Climate, Infectious Disease and Health
An Interdisciplinary Perspective

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a report from
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Executive Summary

A colloquium was convened by the American Academy of Microbiology to discuss research issues relating to the effects of climate on the incidence and distribution of infectious disease. The colloquium was held in Montego Bay, Jamaica, June 20–22, 1997. The principal findings of the colloquium are summarized below.

The global infectious disease burden exceeds several hundred million cases each year, and infectious diseases are estimated to account for one-third of annual human mortality. For many infectious diseases, principally those that are vectorborne, there is a significant amount of data relating diseases incidence to climate or weather factors. With the increasing accumulation of satellite data, a better understanding is emerging of the complex interrelations among weather and climate conditions and the survival and spread of pathogenic microorganisms and disease vectors and hosts.

Annual rainfall and temperature averages are important parameters in the demarcation of bioclimate envelopes within which the occurrence of many infectious diseases is concentrated. These factors also have significant effects on variables, such as vector population size, which are related to disease outbreaks and epidemics. Although more is known about the effects of weather and climate conditions on the prevalence of vectorborne disease, there are important links between these factors and the occurrence of waterborne, airborne, soilborne, and foodborne diseases.

Large-scale weather disturbances like El Niño can have a dramatic impact on the incidence of many infectious diseases, such as malaria and Rift Valley fever. Scientists have discovered numerous connections between the 1991-1995 El Niño and increases in the incidence of diseases, including cholera and hantavirus pulmonary syndrome. El Niño-related increases in sea-surface temperature and sea-surface height in the Bay of Bengal have been associated with a rise in the number of cholera cases in Bangladesh. Recent findings from the 1997-98 El Niño are providing corroborating evidence for a causal relationship between extreme weather events and disease outbreaks.

Better quality and more comprehensive data sets are needed to improve the current understanding of how weather and climate affect the prevalence and occurrence of infectious disease. This information is essential for developing accurate predictive models of disease outbreaks. Research on climate-disease links is interdisciplinary in scope and includes microbiology, epidemiology, ecology, oceanography, climatology, atmospheric sciences, and marine biology. Progress needs to be made in making data sets more accessible to researchers in these and other disciplines.
Introduction

The impact of climate on the incidence and distribution of infectious disease is an important issue for epidemiology and public health. Infectious diseases affect hundreds of millions of individuals every year and have been estimated to account for nearly one-third of annual human mortality (World Health Organization, 1996). A better understanding of how climatic factors affect the spread of infectious disease would be instrumental in improving disease prevention efforts. Such knowledge would surely enhance the ability to predict the health-related effects of both seasonal weather changes and large-scale disturbances such as El Niño.

Climatic factors influence the occurrence and transmission of infectious diseases through multiple direct and indirect effects upon pathogenic microorganisms, vectors, reservoirs, and hosts. An extensive body of literature exists which details associations between variables like temperature and precipitation and the incidence of infectious diseases like cholera and malaria. The evident seasonality of these and other vectorborne and waterborne diseases makes them good candidates for research on the relationship between outbreaks of infectious disease and climatic conditions. For example, the 1993 hantavirus outbreak in the southwestern United States has been traced to the effects of heavy rainfall associated with El Niño. The increase in rainfall produced an abundance of pionon nuts that, in turn, supported a dramatic increase in the population of the deer mouse, the carrier of the virus. That increased mouse population in the southwestern United States is believed to be the cause of the hantavirus outbreak (Wenzel, 1994).

Weather and climate involve largely similar phenomena, but upon different time scales. Weather primarily concerns atmospheric conditions, such as temperature, precipitation, and wind, at a given place and time. Climate encompasses these and other variables characteristic of the physical environment of particular areas over long periods of time. These variables affect the occurrence and prevalence of infectious diseases in ways that are related to the means by which the pathogens are transmitted. Such means of transmission include vectors, water, air, and food.

In order to detect climate-related trends in disease incidence, it is essential that seasonal and interannual variations be distinguished. Unfortunately, the paucity of databases currently available limits what researchers can say about many potential climate-disease links. Much of the information comes from “brush-fire biology,” in which researchers have focused their attention on short-term and emerging epidemics and gathered data over a short period of time. A concerted effort to acquire more complete data sets is required, even after epidemics have waned. Diseases need to be identified for which long-term, high-quality data sets can be readily developed. Modeling studies are also needed to improve the capacity to predict conditions conducive for epidemics of specific diseases, such as cholera and other diarrheal diseases.

Analysis of the effects of climate on the incidence, resurgence, and emergence of infectious disease will augment existing connections between the environmental sciences and public health. A more complete understanding of the complex ecology encompassing climate, infectious disease, and human health will require integration of research efforts across diverse areas, including not only microbiology, epidemiology, and medicine, but oceanography, atmospheric sciences, marine biology, computer modeling, and the space sciences as well.
Influence of Climate on Infectious Disease

Many infectious diseases occur cyclically, and the patterns of occurrence often suggest, sometimes quite strongly, that environmentally dependent factors play a role in outbreaks and epidemics. The causes of these cyclical occurrences are just beginning to be elucidated. A recent World Health Organization (WHO) monograph, entitled “Climate Change and Human Health” (World Health Organization, 1996), reviewed potential adverse effects of global climate change on human diseases. It is evident from that review that more is understood about how weather affects vectorborne than airborne, waterborne, or soilborne diseases. The present report is focused on connections between weather variability and incidence of infectious diseases. The effects of long-term climate change on disease transmission are left for future analysis.

Infectious diseases that are responsive to climate can be divided into two groups. The first group comprises those diseases for which there are clearly documented links between incidence and climate and weather factors. This group is primarily composed of vectorborne diseases, including malaria, hantavirus pulmonary syndrome, dengue, and various forms of viral encephalitis. The second group comprises diseases whose incidence is cyclical, thereby suggesting a link to climate, but for which the potential mechanisms linking climate factors to incidence are either unknown or only tentatively established. Campylobacteriosis and cholera are notable examples of diseases in this category, but recent research on cholera epidemiological patterns has demonstrated a clear association between sea-surface temperature and cholera incidence.

