Climate change and vector-borne diseases: a regional analysis

Andrew K. Githeko,[1] Steve W. Lindsay,[2] Ulisses E. Confalonieri,[3] & Jonathan A. Patz[4]

Current evidence suggests that inter-annual and inter-decadal climate variability have a direct influence on the epidemiology of vector-borne diseases. This evidence has been assessed at the continental level in order to determine the possible consequences of the expected future climate change.

By 2100 it is estimated that average global temperatures will have risen by 1.0–3.5 °C, increasing the likelihood of many vector-borne diseases in new areas. The greatest effect of climate change on transmission is likely to be observed at the extremes of the range of temperatures at which transmission occurs. For many diseases these lie in the range 14–18 °C at the lower end and about 35–40 °C at the upper end. Malaria and dengue fever are among the most important vector-borne diseases in the tropics and subtropics; Lyme disease is the most common vector-borne disease in the USA and Europe. Encephalitis is also becoming a public health concern. Health risks due to climatic changes will differ between countries that have developed health infrastructures and those that do not.

Human settlement patterns in the different regions will influence disease trends. While 70% of the population in South America is urbanized, the proportion in sub-Saharan Africa is less than 45%. Climatic anomalies associated with the El Niño–Southern Oscillation phenomenon and resulting in drought and floods are expected to increase in frequency and intensity. They have been linked to outbreaks of malaria in Africa, Asia and South America. Climate change has far-reaching consequences and touches on all life-support systems. It is therefore a factor that should be placed high among those that affect human health and survival.

Keywords: greenhouse effect; disease vectors; disease transmission; malaria, transmission; Lyme disease, transmission; leishmaniasis, transmission; communicable diseases, transmission; health surveys.

Voir page 1143 le résumé en français. En la página 1144 figura un resumen en español.

Introduction

Human life is dependent on the dynamics of the Earth's climate system. The interactions of the atmosphere, oceans, terrestrial and marine biospheres, cryosphere and land surface determine the Earth's surface climate (*1*). Atmospheric concentrations of greenhouse gases, which include carbon dioxide, methane, and nitrous oxide are increasing, mainly due to human activities, such as use of fossil fuel, land use change and agriculture (*2*). An increase in greenhouse gases leads to increased warming of the atmosphere and the Earth's surface.

In this article, evidence for the past and current impacts of inter-annual and inter-decadal climate variability on vector-borne diseases is assessed on a continental basis with the aim of shedding light on possible future trends, particularly in view of the increased likelihood of climate change.

It is estimated that average global temperatures will have risen by 1.0–3.5 °C by 2100 (*3*), increasing the likelihood of many vector-borne diseases. The temporal and spatial changes in temperature, precipitation and humidity that are expected to occur under different climate change scenarios will affect the biology and ecology of vectors and intermediate hosts and consequently the risk of disease transmission. The risk increases because, although arthropods can regulate their internal temperature by changing their behaviour, they cannot do so physiologically and are thus critically dependent on climate for their survival and development (*4*). Climate, vector ecology and social economics vary from one continent to the other and therefore there is a need for a regional analysis.

The greatest effect of climate change on transmission is likely to be observed at the extremes of the range of temperatures at which transmission occurs. For many diseases these lie in the range 14–18 °C at the lower end and ca. 35–40 °C at the upper end. Warming in the lower range has a significant and non-linear impact on the extrinsic incubation period (*5*), and consequently disease transmission, while, at the upper end, transmission could cease. However, at around 30–32 °C, vectorial capacity can increase

[1]Principal Research Officer, Head, Climate and Human Health Research Unit, Centre for Vector Biology and Control Research, Kenya Medical Research Institute, PO Box 1578, Kisumu, Kenya (email: AGitheko@kisian.mimcom.net). Correspondence should be addressed to this author.

[2] Reader, Department of Biological Sciences, University of Durham, Durham, England.

[3] Professor, National School of Public Health, Rio de Janeiro, Brazil.

[4] Assistant Professor and Director, Program on Health Effects of Global Environmental Change, Department of Environmental Health Sciences, Johns Hopkins School of Public Health, Baltimore, MD, USA.

