Climate Variability and Change in the United States: Potential Impacts on Vector- and Rodent-Borne Diseases

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Diseases such as plague, typhus, malaria, yellow fever, and dengue fever, transmitted between humans by blood-feeding arthropods, were once common in the United States. Many of these diseases are no longer present, mainly because of changes in land use, agricultural methods, residential patterns, human behavior, and vector control. However, diseases that may be transmitted to humans from wild birds or mammals (zoonoses) continue to circulate in nature in many parts of the country. Most vector-borne diseases exhibit a distinct seasonal pattern, which clearly suggests that they are weather sensitive. Rainfall, temperature, and other weather variables affect in many ways both the vectors and the pathogens they transmit. For example, high temperatures can increase or reduce survival rate, depending on the vector, its behavior, ecology, and many other factors. Thus, the probability of transmission may or may not be increased by higher temperatures. The tremendous growth in international travel increases the risk of importation of vector-borne diseases, some of which can be transmitted locally under suitable circumstances at the right time of the year. But demographic and sociologic factors also play a critical role in determining disease incidence, and it is unlikely that these diseases will cause major epidemics in the United States if the public health infrastructure is maintained and improved. *Key words:* dengue fever, encephalitis, global warming, hantavirus, leptospirosis, Lyme disease, malaria, plague, vector-borne diseases. — *Environ Health Perspect* 109(suppl 2):223–233 (2001).
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Vector-borne diseases result from infections transmitted to humans and other animals by blood-feeding arthropods, such as mosquitoes, ticks, and fleas. The vector-borne pathogens, which include viruses, rickettsiae, bacteria, protozoa, and worm parasites, spend part of their life cycle in a cold-blooded arthropod vector and thus are influenced by environmental change. The transmission patterns of these diseases may, therefore, be affected by ambient temperature. However, temperature is only one of many factors that influence transmission dynamics (Figure 1).

Rodent-borne diseases do not always involve an arthropod host and are therefore less directly affected by temperature. Transmission of these infections frequently depends on rodent population density and behavior, which, in turn, depend upon environmental conditions and available food.

Many vector-borne diseases are zoonoses caused by pathogens having nonhuman animals as their natural host. Because they are not part of the natural transmission cycle, humans are only incidentally infected. Zoonoses usually persist in nature in silent transmission cycles between vectors and nonhuman hosts, going undetected unless they spill over and infect the human population. In contrast, the anthropogenic vector-borne diseases, such as dengue fever and malaria, require no animal host and are transmitted from human to human by mosquito vectors. Although these disease-causing pathogens are now rare in the United States, their mosquito vectors are still present.

Mosquito-Borne Diseases

Mosquito-borne diseases were once a major public health problem in the United States. From the 1600s to the mid-1900s, malaria was endemic (with occasional large epidemics) throughout much of the country and into Eastern Canada. Epidemics of dengue and yellow fever occurred regularly during the summer months, as far north as Boston, Massachusetts, and Philadelphia, Pennsylvania. In the 1900s, other mosquito-borne diseases, such as St. Louis encephalitis (SLE) and western equine encephalitis (WEE), appeared in epidemic form. Dengue, yellow fever, and malaria had disappeared by the middle of the twentieth century, although their mosquito vectors were and still are present. Moreover, the incidence of indigenous diseases, such as SLE and WEE, has decreased because of changing agricultural practices, improved housing and sanitation and, in some areas, effective mosquito control.

Dengue. Among vector-borne diseases, dengue is second only to malaria in the number of people affected worldwide. A global pandemic of dengue fever, a mosquito-borne viral disease, began during World War II, intensifying since the 1970s (*1*). Today, population growth, urbanization, and increased movement of people, viruses, and mosquitoes contribute to continued geographic spread and increased incidence of the disease. Although dengue is not endemic in the continental United States, it is endemic in the U.S. Commonwealth of Puerto Rico. In addition, more than 2,706 suspected and 584 confirmed cases of dengue in U.S. residents who had traveled abroad were reported from 1977 to 1995 (*1–3*), but this is considered to be underreported (*4–6*). There have been six reported instances of local transmission (1980, 27 cases; 1986, 9 cases; 1995, 7 cases; 1997, 3 cases; 1998, 1 case; 1999, 17 cases) in Texas over the last 20 years, with most linked to imported cases from Mexico (*3,5,6*).

Concerns that dengue may be introduced to the United States from neighboring countries have heightened disease surveillance and interventions in border cities of Texas. Comparison of dengue incidence between the United States and Mexico showed that 62,514 dengue cases were reported in the three Mexican states adjoining Texas between 1980 and 1999 (*7*), whereas only 64 locally acquired cases were reported in Texas between 1980 and 1997 (*7*). The large difference in disease incidence between U.S. and Mexico border states is probably caused by differences in living standards and human behavior, although this has not been extensively investigated. Factors such as piped water systems, door and window screens, air conditioning, television, and human behavior undoubtedly decrease the probability of the mosquito's feeding on humans in the United

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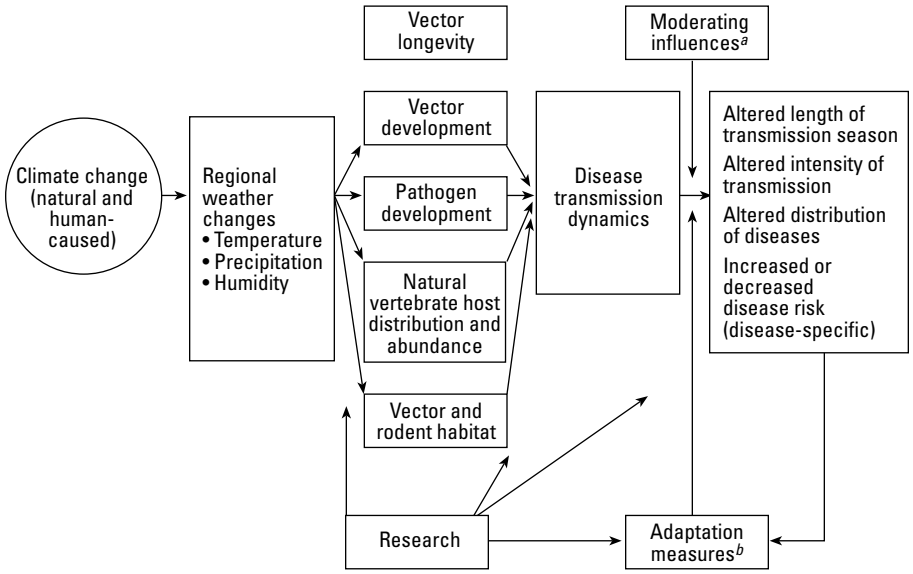

Figure 1. Potential vector- and rodent-borne diseases. [a]Moderating influences include nonclimate factors that affect climate-related health outcomes, such as standards of living, access to health care, international travel, and public health infrastructure. [b]Adaptation measures include actions to reduce risks of adverse health outcomes, such as medical technology (e.g., vaccine development) or use of climate forecasts for early warning of favorable conditions for disease transmission.