Temperature:

Microorganisms carried by vectors, such as mosquitoes, ticks, and other blood-sucking arthropods, are strongly influenced by temperature of the microenvironment within their cold-blooded vector hosts. The survival rates of vectors and the rates of multiplication and transmission of the microorganisms that infect them are temperature dependent (Fig. 1, Reeves, et al., 1994). The physiological relationship between temperature and the malaria parasite and its mosquito vector exemplifies this dependency. The geographical distribution of the Anopheles mosquito and the four species of malaria parasites which infect humans is restricted by low—and probably also high—temperature. Over the low temperature threshold, the rates of development of the parasite and the vector population increase with temperature, thereby increasing transmission capacity. Temperatures in the 20 to 30°C range and humidity above 60% provide optimal conditions for mosquitoes to incubate and transmit the malaria-causing parasites.

![Figure 1. Effect of temperature on transmission rates (the percentage of bites that result in transmission) of Western equine encephalitis (WEE) and St. Louis encephalitis (SLE) viruses by the mosquito, Culex tarsalis. Reeves W.C., Hardy J. L., Reisen W.K., Milby M. M. “The Potential Effect of Global Warming on Mosquito-Borne Arboviruses.” Journal of Medical Entomology: 31(3): 323-332.](image-url)
Precipitation:

Precipitation, especially in the form of rainfall, can affect disease transmission via the effects of normal, as well as severe (i.e., flooding and drought), events on vector populations. Again, malaria serves as an example. In the drier regions of the tropics, low rainfall restricts the breeding of vector mosquitoes, and low humidity reduces the number of mosquitoes that survive to the age required to transmit malaria. A preceding drought may play an important role in the development of malaria epidemics in areas such as the Indian subcontinent, South America, and southern Africa. However, the effects of the amount and temporal distribution of precipitation on the transmission intensity of malaria are not well understood. Existing models for predicting malaria incidence as a function of rainfall have a high degree of inaccuracy. Flooding can influence disease transmission in a number of ways, most notably by increasing run-off and disturbing breeding grounds and habitats. The drowning of rodents that are reservoirs for diseases can lead to increased transmission by increasing human contact with contaminated water.

Wind and Ocean Currents:

The potential for variations in wind and wind patterns to promote infectious diseases is a generally neglected aspect of climate-human health interactions. A notable example of this potential occurs in the “meningitis belt” of Sub-Saharan Africa, where an epidemic form of meningococcal meningitis is associated with the climate conditions of the Sahel. Stretching along the southern rim of the Sahara Desert from Mauritania to Somalia, the Sahel is an area of low rainfall and seasonally harsh temperature variations. Meningitis epidemics, accompanied by high mortality, occur during the hot, dry season with 8- to 14-year cycles (Moore and Broome, 1994). Generally, the disease begins with bacterial colonization of the nasopharynx. It has been postulated that the dry, sand-carrying harmattan winds cause mucosal damage that facilitates the entry of the meningitis-causing bacteria into the body.

Finally, recent research has demonstrated that ocean currents and tides are connected with plankton blooms and cholera epidemiological patterns (Colwell, 1996). Sea-surface temperature, height, and concentration of nutrients in seawater are associated with cholera incidence through their effects on plankton blooms, phytoplankton being a food source of the zooplankton that carry Vibrio cholerae as part of its natural microbial flora.

El Niño-Southern Oscillation:

The El Niño-Southern Oscillation (ENSO) is a dramatic and well-documented recurrent climatic variation that involves a warming of surface waters in the equatorial Pacific, a decrease in barometric pressure in the eastern Pacific, and the weakening of easterly surface winds. These events alter the distribution of rainfall in the tropics and lead to changes in weather patterns over much of the globe. The unseasonably warm temperatures, increased amounts of rainfall, and/or flooding associated with El Niño have been linked to outbreaks of leptospirosis, Rift Valley fever, hantavirus pulmonary syndrome, malaria, and Ross River virus, among other diseases. Recent studies have found an apparent link during the unusually long 1991-95 El Niño between higher seawater temperatures off the coast of Peru and in the Bay of Bengal and an increase in cholera cases in parts of South America and the Indian subcontinent, respectively.
Climate Sensitive Diseases

Colloquium participants developed a working list of infectious diseases whose occurrence and prevalence are, or are likely to be, climate or weather related. These diseases can be grouped according to mode of transmission—vectorborne, waterborne, foodborne, or airborne—recognizing that some, notably certain enteric diseases, are transmitted by ingestion or contact with contaminated water or food. Although the focus of the colloquium concerned infectious human diseases, plant and fish diseases were also considered, with respect to their indirect effects upon human health through ingestion of affected plants or fish.

Vectorborne Diseases:

Climate factors and weather conditions affect the prevalence and distribution of vectorborne diseases by influencing the reproductive success of arthropods and small rodents that transmit pathogenic organisms. By extending the normal range of the disease vector and/or by providing a more hospitable environment for its reproduction, variations in rainfall and temperature can be instrumental in the occurrence of epidemics in areas in which the particular disease is not endemic. Temperature can also be a significant factor in the transmission of viral diseases spread by mosquitoes because warmer temperatures shorten the extrinsic incubation period of the virus, i.e., the time it takes for the virus to transport through the gut and reach the salivary glands of the mosquito.

