration increase of CO_2 (168). Land use changes such as deforestation have also contributed by removing the CO_2-reducing capacity of forested areas. Industrial activity and land use changes (biomass burning) have resulted in emissions of gases like CO and volatile organic compounds (e.g. butane and propane) that undergo photooxidation in the presence of nitrogen oxides (NO_2 and NO) to form tropospheric ozone (O_3), a powerful greenhouse gas. Atmospheric methane (CH_4) has more than doubled from preindustrial levels (168). Current levels are the highest ever observed, including ice core records that date back 160,000 years (30).

Halogenated compounds that do not exist naturally are now present in substantial amounts in the atmosphere and have high greenhouse warming properties in addition to their destructive effect on the stratospheric ozone layer (203).

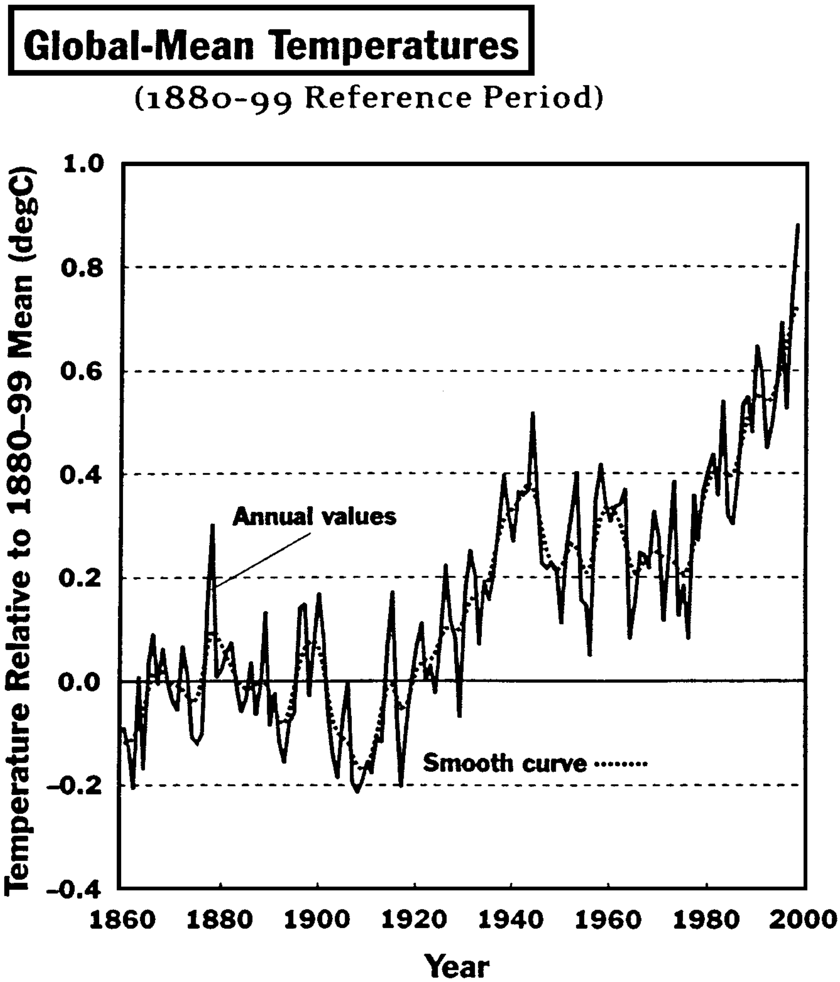

Figure 2 Annual global average surface air temperature changes (land plus marine), 1860–1998, relative to the 1880–1899 mean as a reference period. (Reprinted with permission from reference 196.)

A physical link between global warming and stratospheric ozone depletion has been demonstrated in atmospheric models (173); specifically, the trapping of heat in the troposphere cools the stratosphere and allows further ice crystal formation that can enhance ozone-depleting chemical reactions. A rapid phase-out of chlorofluorocarbon (CFC) sources, as required by the Montreal Protocol and its amendments, has resulted in a slowdown in the growth rates of atmospheric CFCs, particularly CFC-11 and CFC-12 (168). The health effects of stratospheric ozone depletion have been previously reviewed (104, 110).

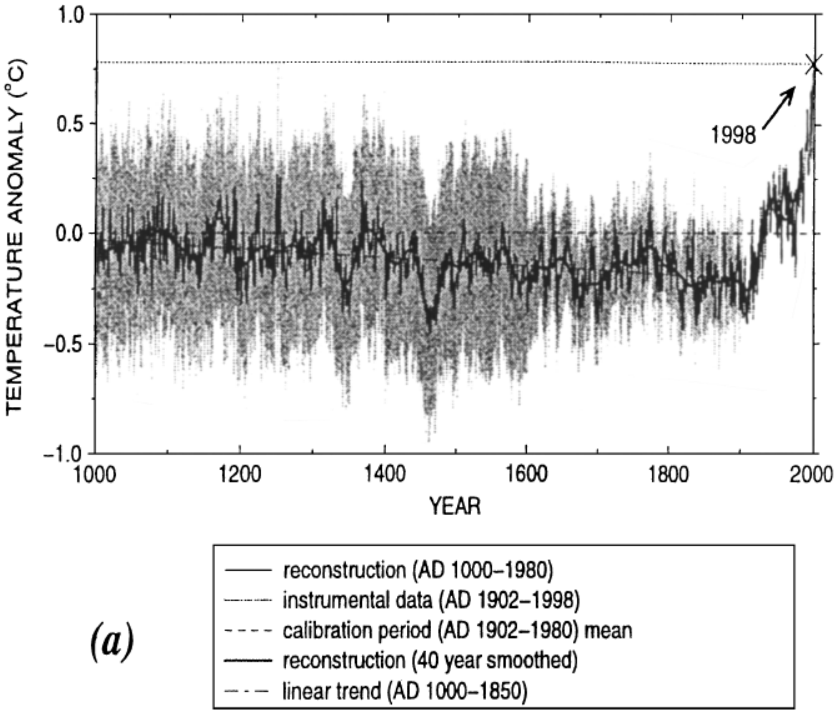

Figure 3 Millennial temperature reconstruction for the Northern Hemisphere. Dark solid line is 40-year smoothed data. Shaded area represents two standard error limits. This data supports the conclusion that the past decade may likely be the warmest in the Northern Hemisphere for the past millennium. (Reprinted with permission from reference 117a.)

Are the Trends Real or a Statistical Blip?

Long-term climate change, whether from natural sources or human activity, is observed as a signal against a background of natural climate variability in space and time. To help resolve this detection issue and understand recent climatic change, historical data of climate variables are needed to estimate natural variability. Instrumental records are restricted to $<$150 years. Previous climates must be deduced from palaeclimatic records, including tree rings, pollen series, faunal and floral abundance in deep-sea cores, isotope analysis from coral and ice cores, and diaries and other documentary evidence. Results of these analyses show that surface temperatures in the mid to late 20th century appear to have been warmer than any similar period of the last millennium (Figure 3).

Projected Climate Change and Sea-Level Rise

Doubling of carbon dioxide is often used to assess climatic responses. Midrange estimates of increases in temperature and sea level between now and the year 2100 are 2.0°C and 49 cm, respectively. The range of these estimates is typically 1.0°C–3.5°C and 20–86 cm, respectively (86, 190).

