Public Health Consequences of Global Climate Change in the United States— Some Regions May Suffer Disproportionately

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Current risk assessments of the likely regional health impacts of global climate change (GCC) are hindered by two factors. First, dose–response relationships between weather parameters and many of the likely health effects have not been developed, and second, reliable estimates of future regional climates across the United States are still beyond the scope of current modeling efforts. Consequently, probabilistic risk estimates of most of the likely regional health impacts of GCC have such a high degree of uncertainty that their usefulness to health officials dealing with regional issues is very limited. With the numerous pressures on today's health care systems, it is understandable that the possible consequences of GCC have received scant attention from regional health care decision makers. Indeed, the consensus among this community appears to be that any increases in health effects associated with GCC will be easily handled by the current health care system. However, such a position may be naive as the potential exists that an unequal distribution of such effects could overwhelm some regions, whereas others may feel little or no impact. This review of the likely regional impacts of GCC has been structured as a semianalytical look at this issue of distributional effects. Because of the lack of dose–response information and reliable estimates of future regional climates, however, it takes a historical perspective. That is, it assumes that the quality and quantity of health risks a region faces under GCC will be directly related to its recent history of health risks from warm weather/climate-related diseases as well as to the size, characteristics, and distribution of the sensitive subpopulations currently residing within its borders. The approach is semiquantitative; however, it uses national data gathered on a regional level and as such should only be used to generate a hypothesis rather than test it. When applied to the United States, its outcome leads to the hypothesis that if indeed history repeats itself, some states or regions may be more greatly affected by GCC than others, not only because historically they are more prone to summer weather/climate-related diseases, but also because they contain a greater proportion of the sensitive subpopulations in the United States. — *Environ Health Perspect* 107(Suppl 1):169–179 (1999). *http://ehpnet1.niehs.nih.gov/docs/1999/Suppl-1/169-179longstreth/abstract.html*

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Background

Ten years ago when I was asked by the U.S. Environmental Protection Agency (U.S. EPA) to develop a review of the possible health effects that might increase in the United States under the conditions of global climate change (*1*), I quickly learned that there was voluminous literature on the relationship of climate/weather and any number of human diseases going

back at least as far as the time of Hippocrates (*2*). Indeed, one weather–disease relationship, heat stress, was sufficiently well characterized to have an occupational health criterion (*3*). For other diseases, e.g., malaria, sufficient information existed for the development of complex models of the relationship between disease and climate (*4*). These models had been used to help identify the risks of these diseases for servicemen stationed in certain locations (*5*).

As a result of reviewing the literature, I identified seven possible health effects that might increase worldwide with global climate change: heat stress, insect- and animal-borne disease, respiratory disease, allergic disease related to environmental allergens, developmental effects, i.e., perinatal mortality and/or preterm birth, health problems due to malnutrition and lack of water, and health problems due to crowding (*6*). Of these only the first five

seemed to be of concern in the United States (*1*).

When this document was submitted for review to the U.S. EPA Scientific Advisory Board, and although they agreed with the finding that a generally warmer climate could lead to increases in these diseases in the United States, several of the document's reviewers contended that the likely impact of such increases in the United States would be trivial and easily handled by the nation's state-of-the-art health care system. These reviewers felt that it would be the ecologic effects that would be disastrous in the United States.

Over the years, none of the subsequent research I reviewed convinced me differently with regard to particular weather–climate related diseases. Although it was clear that the developing world was likely to be at great risk from the increased health effects expected under global climate change, it seemed equally clear that the developed world probably had sufficient resources to withstand what was coming in turns of public health. Indeed, when asked by the Office of Technology Assessment (OTA), to identify and research the one health issue associated with global climate change (GCC) that I thought would most affect the United States, I chose a totally different issue, albeit somewhat related, and that was the importation of communicable diseases by "environmental refugees"—individuals displaced from their home countries by climate change-related disasters, e.g., sea level rise, famine, etc. (*7*).

Contributing to my lack of concern about the health effects of climate change in the United States was the fact that because of the uncertainty in predicting the precise climatic conditions for the most likely health effects (*8*), different modeling efforts indicated that the same region could be at greater risk or at less risk depending on the disease and the model chosen (*4,9*). Furthermore, in the case of some of the more life-threatening infectious diseases such as malaria and dengue, modeling efforts revealed that global warming was not necessary to achieve appropriate conditions for transmission of these diseases. Climatic conditions in the South were

currently perfectly adequate to support the transmission of these diseases. Competent vectors were present; what was lacking was an infected human population of sufficient size to maintain the transmission cycle (4). This seemed a rather remote possibility given the excellence of the American health care system.

As I found out with the OTA project, however, such a conclusion was a rather naive one. Yes, the American health care system is excellent; however, its coverage is far from universal (10). Furthermore, the American public health care system, which should provide a safety net to those without health-care coverage, is under siege economically (11), has by Congressional mandate been specifically denied to immigrants (12), and is gradually losing medical personnel with expertise in tropical medicine necessary to recognize and treat such diseases should they be introduced (13). These factors, in conjunction with the knowledge that there are large numbers of immigrants in certain areas of the United States who rarely if ever come in contact with the American health care system, led to the realization that there might be instances where such infections, once introduced, could gain a foothold in the United States. This in turn led to concern by several groups about the impact of GCC on environmental refugees (7,14).

Even knowing theoretically that certain weather-related infectious diseases, e.g., malaria, could become established in the United States was insufficient to convince me that GCC posed much of a threat the nation's public health. After all, the reintroduction of malaria was not dependent on climate change; in the past 10 years on a variety of occasions mosquito-transmitted malaria has occurred. Such episodes had always been small and apparently self-limited (15–17). A similar rationale was applicable to other infectious diseases such as dengue (18,19); thus, it still seemed unlikely that any of these insults would affect the health of U.S. citizens in any significant way.