Malaria. Malaria is endemic throughout most of the tropics, with a high prevalence in Africa, the Indian subcontinent, Southeast Asia, many South Pacific islands (excluding Polynesia, and parts of South and Central America and Mexico. (It should be recalled that both malaria and yellow fever were endemic in some regions of the United States until the turn of this century.) Some 2.4 billion people live in areas of risk (WHO, 1996), and approximately 350 million new infections occur annually, resulting in over 2 million fatalities. Four species of the Plasmodium protozoa, transmitted by Anopheles mosquitoes, cause this disease in humans. Untreated, malaria tends to be a lifelong affliction, with recurring episodes that last one to four weeks. Its symptoms include fever, headache, and malaise; death (predominantly in young children) may result from neurological damage and progressive coma, pulmonary edema, kidney failure, or shock caused by the collapse of the vascular system.

According to the WHO, malaria is one of the most climate sensitive among vectorborne diseases (WHO, 1996). Malaria provides a well-documented example of the interactions among parasites, vectors, and hosts that affect the transmission of vectorborne diseases. Within the bioclimate envelope, outside of which malaria is not transmitted, transmission intensity depends on interrelations among factors, including vector density, biting rate, and survival of the mosquito. The longevity of the vector is particularly significant because the parasite must undergo a process of development within the mosquito before the disease can be transmitted. This process, termed sporogony, can take 8 to 35 days and occurs more quickly at an ambient temperature between 20 and 27°C. Outbreaks of epidemics in highlands or desert fringes, where malaria is not endemic, are strongly influenced by temperature or rainfall, respectively. Figure 2 shows the cyclical pattern of epidemic malaria associated with El Niño in Venezuela.

Figure 2. Malaria in Venezuela During El Niño
Dengue Fever (Breakbone Fever, Dandy Fever, Solar Fever). Dengue fever is a severe, influenza-like disease accompanied by a rash. It is spread from human to human by Aedes aegypti mosquitoes, which also transmit yellow fever and chikungunya viruses. Dengue viruses are endemic in much of the Caribbean, Latin America, Africa, and Southeast Asia, where some 20 to 50 million infections are estimated to occur each year. In areas where dengue is hyperendemic, a severe and fatal form, dengue hemorrhagic fever, has emerged over the past several decades. Dengue fever is representative of a number of arthropodborne infections (see “Arboviruses,” below) which are transmitted in both tropical and temperate regions in that outbreaks occur during warm weather and the rainy season. Viral transmission is linked to summer or warm weather because the extrinsic incubation period is inversely related to temperature (Watts, Burke, Harrison, Whitmire, and Nisalek, 1987, and Jetten and Focks, 1997).

Tickborne Diseases. Ticks transmit Lyme disease, the most common vectorborne disease in the United States, along with Rocky Mountain Spotted Fever, Ehrlichiosis, and, in Europe, encephalitis. Involved tick and mammal host populations are influenced by land use/land cover, soil type, elevation, and the timing, duration, and rate of change of temperature and moisture regimes. The relationships between vector life stage parameters and climatic conditions have been studied in both the field and laboratory. Generally, ticks are intolerant of very high temperature with low humidity.

Other Arboviruses. There are more than 500 of these viruses, so named because they are arthropodborne viruses. In addition to dengue fever, the many diseases caused by arboviruses include yellow fever, chikungunya, Rift Valley fever, Ross River fever, M urray Valley encephalitis, St. Louis encephalitis, and tickborne encephalitis. Except for the latter, most of these diseases are transmitted by mosquitoes. Epidemic occurrences vary greatly from year to year, and some of these variations have been shown to correlate with El Niño events—e.g., M urray Valley encephalitis and Ross River virus in Australia (Tong, 1998), Rift Valley fever in Africa (Nicholls, 1993), and hantavirus pulmonary syndrome in the southwest United States (Wenzel, 1994). Rainfall is known to affect the prevalence of Rift Valley fever as eggs of the vector Aedes mosquito infected with the virus can lie fallow for years until sufficient rainfall occurs for the eggs to hatch. Field studies in California have also documented an association between temperature and the seasonality and distribution of certain arboviral diseases (Reeves, Hardy, Reisen, and Milby, 1994).

Other Vectorborne Diseases. The occurrence or prevalence of several other vectorborne diseases appears to be influenced by the effects of particular weather or climate conditions on their respective vectors or reservoirs. Leishmaniasis, onchocerciasis (river blindness), and African trypanosomiasis (sleeping sickness) are transmitted by the bites of infected flies, and incidence increases with an expansion of the vector population. Plague is generally more common during warm dry periods, but the effects of flooding on the rodent population increase its transmission as well. Tularemia (rabbit fever) is transmitted by ticks, fleas, and flies. Rabbits and rats are important reservoirs, and flooding increases acquisition of the disease by humans.

Waterborne Diseases:

Waterborne microorganisms have been estimated to account for as much as 80% of the annual mortality due to infectious disease (Clark, 1993). Evidence suggests that warmer temperatures are correlated with an incidence of some of these pathogens, including the bacterium that causes cholera (Colwell, 1996). Flooding and increased run-off are also causes of increased disease transmission to humans.