Small changes in the mean climate can produce relatively large changes in the frequency of extreme weather events [defined as events that exceed a certain threshold (70)]. For example, a general warming is expected to cause more high-temperature events (e.g. extremely hot days) and a decrease in extremely low temperatures (e.g. frost days) (66). Heat waves are likely to increase in severity and frequency with increasing global mean temperatures (78).

Although global warming may affect ocean currents, air currents, and atmospheric humidity, there is little agreement between climate models on the frequency or severity of extreme events over the next century (86). However, warmer temperatures are expected to lead to a more vigorous hydrological cycle. As some models indicate, this could cause an increase in precipitation intensity, suggesting a possibility for more frequent and heavier rainfall events (86). Ironically, concomitant with projections for heavier rainfall events, there are suggestions of reduced soil moisture owing to enhanced evaporation with higher mean temperatures (195).

SUMMARY OF CURRENT AND ANTICIPATED PUBLIC HEALTH EFFECTS OF CHANGING WEATHER AND CLIMATE

Several international and regional assessments have resulted from a growing awareness of climate change. Human population health impacts have been assessed globally (125) and regionally (191) by the IPCC. A task group convened by the World Health Organization (WHO), the World Meteorological Organization, and the United Nations Environment Program undertook a comprehensive assessment of the health impacts of climate change (199). In 1999, a European assessment was prepared by the Working Group on the Early Human Health Impacts of Climate Change, convened by the WHO European Center for Environment and Health (97). In addition, several national assessments have reviewed the potential health impacts of climate change, including those in Australia (141), Japan (7, 8), the United States (152a, 186), Canada (24), the United Kingdom (185a), the Netherlands (119), and the Czech Republic (88, 128). Some targeted analysis for developing countries has been conducted under the U.S. Country Studies Program (12); however, to date, comprehensive health impact assessments have not been conducted in developing countries, even though many of the health effects outlined by the IPCC are projected to affect these populations in particular (127). Furthermore, adding to the uncertainty in climate projections, many physical, biological, behavioral, and sociological confounders have added to the complexity and uncertainty in projecting future health status, and many knowledge gaps remain.

Classification of Health Effects

The potential effects of climate changes on population health have been classified by whether these effects occur via the direct impact of a climate variable, such as increasing temperature or weather variability, or are mediated by changes in indirect mechanisms, such as infectious agents or via ecological disruption (123, 125). To highlight the interrelatedness of these systems, we classify hazardous exposures as physical, physical/chemical, physical/biological, and sociodemographic (see Table 1). Physical hazards to human health include those from thermal stress and extreme weather events; physical/chemical effects include those mediated by exposure to air pollutants; physical/biological effects include those mediated by infectious agents, particularly waterborne and vectorborne microbes, as well as effects on food productivity and pollen and spore levels in air; sociodemographic effects focus on conflict and forced migration as a result of environmental hazards.

Physical Effects

Thermal Stress. Exposure to both extreme hot and cold weather is associated with increased morbidity and mortality compared with an intermediate, comfortable temperature range (92). However, the extent of temperature-related mortality seems to vary with geography. Martens (120) described this relationship as a "V-shaped" function (see Figure 4) based on a meta-analysis of several studies of urban populations selected for the estimation of the effect of temperature changes on mortality. The comfortable temperature range varied between 16.5°C in the Netherlands and 29°C in Taiwan [120; McMichael et al (199) suggested that the relationship is "J-shaped," indicating asymmetry with a steeper slope at higher temperatures.] It should be noted that the majority of temperature/mortality studies have taken place in developed countries and in regions with temperate climates.

In health, the body's thermoregulatory mechanisms can cope with a certain amount of increase in temperature through perspiration and vasodilation of

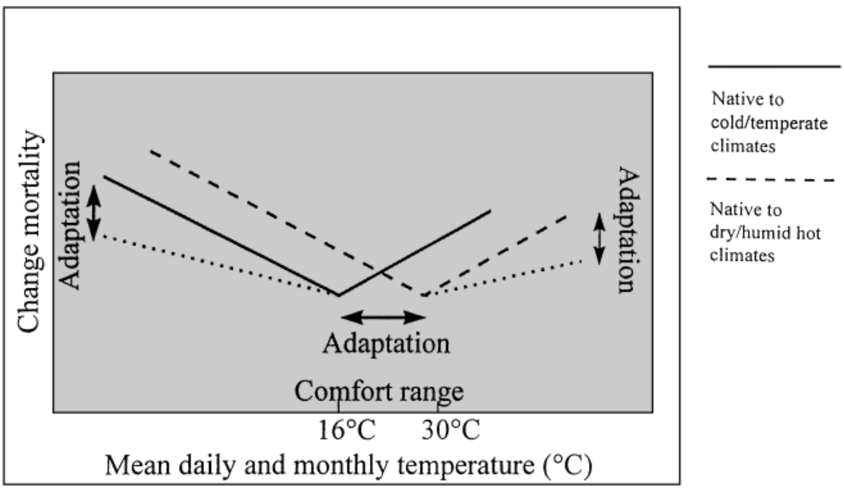

Figure 4 V-shaped relationship between outdoor temperature and mortality. (Reprinted with permission from reference 120.)

TABLE 1 Anticipated human health impacts of global climate change[a]

Health impact category	Mediating process	Health outcomes	Examples of specific diseases or injuries[b]
Physical effects	Increased number of extremely hot days, decreased number of extremely cold days, urban heat island effect	Altered incidence of heat and cold stress	Heat stroke, cardiorespiratory failure
	Extreme weather events Floods, severe storms	Exposure to trauma, loss of shelter	Traumatic deaths and injuries, drowning, PTSD
	Drought	Famine	Malnutrition, impairment of child growth and development
		Exposure to wildfires, respiratory effects of inhaled smoke	Burns, PTSD, COPD, asthma
Physical/chemical effects	Weather effects on air pollutant formation and transport, flooding and release of toxic chemicals from disposal sites	Respiratory diseases	COPD, asthma
		Diseases related to heavy metals or toxic waste	Cancer
Physical/biological effects	Weather effects on disease agents, vectors or their habitats	Altered incidence and geographic distribution of vectorborne diseases	Malaria, dengue fever, encephilitis, hantavirus infection, Rift Valley fever, Ross River virus infection
	Altered marine and freshwater ecology, microbial contamination during flooding	Altered incidence of waterborne and foodborne diseases	Cholera, *Cyclospora* infection, cryptosporidiosis, *Campylobacter* infection, food poisoning, shellfish poisoning, leptospirosis
	Altered food productivity, nutrient value, and plant pathogens	Impaired access to food supplies	Malnutrition, impairment of child growth and development
	Effect on levels of aeroallergens (pollen, spores, etc.)	Respiratory diseases, allergic disorders	Asthma, allergic rhinitis
Sociodemographic effects	Forced migration, overcrowded living conditions, human conflicts (wars)	Infectious diseases, nutritional impairment, mental health problems, exposure to trauma	Diarrheal diseases, malnutrition, impairment of child growth and development, depression, PTSD

[a]Temperature rise of 2°C by the year 2100, sea-level rise of 49 cm by the year 2100, and an increase in hydrologic extremes (86, 190).