States and decrease the probability of dengue transmission.

Despite eradication efforts during the 1950s and 1960s, *Aedes aegypti*, the principal and most efficient epidemic vector of urban dengue, has been common throughout the Southeastern United States for over 220 years. In recent years, however, this species has been displaced in many states by another mosquito species, *Aedes albopictus*, first detected in 1985 in Texas (*8–10*). This species is now a permanent resident of many states in the eastern half of the United States. Although not an important epidemic vector of dengue, it probably is involved in the maintenance cycle of dengue in rural and suburban areas of Asia (*11*).

In Puerto Rico, dengue transmission occurs year round, with a seasonal peak during months with high rainfall and humidity (usually September–November). Large epidemics occurred in 1963, 1969, 1977, 1978, 1982, 1986, and 1994 despite relatively high living standards, an efficient health system, and active disease surveillance (*12*). The factors that determine whether epidemic transmission will occur are complex and not well understood, but involve the interaction of host-, virus-, and vector-associated factors. One factor important in causing epidemics and increasing the severity of disease is the introduction of new dengue viruses to the island by travelers, causing the cocirculation of multiple virus serotypes (hyperendemicity) (*13*). Expanding urban populations in the tropics also permit conditions for endemic transmission and potential cocirculation of multiple serotypes. Approximately 355,000 cases of dengue fever were reported during the 1977 outbreak, at an estimated cost of $10.3 million (*14*). Data from 1984 to 1994 indicated an average of 658 disability-adjusted life-years lost from dengue per million people in Puerto Rico per year, a loss on par with other high-priority infectious diseases such as tuberculosis and malaria (*15*). A recent study by Gubler and Meltzer (*16*) showed a similar economic impact on a global scale.

Yellow fever. Yellow fever is a mosquito-borne viral disease maintained in a forest cycle involving lower primates and canopy-dwelling mosquitoes in tropical Africa and America. Epidemics occur when the virus is introduced into suburban and urban environments where the *Ae. aegypti* mosquito serves as the primary vector among humans (*17*). The reinfestation of many South American tropical cities by *Ae. aegypti* (*18*), combined with low vaccination rates against yellow fever, provides the potential for explosive urban outbreaks (*18,19*). If that occurs, the virus has the potential to spread to Asia and the Pacific, and the United States and Europe could expect a dramatic increase in imported yellow fever cases for the same reasons observed with dengue fever (*20,21*). In the United States, epidemic yellow fever was eliminated through quarantine and mosquito control in some areas and by improved living standards. Although the urban infrastructure in North America today is less conducive to mosquito transmission than that in South America, much of the Southeastern United States is still infested with *Ae. aegypti*. However, it is being displaced rapidly by *Ae. albopictus*, a less efficient vector. There remains a remote possibility that yellow fever could recur in the United States (*19,22–24*).

Viral encephalitis. Arboviral encephalitides are infections of the central nervous system caused by mosquito-borne viruses. Unlike dengue and yellow fever, these infections are currently enzootic (i.e., indigenous in animal hosts) in a wide range of ecologic environments within the continental United States. The natural transmission cycles involve birds and rodents as reservoirs of the viruses (*25*). Human beings are incidental hosts and do not produce sufficient viremia to infect mosquitoes (*26*).

In the summer of 1999, West Nile virus (WNV) was imported into the United States and caused an outbreak of encephalitis in New York; 62 laboratory-positive cases, including seven deaths, were documented (*27*). In 1996, a major WNV epidemic occurred in Romania with a high rate of neurologic infections (*28,29*). These outbreaks illustrate the need for improved surveillance and risk assessment for unexpected introductions of infectious agents potentially brought in by imported animals or humans as international trade and travel increases.

The arboviral disease most commonly causing human epidemics in the United States is SLE. Other common diseases include eastern equine encephalomyelitis (EEE), found in the Eastern United States; La Crosse encephalitis (LAC), found from the Midwest to the Atlantic seaboard; and WEE, found in the western half of the United States and parts of Canada and Mexico. Together, these viruses account for about 65% of encephalitis cases reported by etiology (*30*).

No effective vaccine or antiviral treatment is available for SLE, and the elderly are disproportionately affected (*31*). Major epidemics of SLE have occurred in large cities of the Midwestern and Eastern United States, such as Houston and Dallas, Texas; Chicago, Illinois; Memphis, Tennessee; and Orlando, Florida. The largest was in 1975, when 1,270 laboratory positive cases and 102 deaths were reported in 10 outbreaks in the Midwest (*32*). However, over the past 30 years, a median of 26 SLE cases have been reported each year in the United States (*33*), with most recent activity concentrated in Florida (*34*).

Widespread immunization against WEE prevents equine disease, and human cases are extremely rare. LAC virus is associated with tree hole-breeding mosquitoes and rodents in wood lots, and an average of 75 LAC cases are reported each year. EEE is transmitted among wild birds in swamp habitat by a mosquito (*Culiseta melanura*) that does not normally bite humans (*35*). Although outbreaks are small and human EEE cases are relatively

rare (about five cases per year), case fatality rates approximate 30%, with neurologic sequelae common among survivors. The number of cases is low but the economic impact per case has been estimated at about $3,000,000 (*36*).

In recent years, the number of human cases of arboviral encephalitis has been decreasing, but that may change with the introduction of WNV. It is likely that all of these viruses will persist within their natural enzootic cycles and continue to pose a health risk to the human population whenever ecologic conditions or failed control programs allow increased amplification.

Invasion of imported arboviral mosquito vectors. Imported mosquito species also must be considered. *Ae. albopictus*, the Asian tiger mosquito, was first found in Houston, Texas, in 1985 (*37*). Within a few years it spread to 25 states in the South, mid-Atlantic, and Midwest (*38–40*), often displacing native *Ae. aegypti* (*40,41*). It should be noted that the introduction of *Ae. albopictus* into the United States had nothing to do with climate change (*42*); this species is similar genetically to temperate strains in Asia (*43*). *Ae. albopictus* rarely has been implicated in epidemic dengue and dengue hemorrhagic fever transmission in the Pacific and Asia, and its catholic feeding habits and less frequent contact with humans indicate that it may not increase the risk of dengue transmission in the West (*11*). Its potential importance in the United States is that it is an aggressive diurnal biter and could serve as a bridge vector for viruses such as LAC, EEE, and others, thus potentially increasing human risk to infection (*40*). Under experimental conditions, *Ae. albopictus* is a competent vector for 22 arboviruses (*40*), including all four dengue serotypes (*44*), yellow fever (*45*), Chikungunya (*46*), and Ross River virus (*47*). Although there is still no direct evidence that *Ae. albopictus* transmits human disease in the United States (*40*), eight arboviruses—Cache Valley, Potosi, Tensaw, EEE, Keystone, Jamestown Canyon, LAC, and WNV—have been isolated from this species (*40,48*). In 1997, the mosquito was detected in Peoria, Illinois, an area with long-term LAC transmission (*49*). Surveillance in Peoria showed that *Ae. albopictus* competed well against the resident mosquito species, *Aedes triseriatus*, but there was no evidence that *Ae. albopictus* transmitted LAC virus to humans (*49*).