In this regard, I was like many of the American public health care establishment who if asked for a list of public health priorities certainly would not have included GCC among the top ten (20). However, as I came to realize, such a position might be short-sighted, as it failed adequately to consider two very important aspects of this problem. The first is distribution. There is no reason to believe that increases in these diseases will be equally distributed across

the United States; thus, a small increase in a particular health effect for the United States could represent a large increase for the one or two states in which most of the effect occurred. The second is the systems nature of public health care delivery in the United States. Such systems, which can operate at federal, state, or local levels, have optimized their budgets around the status quo, i.e., with most of their budgets spent to address current public and environmental health priorities. Although such budgets can probably cope with small increases in one or two weather-related health effects, increases in many weather-related effects might require a sufficiently large reprogramming of funds to jeopardize other parts of the system. Thus, for example, if such a system were hit by simultaneous demands to increase vector control programs, increase disease surveillance activities, increase food safety inspections, and increase air pollution regulatory and enforcement activities as well as develop materials for outreach to seniors at risk of heat stress and outdoor sports enthusiasts at risk for vector-borne diseases, the system could either overload or other programs, e.g., prevention programs for drug abuse, health care services for children, might be required to cut back.

This awakening was brought about by an attempt to evaluate possible regional consequences of global climate change on human health in the United States, using as a starting point five weather-related categories of health effects: heat-related illness; air pollution-related diseases; insect- and animal-borne infectious diseases, both endemic and imported; marine-borne diseases; and illnesses and accidents associated with extreme events such as floods and storms. Both the Intergovernmental Panel on Climate Control (IPCC) (21) and the World Health Organization (WHO) (22) have identified these health effects as of possible concern to developed nations under conditions of global warming.

Because it is not yet possible to develop reasonable (in terms of uncertainty) projections of future regional climates using current modeling efforts (21), the review takes a historical approach toward examining this question. A combination of interactions with climatologists and weather forecasters and a continued barrage of news stories about regions suffering from weather-related disasters led to the decision to base this review on a "history repeats itself" assumption, i.e., that a region's current susceptibility to weather-related diseases

could be used to gain valuable insights into its vulnerability to potential public health risks from global climate change.

This review summarizes the results of such an approach when applied to the United States for the categories of health effects identified previously. No attempt was made to examine all individual diseases that might fall within a particular category of health effect; rather, information was gathered on one or more example diseases. Furthermore, although a quasi-analytical approach is used, the intent of this review is to examine the distribution of weather-related diseases across the United States only on the basis of readily available information and from this information develop a hypothesis on regional vulnerabilities. Proof of the hypothesis requires a far more detailed examination of the problem using an approach and data specifically designed for the analysis and regional comparison of temporal trends in these diseases. As discussed in more detail later, this document also presents a similar review of the distribution of susceptible populations in order to examine this additional aspect of vulnerability. Here the goal was to evaluate whether the distribution of susceptible populations would reinforce or offset the vulnerabilities associated with weather-related diseases.

Health Impacts of Concern for the United States

A number of recent reviews on the general subject of global climate change and human health have presented in detail the rationale behind expectations that morbidity and mortality from weather-related health impacts will rise with global climate change (21,22). Risk estimates have been both quantitative and qualitative depending on whether a health effect of concern has an empirical model of the weather–disease relationship developed for the United States. Such models exist for heat-associated mortality (23) and several vector-borne diseases (4,24), but have yet to be developed for health effects associated with algal blooms or extreme weather events (1,21). To date, however, the uncertainty of the estimates from such models makes them of limited usefulness for public health planning. Consequently, the information presented in the next section is drawn principally from historical information.

Heat-Associated Increases in Mortality and Illness

There is a reasonable degree of confidence in predictions that global warming will be

associated with increases in summer death rates, although the precise areas where such increases will occur are not certain (21). Ample evidence demonstrates that extremely hot temperatures are associated with such effects in the United States, particularly in urban environments (1,25–28). Less evidence exists on nonfatal illnesses, but it is a reasonable general assumption that those with similar mechanisms will also increase (21).

The mechanism underlying these deaths is thought to have both a direct component related to the compromise of the body's thermoregulatory systems when subjected to prolonged periods (several days) of thermal stress and an indirect component related to additional stress placed on cardiovascular and respiratory systems by the body having to operate in warmer and more humid environments (2). Infants and the elderly have been more susceptible to this effect, principally because of the more limited physiologic capability of their cardiovascular and respiratory systems to adapt to such stresses (21).

Between 1979 and 1992, excessive exposure to high temperatures in the United States resulted annually in 148 to 1700 deaths. During this period, the highest age-adjusted death rates for heat-related illness (1 per million or greater) occurred in Alabama, Arkansas, Arizona, Georgia, Kansas, Mississippi, Missouri, Oklahoma, and South Carolina (29). Heat waves in parts of the United States in 1980, 1983, and 1988 caused 1700, 556, and 454 deaths, respectively (29). Cities specifically identified as having high heat-related death tolls in the last 20 years include St. Louis, Philadelphia, Chicago, and Milwaukee (30). Interestingly, the southern states show the highest chronic response to heat stress, whereas northern cities show the highest acute response. The latter observation has been suggested to occur because of differences in adaptability and infrastructure, with northern cities having designs more conducive to the development of urban heat islands and buildings that are more difficult to cool (21). It is not clear why southern states have the highest chronic response to heat stress, although it is possible that this is due to differences in the kinds of deaths reported as heat related in the North and the South.

Studies based on two general circulation model scenarios in urban areas that include several from North America predict that the number of heat-related deaths will double by the year 2020 and increase

severalfold by 2050. These numbers may be reduced if changes in climate occur over an extended time so populations can become acclimatized to the new conditions (1,9). Although climate change could also bring milder winters and a drop in winter death rates, the predicted increase in death rates from hotter summers may be such that there is a net increase in deaths associated with changing climate (21).

Increases in Ground-Level Ozone and Other Air Pollutants

Higher temperatures tend to be associated with increases in the criteria air pollutants (ozone, carbon monoxide, sulfur dioxide, lead, nitrogen dioxide, and particulates smaller than 10 microns), thereby leading to a decrease in air quality, especially in urban areas. In 1994, the U.S. EPA (31) estimated that approximately 50 million people live in counties with air quality that does not meet the U.S. EPA health-based standards, i.e., in nonattainment areas. Changes in regional temperature, precipitation patterns, clouds, wind speed and direction, and atmospheric water vapor, all of which could be affected by an increase in the global mean temperature, may affect future air pollution levels and episodes (21).