[b]PTSD, Post-traumatic stress disorder; COPD, chronic obstructive pulmonary disease.

cutaneous vessels (68, 92). The ability to respond to heat stress is thus limited by the capacity to increase maximum cardiac output required for cutaneous blood flow. It is also not surprising that heat-related mortality is affected by wind speed and relative humidity (76, 98). Kalkstein et al have described oppressive (or "stagnating") air masses, which characterize meteorological conditions associated with increased mortality (74). A threshold temperature has been described, related to population location, above which mortality increases more steeply (77). In addition, the risk of death increases substantially when thermal stress persists for several consecutive days coupled with high overnight temperatures (156).

Daily mortality from all causes has been shown to increase during heat waves (199). Analyses in different cities with different baseline weather conditions (in the United States, Canada, the Netherlands, China, and the Middle East) of concurrent meteorological and mortality data have shown that overall death rates rise during heat waves (76, 98). During a heat wave in St. Louis in 1980, the maximum temperature was $\geq$37.8°C for 16 days in July. There were 850 resident deaths in July 1980, compared with 542 deaths in July 1979, a 56.8% increase (73; Figure 5). The health impacts of several recent heat episodes, particularly in developed countries, have also been documented (Table 2).

Although heat exhaustion or heatstroke is an illness more directly related to heat, the majority of deaths resulting from hot weather are associated with preexisting

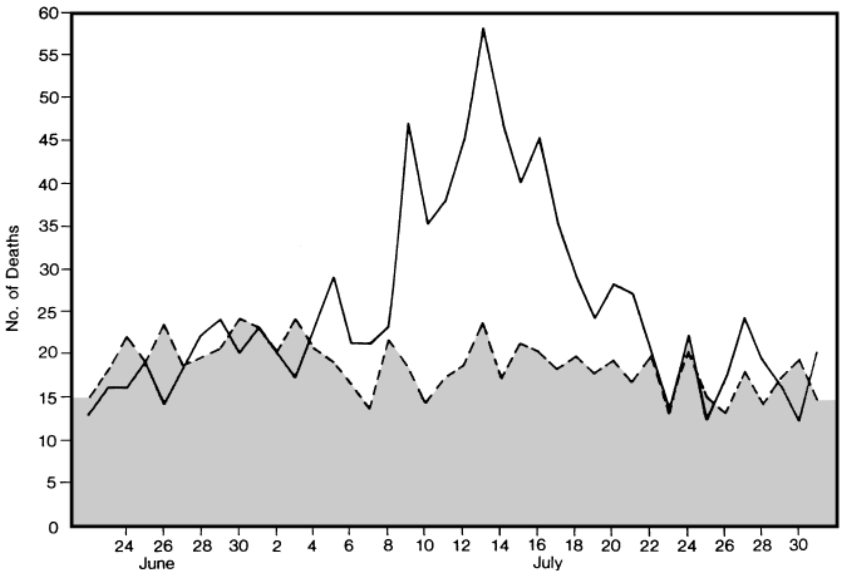

Figure 5 Resident deaths during a heat wave (July 1980) and during the same time in previous years, St. Louis, MO. Deaths are shown by date of occurrence. *Dotted line*, mean values for 1978–1979; *solid line*, mean values for 1980. (Reprinted with permission from reference 73.)

TABLE 2 Health impacts of recent heat episodes

Location	Year	Health impact	Reference(s)
London	1976	15% increase in mortality and ∼520 excess deaths	126
Athens	1987	2000 excess deaths and a 32.5% increase in mortality compared with the same period in previous years	84, 85
Belgium	1994	13.2% increase in mortality in the elderly	166
Chicago	1995	700 excess deaths; the number of hospital admissions increased by 11% (or 1072 persons) and the total number of deaths reported increased by 85% compared with numbers recorded in the preceding year	26, 170, 171
London	1995	15% increase in mortality	162

cardiovascular and respiratory disorders (101, 102). A change in blood pressure, blood viscosity, cholesterol, and/or heart rate associated with physiological adjustment to temperature change may explain the increased mortality from cardiovascular disease (89, 149). The elderly, the very young, persons with impaired mobility, and persons suffering from cardiovascular diseases are disproportionately affected because of their limited physiological capacity to adapt (92). Many countries have an aging population (45, 138), increasing the population at risk if preventive measures do not improve.

Poor housing conditions, the urban heat island effect, and lack of air conditioning have been identified as relevant factors in urban populations in developing countries (91). The V-shaped curve of temperature and mortality, however, implies that, in addition to increased mortality in unusually hot weather, death rates increase with decreasing temperatures. In fact, in temperate and subtropical countries, seasonal death rates are highest in winter (92, 172, 179), mostly from cardiovascular disease (98, 100). Confounding the evaluation of cold-related mortality is the fact that social and behavioral adaptations to cold play an important role in preventing winter deaths in countries of high latitude (38).

Modeling studies have helped to determine whether a reduction in winter-related mortality with warming temperatures would offset excess deaths associated with heat stress in summer. Kalkstein & Greene (75) applied climate change scenarios to weather-mortality relationship data from 44 large U.S. cities to estimate future changes in the relationship. Accounting for possible acclimatization, they concluded that, under the proposed climate scenarios, summer mortality will increase substantially, whereas winter mortality will decrease slightly (75). When considering potential reductions in winter-related deaths under typical climate change scenarios, however, a British study estimated that ∼9000 fewer cold-related deaths would occur annually by the year 2040 in England and Wales (100). Finally, a meta-analysis of 20 international cities found that a larger reduction in winter mortality (compared with increases in summer) would lead to an annual net reduction in mortality (120).

Weather Extremes. Extreme weather events such as severe storms, floods, and drought have claimed millions of lives during the past 20 years and have adversely affected the lives of many more, causing billions of dollars in property damage (148). On average, the number of people killed by disaster yearly between 1972 and 1996 was ~123,000. Africa suffers the highest rate of disaster-related deaths (112), although 80% of people affected by natural disasters are in Asia. There is an increasing trend in the number of people affected (71) and in national economic losses from natural disasters (135). For every person killed in a natural disaster, 1,000 people are affected (71), either physically or through loss of property or livelihood. The incidence and continuation of significant mental disorders, such as post-traumatic stress disorder (PTSD), may substantially affect population well-being. This depends on the unexpectedness of the impact, the intensity of the experience, the degree of personal and community disruption, and long-term exposure to the visual signs of the disaster (55, 56). Human impacts occur when climate hazards and population vulnerability converge. Those communities that are most exposed and have the fewest technical and social resources are at highest risk. Population concentration in high-risk areas such as floodplains and coastal zones also increases vulnerability. Degradation of the local environment can also contribute significantly to vulnerability. For example, Hurricane Mitch, the most deadly hurricane to strike the Western Hemisphere in the last 2 centuries, caused 11,000 deaths and thousands of others reported missing in Central America. Many fatalities occurred as a result of mudslides in deforested areas (140).

Projections of the effects of climate change on the severity, frequency, and geographic distribution of extreme weather events may have a range of impacts on human morbidity and mortality. However, because of the uncertainty in these projections, it is difficult to quantify the health impacts.