Malaria. Malaria is currently the world's most widespread and serious vector-borne disease. Although malaria was once controlled effectively in many parts of the world, disease incidence has increased greatly over the past two decades because of a variety of demographic, political, societal, and public health changes (*22,50*). The United States has competent malaria vectors, with each area of the country having its own species of *Anopheles* mosquitoes. *Anopheles quadrimaculatus,* for example, occurs in the east, and *Anopheles hermsi* and *Anopheles freeborni* occur in southern California. Many anopheline species can transmit malaria, including the two most common species of malaria parasite, *Plasmodium falciparum* and *Plasmodium vivax* (*51*).

The initial decline in malaria in the United States was attributed to a population shift from rural to urban areas, improved water management, improved housing and nutrition, better standards of living, and greater access to medical services (*42*). Vector control and improved case finding and treatment were important in eliminating malaria from the Continental United States by 1950.

Since 1957, nearly all malaria diagnosed in the United States has been imported. About 1,200 cases of malaria are reported annually, making it the most common imported vector-borne disease, and many cases likely go unreported. There are reports of malaria acquired through local mosquito transmission in nearly all parts of the United States, and this number may be increasing because of increased immigration/travel. Most cases occur in rural areas among migrant farm workers (*22*). Although such locally acquired malaria cases result in only a few cases per outbreak, many U.S. areas are at risk for limited local transmission. Recent small outbreaks in urban or suburban areas have occurred in New Jersey (1991), New York (1993 and 1999), Texas (1993), Michigan (1995), and Georgia (1999) (*52*).

Tick-Borne Diseases

Lyme disease. Lyme disease was first discovered in the United States in 1975. Since surveillance began in 1982, the number of reported cases per year has increased from 497 to 15,934 cases in 1998, making it the most common vector-borne disease in the United States today. Lyme disease, caused by infection with the spirochete *Borrelia burgdorferi,* is transmitted to humans in the upper Midwest and Northeast by the hard tick *Ixodes scapularis* and in the West by *Ixodes pacificus.* Transmission is seasonal, with the peaks in June and July associated with the questing period of the nymphal stages of the tick. Cases have been reported in all states and the District of Columbia, with over 90% occurring in 10 states: in the Northeast (Connecticut, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, Rhode Island), Upper Midwest (Minnesota, Wisconsin), and California (*50,53*).

The rapid emergence of Lyme disease is linked to changes in land use patterns (*22*), such as farmland reforestation and residential development within wooded areas. New-growth forests with extensive edge (between forest and open land) led to an explosion in deer populations, which are the primary hosts for adult ticks. The close proximity of people, tick vectors, white-footed mice (the reservoir host for the bacteria), and deer in suburban settings has enhanced disease transmission (*22*). Improved surveillance, case definition, clinical and laboratory diagnosis, and reporting have increased the number and accuracy of the cases detected.

Other tick-borne diseases. Rocky Mountain spotted fever (RMSF) is a bacterial disease caused by *Rickettsia rickettsii* that is distributed throughout much of the United States, parts of Canada, and Central and South America. RMSF is transmitted by several species of *Ixodid* (hard) ticks. Natural reservoirs include rodents and other mammals, including dogs.

In recent years, about 800 cases were reported annually in the United States, of which 3–5% were fatal. If left untreated, case fatality rates can be as high as 13–25%, especially in the very young and elderly (*54*). Most RMSF cases occur in the eastern United States (New York to Florida) and in the South (Alabama to Texas) and are most common between April and September, although transmission can occur during warm winters (*55*). The transmission season is longer in warmer regions.

Human ehrlichiosis, first recognized in the United States in 1986, is a tick-borne disease caused by several species of bacteria of the subfamily *Rickettsiaceae*. Since 1986, more than 500 cases have been reported to the Centers for Disease Control and Prevention (CDC). Infection can be severe and is occasionally fatal. Like Lyme disease, ehrlichiosis is maintained enzootically by *Ixodid* tick transmission among animal reservoirs (*56*), such as white-tailed deer and rodents, and is found in mild climatic conditions (e.g., southern latitude, low elevation) (*57*).

Most ehrlichiosis cases are reported in the Southeastern United States and South-Central States during spring and summer, though cases have also been reported in the Northeast and Midwest (*58*). Since 1986, rodents from 14 states were found to have been infected with erhlichia (*59*). Rodent samples collected between 1984 and 1988 in Baltimore, Maryland, suggest that ehrlichiosis was present in mice at least 12 years before human cases were first recognized (*60*). The two main ehrlichia that cause disease in the United States and animal cycles of the bacteria are likely to exist in areas where human disease is not yet confirmed (*59*).

The *Ixodes* tick is also the carrier of *Babesia microti,* the infectious protozoan agent that causes babesiosis. Most cases in the United States have occurred in the Northeast

(*61*). Coinfection of babesiosis also occurs with Lyme disease and ehrlichiosis.

Tularemia is an acute bacterial disease transmitted to humans by hard ticks, biting flies, and direct contact with infected wild animals such as rabbits, hares, muskrats, and beavers. The disease is most prevalent during June–August, particularly following floods. Clinical manifestations are varied, but fatality rates among untreated patients may be as high as 60%. In the United States, reported cases decreased from about 1,400 per year in the 1950s to around 100 per year today. Cases occur primarily in the Northeastern, Southeastern, and Western United States (*62*).

Colorado tick fever is a viral zoonosis of small mammals, endemic to mountainous regions above 5,000 feet in the Western United States and Canada. The disease is usually associated with recreational exposure, e.g., among hikers and hunters (*63*). Tick-borne relapsing fever is caused by a spirochete found naturally in several rodent species and transmitted to humans by soft ticks. The disease occurs primarily in mountainous areas of the western United States, and human infection is usually associated with exposure in mountain cabins that are not rodent proof.

Flea-Borne Diseases

Plague. Plague is a bacterial disease transmitted by the bite of infected fleas, by direct contact with infected animals, and by inhaling infective bacteria. Although only 200 cases were reported worldwide in 1981, there has been a resurgence of epidemic plague, focally in all major regions of the world and particularly in Africa, where about 3,000 cases are now reported annually. In the United States, plague circulates enzootically among wild rodents from the pacific coast to the western edge of the Great Plains, with incidental transmission to humans. The last urban plague epidemic in the United States occurred in 1924; at present, an average of 14 human cases occur in the United States per year (*64*), with a 2-fold higher incidence in adult males than females (*65*). The largest numbers of cases occur in New Mexico, Arizona, California, and Colorado (*64*).