For example, the influence of meteorologic conditions, particularly temperature, on ozone concentrations is well established. The relatively high urban ozone levels in 1983 and 1988 were likely due in part to the hot, dry, stagnant conditions that occurred in various areas of the country (32). Such increases in ozone levels have been associated with increases in the incidence of asthma, allergic disorders, and cardiorespiratory disorders and deaths (21).

Children are at higher risk from such increases than adults because their lungs are still developing and they spend more time outdoors in summer when ozone levels are higher (33). In addition, members of racial/ethnic minorities with low incomes have a disproportionate risk of being affected by increased ozone levels because they more often live in urban areas where such increases more frequently occur (34). Demographic trends such as population aging, urbanization, and increasing levels of disability and chronic illness may also increase vulnerability to these potential impacts among populations in developed countries such as the United States. Although uncertainties remain, it is likely that an increase in global temperatures would worsen urban air quality problems by

increasing the number of nonattainment areas, increasing the rate of natural emissions of hydrocarbons, and increasing the formation of acidic material such as sulfates (1,21).

Increases in Insect- and Animal-Borne Diseases

Increases in temperature and humidity have been predicted to lead to ecologic conditions more favorable to the survival of a variety of vectors, hosts, and the infectious agents they transmit, thereby increasing the likelihood of a variety of infectious diseases (6,22). These climate changes may favor expansion of already endemic diseases, e.g., arbovirus encephalitis, hantavirus pulmonary syndrome, or could increase the likelihood that imported diseases such as malaria and dengue will become endemically established in the United States.

Endemic Diseases. A number of insect- and animal-borne diseases currently affect populations in the United States. Generally the numbers of individuals affected are small, although in the past larger outbreaks of some of theses diseases (e.g., arbovirus encephalitis) have occurred (35). For this review, examples of two types of these diseases have been chosen for evaluation—arbovirus encephalitis, which is transmitted by a mosquito and hantavirus pulmonary syndrome, which is transmitted by virus shed by a rodent host.

Cases of mosquito-borne, arbovirus-induced encephalitis are diagnosed every year in certain regions of the United States (35–37). Historically, cases or other evidence of viral infection (i.e., antibodies to the virus) have been found in nearly every state (35). In 1994, 100 human cases were reported from 20 states (36); in 1996 and 1997 there were 286 cases reported in 19 states. However, more than half the latter cases occurred in a single state—West Virginia (37). In recent years most cases have been caused by viruses of the California serogroup, followed in prevalence by St. Louis (SLE), Western equine encephalitis (WEE), Eastern equine encephalitis (EEE), and Powassan encephalitis (36,37). WEE and EEE, although they do cause human disease, are found principally in susceptible animals, particularly horses. Previous outbreaks of arbovirus encephalitis in animals generally have preceded human outbreaks by 2 to 3 weeks, therefore cases in animals have been used as sentinels for human outbreaks (35). Studies of SLE and WEE indicate that

human outbreaks have been correlated with periods when temperatures exceeded 85°F for several days and epidemics generally occurred south of the 70°F June isotherm, although northerly outbreaks have occurred during unseasonably warm years. Recent evidence from field studies in California suggest that a 3 to 5°C increase in average temperatures will cause a significant northern shift in both WEE and SLE and the disappearance of WEE in southern endemic regions (38). However, the influence of variables such as precipitation and extent of a rise in sea level was not accounted for in these studies nor were the effects of warmer winter temperatures, which may potentially amplify viral production (39). In addition, no estimates have been made of the potential increases in the numbers of human cases under scenarios of climate change.

Weather events such as droughts and floods are thought to contribute to human outbreaks of other infectious diseases present in the United States. For example, the rodent-borne hantavirus pulmonary syndrome that emerged in the southwestern United States in 1992 and 1993 appears to have been spawned by an anomalous weather event, e.g., a drought that drove the mouse host populations into human habitats in increasing numbers and increased human exposure to virus-contaminated dust (40,41). The first report described illnesses in the Four Corners area of New Mexico, Arizona, Utah, and Colorado. Subsequent reports have documented detection of hantavirus-related illness in at least 17 states (42,43). In most cases the deer mouse is thought to be the primary reservoir of the virus. In the Southeast and the Atlantic seaboard, however, other reservoirs such as the cotton rat are suspected (43).

Imported Diseases. Several vector-borne diseases such as dengue fever and malaria, although not presently endemic in the United States, frequently are diagnosed in travelers visiting or returning here (44,45). Mosquito vectors for these diseases currently are found mostly in the southern United States, but one, the Asian Tiger Mosquito, *Aedes albopictus*, has been identified in areas as far north as Michigan (46).

Dengue fever is routinely imported into the United States by travelers returning from locations where the disease is endemic (47). Although the principal vector, the *Aedes aegypti* mosquito, was nearly eliminated from the Americas in the 1960s,

it is now found widely throughout the region (45). In the United States, mosquito-transmitted dengue is rare, although it has been detected in Texas on several occasions, even as recently as 1995 (48). Factors present in the United States, particularly in the South, that can support establishment of an endemic state include: *a*) the presence of two potential mosquito vectors, *A. aegypti* and *A. albopictus*, which have been found across the South and occur in populated areas; *b*) unscreened dwellings or gardens that allow mosquito–human contact; *c*) lack of vaccine to protect against disease and lack of natural immunity in the U.S. population; and *d*) lack of familiarity with the disease by American physicians, which potentially can lead to extended disease transmission before control measures are implemented. However, factors that prevent the establishment of a widespread and sustainable endemic state include: *a*) the mosquito density required for disease transmission may not exist over areas sufficiently large to maintain the infection in exposed populations; *b*) extensive use of air conditioning and window screens in the most densely populated areas restricts human contact with the mosquito vector; and *c*) the amount of free circulating viruses in the bloodstream necessary to continue disease transmission lasts on average only 4 to 5 days. In the absence of a sizable infected population, this is a very short time within which vector–host contact must be made (44).