Floods. The health impacts of floods may be divided into the immediate, medium term, and long term. Immediate effects are largely deaths and injuries caused by drowning and being swept away by the current (117). Medium-term impacts include diseases arising from disruption of water purification and sewage systems, vectorborne diseases from stagnant water, decreases in nutritional status (especially in children), release and dissemination of toxic chemicals from storage or waste disposal sites, and increased respiratory diseases from crowding of survivors, often with limited shelter. The health impacts of several recent floods have been recorded. River floods in central Europe in 1997 left >200,000 people homeless and >100 people were killed (71). An increased risk of river flooding in Europe owing to climate change is likely (13, 39). In Bangladesh in 1988, watery diarrhea in a population displaced by floods was the most common cause of death for all age groups <45 years old, followed by respiratory infection (176). In Bangladesh and Sudan, the proportion of severely malnourished children increased after flooding (32, 198). Mental health effects were evident in Poland, where 50 suicides were attributed to the floods in 1997 (167).

Severe Storms. By their violent nature, severe storms (tropical cyclones/ hurricanes and tornadoes) have the potential to cause tremendous morbidity, mortality, and property loss. In developing countries, populations remain vulnerable owing to high densities of people living in unprotected floodplains, lack of proper and accessible shelters, and inadequate credible early-warning systems. Even in the developed United States, as recently as 1999, Hurricane Floyd caused widespread public health risks; nearly 40 billion gallons of hazardous hog waste threatened water supplies for months after the storm (143).

The health implications of tropical cyclones are exemplified by a 1991 cyclone that hit a densely populated, low-lying (and therefore extremely vulnerable) area of Bangladesh. Affected people are said to have numbered 10 million, with 138,000 dead, 460,000 wounded, and 1.63 million homes lost. Sociocultural factors may help to explain the disproportionately greater mortality among children and women, because women depended on male members for a decision to leave their homes (15).

Historical analysis shows that hurricanes form only in regions where sea surface temperatures are >26°C (54). A modeling study concluded that a sea surface warming of slightly >2°C would intensify hurricane wind speeds by 3–7 m/s (or 5%–12%) (94), although predicting the number of hurricanes that will make landfall is currently not possible. In addition, sea surface warming will necessarily cause sea level rise. A 1-m sea level rise would inundate low-lying areas, affecting 18.6 million people in China, 13.0 million in Bangladesh, 3.5 million in Egypt, and 3.3 million in Indonesia (177; Figure 6).

Drought. Drought affects population health primarily via its impact on food production. In early 1991, for example, 4.3 million people faced starvation as a result of drought in northeast Africa (3). Malnutrition and starvation often occur when a preexisting situation of food shortage worsens (43). Marasmus, the most common type of protein energy malnutrition, results in weakness, cachexia, anorexia, and ultimately death.

Many famine-related deaths are linked to infection (184) through weakened bodily defenses and lack of clean water for personal hygiene. Micronutrient deficiencies, such as that of vitamin A, can lead to increased susceptibility to respiratory and gastrointestinal infections. Diarrheal diseases (from fecal contamination of water supplies), scabies and conjunctivitis, and other conditions such as trachoma are associated with poor hygiene and result from a breakdown in sanitation if water resources become depleted. Poor sanitation is also the result of inadequate living conditions that can be brought about by forced migration caused by food shortages (see Sociodemographic effects).

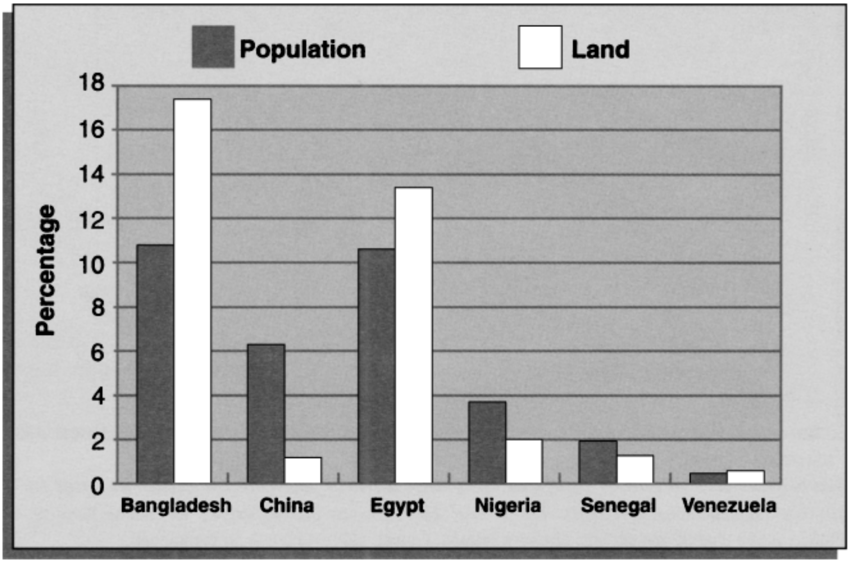

Figure 6 International lands and populations at risk from a 1-m sea level rise. Graph shows the percentages of populations and land affected. (Reprinted from reference 177, as adapted from Strzepek KM, Smith JB, eds. 1995. *As Climate Changes: International Impacts and Implications.* Cambridge, UK: Cambridge Univ. Press.)

The Sahel region in sub-Saharan Africa is particularly vulnerable to the effects of drought caused by increasing desertification, exacerbated by overcultivation and overgrazing. In 1973, ~100,000 people died as a result of drought in the Sahel (3). Prolonged and more frequent periods of drought associated with climate change could have widespread consequences for population health in the Sahel and other parts of the world threatened by desertification (199).

Drought-induced wildfires can cause direct injury and have the potential to affect air quality. Fire smoke carries a large amount of fine particles that exacerbate cardiac or respiratory problems, such as asthma and chronic obstructive pulmonary disease (41). For example, drought-induced fires in Florida in 1998 were associated with increased hospital emergency room visits for asthma, bronchitis, and chest pain (28). In Central America, fires aided by extreme drought burned ~1 million acres in 1998. At least 60 people lost their lives fighting the fires (52), and air quality-related respiratory health effects were reported as far away as southern Texas (182).

El-Niño/Southern Oscillation (ENSO). The El Niño/Southern Oscillation (ENSO) is an example of a natural climate fluctuation. ENSO events are typified by the build-up of high atmospheric pressures over the southeastern Pacific and of low pressure over Indonesia. These in turn result in oscillating fluctuations in wind and ocean currents, leading to changes in regional temperature and precipitation patterns. Although there is speculation about whether long-term climate change could also affect the frequency of the ENSO, these natural coupled interactions between the ocean and atmosphere remain the most prominent global-climate system within a 3- to 5-year period (163). As such, these events provide a good model for assessing the effects of a more variable future climate (150).

ENSO influences climate in distant regions via so-called "teleconnections" (50). Consistent temperature and precipitation changes are seen in specific areas of the globe: droughts in Southeast Asia, heavy rainfall in areas of South America, mild winters over western Canada and parts of the northern United States, and wet winters over the southern United States are some examples (Figure 7).

ENSO-related extreme weather events can have a significant impact on population health (96). In addition, ENSO events also have a significant economic impact on developing countries in the tropics, primarily through their effects on food production (199). The 1997–1998 El Niño event was one of the two strongest of this century. It was associated with extremely dry conditions and devastating fires in many areas of the world and with extensive flooding in others. For example, in Southeast Asia, air pollution episodes of biomass smoke from drought-exacerbated fires in Indonesia affected large population centers and, in some areas, exceeded by over sixfold the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (23). Severe flooding affected wide areas of Peru, Equador, Argentina, and Uruguay. Daily rainfall totals often exceeded 7.5–12.5 cm. Overall, $>$500 people died, and almost 1 million people were impacted in some way by the flooding (139). ENSO-related impacts on biological systems, such as those on infectious diseases, are discussed below.