Rodent-Borne Diseases

Hantavirus pulmonary syndrome. There are at least 30 different hantaviruses worldwide (genus *Bunyavirus*), many of which can cause severe, often fatal, illness in humans (*66*). These viruses are carried by numerous rodent species and transmitted to humans through rodent urine, droppings, and saliva. In 1993, a previously unknown hantavirus, Sin Nombre, emerged in the Four Corners region of the rural Southwestern United States, causing an acute respiratory disease named hantavirus pulmonary syndrome (*67*). As of 1997, over 164 cases were confirmed in the United States and over 400 in the Americas, with a fatality rate of 45% in otherwise healthy individuals (*68*). The severity and wide geographic distribution of this rodent-borne disease prompted intensive collaborations between public health investigators and ecologists to determine the factors leading to infection in host rodents and humans (*66,69*). Cases most frequently have been associated with indoor exposure after infected field rodents invade buildings, usually during harsh ecologic conditions following favorable weather periods.

The development of a human vaccine has been proposed but is unlikely to be commercially feasible in the Americas. Likewise, rodent control may also be impractical given the wide geographic range of hantavirus infection among feral rodent species (*70*). Studies are ongoing to determine whether a vaccine for wildlife, analogous to the one successfully developed and used against rabies, will be practical (*71*).

Leptospirosis. Leptospirosis is an acute febrile infection caused by bacterial species of *Leptospira* that affect the liver and kidneys. It is probably the most widespread zoonotic (animal-to-human transmission) disease in the world, and it is particularly common in the tropics. Infection is caused by exposure to water, damp soil, or vegetation contaminated with the urine of infected wild and domestic animals (e.g., dogs and rodents) (*72*). Outbreaks often occur after heavy rainfall during floods. The disease is strongly associated with rice and sugarcane farming, mining, and work with sewage and slaughterhouses. Leptospirosis also has been linked to outdoor recreation such as white water rafting and camping.

Although only 50–150 leptospirosis cases are reported annually in the United States, the disease is underdiagnosed (*73*). A study found leptospira in 90% of rats sampled in Detroit, Michigan, and a significantly higher exposure to the organism was found in inner-city children (over 30%) versus suburban children (*73*). In inner-city Baltimore, leptospiral antibody prevalence was 16% and associated positively with age, sex, race, and bird ownership (*74*).

Finally, antibody to hepatitis E is widespread in rats in the United States (*75*). This serious viral illness has been linked to maternal mortality in the developing world. High prevalence levels now found in rats in the United States increase the likelihood that human infection may be possible in industrialized countries, though the role in human epidemiology remains to be defined.

Role of Climate

The ecology, development, behavior, and survival of arthropod vectors and hosts and the transmission dynamics of the diseases they transmit are strongly influenced by climatic factors. Temperature (in all seasons), rainfall, and humidity are especially important, but other factors such as wind and the duration of daylight can also be significant. In particular, daily maximum and minimum temperatures affect the pathogen's rate of multiplication within the insect, which in turn affects the rate of salivary gland infection and hence the likelihood of successful transmission to another host. If the development time of the pathogen exceeds the life span of the insect, transmission cannot occur; vector longevity is thus very important and can be shortened by elevated temperatures. It is the complex interplay of all these factors that determines the overall effect of climate on the presence or absence and local prevalence of arthropod-borne diseases. Human activities and behavior are also crucial to determining whether transmission to humans will occur. The location of homes in relation to the breeding sites, the structure of buildings, the materials used to build them, and the daily patterns of human behavior—social life, work, rest, and recreation—can all be important.

Mosquito-Borne Diseases

In the United States, changes in lifestyles and living conditions were major factors in the disappearance of malaria, dengue, and other mosquito-borne diseases. Unless living standards deteriorate drastically, such factors will remain dominant. In many regions, summer temperatures are higher than in much of the tropics where the diseases remain common. If the present warming trend continues, strategies to avoid these temperatures—particularly indoor living and air conditioning—are likely to become more prevalent. Consequently, the proneness to epidemics, already very low, will continue to decline (*9,20,42,50,76*).

This does not mean that disease will be entirely absent, and some diseases are reappearing in urban areas. International travel and population movement will facilitate introductions from other parts of the world. For example, in 1997 the World Health Organization recorded 12,328 cases of imported malaria in the European region. Such cases occasionally lead to summertime transmission, recently reported as far north as Toronto, Canada, and Berlin, Germany. However, in all developed countries, such outbreaks are likely to be small, easily contained, and confined to a limited geographic area.

Climate-related natural disasters may change the dynamics of human–mosquito contact; floods may create conditions that allow mosquito proliferation and enhance

mosquito–human contact (e.g., residents in a disaster area and recovery workers working outdoors or living in substandard storm-damaged housing) (*77*). Although encephalitis epidemics do not consistently follow hurricane- or flood-related disasters in the United States, arbovirus activity has been detected in mosquitoes and host animals after numerous disasters (*77,78*) (Table 1).

Dengue fever and climate sensitivity. In the laboratory the rate of dengue virus replication in *Ae. aegypti* mosquitoes increases directly with temperature (*79*). Models have been developed to explore the influence of projected temperature change on the incidence of dengue fever (*80*). General circulation models (GCMs) of climate change scenarios on a global scale were linked to a simulation model of dengue fever. These models suggest that relatively small increases in temperature in temperate regions, given viral introduction into a susceptible human population, should increase the potential for epidemics (*81,82*). However, epidemic potential depends on the interaction of many virus, host, and environmental parameters, and the models cannot accurately predict actual risk of human cases without incorporating site-specific human, viral, and environmental determinants of transmission. For example, the summer mean temperature in the Southeastern United States is actually 2–3°C higher than in Caribbean islands. Yet the latter experience major epidemics of dengue fever, whereas the United States does not, despite the fact that the mosquito vectors are present and there has been increased imported dengue in the past 20 years.

Encephalitis and climate sensitivity. Epidemics of SLE generally occur south of the 20°C June isotherm (*83*), but northerly outbreaks have occurred during unseasonably warm years (*30*). Outbreaks of SLE are associated with several-day periods when temperatures exceed 85°F (30°C) (*84*), as was the case during the 1984 California epidemic (*85*). Precipitation patterns also affect transmission (*17*). In the West, increased snowpack and river runoff increase *Culex tarsalis* abundance (*78*); in the Midwest, epidemics have been associated with decreased rainfall that allows *Culex pipiens* species to increase in urban drainage systems (*86*); in Florida, increases in transmission have been associated with epic rainfall events that trigger oviposition and blood feeding by *Culex nigripalpus* (*87*); and in the Eastern United States, outbreaks of SLE appear to be associated with the sequence of warm, wet winters, cold springs, and hot dry summers. The factors underlying this association remain a matter for speculation (*78,88*).