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substantially owing to a reduction in the extrinsic incubation period, despite a reduction in the vector's survival rate. Mosquito species such as the *Anopheles gambiae* complex, *A. funestus, A. darlingi, Culex quinquefasciatus* and *Aedes aegypti* are responsible for transmission of most vector-borne diseases, and are sensitive to temperature changes as immature stages in the aquatic environment and as adults. If water temperature rises, the larvae take a shorter time to mature (*6*) and consequently there is a greater capacity to produce more offspring during the transmission period. In warmer climates, adult female mosquitoes digest blood faster and feed more frequently (*7*), thus increasing transmission intensity. Similarly, malaria parasites and viruses complete extrinsic incubation within the female mosquito in a shorter time as temperature rises (*8*), thereby increasing the proportion of infective vectors. Warming above 34 °C generally has a negative impact on the survival of vectors and parasites (*6*).

In addition to the direct influence of temperature on the biology of vectors and parasites, changing precipitation patterns can also have short- and long-term effects on vector habitats. Increased precipitation has the potential to increase the number and quality of breeding sites for vectors such as mosquitoes, ticks and snails, and the density of vegetation, affecting the availability of resting sites. Disease reservoirs in rodents can increase when favourable shelter and food availability lead to population increases, in turn leading to disease outbreaks. Human settlement patterns also influence disease trends. In South America, more than 70% of the population is urbanized and therefore only a small proportion is exposed to rural infections. In Africa, in contrast, more than 70% of the population lives in rural areas, where vector control, e.g. removal of larval breeding sites, is often difficult. Dengue fever is largely an urban disease, however, and will be more important in highly urbanized communities with poorly managed water and solid waste systems.

The recent literature includes a number of disease-specific reviews. This review offers a regional perspective, attempting to capture the essential events observed under different climate variations and expected as a result of climate change.

Africa

The tropical African climate is favourable to most major vector-borne diseases, including: malaria, schistosomiasis, onchocerciasis, trypanosomiasis, filariasis, leishmaniasis, plague, Rift Valley fever, yellow fever and tick-borne haemorrhagic fevers. The continent has a high diversity of vector-species complexes that have the potential to redistribute themselves to new climate-driven habitats leading to new disease patterns. These organisms have different sensitivities to temperature and precipitation.

By 2050 it is estimated that the Sahara and the semi-arid parts of southern Africa may warm by 1.6 °C, while equatorial countries such as Cameroon, Kenya and Uganda could experience rises of 1.4 °C (*3*). Recent analysis of global mean surface precipitation over the period 1901–95 indicates that precipitation trends vary across the continent. Precipitation appears to be increasing in east Africa but decreasing in west and north Africa (*9*). These are broad overviews, however, and the trends may have low certainty at a more local level.

Climate change will have short- and long-term impacts on disease transmission. For example, a short-term increase in temperature and rainfall, as was seen in the 1997–98 El Niño — an example of inter-annual climate variability — caused *Plasmodium falciparum* malaria epidemics (*10*) and Rift Valley fever (*11*) in Kenya. This may have been due to accelerated parasite development and an explosion of vector populations. However, these same changes reduced malaria transmission in the United Republic of Tanzania (*12*). There is emerging evidence that, in addition to seasonal extreme climatic events, there is a general elevation of mean temperatures and, in some cases, precipitation (*9*). For example, the mean rate of temperature change in Africa over the period 1901–95 was 0.39 °C per century. Although there has been a reduction in precipitation in many parts of the continent, there has been a mean increase of 300 mm per century in east Africa. Such changes are likely to support rapid development of malaria vectors and parasites in regions where there has previously been a low-temperature restriction on transmission. On the other hand, increased warming will have a negative effect at the high end of the temperature range of malaria vectors. The negative effect of reduced precipitation and drought have been seen in Senegal, where *A. funestus* has virtually disappeared and malaria prevalence has dropped by more than 60% over the last 30 years (*13*).