Physical/Chemical Effects: Weather and Air Pollutants Weather influences the dispersal and ambient concentrations of many pollutants. For example, large high-pressure systems often create a temperature inversion, trapping pollutants in the boundary layer at the Earth's surface. Also, increases in temperature of the troposphere together with UV radiation enhance the photochemical reactions that produce secondary oxidants such as ground level ozone (2, 29, 36).

Exposure to ozone heightens the sensitivity of asthmatics to allergens and impairs lung function, especially in children and the elderly (10, 95, 169). Over a 15-year period, daily mortality was compared with hot days in summer and high ozone levels in Philadelphia, PA (130). In London, the most consistent association with respiratory disease hospital admissions was observed for ozone, with the strongest effects occurring during the warmer part of the year (154). In Mexico City, ozone has been linked to increased hospital admissions for lower respiratory infections and asthma in children (161).

Global warming theoretically could increase average ambient concentrations of ozone and an increase in the frequency of episodes of ozone pollution (186). This relationship is nonlinear, with a stronger correlation seen at temperatures $>32^\circ$C.

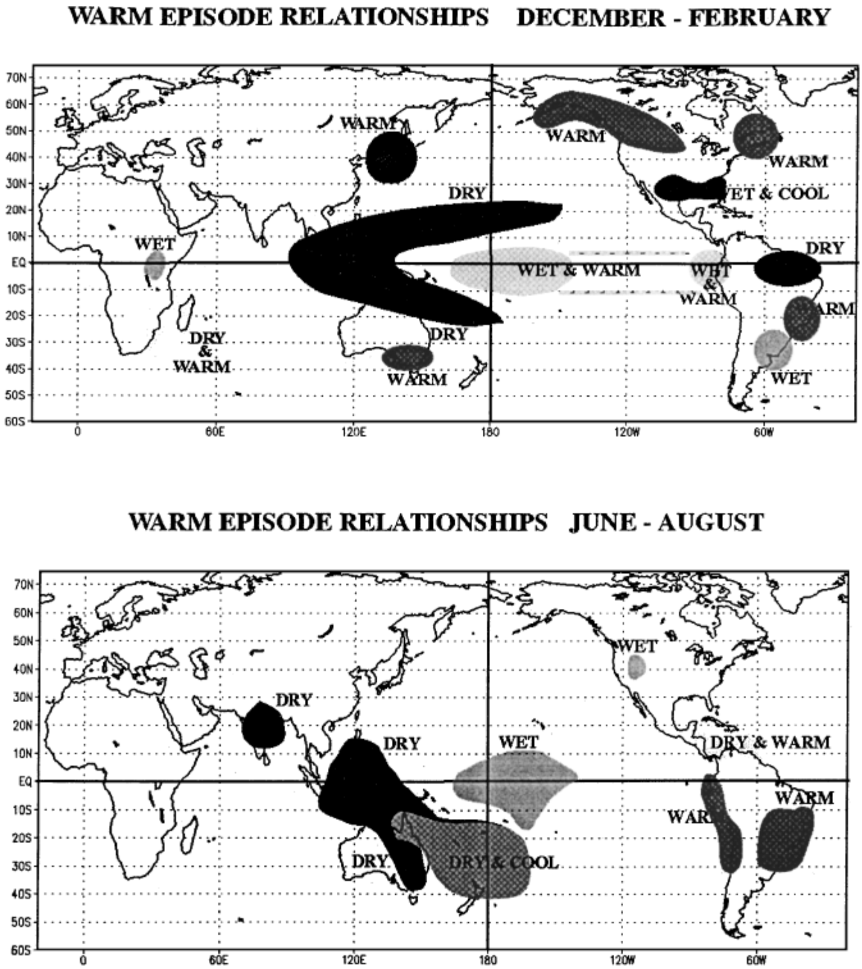

Figure 7 Effects of El Niño/Southern Oscillation (ENSO) on climate in distant regions in winter and summer months. Marked regions represent the "teleconnections" of ENSO, where weather effects are most consistent across past ENSO events and where predictions are therefore most reliable. (Reprinted from reference 142.)

In the eastern United States and in Europe, most days when the levels of ozone exceed air quality standards occur in conjunction with slowly moving high-pressure systems that occur at around the summer solstice (144). This is the period of greatest sunlight, when solar radiation is most intense and air temperatures are high. The relatively high levels of ozone in the United States during 1988 and 1995 were likely caused in part by hot, dry, and stagnant conditions. During 1995, one of the hottest years on record, 32% of Americans (71 million people) resided in counties in which ozone levels exceeded the EPA's National Ambient Air Quality Standards

(188). Episodes of high levels of ozone generally last from 3 to 4 days on average and extend over a large area, that is, an area >600,000 km^2. Studies estimating the impact of climate change on ozone production are limited in number. Most studies find an increase in ozone formation with higher temperatures (58, 133), but increasing UV flux may have an even stronger effect than elevated temperatures (132).

Both chronic and acute exposures to fine particles cause increased mortality (37, 155, 169). Concurrent hot weather and particulate air pollution can have interactive impacts on health (83, 174, 175). A coordinated project in 12 European cities (84) has found that the effects of sulfur dioxide and black smoke on mortality were stronger during the summer (84). Bobak & Roberts (16) found that the risk of death per increase in SO_2 and black smoke was increased by temperature.

Levels of sulfate have been found to significantly correlate with relative humidity in the summer (9). The concentration of resultant acid aerosols was a strong predictor of summer hospital admissions for respiratory causes. On peak pollution days, summertime haze (comprising mostly ozone and acid aerosols) was associated with about half of all respiratory admissions (183). These atmospheric chemical reactions are, therefore, essential in understanding potential health risks under changing climate conditions, including temperature and humidity.

Recent studies have examined the health effects of exposure to extreme heat and air pollution to determine whether there are potential synergistic effects related to simultaneous exposure. Katsouyanni et al (83) found interactions between high levels of sulfur dioxide and high temperature (30°C) in Athens, Greece. Sartor et al (166) found that mortality during the Belgium heat wave of 1994 was correlated with the mean daily temperature and 24-h ozone concentration from the previous day. However, Samet et al (165), for example, found little evidence that weather conditions modified the effect of pollution. Teasing out the effect of climate from air pollution and addressing potential synergistic effects warrants further investigation.

Physical/Biological Effects of Climate Variability

Annual Cycles of Infectious Diseases. The distribution and seasonality of important infectious diseases are likely to be affected by climate change (125, 150). In sub-Saharan Africa, epidemics of meningococcal meningitis consistently erupt during the hot dry season and subside soon after the onset of the rainy season (131). In contrast, transmission of many vectorborne diseases is confined to the rainy season. Most malaria deaths, for example, generally occur at the end of the rainy season (57), although this is not the case for some parts of the world.