Field studies in California suggested that a 3–5°C increase in average temperature may cause a northern shift in the distribution of both WEE and SLE viruses and a decreased range of WEE in southern California (*89,90*). Viral development time in the mosquito at higher temperatures is detrimental to WEE virus and is an important factor driving these results (Figure 2) (*89,90*). In the Eastern United States, wind can play a role in dispersing mosquitoes potentially infected with EEE as far north as upstate New York and Michigan (*91*) (Table 1).

Malaria and climate sensitivity. The temperature threshold for the development of *P. falciparum* and *P. vivax* in their anopheline hosts is 18°C and 15°C, respectively. The incidence and prevalence of malaria may be

Table 1. Some effects of weather and climate on vector- and rodent-borne diseases.[a]

Vector-borne pathogens spend part of their life cycle in cold-blooded arthropods that are subject to many environmental factors. Changes in weather and climate that can affect transmission of vector-borne diseases include temperature, rainfall, wind, extreme flooding or drought, and sea-level rise. Rodent-borne pathogens can be affected indirectly by ecologic determinants of food sources affecting rodent population size, and floods can displace and lead them to seek food and refuge.

Temperature effects on selected vectors and vector-borne pathogens
- Vector
  - Survival can decrease or increase depending on the species (*88,90*)
  - Some vectors have higher survival at higher latitudes and altitudes with higher temperatures
  - Changes in the susceptibility of vectors to some pathogens—e.g., higher temperatures reduce the size of some vectors (*129–131*) but reduce the activity of others (*9,132*)
  - Changes in the rate of vector population growth (*133*)
  - Changes in feeding rate and host contact (which may alter the survival rate) (*131,134*)
  - Changes in the seasonality of populations (*135*)
- Pathogen
  - Decreased extrinsic incubation period of pathogen in vector at higher temperatures (*79,136,137*)
  - Changes in the transmission season (*89,131*)
  - Changes in distribution (*83*)
  - Decreased viral replication (*90*)

Effects of changes in precipitation on selected vector-borne pathogens
- Vector
  - Increased rain may increase larval habitat and vector population size by creating a new habitat
  - Excess rain or snowpack can eliminate habitat by flooding, thus decreasing the vector population size
  - Low rainfall can create habitat by causing rivers to dry into pools (dry season malaria)
  - Decreased rain can increase container-breeding mosquitoes by forcing increased water storage (*80*)
  - Epic rainfall events can synchronize vector host-seeking and virus transmission (*87*)
  - Increased humidity increases vector survival (*138*); decreased humidity decreases vector survival
- Pathogen
  - Few direct effects but some data on humidity effects on malarial parasite development in the anopheline mosquito host.
- Vertebrate host
  - Increased rain can increase vegetation, food availability, and population size
  - Increased rain can also cause flooding and decrease population size but increase contact with humans
  - Decreased rain can eliminate food and force rodents into housing areas, increasing human contact, but it can also decrease population size

Increased sea level effects on selected vector-borne pathogens
- Alter estuary flow and change existing salt marshes and associated mosquito species, decreasing or eliminating selected mosquito breeding sites (e.g., reduced habitat for *Culiseta melanura*)

[a]The relationship between ambient weather conditions and vector ecology is complicated by the natural tendency for insect vectors to seek out the most suitable "microclimates" for their survival (e.g., resting under vegetation or pit latrines during dry or hot conditions or in culverts during cold conditions).

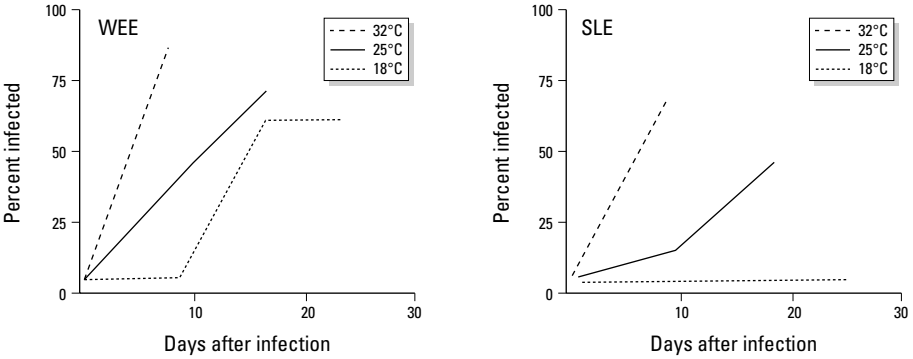

Figure 2. WEE and SLE viral development and temperature. Data from Reeves et al. (*90*).

limited by altitude (*92*), a good proxy for temperature, but malaria transmission depends on many factors besides temperature. Although malaria tends to be seasonal, there is substantial interannual heterogeneity of malarial incidence around the globe (*93,94*). Extremes of rainfall (both drought and floods) associated with El Niño events are linked to variability in malarial incidence in different regions (*95,96*).

Some biologic modeling of the potential impact of climate variables, primarily temperature increases, on malaria as done on a global scale projected net increases in the geographic area and season for potential malaria transmission (*97,98*). However, a statistical–empirical model approach that used the baseline number of people currently living in malaria-endemic regions (*99*) found no significant net change in malaria projected by the year 2080. It is possible that small increases in minimum temperature in cooler regions may disproportionately increase malaria transmission (*100,101*), provided there are no socioeconomic barriers to transmission as there are in the United States. It is difficult to extrapolate the data from these global malaria/climate models (*100*) from the situation in Africa (*102,103*) or from El Niño/malaria studies conducted in South America (*96*) to the United States.

In temperate countries, people rarely are bitten by anopheline mosquitoes unless they live near mosquito-breeding sites. Even then, window screens or human behavior of staying indoors in closed, air-conditioned houses in the evening limits human–mosquito contact. This is underscored by the fact that even though the United States has experienced increased frequency of local transmission as the result of increased imported disease in the past decade, all of the incidents have resulted in only 1–3 cases and have involved migrant workers or immigrant populations living in substandard housing (*50,104*). Other nonendemic countries have also reported malaria recently. After 40 years of being malaria free, transmission of *P. vivax* malaria by local vectors has been reported in Italy (*105,106*). In France, about 5,000 imported cases are reported per year, but local transmission has rarely been reported. However, a major resurgence of epidemic malaria has occurred in the southern republics of the former Soviet Union because of the breakdown of public health services (*107*).

Various factors would either promote or deter the recurrence of autochthonous malaria in the United States if climate conditions continue to warm. For example, increased travel and commerce have brought and will continue to bring infected travelers and/or vectors to the United States. Also, drug resistance may lessen our ability to treat malarial infections. On the other hand, factors that make sustained endemic or epidemic transmission unlikely include current land use and agricultural practices, improved housing, improved mosquito control, and human behavioral avoidance of mosquitoes (e.g., time spent indoors with screened windows and air conditioning) and led to the elimination of malaria in the United States historically; these conditions are unlikely to change with global warming. Moreover, most areas have good medical services, and there is effective treatment for malaria (with the caveat that vigilance for drug resistance will always be of concern).