Vector species in Africa have adapted to ecosystems ranging from humid forests to dry savannas. As these ecosystems change so will the distribution of vectors species. For example, for trypanosomiasis vectors, although *Glossina morsitans* is mainly a savanna dweller, *G. palpalis* is a riverine species preferring to rest under dense vegetation. Factors that alter the resting sites for adult tsetse flies, such as long-term changes in rainfall, can affect the epidemiology and transmission of trypanosomiasis, although long-term vegetation change is a slow process. *Anopheles gambiae* prefers the wet and humid zones, while *A. arabiensis* has adapted to drier climates (*14*). The distribution and relative abundance of these species can be predicted fairly accurately using current climate models (*15*) and could be used to indicate future changes in vector distributions associated with our changing climate. In Senegal, *Biomphalaria pfeifferi* snails transmit *Schistosoma mansoni* during the rainy season, while *Bulinus globosus* is responsible for transmission of *S. haematobium* during the dry season (*16*). In the United Republic of Tanzania, rainfall patterns have a distinct influence on *B. globosus* densities (*17*). Furthermore, using data collected from Zimbabwe, a simulation model that allows variable annual rainfall predicted fluctuations in *B. globosus* abundance over two orders of magnitude over time-scales of ten years or more (*18*). Long-term changes in precipitation can therefore be expected to alter the distributions of snails and in turn the disease pattern.

Adaptation strategies to climate change, such as irrigation, can increase the risk of malaria (*19*) and schistosomiasis (*20*) transmission.

Factors such as social economics, health-seeking behaviour, geographical location, and population growth will determine the vulnerability of populations to climate change. For example, with the exception of South Africa many of the countries affected by highland malaria such as Ethiopia, Kenya, Madagascar, Rwanda, Uganda, the United Republic of Tanzania, and Zimbabwe have a per capita gross domestic product in the range US$ 106.8–505.5, and many of them have a negative income growth (*21*). This may suggest a low resource allocation for health at the institutional and individual levels. Moreover, chloroquine, the mainstay of malaria treatment for many decades, has proved to be ineffective in many parts of the world, particularly against falciparum malaria. Alternative drugs have been developed, but they are frequently less safe and are 50–700% more expensive than chloroquine (*22*). In many of the poorer countries, more than 60% of malaria cases are treated at home (*23*), which is now likely to result in treatment failures owing to drug resistance, particularly among non-immune populations.

Destruction of forests to create new human settlements can increase local temperatures by 3–4 °C (*24*) and at the same time create breeding sites for malaria vectors. These phenomena can have serious consequences on malaria transmission in the African highlands.

At equatorial latitudes, e.g. the east African highlands, malaria transmission may become more intense at higher altitudes (*25*) where individuals have low immunity. At lower latitudes in southern Africa, more intense transmission is likely to be felt above 1200 m. Extreme weather events that cause flooding will intensify the transmission of desert malaria and Rift Valley fever (*26*). Since 1988, there have been numerous reports of malaria epidemics in east and southern Africa. For example, malaria epidemics have spread from 3 to 13 districts in western Kenya and, in some areas, outbreaks have become annual events (*27*). During this period, there has been an increase of about 2 °C in the mean monthly maximum temperature in the region between the coordinates 2°N–2°S and 30°E–40°E (A.K. Githeko, unpublished data, 1999). Further climate-linked malaria epidemics have been reported in Rwanda (*28*) and the United Republic of Tanzania (*29*). In western Kenya, the mean annual monthly temperature at 2000 m has been 18 °C, the threshold temperature for *P. falciparum* transmission. Theoretically, further warming should affect areas above 2000 m in east Africa.

Current episodes of climate variability in Africa are likely to intensify the transmission of malaria in the eastern and southern highlands but its effects on transmission of other less climate-sensitive vector-borne diseases is not yet clear.

While climate is an important co-factor in malaria epidemiology, drug resistance, reduced purchasing power and poor health infrastructures may be more important, as these are the tools and resources that reduce the impact of disease. Moreover, while climate is likely to primarily affect the highlands, drug resistance affects the entire malaria landscape.

Europe

Europe has warmed by a mean of 0.8 °C over the last 100 years (*2*). These changes have not been uniform, with the greatest warming has occurred in winter and in the north. If this trend continues, it is likely to reduce the high over-wintering mortality of vectors and new areas will become suitable for transmission. Changes in rainfall patterns are less predictable, although it is likely to become wetter in winter and drier in summer. While it is likely to become wetter in the north, it will get drier in the south and east of the continent (*2*). The consequences of these changes are difficult to predict. For example, in areas where rainfall declines and wetlands dry out, there may be fewer potential mosquito-breeding sites. However, such a reduction in mosquito production may be partly offset if mosquitoes find alternative breeding sites, such as pools created in a drying stream-bed or in water butts used by gardeners to conserve rainwater.