Diarrheal diseases show such a strong cyclical periodicity that climate is widely assumed to play some role in epidemic outbreaks. In Scotland, for instance, human *Campylobacter* infections have a seasonality that is characterized by regular, short-duration peaks in the spring, which have been recorded every year since 1983 (34). In Peru, prevalence of the diarrheal disease caused by *Cyclospora* infection peaks in summer and wanes during cooler winter months (115). Cholera

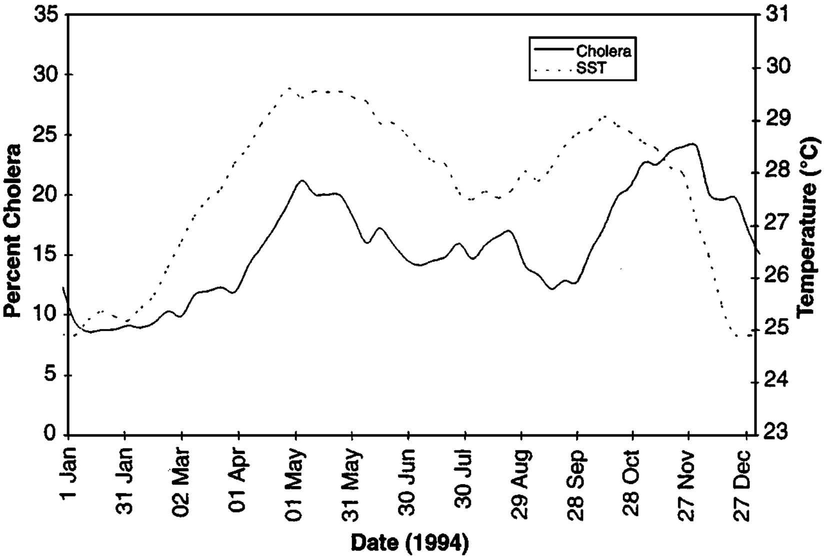

Figure 8 Relationship between sea surface temperature and cholera case data in Bangladesh from January through December 1994. (Reprinted with permission from reference 33.)

outbreaks occur seasonally in Bangladesh, with consistent patterns associated with monsoon seasons, sea surface temperature, rainfall, and zooplankton populations (33; Figure 8).

Interannual Variability. Infectious diseases demonstrate year-to-year fluctuation beyond seasonal patterns. Bouma & colleagues have shown that many epidemics of malaria are associated with El Niño-driven climate extremes (17–21). The 1997–1998 El Niño resulted in torrential rain in parts of East Africa and a malaria epidemic in the southwestern Ugandan highlands (93, 105). However, El Niño is certainly not responsible for all epidemics; the extreme Ethiopian epidemics in 1953 and 1958, which resulted in thousands of deaths, did not occur in El Niño years. It is conceivable that, in some areas, exceptionally heavy rains may wash larvae from their breeding sites, resulting in reduced malaria (151).

In the southwestern United States, rodent-borne hantavirus has been linked to El Niño-driven flooding leading to an upsurge in mouse populations (194), and a similar response may occur with plague in East Africa. The incidence of mosquito-borne Rift Valley fever varies in association with El Niño-driven flooding in East Africa (146), as demonstrated by the serious outbreak in Kenya during the strong El Niño of 1997–1998 (109). Although not always El Niño related, other infectious diseases are associated with extreme weather events. For example, flooding and hurricanes have been responsible for outbreaks of the spirochetal zoonosis leptospirosis in Nicaragua and Barbados (27) and Brazil (94a).

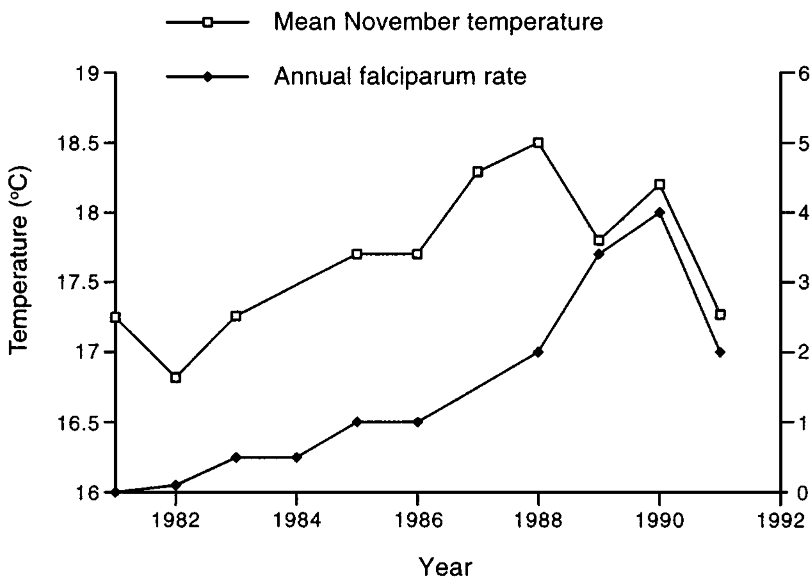

Figure 9 Variations in November temperatures and annual *P. falciparum* malaria rates in northeast Pakistan between 1981 and 1991. (Reprinted with permission from reference 19.)

Vectorborne Diseases—Malaria. Malaria is well-known to be influenced by weather conditions. Wet and humid environments provide the breeding sites and prolong the life of malaria mosquitoes (107). Temperature governs the rate at which mosquitoes develop into adults, determines how frequently they blood-feed (and, therefore, acquire parasites), affects adult mosquito survival, and governs the incubation time of the parasite in the mosquito. In Rwanda, increasing ambient temperatures and high rainfall in 1987 and 1988 were correlated with a steep increase in malaria incidence (111). Increases in temperature have also been linked to malaria epidemics in Zimbabwe (47) and Pakistan (19; Figure 9).

Occurrence of malaria also closely parallels altitude (180), a good proxy for temperature. The minimum temperatures for development of the parasites *Plasmodium falciparum* and *P. vivax* are ~18°C and ~15°C, respectively, limiting the spread of malaria at cooler, higher altitudes. The highlands of Africa represent an ecological zone of special concern, where malaria incidence is on the rise (108). In a site situated at 2000 m in western Kenya, malaria outbreaks have been observed to occur when mean monthly temperature exceeds 18°C (116) and rainfall is >150 mm/month (49). Areas vulnerable to a shift in malaria transmission are thought to be located in the African highlands above 1000 m, where, during the five wettest consecutive months of the year, the ratio of precipitation to potential evapotranspiration is >0.5 and the minimum temperature is ≥15°C (151; Figure 10). Environmental monitoring in these transitional zones is a priority to detect any change in disease driven by warming trends, assuming confounders such as human migration patterns can be addressed.