The vector and climate conditions required for the transmission of malaria are similar to those for dengue and are already present in several cities in the South such as Miami, Key West, and Orlando, Florida (4). Imported cases routinely number in the hundreds (45). Cases acquired in the United States are much rarer and often attributable to either congenital malaria or acquisition of the parasite through blood transfusion (44). Occasionally, local transmission, presumably from infected mosquitos, has been observed (15–17), but such outbreaks have been limited in scope. Modifying factors similar to those discussed previously for dengue also apply to malaria, thus, as long as the current infrastructure and health care systems are maintained, reestablishment of this disease seems unlikely (4,17). However, should compromise of health care delivery and infrastructure systems occur on a scale equivalent to that observed in Florida in

the wake of Hurricane Andrew (49), the potential exists for reestablishment of this disease. Malaria cases must be reported; in May of 1996, for example, the cumulative annual number of cases in the United States was 406 (50).

Increases in Diseases Associated with Marine Organisms

Changes in sea surface temperatures and in wind, water current, and storm patterns can also change the dynamics of the marine ecosystem, leading to more effective transfer of disease by marine organisms. Higher sea surface temperatures reduce dissolved oxygen, and within limits, stimulate photosynthesis and metabolism, which favor the growth of toxin-producing species of phytoplankton (algal blooms) (21) as well as several vibrio pathogens (51–53) including the one associated with cholera, *Vibrio cholerae* 01 (54). Food poisoning outbreaks across the United States have been associated with the consumption of shellfish or fish contaminated with the algal toxin, or the *vulnificus* and *parahaemolyticus* vibrios. Most of the largest outbreaks have occurred in coastal states; however, cases have also been detected in inland states that have received shipments of contaminated fish or shellfish. Cases range in severity from mild to fatal depending on the toxin or pathogen present and the treatment given. In immunocompromised patients or those with liver disease, consumption of oysters contaminated with *parahaemolyticus* has been fatal (53); such severity is rare in cases associated with toxin-contaminated shellfish. Outbreaks due to fish contaminated with algal toxins are more common and can result not only from the consumption of fresh fish but also from consumption of canned and frozen fish (55).

Researchers have also associated such algal blooms with outbreaks of cholera in Bangladesh, and recently other researchers have found that zooplankton and to a lesser extent, phytoplankton, can be carriers of a dormant form of cholera that only requires appropriate levels of essential nutrients and warmth to become fully infectious. Although a number of cholera cases have been diagnosed in the United States, either from contact with travelers or through consumption of contaminated imported food, there is no evidence of cholera cases from the consumption of seafood taken from U.S. waters. However, a strain of *V. cholerae* 01 indistinguishable

from that associated with the 1992 epidemic in Latin America was detected in oysters taken from Mobile Bay during the summers of 1991 and 1992 (54). The source of the vibrio was unknown; however, one possibility is contaminated ballast water. If this were the case, ports with a significant international maritime role may be more at risk.

Increased temperature is not the only factor likely to contribute to more algal blooms. Growth in human populations along coastlines increases the supply of nutrients (nitrogen and phosphorus from agricultural runoff) as well as human waste contributed to marine systems, thus increasing the source of infectious agents such as cholera. At the same time, accompanying development often destroys wetlands that serve as filters for pollutants, and habitat for spawning and juvenile fish and shellfish populations. Finally, overharvesting of fish and shellfish populations in combination with loss of their spawning and nursery areas is reducing the populations of fish and shellfish that feed on phytoplankton and zooplankton, which further disrupts ecosystem dynamics (21).

Increases in Accidents and Disease Associated with Extreme Events

There is concern that global warming because it increases heating and the water vapor content of the atmosphere will increase convective instability and consequently spawn more frequent and/or more severe storms. This could lead to both immediate and delayed increases in the rates of death, injury, infectious diseases, and psychologic disorders. In the United States, major storms, both hurricanes and tornados, have been associated with significant mortality, illness, psychologic injury, and destruction(49,56,57) Immediate effects (within one month) have included deaths or illness associated with stress, trauma, or the mishandling of electrical wires as well drowning at sea or in flash floods (49,56). Similarly, flood disasters can have equivalent effects both directly and as a result of impaired infrastructure. Floods in Iowa in 1993 led to significant impacts on the availability of health care services as well as to damaged water and sewage systems that serve more than a third of the state's population. A number of counties had increases in hospital emissions due to flood-related injuries and illnesses as well as increases in problems with vectors (58). Similar but less severe effects were observed in Missouri in 1993 (59).

Extreme events such as droughts and floods also have been associated with increased contamination of water sources with fecal material, agricultural runoff (which contains pathogens such as cryptosporidium), and toxic chemicals (21). This situation can lead to increases in food- and waterborne infections and exposures. Such increases in infection can occur not only from contamination introduced locally, but also from contamination introduced remotely if changes in the food supply occur because of drought- or flood-associated crop failures. Such infection outbreaks are also more likely because of the world's move to a more global economy. Outbreaks of enteric diseases such as hepatitis, shigellosis, Escherichia coli-induced gastroenteritis, giardiasis, and cryptosporidiosis frequently have been traced to exposure to contaminated water or to produce washed in contaminated water (60–63).

Regional Distributions of Impacts

As a first step in identifying possible regional vulnerabilities to adverse health impacts from global climate change, information on the geographic distribution of selected diseases was taken from the cited references and developed into the graphic presented in Figure 1. States were considered to be at particular risk from various climate change-related impacts (and marked with the icons provided in the legend) if they historically achieved a certain level of impact. In the case of the chronic effects of heat-related illness, states were considered at particular risk if they averaged a rate of one heat-related death per million annually between 1979 and 1992 (26). They were considered to be at risk from the acute effects of urban heat waves if there were reports in the literature describing significant mortality during heat waves over the past 15 to 20 years (25,29,30,63–65) or if recent modeling efforts indicated the likelihood of an impact (9,21). For risk from air pollution-related health effects, states were considered at risk if they currently had one or more areas of nonattainment for ozone according to the U.S. EPA (66).