Cholera. Cholera is a debilitating, potentially fatal, disease caused by the bacterium Vibrio cholerae. It is spread by bathing in or drinking contaminated water and by ingestion of contaminated food. There have been seven cholera pandemics (worldwide epidemics) since 1816. The seventh and current pandemic began in 1961 and is the longest one to date. Cholera symptoms include explosive, watery diarrhea; vomiting; and abdominal pain. Mortality rates are highest among untreated patients under 2 years of age. Cholera is now affecting more nations worldwide than at any other time during the 20th century (Watson, Zinyowera, and Moss, 1996), and it remains endemic in India, Bangladesh, and Africa. In the United States, the bacterium is present in the Gulf Coast of Texas, Louisiana, and Florida, the Chesapeake Bay, the California coast, and coastal waters to the north.
Cholera outbreaks occur seasonally and are associated with monsoon seasons, warm temperatures, heavy rainfall, and increased plankton populations. *V. cholerae* occurs in riverine, brackish water, and estuarine ecosystems, being part of the natural flora of plankton. *V. cholerae* is found in the gut of, and attached to the surface of, both freshwater and marine copepods. The bacterium reproduces on the copepods and appears to be able to enter a dormant, nonculturable state during seasons of zooplankton decline. The factors that trigger entrance into and exit from this dormant state are as yet undetermined, although evidence for genetic regulation of the process has been obtained. Associations among sea-surface temperature, sea-surface height, and disease incidence have been found in Bangladesh (Colwell, 1996) (Fig. 3, Colwell, 1996), and links between El Niño and the 1991 and 1997-98 epidemics in South America are being investigated. A current hypothesis suggests that outbreaks are related to plankton blooms associated with warmer sea-surface temperatures (Colwell, 1996). The phytoplankton blooms are a food source for the copepods upon which the cholera bacterium thrives. Movement of tidal waters carry the algal blooms and copepods towards land and into rivers, bringing the bacterium into contact with humans who use this water for bathing or as a source of drinking water.

**Leptospirosis.** Leptospirosis is a bacterial disease caused by the microorganism *Leptospira interrogans*. The rat is the primary host, and humans acquire the disease through contact with urine-contaminated water. The organism enters the body through broken skin or the mucus membranes of the nose or mouth. Symptoms range from fever and chills to jaundice and kidney damage. An outbreak of leptospirosis has occurred in Nicaragua during flooding (CDC, 1995). Increased numbers of the organism are found in standing water during the late summer.

**Schistosomiasis.** Schistosomiasis comprises a complex of parasitic infections caused by mammalian blood flukes of the genus *Schistosoma*. Infection is acquired by exposure to fresh water containing infected snails, the intermediate host. Schistosomiasis is the most prevalent waterborne disease and is estimated to affect some 250 million people worldwide, principally in tropical Asia, Africa, South and Central America, and the Caribbean. Five species of *Schistosoma* account for most human infections. Symptoms include fever, abdominal pain, diarrhea, and liver tenderness. Potential climate links to transmission include the effects of seasonal temperature variations on the population dynamics of the parasite and intermediate host (Shope, 1992). Infections do not occur on the East African plain during the hottest months of the year because the water is too warm. Since the disease is associated with irrigation, climate-related impacts on agricultural water supply are expected to alter its distribution (Jetten and Focks, 1997).

**Other Waterborne Infectious Diseases.** Rainfall, flooding, and agricultural run-off are potentially associated with the spread of many waterborne infectious diseases, including giardiasis (traveler’s diarrhea) and cryptosporidiosis. Cryptosporidiosis is a parasitic disease often spread by contact with surface run-off contaminated by feces of infected cattle. It can cause fever and diarrhea in immunocompetent individuals, and severe diarrhea and death can occur in immunocompromised individuals. Giardiasis is a parasitic infection that also causes mild to severe diarrhea. Heavy rain and increased run-off of contaminated water are believed to be related to increased transmission.

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Foodborne Diseases:
Transmission of infections via food causes significant illness in both developed and developing countries. The microorganisms responsible include viruses, bacteria, and protozoa. Morbidity depends on the pathogen, the susceptibility of the human population, and the medical care available. Diarrheal diseases show such a strong cyclical occurrence that climate is widely assumed to play some role in all epidemic outbreaks. During periods of higher ambient temperatures, the prevalence of foodborne illnesses caused by pathogens that replicate on foods at ambient temperatures is likely to rise. Production of staphylococcal toxins is also associated with temperature.

Campylobacteriosis. Campylobacteriosis is a common diarrheal disease of bacterial origin which is generally acquired by drinking contaminated milk or water or by eating improperly cooked meat or fowl. Pronounced seasonality has been observed, with peak incidence occurring during the spring. The onset of the peak period has been predicted to the exact week in the United Kingdom. In Scotland, short-duration peaks in the annual number of human campylobacter infections have been recorded during the spring every year since 1983. Between one-fifth and one-third of the campylobacteriosis cases in Scotland in a given year occur within a 6- to 8-week time span. The peak period starts abruptly in the first or second week of May, and incidence is markedly reduced by July. The source and principal transmission route of these campylobacter infections have not been determined; it is not known whether these infections vary in significant ways from infections that occur outside the peak period.

Other Foodborne Diseases. Cyclospora cayetanensis is a recently identified diarrheal disease pathogen. Data collected in Peru indicate an association between temperature and prevalence of infection (Fig. 4, Madico, 1997). Disease incidence during the winter of 1997 was higher than usual, due to warmer conditions resulting from the strong El Niño. Salmonella enteritidis is a leading cause of food poisoning worldwide. Infection results from eating improperly prepared, contaminated food, usually meat or dairy products, but also uncooked or undercooked eggs. Seasonal peak of its incidence coincides with peak climatological temperatures.
Airborne Diseases:

Most airborne diseases are spread through respiratory tract secretions and can be carried by the wind or be transmitted within buildings by air-handling systems. Inhaled wind-blown spores are also a source of infectious disease. The seasonal variability of many respiratory diseases suggests a weather-related factor in their transmission.

Meningococcal Meningitis. Meningococcal meningitis is caused by the bacterium Neisseria meningitidis. Transmission results from droplets and is facilitated by direct contact with an infected person. Symptoms include fever, stiff neck, vomiting, severe headache, and convulsions, and coma can occur in a few hours. Incidence in Sub-Saharan Africa shows marked seasonal variability as epidemics occur in the hot, dry season and subside during the rainy season (Moore and Broome, 1994). Peak meningitis incidence in Nigeria has been determined to be significantly correlated with highest mean temperature and inversely correlated with absolute humidity. See “Wind and Ocean Currents,” above, for a discussion of the possible role of the harmattan winds in disease transmission.