Tick-Borne Diseases

Ticks and their mammalian hosts are influenced by land use, land cover, soil type, elevation, and weather conditions (*108–111*). One disease, RMSF, has been modeled under climate-change scenarios (*112*), which show summertime temperatures in the Southeast becoming too hot for tick survival and the consequent reduction in the risk of RMSF (Table 1). However, tick-borne/climate–related models have limitations. For example, the effect of climate change on the presence of nonmammalian hosts, such as lizards, that may act as a zooprophylaxis requires further study.

Rodent-Borne Diseases

The potential effects of climate variability and change on infectious agents transmitted by mammals to humans are more uncertain and have received less attention than have vector-borne diseases. Because El Niño events may lead to increased rainfall in certain regions of the United States, studying such events may allow a better understanding of the potential implications of one climate-change scenario on rodent population fluctuations and patterns of diseases, such as hantavirus and plague. On the other hand, consistent increased rainfall will likely change the ecology of these regions and thus the ecology of the disease.

Hantavirus and climate sensitivity. Ecologic changes promoting rapid increases and then decreases in rodent populations have a marked association with size of hantavirus disease outbreaks (*67*). The changes that affect rodent population dynamics are often weather related and include the combination of unusually high rainfall followed by drought. For example, the U.S. Four Corners outbreak in 1993 was preceded by a dramatic increase in rainfall associated with the 1992–1993 El Niño. This led to increased rodent food resources, a focal 20-fold increase in the rodent population, and an increased risk of human disease (*113,114*). By 1995, both the rodent population and human cases had decreased dramatically (*113*). A similar pattern of above-average rainfall followed by drought was observed preceding an outbreak of hantavirus pulmonary syndrome in Paraguay during 1995–1996 (*115*).

Since the 1993 hantavirus pulmonary syndrome outbreak, longitudinal studies have monitored animal reservoir populations in the Southwestern United States (*66,69*). Models combining satellite images of weather conditions and human disease surveillance also were developed to allow regions at increased risk to be identified with sufficient lead time for public health intervention (*114*).

Leptospirosis and climate sensitivity. Extreme flooding or hurricanes can lead to outbreaks of leptospirosis. The October 1995 epidemic of leptospirosis in Nicaragua followed heavy flooding (*116*). A case–control study showed that a 15-fold risk of disease was associated with walking through flooded waters (*117*). High-risk factors also included having rodents or dogs in the household. A large epidemic of leptospirosis overlapped with an outbreak of dengue in 1996 in Salvador, Brazil (*118*). The peak of the epidemic occurred 2 weeks after severe flooding in the area. Poor living conditions were associated with increased risk. Forty-three percent of the patients were misdiagnosed as having dengue fever and hence not treated with antibiotics.

Plague and climate sensitivity. Some studies have found that ambient temperature, rainfall, and relative humidity, along with rodent habitat, affected the seasonal abundance of rodent fleas in the western United States (*119–121*). Climatic events such as periods of increased precipitation or drought also strongly affect rodent population dynamics, largely through effects on food availability (*122–125*). Flea-borne plague incidence has been found to rise in conjunction with increasing rodent populations following unseasonal winter/spring precipitation in New Mexico (*126*). Responses of both fleas and rodents to climatic factors vary considerably from species to species. The association of climate and habitat on the incidence of human plague somewhat resembles that postulated for the effects of these factors on the occurrence of human hantavirus cases.

Table 2 lists field and modeling studies on vector-borne diseases and climate variability and change. The current infectious disease models do not do well at predicting future incidence of disease because they lack an adequate characterization of the feedback effects between weather-related changes in the ecology and the spread of infected vectors and disease. Yet even though no model can accurately simulate real life, models are useful in conceptualizing dynamic processes and their outcomes. Multiple iterations of well-conceptualized models help identify key

knowledge gaps and guide empirical studies that ultimately will lead to improved models. At present, long-term regional weather and ecologic predictions still remain major barriers to predicting future changes in vector-borne disease risks.

Adaptive Capacity

Understanding the vulnerability of the United States to changes in the ranges or rates of vector-borne diseases is the first step in addressing adaptive capacity. Adaptation involves the ability to change behavior or health infrastructure to reduce the potential negative impacts of climate change. Adaptation is a function of a number of societal systems, including access to financial resources (both for individuals and populations), technical knowledge, public health infrastructure, and capacity of the health care system. Adaptation can be viewed as taking place on two levels: autonomous adaptation, which is the natural or spontaneous response to climate change by affected individuals; and purposeful adaptation, which is a planned response to climate change, typically by governmental or other institutional organizations. Anticipatory adaptations are planned responses that take place in advance of climate change. It is important to identify and prioritize anticipatory adaptations to prevent irreversible adverse impacts that can not be mitigated after they occur. Some examples of adaptive options are:

Environmental controls

- Mosquito control programs (e.g., with pesticides or predator fish species)
- Community elimination of aquatic breeding sites
- Window screens, air conditioning, and other personal protective measures.

Technologic or administrative controls

- Vaccine, pharmaceutical, and pesticide development
- Improved and expanded surveillance efforts
- Education initiatives for health care givers
- Behavioral controls
- Proper clothing and use of repellents
- Following of instructions for prophylactic measures when traveling abroad.

Little quantitative information is available on adaptation to climate change. Insights on potential vulnerabilities and recommendations for policies to promote adaptation can be gained from past experiences in public health. For example, many formerly endemic mosquito-borne diseases such as malaria, dengue fever, and yellow fever are rare or have disappeared, primarily because of changes in living conditions (such as adequate housing, the use of screens on doors and windows, and the use of air conditioning), changes in behaviors (such as watching television instead of sitting outside during biting times), and public health interventions (such as vector control programs). Although changes in the range of both *Ae. aegypti* and *Ae. albopictus* could occur with changing climate, the above factors plus the current public health infrastructure, including active disease surveillance and selected vector control, reduce the risk of the increased transmission potential of the disease agents that can be carried by these mosquitoes. Maintaining this infrastructure is important to ensure that the risk does not change with changing climate. Prioritizing disease risks will differ across the country because of geographic and climatologic variability; therefore, adaptive responses must be tailored to region.

The capacity to adapt to potential changes in climate will depend on many factors, including at least maintaining the current level of public health infrastructure; ensuring active surveillance for diseases with potentially large public health impacts; continuing research to further our understanding of the associations among weather, extreme events, and vector-borne diseases; and continuing research into medical advances required for disease prevention, control, and treatment, such as vaccines and methods to deal with drug-resistant strains. For example, very high

Table 2. Examples of field or modeling studies of climate variability and change.