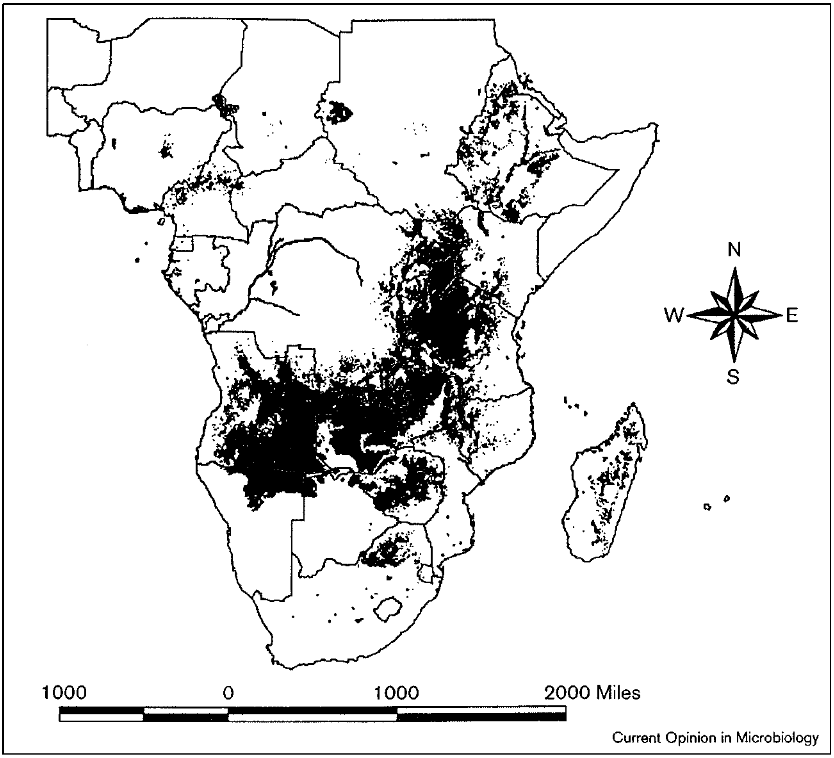

Figure 10 Areas vulnerable to malaria in the African highlands. Shaded regions are above 1000 m and, during the five wettest consecutive months of the year, have a ratio of precipitation to potential evapotranspiration >0.5 and a minimum temperature of ≥15°C. These regions may be most at risk for new malaria transmission with warming. (Reprinted with permission from reference 151.)

Locally transmitted malaria and an increase in international travel have led to reports of cases in such areas as Australia, Europe, and North America, where malaria had been eradicated (193, 201, 205). Climate change may increase the risk of reintroduction of malaria unless programs to control vectors are maintained or increased (202). Main areas of concern are those that have had a deterioration of their health care systems, such as some of the republics of the former Soviet Union. These socioeconomic factors are thought to be responsible for the recent establishment of malaria in three Eastern European countries [Azerbaijan, Tajikistan, and Turkey (153)].

Other Vectorborne Diseases. Other climate-sensitive vectors that carry diseases include mosquito-borne arboviruses, the agents of dengue and yellow fever, encephalitis, and epidemic polyarthritis (from Ross River virus infection). Dengue fever, a mosquito-borne viral disease, has become a widespread tropical urban health problem (60, 61). Between 250,000 and 500,000 cases of the more severe form of this disease, dengue hemorrhagic fever/dengue shock syndrome, occur yearly worldwide (11). Dengue transmission has a seasonal peak during months with high rainfall and humidity (59). Focks et al (46) have developed simulation models for *Aedes aegypti* mosquito transmission of dengue that can be highly predictive, given weather parameters, a local breeding-site inventory, and the immunity status of the human population of interest.

Regarding other arbovirus-derived diseases, human outbreaks of St. Louis encephalitis are correlated with warm wet winters followed by dry summers, especially if several days pass with temperatures exceeding 85°F (129). Ross River virus-caused epidemic polyarthritis in Australia shows a positive association with increases in minimum temperatures and rainfall (185). However, disease dynamics and insect ecology in relation to climatic variables are complex. For example, field and laboratory studies of St. Louis encephalitis (157), as well as studies of dengue virus, indicate that higher temperatures hasten viral development or extrinsic incubation period inside the mosquito (192). On the other hand, higher temperatures reduce adult mosquito survival. In addition to the increased potential for some disease vectors to spread with climate warming, certain diseases (e.g. visceral leishmaniasis, transmitted by sand flies) have become important coinfections with HIV (35), which may further increase their spread.

Climate change may both extend the length of the transmission season and facilitate the spread of tick-borne diseases, including encephalitis and Lyme disease, to higher latitudes and altitudes. The distribution of ticks depends on climatic factors, availability of suitable hosts (usually mammals and birds), predators, and habitat (51, 197). A study in a highly endemic region of Sweden found that the incidence of tick-borne encephalitis increased with extended spring and summer seasons during 2 successive years (106). On the other hand, in equatorial regions excess heat may reduce tick survival and disease risk (160).

Simulation Modeling of Vectorborne Diseases. Climate change modeling studies of selected vectorborne diseases have found increases in the potential transmission of mosquito- and fly-borne diseases caused by anthropogenic warming and precipitation changes. Transmission factors thought to be temperature sensitive include mosquito density, feeding frequency, survival, and extrinsic incubation period (22). Yet actual risk, as opposed to potential global or regional risk, will depend on site-specific factors. For example, local factors associated with the spread of malaria include mosquito control programs, insecticide and drug resistance, human population growth and movement, land use changes, and access to health care (134, 159).

Some global and regional modeling studies on malaria (108, 118, 120a–122) have found an increase in potential transmission under climate change scenarios, particularly in temperate zones or in tropical highlands. Similar results are found for dengue fever at the global scale (72, 152), showing a lengthened transmission season and younger age of disease onset. Rogers & Randolph (160) found that a 3°C warming in eastern Africa could extend northward the range of tsetse flies. Many of these global and regional projections, however, cannot be used at the local level, where extensive model parameterization is required to achieve a useful predictive model for preventive applications. Studies also show less transmission in some cases. For example, in the southeastern United States, future warming from doubled CO_2 may reduce tick survival and subsequent risk of Rocky Mountain spotted fever (63). Haile (63) also found no increase in malaria transmission in the southern United States with warming.

Waterborne Diseases Waterborne diseases are particularly sensitive to changes in the hydrological cycle. In developing countries, water shortages cause diarrheal disease through poor hygiene (202). Those who are weak or have reduced capacity to adapt are most at risk. In 1995, 3.1 million people died from diarrheal diseases, 80% of them children (200). On the other extreme, flooding can contaminate drinking water from watershed runoff or sewage overflow.

Cryptosporidiosis, a zoonotic disease associate with domestic livestock, can result from drinking-water contamination (where the oocyst is resistant to chlorine treatment) during periods of heavy precipitation. In 1993, an outbreak of cryptosporidiosis in Milwaukee, WI, which resulted in 403,000 reported cases, coincided with unusually heavy spring rains and runoff from melting snow (114). Similarly, the numbers of oocysts of *Giardia* and *Cryptosporidium* species found in the Delaware River were positively correlated with the amount of rainfall (5).

In the marine environment, warm water and nitrogen favor blooms of dinoflagellates that cause red tides, which can cause paralytic, diarrheic, and amnesiac shellfish poisoning (42). During the 1987 El Niño, a red tide of *Gymnodinium breve*, previously confined to the Gulf of Mexico, extended northward after warm Gulf stream water extended far up the East Coast, resulting in human neurological shellfish poisonings and substantial fish kills (181). Similarly that year, an outbreak of amnesic shellfish poisoning occurred on Prince Edward Island when warm eddies of the Gulf stream neared the shore and heavy rains increased nutrient-rich runoff (65).

Vibrio species (e.g. *V. vulnificus* and *V. parahaemolyticus*) also proliferate in warm waters. Copepods (or zooplankton), which feed on algae, can serve as reservoirs for *V. cholerae* and other enteric pathogens. For example, in Bangladesh, cholera follows seasonal warming of sea surface temperature that can enhance plankton blooms (33; Figure 7).

Recent analysis of childhood diarrheal disease in Lima, Peru, showed a strong effect of the 1997–1998 El Niño event. During that unseasonable winter, the ambient temperature in Lima increased to >5°C above normal, and the number of daily admissions for diarrhea increased by >200%, compared with expected trends based on the prior 5 years. For each degree centigrade of increase in mean ambient temperature, the number of admissions increased by 8% (31).