The most important vector-borne diseases in Europe and some of the countries of the former Soviet Union are malaria and Lyme disease, which are transmitted by mosquitoes and ticks, respectively. The evidence that climate change has increased the risk of these diseases is weak, because of the relatively subtle changes in climate to date and the overriding impact of major environmental changes created by expanding populations, alterations in agricultural practice and changing socioeconomic conditions. However, there is no room for complacency, as the capacity exists for an increase and expansion of many vector-borne diseases in many parts of the continent.

Malaria was once common in many parts of Europe (*30, 31*) and occurred almost as far north as the Arctic circle (*32*), although it was most common on the northern fringes of the Mediterranean shore and in eastern continental Europe. Recurrent outbreaks have occurred in eastern Europe, in Armenia, Azerbaijan, Tajikistan and Turkey (*33*). However, none of these outbreaks was associated with climate change but rather with deteriorating socioeconomic conditions, hydro-agricultural development schemes, movement of infected cases and the cessation of malaria-control activities.

Local transmission of malaria in western Europe is possible, but is likely to be restricted to a few individuals and be sporadic in nature. In Italy, where malaria was eradicated 40 years ago, local transmission of vivax malaria has recently occurred (*34, 35*). The climate in western Europe is more suitable for transmission of vivax malaria, a more benign parasite, than the frequently lethal, falciparum malaria, mainly because it can develop more quickly at lower temperatures (*36*). The dynamics of transmission are further complicated because vectors may transmit only specific strains of a parasite. For example, the vector *Anopheles atroparvus* is refractory to tropical strains of falciparum malaria (*37–39*) but not European ones (*40, 41*). Climate change may contribute to the expansion of the disease to northern latitudes (*42*). However, of far greater importance in the newly independent states in eastern Europe is the increasing poverty, the mass movement of refugees and displaced people, and the impoverished health systems, which all contribute to an increase in malaria.

Occasional outbreaks of malaria in Europe arise when infective mosquitoes are imported from the tropics by aircraft. Since 1969, there have been 60 such cases reported from a number of European countries (*43*). A far greater problem is the growing number of patients who contract malaria overseas. In the United Kingdom there are around 2000 cases each year (D. Warhurst, personal communication). This is particularly worrying because of the rapid spread of multidrug-resistant strains of the parasite; the occurrence of cases of untreatable malaria remains a distinct possibility.

As the climate warms, many vectors — not just those that transmit malaria — are likely to expand their ranges within Europe and new vector species may be introduced from the tropics. A major vector of dengue fever, *Aedes albopictus*, has spread to 22 northern provinces in Italy since being introduced eight years ago (*44*). Arboviruses transmitted by mosquitoes can cause significant morbidity and mortality in Europe (*45*). West Nile virus caused outbreaks in France in the 1960s and in Romania in 1996. There have also been outbreaks of Sindbis virus disease in northern Europe over the past two decades, and numerous other viral infections have been reported. Predicting when and where such outbreaks will occur is extremely difficult, but it is possible to define suitable areas if the climate envelope in which the vector resides can be identified and mapped (*46*).

Tick distributions are also closely linked with climate, and there is growing concern that tick-borne diseases, such as Lyme disease and tick-borne encephalitis, may be increasing in northern Europe (*47*). Although adult female ticks are most often infected, it is the more abundant nymphs that are the most important source of infection. Tick larvae and nymphs feed on small vertebrates, such as mice and birds, while adults feed on larger hosts, such as deer and cattle (*48*). While milder winters will reduce tick and host mortality and extend the period when ticks are active, drier summers will increase tick mortality. There is recent evidence that the northwards movement of the tick *Ixodes ricinus* in Sweden was related to the milder climate experienced in the 1990s (*49*). However, a note of caution is necessary since this change could also be related to the greater abundance of hosts, such as roe deer.

Leishmaniasis is endemic in many parts of southern Europe and is an important co-infection with human immunodeficiency virus (HIV). Since 1990, there have been 1616 co-infections reported largely from Spain, southern France and Italy (*50*). As the climate becomes warmer, the sandfly vectors of leishmaniasis may become more abundant, spreading north. Long hot summers are also ideal for other flies and the possibility exists of increasing cases of diarrhoea transmitted by houseflies, *Musca domestica*, and other species of synanthropic flies.