Study	Findings[a]
Encephalitis	
Reeves and Hammon, 1962 (*78*)	One hundred human cases of WEE and 89 cases of SLE occurred in Kern County, California, following the Tehachapi earthquake and *flood* of the Kern River in 1952.
Nasci and Moore, 1998 (*77*)	Fifty-five human cases of WEE and 12 of SLE occurred in Minnesota after the Red River *flood* of 1975.
Reisen et al., 1993 (*89*) Reeves et al., 1994 (*90*)	1°C increase in *temperature* corresponds with a 1% decrease in adult *Culex tarsalis* mosquito daily survivorship but shortened viral development time in the mosquito. Conclusion: A 3–5°C increase in average temperature may eliminate WEE from the United States and cause a northern shift in the distribution of both WEE and SLE outbreaks in California.
Sellers and Maarouf, 1990 (*91*)[b]	Analyses of *wind trajectories* indicated that mosquitoes potentially infected with EEE virus could be carried by storm fronts from North Carolina northeastward as far as upstate New York and from western Kentucky to Michigan.
Dengue	
Jetten and Focks, 1997 (*81*)[b] Patz et al., 1998 (*82*)[b]	In the dengue fever simulation model (DENSiM), Jetten and Focks projected that increasing temperature would increase the length of transmission season in temperate regions. Patz et al. applied DENSiM to *future climate* scenarios generated from general circulation models (GCMs). These models projecting potential epidemic transmission are sensitivity analyses only; human cases can not be determined since the models used in these studies are not fully parameterized and therefore cannot be used for regional predictions.
Malaria	
Haile, 1989 (*112*)[b] Martin and Lefebvre, 1995 (*139*)[b] Martens et al., 1995 (*97*)[b] Rogers and Randolph, 2000 (*99*) Martens et al., 1999 (*98*) Lindsay and Martens, 1998 (*103*)	Except for Rogers and Randolph, who used statistical modeling, these studies used biologic process models and GCMs of *future climate change scenarios*. Haile (in 1989) found little change in malarial transmission risk in the United States. As with the dengue simulations, this and the other studies projecting potential epidemic malaria transmission are only sensitivity analyses; because these models are not fully parameterized, they cannot be used for regional prediction.
Bouma et al., 1997 (*96*)	*El Niño* events were linked to variability in malarial incidence in Colombia and Venezuela, South America.
Tick-borne disease	
Haile, 1989 (*112*)[b]	*Future warming* from double carbon dioxide in the Southeast may reduce tick survival and subsequent risk of Rocky Mountain spotted fever.
Amerasinghe et al., 1993 (*108*)	There was a significant correlation between Lyme disease tick density and *rainfall and elevation*.
Mount et al., 1993 (*109*) Glass et al., 1994 (*110*) Wilson, 1998 (*111*)	Tick abundance was predicted by land use, land cover (especially forest edge), soil type, elevation, and the timing, duration, and rate of change in *temperature and moisture*.
Rodent-borne disease	
Trevejo et al., 1998 (*117*)	A 15-fold increased risk of leptospirosis was associated with walking through *flooded waters* (Nicaragua).
Ko et al., 1999 (*118*)	An urban oubreak of leptospirosis in Salvador, Brazil, peaked 2 weeks after severe flooding.
Engelthaler, 1999 (*113*)	The Four Corners hantavirus outbreak in 1993 was preceded by a dramatic increase in rainfall from the 1992–1993 *El Niño*, with a 20-fold explosion in the rodent population.

[a]Weather parameter italicized. [b]Maintenance and transmission of these disease agents in nature depend on many complex ecologic interactions among the vector, the pathogen, the vertebrate host, and the environment. Therefore, these models should be considered only sensitivity analyses, not predictive models.

priority should be given to development of more effective mosquito control and vaccines for the two major vector-borne diseases, malaria and dengue. Both are maintained primarily in a mosquito–human–mosquito transmission cycle and could be prevented effectively by immunizing humans. Although progress on vaccines for both diseases has been promising in recent years, it will likely be another decade before safe and effective vaccines are available for public health use. Therefore, funding for vaccines should not occur at the expense of research needed to understand environmental determinants of disease transmission and mosquito control methodologies. In addition, research is needed to identify adaptation needs, to evaluate adaptation measures, and to set priorities. The goal is to prevent, rather than treat, disease to reduce human suffering.

CDC Arbovirus Surveillance and Response Activities

Surveillance. Arbovirus transmission within the United States is monitored by state and local health departments and the CDC Division of Vector-Borne Infectious Diseases (CDC-DVBID). The CDC obtains information through well-organized, systematic processes [e.g., National Electronic Telecommunications System Surveillance (NETSS)] and through a loosely organized network of workers in both state and local health departments and municipal mosquito and vector control agencies. Incoming information is received via phone, fax, mail, and an e-mail listserver (VECTOR) maintained by DVBID.

Human arbovirus cases are required to be reported by the state health departments and are monitored through NETSS, as are other reportable diseases in the country. Summaries of arbovirus cases are routinely disseminated to all 50 state health departments and certain key counties and diagnostic laboratories through the VECTOR listserver.

The arboviral equine encephalitides also cause veterinary disease, and cases may be reported to health or agriculture departments in the states. Certain health departments and veterinary diagnostic laboratories, including the U.S. Department of Agriculture-National Veterinary Services Laboratory, provide information regarding veterinary cases to CDC-DVBID. This information is summarized and disseminated via the VECTOR listserver.

Nationwide, routine entomologic and environmental surveillance for arbovirus transmission activity is conducted by certain states that maintain intensive, statewide surveillance programs to monitor enzootic and epizootic arbovirus transmission activities. A few large counties and municipal mosquito control districts also conduct surveillance programs. CDC-DVBID supports these surveillance programs.

Response. Information is regularly evaluated on environmental surveillance and human and veterinary cases, and summaries are provided to health department workers via the VECTOR listserver. If trends suggest increases in transmission activity or abnormally early or late transmission activity, CDC-DVBID alerts the state health department(s) involved and offers diagnostic laboratory support and on-site epidemiologic assistance by DVBID staff in evaluating the epidemic, enhancing surveillance activities, and coordinating emergency vector control activities.

Gaps in surveillance and response capabilities. Gaps in surveillance and response capabilities are related primarily to the lack of surveillance infrastructure and lapses in communication systems. First, human case surveillance via NETSS is slow. The time lag between the diagnosis and confirmation of an arbovirus case and its appearance in NETSS is often quite long. Moreover, results of human diagnostic tests done in commercial laboratories may not be communicated to the state health department.

Veterinary case surveillance and reporting of cases must be integrated better with public health activities. Veterinarians sometimes do not obtain samples or request appropriate diagnostic testing. Results of samples that are tested often are not communicated to state or county health departments for timely evaluative follow-up, and few states require reporting of veterinary arbovirus cases. Better communication among human public health agencies, veterinary services, and organizations is essential.