Food Productivity Several factors come into play when predicting the impact of climate change on crop and livestock production. First are the direct effects of temperature, precipitation, CO_2 levels (e.g. the CO_2 fertilization effect), and extreme climate variability and sea level rise (158). Next are the indirect effects of climate-induced changes in soil quality, incidence of plant diseases, weed and insect populations, and enhanced food spoilage from heat and humidity. In the United Kingdom, a strong relationship between the incidence of food-borne disease and temperature during the month preceding the outbreak has been found (14), suggestive of food poisoning or spoilage. The last 2 decades have seen a continuing deterioration of food production in Africa, caused in part by persistent drought. Finally, the extent to which adaptive responses are available to farmers must be considered.

Developing countries already struggle with large and growing populations and malnutrition, and they would be particularly vulnerable to changes in food production. Some regions, such as areas in Africa, are expected to experience marked reductions in yield, decreases in production, and increases in the risk of hunger as a result of climate change. One analysis indicates that, by the year 2060, an additional 40–300 million people—relative to a projected baseline of 640 million people—could be at risk from malnutrition from anthropogenic warming (164).

Aeroallergens (Pollen, Spores, Molds, etc) The concentration in outdoor air of many aeroallergens depends on season of the year and has been associated with a variety of meteorological conditions (25, 53, 145). In Europe, for example, birch pollen increases with temperature (1). Also, in the United Kingdom, a study found an increase in asthma outbreaks following thunderstorms (25).

The pattern of seasonal allergic disorders, such as asthma and allergic rhinitis (hayfever), could be affected by the impact of climate change on the production of aeroallergens (199). Outpatient visits for hay fever coincide with the onset and duration of pollen season; on the other hand, the exacerbation and seasonal distribution of asthma are more complex. In temperate climates, asthma peaks in the pollen season and again later in the year, whereas, in the tropics, asthma increases in the wet season (99, 113). However, there is no convincing evidence that high airborne pollen levels increase hospital admissions for asthma (6).

Sociodemographic Effects

Sea level rise and perturbations of the hydrologic cycle can cause recurrent or more severe flooding of coastal communities, leading to forced migration (136, 137). Of the world's 20 current megacities, 13 are vulnerable to these assaults because they are at sea level. For example, rising seas could result in salination of coastal freshwater aquifers and disrupt storm water drainage and sewage disposal (see Figure 5). Furthermore, there is evidence that factors such as environmental degradation and unequal access to resources (such as food and water supplies) can result in heightened tensions leading to violent conflict among susceptible groups (67).

The implications could be extensively far reaching and may, in fact, represent the "iceberg" beneath the "tip of the iceberg" regarding health consequences of climate change. Integrated risk assessments that include these types of repercussions are essential to obtain a comprehensive understanding of climate change health impacts.

PREVENTION OF WEATHER-RELATED THREATS TO PUBLIC HEALTH

Improved methods for monitoring health indicators, including enhanced surveillance of diseases that are sensitive to climate, should be developed to detect and respond to the impact of climate change on human health. Most current surveillance systems for infection have been designed to detect particular causes (e.g. food-borne disease) and individual risk factors (e.g. overseas travel or immune deficiency). The monitoring of climate change requires a different perspective. The epidemiological challenge is to take a more holistic approach to the causes of infection, examining the possible influence of climate both on the environmental sources of pathogens and on human behavior. Another challenge for studies of climate is the size of data sets required; although trends in any one country will be a starting point, improved coordination of data on health outcomes among countries will be needed.

The effects of extreme weather events such as heat waves, weather-related episodes of air pollution, and floods need to be included in the enhanced surveillance to assess their future impacts. The risk of coastal flooding will also increase unless sea defenses are upgraded in response to a rise in sea level. There is a need to link health surveillance activities with global monitoring systems that are being developed for the climate, oceans, and Earth's surface (64).

Finally, more emphasis must be placed on sustainable development practices. In weather disasters, local ecological degradation, in combination with development in high-risk areas, makes populations more vulnerable to extreme weather events.

RESEARCH CHALLENGES

Climate change represents a uniquely different environmental risk factor that will cut across multiple sectors on which human health depends. Proper assessment of the impacts outlined above demands a multidisciplinary approach among health scientists, climatologists, biologists, and ecologists. Other relevant disciplines include social and behavioral sciences, political science, and areas of study that explore the relationship of humans to the natural world. More research is needed to determine the extent to which populations will be able to acclimatize physiologically and behaviorally to future increases in warmer weather. In addition, much of the published research on heat and mortality relates to populations in temperate regions (e.g. 75). There is a need to expand the knowledge base by studying populations in different regions around the world.

New research tools are required to address these cross-cutting, ecologically complex, and long-term public health challenges, including the following:

1. Time series and regression analyses of historical data, including analog situations of extreme climate variability (e.g. El Niño)
2. Geographic analysis of disease incidence based on weather and land use/land cover variables (taking advantage of geographic information systems and satellite remote sensing)
3. Scenario-based mathematical and predictive modeling with uncertainty analysis
4. Generalized integrated assessments that include demographic, social, and economic disruptions

Such methods are vital to help interface between short- and long-term hazards and quantitative and qualitative results and to identify key knowledge gaps for more targeted investigation.

For any of these analytical methods, human health data are the most unreliable because of reporting bias and variability in detection methods. There is a critical need for capacity building to improve surveillance and monitoring, in turn, to detect changes that may be a result of global climate and ecological change. Yet surveillance alone is not sufficient to prevent illness, and continued efforts to develop predictive models should be a priority.

Predictive models are essential to improving proactive health measures. Even though no model can completely simulate real life, models are useful in conceptualizing dynamic processes and their outcomes. Although empirical studies have limits, they are the foundation on which modeling parameters are determined. Although not necessarily more accurate, mathematical models can achieve a better conceptual representation of interrelated systems.

CONCLUSIONS

New understanding of linkages between public health and global ecology is emerging in the literature (123). While some beneficial health effects may come from global warming, a majority of the projected health impacts of climate change may be adverse, and some will likely occur on a larger geographic scale than most other environmental health impacts (125). The long-term and complex problems posed by climate change may not be readily discernible over short time spans and therefore demand an expanded effort in scenario-based risk assessment in parallel with historical validation.

The results of the studies reviewed in this article must be viewed in the context of many other environmental and behavioral determinants. Future studies must consider, along with climatological factors, key variables such as poverty, sanitation, land use changes, and public health surveillance and mitigation programs. Studies of potential risk at the level of global climate models, although instructive, can be translated directly into actual risk or vulnerability only when these local factors are included in assessments.

Analyzing the role of climate in determining human health outcomes will require interdisciplinary cooperation. Increased disease surveillance, integrated modeling, and use of geographically based data systems will afford more anticipatory measures by the medical community.

The potential human health impacts of climate change on future generations and the difficulty of reversing ecosystem changes once they have occurred warrant increased efforts by the medical community to address this problem in a concerted and timely fashion. Operating under the precautionary principle, actions are required in the face of uncertainty if the potential threats are great enough. Primary preventive measures to avert climate change, including reduction of greenhouse gas emissions and preservation of greenhouse gas sinks through appropriate land use policies, must be considered in view of the scale of health impacts and the time frame in which confirming information may emerge. Understanding the linkages between climatological and ecological change as determinants of disease will ultimately help in constructing predictive models to guide effective disease prevention.

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