For insect- and animal-borne diseases, several different criteria were used to assign an icon to a state. A state received an icon for arbovirus encephalitis if it had had a recent history of human cases of arbovirus encephalitis (36,37) or if it were reported in Grimsted (35) as having cases, outbreaks, or evidence of elevated antibody levels in

humans. States were assigned an icon for hantavirus infection if they had a documented case of infection (40–43). States were placed in the high risk category for the imported infectious diseases evaluated if they reported several cases of dengue in the most recent surveillance report (44) or 10 or more cases of malaria in any of the last four summaries of notifiable diseases (67–70).

States were considered to be at risk from algal bloom-related illness if they had a past history of algal blooms or food poisoning from fish or shellfish (21,51–55). Similarly, a recent history (last 10 years) of marked morbidity or mortality associated with floods or storms placed the state in the high risk category for extreme event-related health effects (49,56–59).

Populations at Special Risk

In the process of developing Figure 1, it became apparent that states in certain regions of the country historically deal with a greater variety of warm weather-related health effects than other regions. Thus, for instance, the public health establishments of most of the Gulf coastal states traditionally deal with algal blooms and/or shellfish contamination (51–55), frequently detect multiple cases of viral encephalitis (35–37), malaria (67–70), and/or dengue (44,47–48), and frequently deal with the aftermath of violent storms (49,56,57). In addition, many of these regions also have to contend with air pollution from tropospheric ozone (66) and mortality from heat waves (25,28–30). In a few cases, they must also be concerned about hantavirus infections (41,42). In comparison, most of the Great Plains states have had to be concerned about only one, or at most two, of these effects.

At the same time, it occurred to me that some of the states that experience the greatest number of weather-related health effects had other characteristics that might augment or enhance their degree of vulnerability to these effects. Florida, for instance, has the greatest percentage of residents over 75 (71) and many of the southern coastal states have greater than average infant mortality rates (71). According to a variety of reviews (1,6,21), such populations are among the most sensitive to weather-related health effects. Therefore, it is reasonable to conclude that increased vulnerability to such effects might arise from having a disproportionate percentage of one or more sensitive subpopulations.

To examine this idea, I scanned the literature to identify a set of sensitive
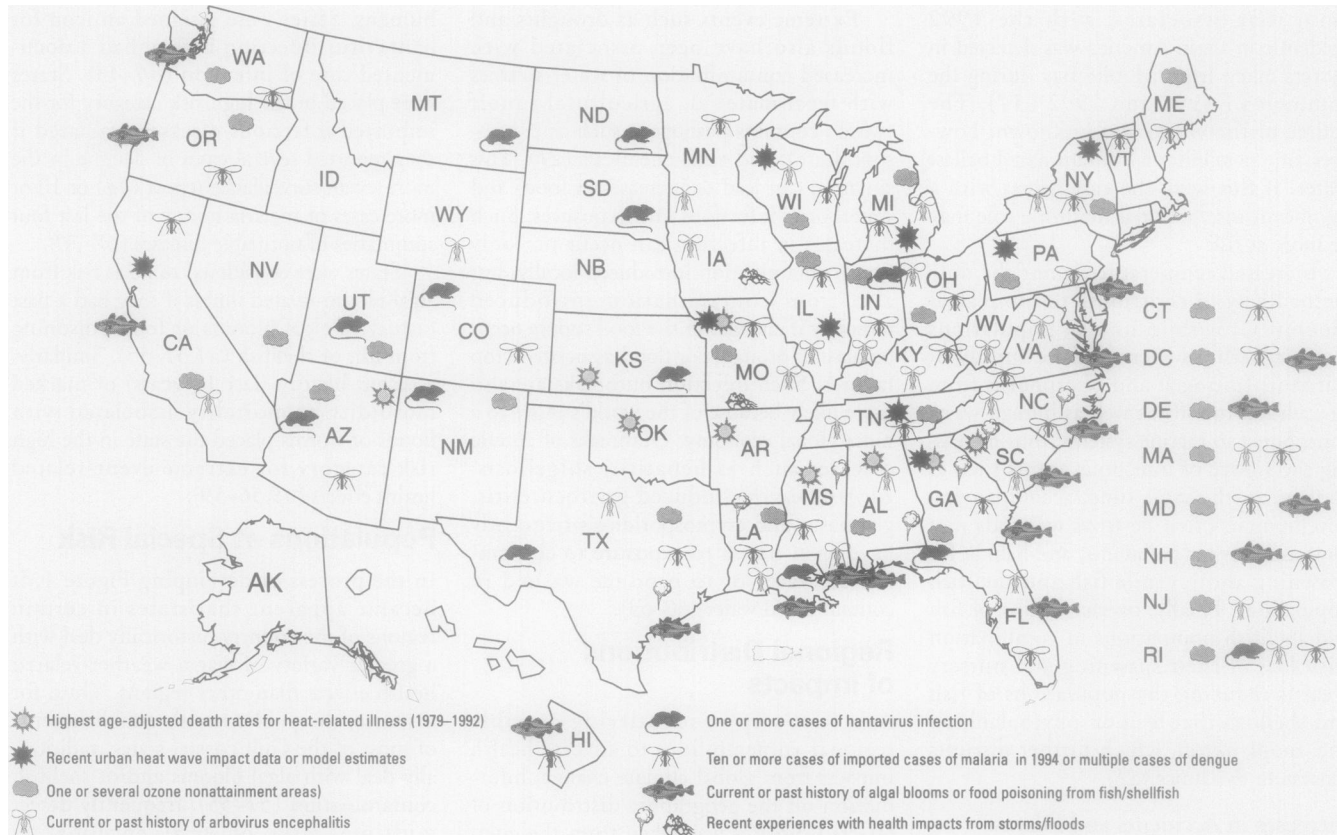
Figure 1. Geographic distribution in the United States of weather-related health effects.

subpopulations. Subpopulations indicated to be at especial risk for weather-related illness included the elderly, the very young, the poor, those with pre-existing disease, and those without medical insurance (1,6,21).