Coccidioidomycosis. This lung disease is caused by a soil microorganism, Coccidioides immitis, which is found in the semidesert areas of the Western Hemisphere. Infection is acquired by inhalation of spores. Extremes in the hydrologic cycle may potentiate this disease (Watson, Zinyowera, and Moss, 1996). Incidence is associated, especially during El Niño conditions, with drought conditions preceded by flooding.

Other Airborne Diseases. Respiratory syncytial virus commonly causes bronchitis and mild upper respiratory tract infections and can cause severe, even fatal, lower tract problems, especially among infants. There is strong seasonality in the incidence of the virus, with a peak occurring in the fall. The bacterial pneumonia, legionellosis (Legionnaires’ disease), occurs when the infecting organism grows in air-conditioning cooling towers and is dispersed through the air-handling system of a building. Free-living amoebae in air-conditioning systems may serve as a reservoir. Increased usage of air conditioning may affect prevalence and seasonal incidence.

Plant and Fish Diseases:

Weather-related conditions can indirectly influence human health by stimulating plants to produce a range of toxic chemicals, called mycotoxins. Consumption of such plants can cause negative health effects. Depending upon the plant, inadequate water or excessive salt or moisture at harvest can increase the likelihood of fungus infection and the production of mycotoxins. Perhaps the best known mycotoxins are the aflatoxins, a group of potential liver cancer-causing chemicals produced by Aspergillus flavus, a mold that grows on grains and peanuts. M ycotoxins may indirectly influence the susceptibility of humans to other diseases because chronic exposure to mycotoxins can depress the immune system. Moisture can also facilitate infection of plants by a variety of pathogens that induce the plants to produce defensive compounds (phytoalexins) to protect themselves. These compounds are known to be toxic to humans and animals. Fish diseases are cyclical, but the causes of periodicity are relatively unknown. Diseases in fish that are caused by rhabdoviruses have been cured by raising, or in some cases lowering, the temperature of the water in which the fish are grown. This technique is well described for four fish diseases and is used in aquaculture and mariculture (Shope and Tesh, 1987).
Research Priorities

Despite the amount of data that has been accumulated on the relationships between infectious diseases and weather and climate, large gaps in our knowledge exist. Not only are there questions about the size and distribution of the global disease burden, but the strength of many of the postulated relationships, in comparison with the effects of other factors on disease incidence, remains to be determined. Far greater knowledge is needed about the mechanisms by which climate and weather influence the proliferation, distribution, and infectious capacity of microorganisms. Those diseases with a clear link to weather conditions should be studied in greater detail to uncover the causal relations that underlie the apparent connections in order to improve the capabilities of public health systems. Closing the gaps that remain will take the combined efforts of scientists in disciplines ranging from meteorology to molecular biology. A strategy for realizing these goals can be developed by incorporating improvements in data collection, modeling, and research collaboration.

Field Studies and Long-Term Data Sets:

Field studies are generally designed to be intensive, short-duration analyses of selected phenomena. Often they are undertaken in response to an outbreak of a specific disease and may focus on the immediate factors involved at the epidemic site. Long-term data sets are developed over time and provide more extensive information on the pathways connecting climate, ecosystems, and human health. There are important intrinsic relationships between field studies and the development of long-term data sets. Not only do field studies provide the basis for creating long-term data sets, but the results obtained in each type of study are used to refine further studies of the same or similar phenomena. Thus, the patterns and associations evident in long-term studies can be used to orient the quick-response, intensive investigation of specific disease outbreaks.

The issue of data quality is of paramount importance for field studies. The following discussion is limited to general concerns about the circumstances under which data on climate variables and disease incidence are collected. Determination of the well-foundedness of particular theoretical explanations of disease-climate interactions was not within the scope of the colloquium. A subsequent section of this report addresses the importance of databases for research on links between infectious disease and climate.

Meteorological data tend to be of comparable quality, despite being gathered at different recording stations around the globe. These data include information on day and night temperatures, winds, relative humidity, ice and cloud cover, sea-surface and cloud-top temperatures, and atmospheric CO₂ and nitrous oxide concentrations. Morbidity and mortality data are much less standardized, in terms of collection method and recording format, and are subject to variations in reliability. Worldwide, only a fraction of infectious disease cases are treated, a consideration that affects interpretation of the data gathered in medical or public health settings. The reliance upon passive reporting can also lead to problems in the under-reporting of the disease burden, for reasons of national chauvinism or economic considerations, such as tourism. There are, however, good-quality data sets on human disease. The World Health Organization (WHO) is the primary agency for the worldwide reporting of infectious disease, and its program on polio eradication, for example, is a model for the collection of reliable data.

Important questions remain to be answered in terms of whether the right environmental, ecological, and weather data are being collected for meaningful analysis. There are also uncertainties to be resolved regarding the integration of data from diverse studies, the design of interdisciplinary analyses, and the establishment of more complete and systematic monitoring and surveillance programs. One promising method of investigating the path-
ways connecting climate, pathogens, and human health is the measurement of genetic markers of particular microorganisms as a means of tracing the pathogen through the ecosystem. Large-scale weather disturbances, such as El Niño, offer opportunities for cross-disciplinary collaboration on research projects using different methodologies to analyze the effects of such phenomena. One example of such research is an ongoing study being coordinated by the National Oceanic and Atmospheric Administration (NOAA) and the International Research Institute to examine the effects of the 1997-98 El Niño-related weather events on infectious disease and human health (The ENSO Experiment).

Well-designed field studies are also needed to assess the impact of different microenvironments on the incidence of infectious disease. Microenvironmental variables can affect the viability of pathogens and can create or enhance conditions that are conducive to disease transmission. Although laboratory studies have demonstrated the adverse effects of high temperatures on survival of mosquitoes that carry dengue fever, field studies have not yet documented this relationship. This is most probably a result of the vector’s survival in microhabitats, such as underground storm drains, houses, or even leaf cover.