Environmental and entomologic surveillance programs monitoring arbovirus transmission activity in vectors and vertebrate hosts are highly variable. Some states (e.g., California, Florida, New Jersey) maintain well-designed, comprehensive surveillance programs that monitor enzootic and epizootic transmission activity, veterinary cases, and human cases. Within several states, large counties (e.g., Harris County, Texas) also maintain intensive environmental surveillance programs. Other states and counties maintain only marginally effective or no environmental or veterinary surveillance programs. Support for arbovirus surveillance programs is frequently a very low priority in state health departments, and interest and capability regarding arboviruses have lessened over the past 20–30 years. Finally, surveillance and reporting technique differences make evaluation of data difficult.

In summary, there is no systematic method of assembling a national database of environmental or veterinary surveillance data, and most data are provided to CDC voluntarily. Guidelines for arbovirus surveillance have been published (*128*), but the infrastructure required to implement effective surveillance and prevention programs is not available.

Research Needs and Data Gaps

Weather and climate are important parameters in the epidemiology of vector-borne diseases. The effects of such variables as temperature and rainfall are very complex, influencing the vector and its interaction with both habitat and vertebrate hosts, all of which determine whether a disease pathogen will be present and, if so, whether transmission will be endemic or epidemic (Figure 3). Without well-designed research to understand these interactions, accurate projections of the potential effects of climate change on disease will remain elusive.

Climate change is likely to affect the transmission patterns of vector-borne pathogens, but more research is needed to clarify the interactions of weather variables and the diseases they affect. There is a need for information on how zoonoses persist in nature and what triggers their amplification and initiation of secondary cycles that increase the risk of human infection. Some diseases may increase but others may decrease. How these pathogens persist and what triggers amplification must be understood before the role of weather and long-term climate trends can be fully determined.

There has been an increase in the number of imported cases of dengue and malaria in the United States since the 1980s, as well as increased local transmission (*1,50*). The differential dengue incidence rates at the U.S.–Mexico border illustrate deficiencies in knowledge regarding the specific socioeconomic determinants of disease and its prevention.

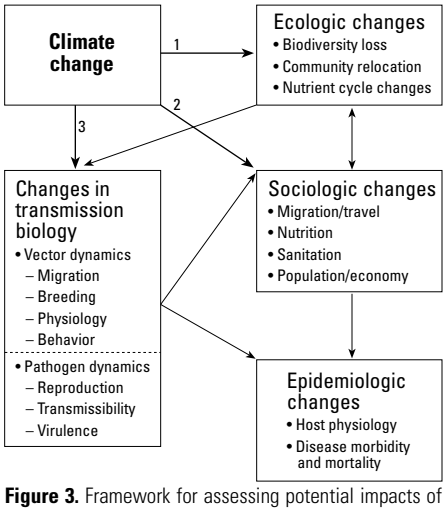

Figure 3. Framework for assessing potential impacts of climate change on vector-borne diseases. Arrows 1, 2, and 3 indicate direct climate change effects. Data from Chan et al. (*4*).

Malaria research is one example of our lack of understanding of the potential implications of climate change for the United States. It has been demonstrated for 50 years that when malaria is reintroduced into this country, the sociologic and ecologic conditions limit human–mosquito contact, and the public health system has been able to suppress disease outbreaks quickly. There have been no rigorous assessments of the behavior and vector competence of U.S. *Anopheles* since the 1950s. Public health focus has been on case detection and treatment, but attention should include monitoring of the indigenous *Anopheles* mosquitoes.

There is a need for well-designed, multidisciplinary field research on diseases in their natural habitats to discern better the effect of weather on the natural maintenance cycles, disease incidence, and epidemic potential. Contemporary process-based mathematical models can be useful tools to explore the interaction of variables in the transmission dynamics of a disease. See Table 3 for further recommendations for surveillance and modeling needs. Certainly as a foundation for such modeling, improved epidemiologic surveillance at all levels of the health system is important.

Only limited databases are available to address the health impacts of extreme climate variability and change. Much of the information comes from epidemic investigations in which researchers focus on a single event and gather data for only a short time. A concerted effort to acquire more complete, long-term data sets is essential. Resolving the many questions about associations among weather, climate, and disease will require the identification of model systems or diseases, which would enable the development of long-term, high-quality data sets, and sustained funding to make this research possible.

Although it is likely that warming trends and other changes projected by global circulation models could affect vector- and rodent-borne diseases in the United States, the details and degree of these effects are uncertain. In addition, we do not know how projected climate change will affect the complex ecosystems required to maintain disease. Understanding these issues will require considerable research on the influence of weather and climate on these pathogens in their natural transmission cycles. In the future, assessments that integrate global climate scenario-based analyses with local demographic and environmental factors are needed to guide comprehensive, long-term preventive health measures.

Table 3. Proposed research agenda for climate change and infectious disease.[a]

Climate modeling
Continue to improve regional climate analyses and models at the spatial and temporal scales appropriate for projecting the climate variables most useful to research on the health impacts of climate change.
Ecosystem dynamics and habitat alteration
Relate the biology of pathogens and vectors to ecosystem dynamics at various time scales (e.g., seasonal, interannual) and the scale of plant–community succession.
Determine how habitats (land, freshwater, and marine) are altered by climate change.
Determine how habitat alteration and the consequent changes in ecosystem dynamics affect the biology of pathogens and vectors.
Disease surveillance
Improve morbidity and mortality surveillance for selected diseases, including active surveillance with laboratory confirmation in areas of special interest.
Improve methods of detecting pathogens in vectors and in the environment.
Technologies for disease prevention and mitigation: Assess existing technologies and develop new ones, such as
Vaccines
More effective, sustainable approaches for vector control
Rapid methods for field diagnosis of disease
Genetic techniques for identifying vectors and pathogens
Disease transmission dynamics
Elucidate the biologic, biophysical, and biochemical interactions among pathogens, vectors, and hosts that influence disease transmission.
Develop disease transmission models that accurately incorporate these complex interactions.
Data sets for empirical studies
Link climate, health, and ecology data by employing new, integrated approaches such as geographic information systems.
Provide easy access to quality-controlled data.
Ensure compatibility and consistency over all time scales.
Enable the mining of historical direct and proxy data sources to extract priority variables.
Integrated assessments
Integrate health and climate indicators, socioeconomic changes, and technologic changes in assessment models.
Apply these integrated models to project scenarios for alternative futures.
Develop strategies for cost-effective intervention and study their consequences for alternative scenarios.
Seek improved methods for valuation and aggregation of health effects and other effects of climate change.
Capacity to detect, understand, and respond to surprises (unexpected events).
Improve the capacity for early detection, understanding, and effective response to unexpected emergence of disease, increased disease incidence, or nonlinearities in ecosystem dynamics and climate.

[a]Summary from the workshop "Climate Change and Vector-borne and Other Infectious Disease: A Research Agenda," conducted by the Washington Advisory Group, October 1997, Washington, DC. Sponsors included the Electric Power Research Institute, National Aeronautics and Space Administration, National Institute of Allergy and Infectious Diseases, National Institute of Environmental Health Sciences, and U.S. Department of Energy. Data from Washington Advisory Group (*127*).

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