Most of the information that identifies these populations as sensitive is empirical [e.g., Kilbourne (26)], although often there are additional data that point to underlying mechanisms. Below is a brief synopsis of some of the characteristics thought to be responsible for the special susceptibility of these various populations to weather-related health effects. The exact magnitude of the increased risk associated with each characteristic is difficult to judge; suffice it to say that it varies from disease to disease and that for a given individual it increases with the presence of each additional characteristic, e.g., the elderly poor are at greater risk than the elderly affluent.

The Elderly

As a general rule, the elderly are likely to be more susceptible than the general population to most of the environmental insults discussed previously. A variety of factors

can contribute to such increased sensitivity to heat waves (27). As summarized by Kilbourne (27) and the WHO (22), included are host factors such as a drop in the efficiency of thermoregulatory systems, an increase in the temperature at which sweating begins, a decrease in the ability to perceive changes in temperature, and pre-existing conditions such as cardiovascular or pulmonary diseases. Also included are environmental factors such as the use of medications, e.g., major tranquilizers and anticholinergics, that increase susceptibility to heat stroke (27).

Similar impairments make the elderly more susceptible to the acute effects of increased air pollution. They are more likely to have underlying (cerebrovascular, cardiovascular, and respiratory) illnesses that can become crises under conditions of impaired respiration (22); they are also known to have a diminution in the lung's ability to clear inhaled materials (72), which places them at increased risk for adverse effects, such as fibrosis and cancer, from sustained exposure to such materials. The elderly also are more susceptible to infectious diseases because of a decline in

their immune systems. They do not make antibody responses as well and their cellular defenses are not as effective as those of their younger counterparts. Some of this may be related to poor nutrition, but there is also evidence of a decline with age in certain immunologic functions independent of nutritional status (73).

The elderly are also more vulnerable to threats from storms and floods because their abilities to respond quickly to stressors are diminished and because they are often less ambulatory and thus less able to evacuate quickly and are more prone to accidents (74–76).

The Young

The young are in many ways like the elderly, although in their case it is not a loss of function but rather that they have not yet acquired certain functions. In the case of heat stress, sensitivity to heat is greatest in children less than a year old whose thermoregulatory systems have not developed to adult potential. Children who are ill, particularly with diarrheal diseases, are particularly vulnerable, possibly because dehydration also compromises the

thermoregulatory system by decreasing perspiration (27).

In the case of air pollution, children are more at risk than adults because they have a greater ratio of lung volume to weight so their intake on a per-weight basis is also greater (77). In addition, their respiratory systems are less effective in clearing foreign particles than those of adults, and their abilities to detoxify pollutants through metabolism is also less fully developed (78). These factors also contribute to increased susceptibility to infectious disease, which is augmented because their immune systems are still developing and therefore are not yet fully competent (79). Children also spend more time outside than adults, so they are more frequently exposed to environmental threats such as air pollution or insect- and animal-borne diseases.

The Poor

Death during heat waves in the United States is mainly an urban phenomenon that disproportionately affects areas with low income populations. This special susceptibility of populations living in urban areas may be due partly to the tendency of the urban architecture (masses of brick, concrete, stone, and asphalt) to absorb solar heat energy during the day then radiate it back at night thus continually maintaining a heated environment. This "heat island" effect coupled with other urban characteristics, e.g., lack of shade trees and the tendency of tall buildings to decrease wind velocity and thus the cooling effects of moving air, results in a much greater increase in ambient temperature than in nonurban areas. Rural and suburban environments, which not only cool off at night but are much more likely to be open to air flow and to use shade trees for landscaping, thus are much less likely to be associated with heat-related illnesses. In addition, the poor may be at greater risk because they are less able to afford air conditioning or to engage in other strategies that can reduce heat stress, e.g., leaving the city during peak heat or visiting air-conditioned environments (27).

Susceptibility of the poor to other environmental diseases may also be related to their lack of resources. Poor nutrition and crowding may increase their susceptibility to infectious diseases because of compromised immune systems (79), substandard housing may increase their risk during floods and storms because of the greater likelihood of building collapse, and residence in an urban area increases their likelihood of exposure to air pollution (31).

Those with Preexisting Disease

As discussed above, a number of conditions contribute to special sensitivity to heat stress; these include cerebrovascular, cardiovascular, and respiratory diseases as well as those diseases that lead to dehydration (1,21,27). Some of the same diseases also are associated with greater sensitivity to air pollution, e.g., respiratory and cardiovascular diseases. In addition, as mentioned previously certain medications can enhance susceptibility to heat stress (27).

Diseases/treatments that suppress the immune system (e.g., AIDS, kidney transplantation) often lead to greater susceptibility to infectious and possibly contribute to increased rates of morbidity and mortality from the environmental infectious diseases (79). Finally, diseases of cognitive function, e.g., Alzheimer's, can make it more difficult to respond appropriately to the threats associated with such events as floods or storms.

Those without Medical Insurance

Individuals without medical insurance are more susceptible to weather-related health effects because they do not routinely see health care providers (80) and therefore frequently miss early treatment of these diseases that might limit morbidity and mortality (81,82). Such individuals are more likely to draw on public resources when they finally receive treatment and the treatment required then may be much more expensive than that which would have been administered at earlier stages of the disease.

Immigrants are a special case of those without medical insurance because recent U.S. legislation specifically denies most recent immigrants access to federal health care services such as Medicare and Medicaid (12).

## Regional Distribution of Susceptible Populations and the Resources on Which They Draw

In order to evaluate the regional distribution of susceptible populations, an approach similar to that used to develop Figure 1 was applied using data from the 1994 County and City Data Book (71) and the 1994 Statistical Abstract of the United States (83). In some instances, these references did not provide statistics on the geographic distribution of the precise subpopulation of interest, so a surrogate was used. Thus, although the very young might best be described as children under 1 year of age, information on children under 5 years of age was used, as this was the youngest group for which geographic distribution information was presented (83). The statistic used for the elderly was individuals over 75 years of age. For the subpopulation of those with preexisting disease, the statistics evaluated were mortality from cardiovascular and chronic obstructive respiratory disease based on the argument advanced by the IPCC that morbidity would likely mirror mortality (21). Thus the states with a greater incidence of mortality from these diseases likely would have a greater incidence of individuals with these diseases.