Modeling Synthesis:

Models and field studies are used in complementary ways to analyze the connections among climate and weather factors, disease incidence, and human health. Models are tools designed for specific purposes and range from simple conceptual representations to complex mathematic systems. In the type of research being discussed here, models are used to relate data on weather, ecology, and disease to support explanations and predictions of events such as disease outbreaks. The data used as the informational foundation for these models come primarily from field studies and contemporary data sets, but are also drawn from historical meteorological data series and health statistics, as well as geographical comparisons.

The gathering of data through diagnostic studies of disease and disease parameters in real time is an essential activity in both constructing models and testing their validity. Over time, a “virtuous circle” of interactions among model development, data collection, and model testing can generate more sophisticated models of the dynamic relations within the ecosystem. Existing data on weather variables and disease incidence go back more than 100 years for many of the developed industrialized countries and for some of the developing countries as well. This historical record is a valuable source of information on baselines and trends in incidence patterns and climate variables. Geographical comparisons of the disease burden in different climates are another important resource for gaining insight into the effects of variables, such as temperature, rainfall, and humidity, on disease prevalence.

Most of the modeling that is done of linkages between environmental variables and human diseases has a single-disease focus. In this approach, the potential impact of various climate- or weather-related factors on the incidence of a particular disease, such as cholera, is investigated. Quite often, the variables of interest are disease specific. Another approach, which is more commonly used in analyzing plant rather than human diseases, is known as deterministic modeling. Instead of focusing directly on one disease, a set of system variables—such as temperature, humidity, ultraviolet radiation, cloud cover, salinity, and vegetation—is modeled to gauge how these variables determine such things as, for example, the size of a vector population. These models are quite complex and have proved to be difficult to validate.

Issues of geographical scale and duration of disease transmission and questions of relevant environmental
parameters and disease indicators are central to model design. Depending upon the disease and the interactions of importance, the geographical scale for models of weather-disease links can range from less than 1 to more than 200 km$^2$. In the case of malaria, an event such as El Niño can affect the normal geographic distribution of both the disease vector and parasite. Consequently, a large-scale model is needed to assess the range of such an event’s effects. Certain diseases exhibit peak incidence periods that correspond to seasonal cycles of temperature and rainfall. Models must be designed to take into account the occurrence of the peaks, their duration, and the interval between them. Biotic factors, such as vector species and vectorial capacity, can also alter the dynamics of what constitutes a minimum window of transmission. A variety of models are needed, not only to organize and assess the new data that are being collected, but also to extract relevant information from the data that are already available.

The impact of human behavior is a potentially significant confounding variable for assessments of the effects of weather-related conditions on disease prevalence and occurrence. Individual and group behavior can cause changes in transmission patterns or exposure to vectors and can affect the survival and distribution of the pathogens themselves. Inadequate sanitation and drinking water, overcrowding, and improper use of antibiotics are some of the factors that can contribute to an increase in disease incidence. Alternatively, expanded access to clean water and improvements in housing and medical care can reduce the infectious disease burden. Fully integrated climate/disease models must incorporate the impacts of human activities, as well as variations among vector species and their breeding ecologies, in predicting disease risk.
Collaboration and Communication

A well-planned, effectively led, and adequately funded international collaborative research effort will be instrumental in furthering our understanding of the linkages among climate, infectious disease, and human health. Such a project would build on existing strengths, expand scientific studies both in number and duration, and require a focused leadership committed to and capable of nurturing long-term interdisciplinary research. Keeping in mind the limited financial resources available to the research community, some examples of what is needed and what could be accomplished are detailed as follows:

**New research centers and partnerships.** Some academic and regional health centers around the world have already begun interdisciplinary work on analyzing the relationships among weather, disease, and human health. Governmental and nongovernmental organizations should establish new research centers for studying these linkages and forge more and stronger partnerships between existing centers to carry out new studies. Examples of such existing programs in the United States include the separate cooperative efforts of the Centers for Disease Control and Prevention (CDC) and the National Air and Space Administration (NASA) with universities. Overseas, there are several WHO collaborative centers with academic institutions.

**Strong leadership.** Experience has shown that differences in leadership can account for the success or failure of multidisciplinary work. Even when the issues under investigation warrant an interdisciplinary approach, there are strong personal and professional incentives for remaining within existing perspectives and using traditional methods of analysis. Research into climate-health linkages requires a wide variety of disciplines. Strong leadership is needed to unify interdisciplinary teams and discourage the tendency of scientists to choose a more narrow, familiar focus.

**Long-term funding.** A lack of funding remains a major barrier to the intensive, interdisciplinary research and analyses required to achieve a clear understanding of the effects of climate and weather on the incidence of infectious disease. A major difficulty stems from the simple fact that research cycles rarely exceed five years. The complex and comprehensive research needed to chart climate and health interactions requires observations in a given locale for many years, necessitating much longer funding cycles appropriate to the time scale of the phenomenon under study. A funding cycle of 25 years is adequate and appropriate but rarely, if ever, approved by most funding agencies. Research on data analysis methods and the synthesis of results from disparate studies is also needed. Unfortunately, data analysis is often underfunded in large studies, particularly in the life sciences. The bulk of funds for large-scale studies is spent on data collection, and the allocation of resources to synthesis and analysis is all too often inadequate. More attention should be focused on changing the prevailing lack of interdisciplinary perspective of funding agencies in order to garner the kind of research support that is needed.

**Language and terminology.** Each scientific discipline has its specialized terminology and jargon. Climatologists have a very specific language, and public health experts have a unique language they rely upon in their work. The same word does not always convey the same meaning for researchers in two different fields. Effective interdisciplinary work will require articulation of a shared set of concepts and a widespread capacity to summarize data for use by individuals with different scientific backgrounds.