Figure 2 displays the geographic distribution of sensitive populations discussed previously. A shaded icon was used for those five states (the top 10%) with the greatest percentage/incidence of their population with a particular sensitivity characteristic. Black icons were used for those states in the top quartile (i.e., top 25%). Again, the picture is clear; on the basis of these metrics, some states appear to have a disproportionate share of sensitive subpopulations.

Again, there are a number of caveats. First, some of these metrics are or may be related to one another, i.e.,the high percentage of individuals without health insurance in Texas could be related to the fact that a large percentage of the state's population is immigrants. In addition, it is not likely that all susceptible populations will have equal impact on state and federal budgets if they are affected adversely by regional warming. The response to unusual warming of a single susceptible population if it were highly sensitive, of sufficient size, and widely distributed could place more demand on the health care system than that associated with several smaller, less sensitive populations

The presence of a greater number of susceptible individuals in the population could have several consequences for a state. Not only could it affect the incidence of a particular effect—e.g., hospital admissions associated with air pollution episodes are likely to be greater in areas with a higher incidence of respiratory disease—but it is also likely to increase the morbidity and mortality from particular effects, and in states with high proportions of poor, and populations without health insurance, it is also likely to pose a greater burden on public health care resources.
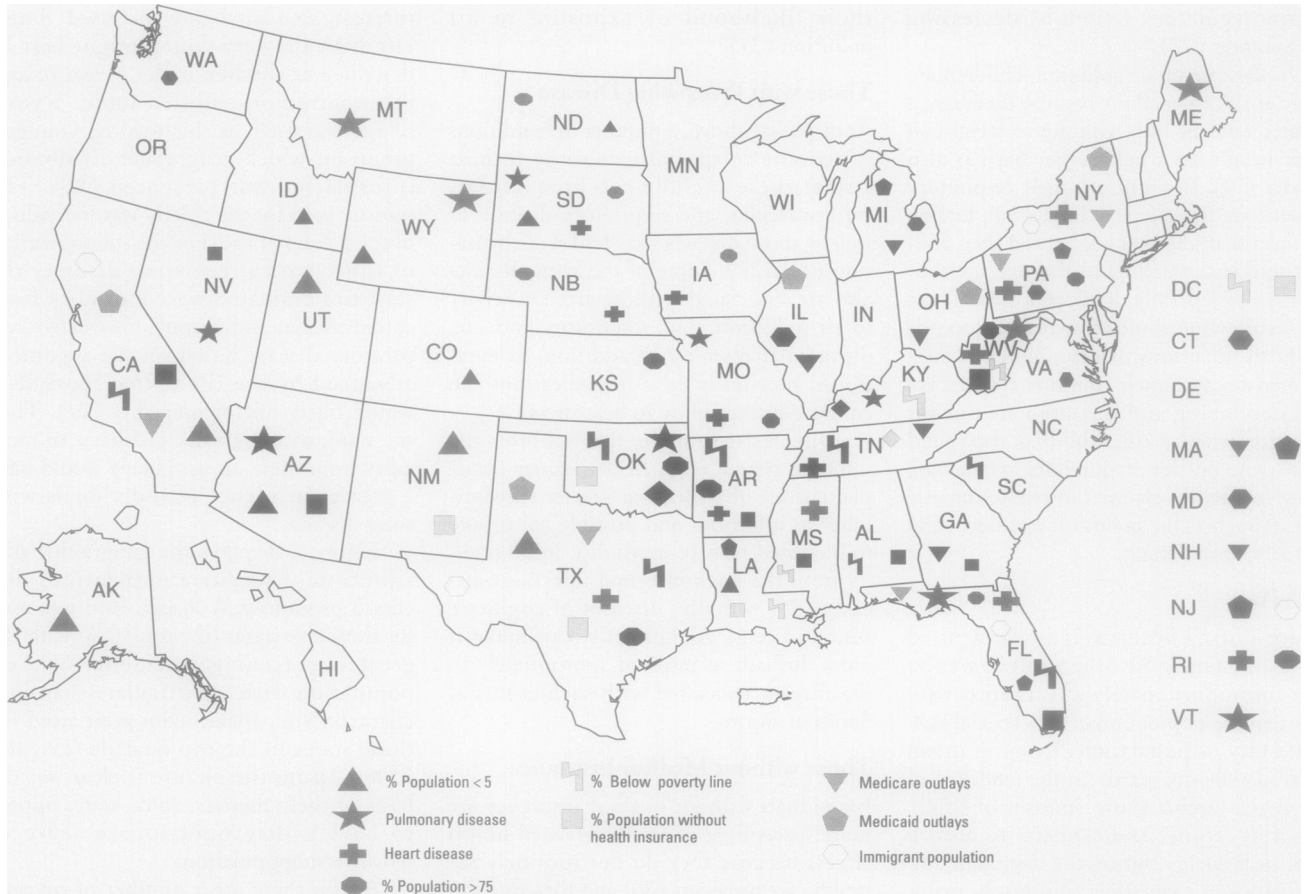
Figure 2. Geographic distribution in the United States of sensitive subpopulations. Shaded shapes, worst 10%; black, worst 25%, based on *1994 Statistical Abstract of the US (83)*.

Having both a large number of possible health outcomes the incidence of which might increase under GCC and multiple highly susceptible populations could have serious consequences for states so affected. Currently, if states have to contend with these health effects, they are dealing with effects that occur at levels within the normal range, i.e., effects encountered on a routine basis, with only an occasional surge above the status quo, i.e., a disaster now and again. How will state budgets be affected if the status quo changes, even a small change, for all these weather-related health effects, simultaneously? Not only will there be additional drains on public health care resources, but increased spending may be required for a variety of other programs, e.g., disease surveillance, vector control programs, air pollution prevention, regulation, and monitoring, and seafood monitoring.

Also, what will this do to Medicare and Medicaid budgets? Many states with the high percentages of susceptible populations already have high Medicare and Medicaid budgets (Figure 2); if GCC exacerbates weather-related health effects and the qualification criteria for these programs remain the same, demands on these budgets are also likely to increase along with the demand for federal services related to these effects, e.g., air pollution monitoring.

Next Steps

As mentioned previously Figures 1 and 2 present results of a preliminary attempt to determine whether there is merit in further exploring the hypothesis that certain regions may be more vulnerable than others should global warming occur. This was a crude demonstration of the proposed approach because it evaluated a limited set of weather-related diseases, a limited set of susceptible populations, and used only nationally available data. Although sufficient as a demonstration, a more detailed implementation will be required as a basis for action, preferably using county-level data so that the overlap of susceptible populations and likely diseases can be better assessed.

This approach can be expanded in several ways. First, it seems likely that given the recent El Niño-related changes in regional climates in the United States, this hypothesis could easily be tested by comparing health care statistics for the past two decades between the set of states identified to be at high risk by this review and the set of states identified to be at low risk for weather-related effects. One would predict that on the basis of this hypothesis, per-capita Medicare and Medicaid spending for certain diseases would have shown a far greater increase in the set of high-risk states than in the set of low-risk states. Such an analysis would have to be conducted carefully, of course, because there may be state-to-state variations in how certain diseases are diagnosed and treated. However, because the comparison would first be between decades within a state followed by a comparison of high-risk states versus low-risk states, the largest confounder is likely to

be changes over time within a state and these should be easier to detect.

A second way to expand this approach would be for states to use this method to assess their own vulnerability. As a starting point, states may need to determine if there were any systematic changes in the incidence of environmentally related diseases when statistics from the past two decades are compared. Both increases and decreases should be noted, as it is likely that a warmer climate would result in decreases in some environmentally related diseases, e.g., hypothermia, and it is conceivable that such decreases could offset increases in diseases such as those discussed above. Diseases other than those discussed previously also might need to be examined. Insect- and animal-borne diseases such as erhlichiosis (83) and Lyme disease (84) are acquired principally in the spring and summer; therefore, a change in climate that lengthens those seasons or permits ticks to overwinter could lead to increases in the incidence of these diseases. Disease incidence might also be increased if warmer winters, particularly in the North, permit humans to enter tick-infected habitats earlier in the season or result in increases in the population size of intermediate hosts such as deer and rodents.

Foodborne diseases such as *Salmonella enteritis* (85), listeriosis (61) and *Cyclospora* infections (86) have come to be of sufficient concern in the United States that in 1994 the Centers for Disease Control instituted an active surveillance system (87). Warmer temperatures encourage the growth of many of these organisms. Thus it is reasonable to expect that a warmer climate could result in a greater degree of source contamination, e.g., raw or uncooked eggs in the case of salmonella, as well as a greater degree of food contamination from improperly handled foods, e.g., homemade mayonnaise (88). Similarly, recent statistics on waterborne diseases in the United States suggest that these diseases occur with greatest frequency during the summer months and that, at least in the case of infectious agents, in more northern states (89). Therefore, if climate change results in longer summers in the north, it may also result in an increase the incidence of waterborne and foodborne diseases in these regions.

A final group of diseases that could be affected by GCC are those associated with exposure to summer weather–climate related allergens. Several factors might contribute to a change in the incidence or

severity of such diseases under GCC. First, a warmer climate could result in a longer growing season in some regions and a longer period of pollen production, which might prolong the hayfever season. Similarly, to the extent that GCC results in a more humid environment, increases in allergic reactions to molds and fungi can be expected. Finally, warmer temperatures and the air pollution associated with them may result in a greater incidence or severity of allergic reactions that trigger asthma attacks.

Some other susceptible populations were not evaluated in this review. In situations where surrogates such as the very young were used, a state's true vulnerability might better be assessed using statistics for those under 1 year of age, or perhaps birthrate statistics. Similarly, vulnerability associated with the elderly poor or the elderly population over 85 years of age may be of greater concern than that associated with the proportion of the population over age 75. Finally, certain preexisting illnesses, asthma, for example, may actually be a cause for greater vulnerability than the predisposing illnesses evaluated in this review.

Should a state or a region desire to assess its vulnerability to weather-related diseases using the approach outlined here, it might be best to focus only on those diseases that are currently problematic in their area, where problematic is defined by area health care professionals. Some of the reasons a disease might be considered problematic include a wide distribution, severity of effect, and recalcitrance to or expense of, treatment or containment. After identifying the set of diseases of concern, health officials must examine information on the historical distribution of these diseases at the county level in conjunction with information about current size, distribution, and economic characteristics of sensitive subpopulations to determine whether there is an overlap of the geographic distributions of these diseases and their susceptible populations. For instance, Florida has a history of arbovirus infections and also has a large elderly population; however, if most of the elderly are located in the counties of southern Florida and most of the encephalitis cases occur in the counties of western Florida, the state's vulnerability is not as great as it might appear looking at the issue on the basis of state-level statistics.

If a state's relative proportion of a sensitive subpopulation changes or if the distribution of the population by county changes, both federal and state public

health officials need to be sensitive to the implications of such changes for their services. If certain counties contain a disproportionate percentage of a state's sensitive subpopulations, they may need more resources. If a state begins to experience an upward trend in the number or intensity of disasters with which it must deal, it may need to examine the pattern of these disasters to determine if a larger reserve budget is required or if more advance planning dedicated to reducing the impact on sensitive subpopulations is needed.

Federal officials need to be alerted that stress placed on their programs by the aging of the U.S. population is likely to be exacerbated because of the elderly represent a sensitive subpopulation for these weather-related effects. Similarly the stresses associated with increases in the percentage of the population below the poverty level may be exacerbated by the particular sensitivity of this population to these effects.

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