**Communication.** Communicating the findings of climate-health research outside the scientific community is a task whose importance should not be overlooked by researchers engaged in such analyses. This point is not simply re-
lated to the problem of assuring adequate long-term funding to study the issues. Unless policymakers and the public comprehend the issues and their importance for society, it is unlikely that adequate support for research will be forthcoming, but neither will the impetus for intervention be engendered. It is fair to say that policymakers and the public lack a ready understanding of the science associated with climate and infectious disease. But that does not imply lack of interest. A strategy needs to be developed for raising the salience of the issues for the public. Such an approach should note the successes that have occurred with the eradication of polio and smallpox and emphasize that small percentage changes in the incidence of even indirectly weather- or climate-sensitive diseases, such as influenza or tuberculosis, can have a more substantial impact on society than a dramatic augmentation of a rare disease. Early warnings of changes in weather conditions that are favorable to epidemics of infectious disease can trigger enhanced public action, hence predictive models developed from an interdisciplinary research program can be enormously persuasive.
Databases

Databases compiled from meteorological, oceanographic, epidemiological, environmental, microbiological, and ecological studies are essential for the analysis of connections among climate, infectious disease, and human health. The interdisciplinary nature cannot be overemphasized, relative to infectious disease monitoring and prediction. In addition to the myriad of databases containing potentially relevant information, there is an ever-increasing accumulation of environmental data from weather satellites. The number and type of databases that are applicable to the analysis of climate-disease links need to be identified and catalogued. Many of these databases are in formats that are not easily accessible to a wide range of researchers. These data need to be synthesized and made available, especially for development of models.

Current research into the relationships between disease incidence and weather and climate factors is increasingly focused on the development and testing of more robust models of the causal pathways that link environmental conditions to disease transmission. There are numerous studies and databases which detail associations between values for particular weather parameters and disease incidence. In order to move beyond identification of statistically significant correlations to the confirmation of hypothetical relations of causality, more site-specific, parameterized models must be developed that relate the environmental conditions in particular areas to the occurrence of specific diseases. A comprehensive, site-specific dengue fever transmission model exists that has been validated in some locations (Focks, et al., 1995). The process of collecting and organizing data necessary to formulate and test models of this kind is still at an early state for many other infectious diseases. For example, relationships among sea-surface temperature, sea-surface height, and cholera incidence have only recently been examined in a systematic manner. The use of satellites has made it possible to collect the data needed to explore these connections adequately. A comparable interdisciplinary focus will be necessary to create the databases needed for systematic analysis of environmental factors associated with prevalence of other infectious diseases.

An example of the contribution that interdisciplinary research can make to the study of infectious diseases can be found in a project funded by the Rockefeller Foundation earlier in this century. From the 1930s until the 1950s, the Rockefeller Foundation funded investigators around the world in field research on yellow fever. Starting in the early 1950s, a network of interdisciplinary field research laboratories was established to study yellow fever and other arboviruses in Brazil, Trinidad, Colombia, South Africa, Nigeria, Egypt, and India. Entomologists, medical zoologists, ecologists, and physicians worked together in complex relationships which underlie the cyclical maintenance of yellow fever and other viruses in African, Asian, and American jungles. In so doing, the Rockefeller researchers discovered a “universe” of viruses maintained in complex cycles of transmission between animals and insects. From time to time, and often in response to weather factors, these viruses escaped from these cycles and infected human beings. The information gathered in this work was collected centrally, data were exchanged and published, and the knowledge of hundreds of vectorborne diseases was thereby expanded. Today, each of these laboratories has been nationalized. Most of them continue, although some at reduced levels, and they are no longer networked together. Without a mechanism for keeping the laboratories functioning and the research funded, an important resource for investigating the emergence of new, environmentally linked diseases has essentially been lost. When it was in operation, the system worked well and serves as an historical model for development of future centers focused on emerging and re-emerging diseases.

Key Databases:

A catalogue of existing databases relevant to research into climate-disease links would be a useful addition to the literature. Compiling such a list, however, would be a serious undertaking in itself. There are numerous such databases, ranging from those maintained by international agencies to small data sets compiled by discrete research communities. The following overview is merely illustrative and serves to highlight the importance of developing
data information systems that will allow researchers to make optimal use of various kinds of available information.

The World Weather Watch of the World Meteorological Organization (WMO) encompasses ca. 800 stations operated by the weather services of nations around the globe. The network comprises a number of weather, climate, and hydrology efforts intended to support government, commercial, and academic interests and activities. These interests include the optimal scheduling of agricultural planting and irrigation, planning for energy distribution systems, and basic research on environmental problems. Information on current weather, changes of seasons, and long-term climatologic trends and characteristics is documented.

The WHO supports a major international database focused on the incidence of infectious diseases worldwide. The CDC maintains data on infectious diseases in the United States, including, for example, information on dengue fever in Puerto Rico. Various databases of the National Oceanographic and Atmospheric Administration (NOAA) hold important information on environmental parameters, including cloud cover and atmospheric and sea-surface temperatures.

Many more data sets are maintained by smaller communities of scientists and may not be familiar to other potential users. For example, there are Japanese, Indian, and Brazilian databases composed of satellite meteorological observations. A global change master directory is being produced which is intended to become a resource for international weather and climate information. Global climate information and related data being collected in the United States are now required to be maintained in a format compatible with this global change master directory. Satellites that collect information on weather conditions over land and sea provide an increasingly important source of information. The Tropical Rainfall Measuring Mission, a joint project of the United States and Japan designed to measure rainfall in the tropics, is an example of a new database that is being developed. The data obtained from this project will be correlated with disease incidence to establish a matrix for analyzing the correlations between rainfall and infectious disease.

**Database Accessibility:**

Few of the existing databases are either coordinated or designed to communicate with one another, a situation that hinders the exchange and use of information among research teams within and across scientific disciplines. The CDC is experimenting with a data information system capable of “translating” electronic data from various medical data systems. This system requires that the electronic data be in a data format known as Health Level 7 (HL7). HL7 is not an information program per se, but is a method of formatting electronically transmitted information. This data format defines where in the data stream certain information bits will be located. It does not define the information itself. Thus, scientists can use their own local codes or standardized dictionaries to download the information. CDC, commercial software companies, and health care providers have agreed to use HL7 as the standard means for formatting electronic data. CDC’s demonstration project, employing the HL7 format, in collaboration with several state public health departments, allows public health practitioners to access medical information from hospitals, physicians, and private clinical laboratories. This system of “translating” information from diverse data programs, thereby making data from diverse sources accessible to difference users, is promising and should be expanded.

Progress in research depends on the availability and accessibility of quality data, yet financial considerations concerning access to data are becoming increasingly an impediment. The flow of information to researchers is threatened by attempts to commercialize data that historically have been freely available for scientific inquiry. The WMO has proposed mechanisms for charging for the cost of reproducing and mailing data compiled by global monitoring systems. The World Intellectual Property Organization has advocated the copyrighting of digitized data sets. Such proposals are harbingers of restrictions that may ultimately determine who can afford to do this kind of research. At the very least, this situation indicates the economic value of data sets and the need to view data management as a legitimate cost of research, much like reagents and laboratory equipment. Funding agencies should acknowledge these costs and be prepared to accept them as part of the cost of doing research.
Progress in understanding links between climate and infectious disease will require more extensive collaboration among researchers across disciplinary boundaries. There is also the need to disseminate more effectively results of this research, both within the academic community and among policymakers and the public at large. Education and training are important aspects of the overall effort.

Although the leading edge of interdisciplinary research is most often driven by accomplished researchers who have been trained in a traditional field of study, subsequent advances are fostered by incorporating these results in the education and training of younger researchers. At present, productive study of the relationships between infectious disease and climate includes microbiology, climatology, ecology, biostatistics, social science, computer modeling, medical entomology, epidemiology, medicine, veterinary science, botany, zoology, limnology, oceanography, space science, and geography. Although establishing degree-granting programs of climate-disease studies may be premature, ways of disseminating the results of this research through universities and medical schools should be developed. For example, surveillance methods for the study of infectious diseases are now being effectively taught at the undergraduate level, and students can be involved with surveillance programs as an effective mode of teaching. Studies of interrelations among infectious disease, climate, and demographic variables can be made part of the curriculum for many disciplines. Medical school education, particularly in epidemiology and public health, should be broadened to include the environmental sciences and ecology. Successful interdisciplinary research programs are cumulative and the skills required to collect and analyze data and develop and test predictive models of climate-disease links must be deliberately nurtured and developed.

Journals that publish results from interdisciplinary studies are important for the development and acceptance of new fields of study. For long standing reasons, most journals are disciplinary based, although a few exceptions exist. Unfortunately, it can be hard to find a venue for publishing research that does not directly track existing specializations. For example, it would be difficult to find an appropriate journal for publishing reports prepared by upper-atmosphere scientists working with malaria specialists and geologists. Additionally, there is a potential problem confronting broadly based journals in that scientists with interests in interdisciplinary work may not subscribe to journals outside their field. An interdisciplinary journal focused on climate and infectious disease would be invaluable to climate and health professionals as a locus for publishing research findings.

Research on climate-disease links is global in scope, and such research should include scientists from all countries, especially those from developing countries who may lack access to resources that are more readily available elsewhere. Language incompatibilities and funding insufficiencies can be potent barriers to the dissemination of leading edge information and scientific discovery. It is important that mechanisms be developed to enhance research into climate-disease links in areas where climate-sensitive diseases are prevalent. In order to make the case for the importance of such studies, the issue can justifiably be put in the context of economic development, since the health consequences of these diseases disproportionately affect the developing world and effectively impede development. Given the distribution of the global disease burden and the transmissibility of infectious disease in an increasingly interconnected world, the study of climate-disease links is of worldwide concern. Developed and developing countries alike should be receptive to supporting and participating in these studies, because the work directly affects the standard of living and well-being of humans globally.
Recommendations

Colloquium participants developed the following recommendations at the concluding plenary session:

• With the increasing availability of satellite data, research into climate-disease links is on the threshold of a qualitative and quantitative transformation, in terms of the kinds of analyses that can be conducted. It is essential that long-term research projects, exceeding the usual funding cycle of 2-3 years, be supported. Given existing financial constraints, rollover funding of promising high-impact projects targeted to diseases with strong links to climate and weather factors should be encouraged.

• Networking of databases should be recognized as essential for enhancing research in climate and health. Researchers require access to data from a variety of sources, and standardized formats for collection and organization of data are key to making data widely available to researchers in a variety of disciplines. Database maintenance and synthesis of data from diverse studies are fundamental to research in climate-disease interactions. The cost-effectiveness of pursuing these activities should be emphasized.

• Since research into questions of relationships between climate and infectious disease is interdisciplinary in scope, journals should be encouraged to publish the result of studies that fall outside of or straddle traditional disciplinary boundaries. Whether or not there is a need for new journals, ways of improving the profile of research into climate-disease links should be developed to ensure that this research is published and disseminated within the scientific community.

• Education and training of new researchers is important to advance this new interdisciplinary field. Studies of the links between climate factors and disease incidence can productively be incorporated into the curriculum of graduate and medical schools, notably in epidemiology, and incentives should be created to encourage postdoctoral programs in analyzing these connections.

• An asymmetry exists between public interest in and knowledge about climate, infectious disease, and health. Efforts need to be made to communicate effectively results of studies dealing with these issues. Given the high level of public interest in the subject of infectious disease, scientific societies should become more adept at providing this kind of information in timely, accessible, and understandable means.
References