Although sporadic incidents of malaria, Lyme disease and leishmaniasis have been observed in western Europe, good surveillance systems and health infrastructure will be able to contain large-scale outbreaks. However, this may not be the case for some countries in eastern Europe. Moreover, declining economies and civil unrest may precipitate conditions conducive to disease outbreaks.

South America

The most important climate-sensitive vector-borne-diseases in South America as far as the numbers of people affected are concerned are malaria, leishmaniasis, dengue fever, Chagas disease and schistosomiasis. The numbers of cases of these diseases reported to the Pan American Health Organization in 1996 are shown in Table 1 (*51*).

In recent years, the number of new cases of cutaneous leishmaniasis has varied from 250 per year in Bolivia (1975–91) to 24 600 in Brazil (1992) and there were around 9200 cases of onchocerciasis in 1992 in various countries including Colombia, Guatemala and Venezuela (*52*).

Other vector-borne diseases with relatively low number of cases occurring each year, and which may be sensitive to climate shifts, are yellow fever (522 cases in 1995), plague (55 cases in 1996), Venezuelan equine encephalitis (25 546 cases in 1995), and other arboviral infections (*51*). Up to 1991, in the Brazilian Amazonian region alone, 183 different types of arbovirus were isolated and

Table 1. **Distribution of cases of vector-borne diseases in South America reported to the Pan American Health Organization in 1996** (ref. *51*)

Disease	No. of cases
Malaria	877 851
Dengue fever	276 758
Chagas disease[a]	5 235 000
Schistosomiasis	181 650

[a] The number of cases of Chagas disease has been estimated from the number of people exposed.

34 are known to cause human disease, sometimes in explosive epidemics. One of these, Oropouche fever virus, is known to occur in cycles associated with the beginning of the rainy season (*53*).

The most widespread and severe climate-sensitive vector-borne disease in South America is malaria. Studies have shown that unusually dry conditions (for example, those caused by weather related to the El Niño–Southern Oscillation phenomenon in the northern part of the continent) are accompanied or followed by increases in the incidence of the disease. This has been documented in Colombia (*54, 55*) and Venezuela (*56*).

Preliminary observations in northern Brazil indicated a decreasing trend in malaria prevalence during the El Niño–Southern Oscillation year (0) (dry conditions), when the usual seasonal peaks of malaria disappeared. The disease tended to resume to its former endemic and epidemic levels by the end of the El Niño–Southern Oscillation (+1) year, when rainfall resumed the usual levels (U. Confalonieri, unpublished data,1999). However, in Bolivia (*57*), Ecuador (*58*) and Peru (*59*) the opposite phenomenon was observed; malaria increased after heavy rains associated with the 1982–83 El Niño–Southern Oscillation were followed by floods. Furthermore, in Ecuador, indirect factors, such as population migration and the breakdown of the heath services, contributed to the epidemics (*59*).

Heavy rains associated with the 1991–92 El Niño–Southern Oscillation were linked to the spread of the malaria vectors from endemic areas in Paraguay to Argentina (*60*). Changes in the temperate ecosystem of southern South America brought about by climate change would allow *Anopheles darlingi* to extend its habitat southwards (*61, 62*).

Recent estimates based on the Hadley Centre's coupled atmosphere–ocean general circulation model (HadCM3) projected that the additional number of people at risk of infection due to year-round transmission of malaria in South America will rise from 25 million by year 2020 to 50 million by 2080 (*63*).

The impact of climate change on the annual run-off over South America has been studied using different general circulation models (*64*). The climate change scenarios consistently projected increases in run-off over the north-west of South America where malaria is known to be endemic. Although the importance of soil moisture for the breeding of *Anopheles* vectors has been demonstrated in Africa (*65*), the association between the water cycle and malaria transmission has not been studied empirically in the Americas.

In the north-east of South America, a region subject to periodic droughts, the resurgence of visceral leishmaniasis (kala-azar) has been observed, for example, in some urban areas of Brazil (*66, 67*). In the cities of São Luis and Teresina, important epidemics were observed in 1983–85 and 1992–94, periods that coincided with major droughts caused by El Niño. In the State of Maranhão (Brazil), close to the Amazon Region, an important increase in imported malaria was also observed in the early 1980s, which subsequently became more frequent than the autochthonous form of the disease. The most plausible explanation for these increases is drought-driven human migration. In the case of the kala-azar outbreaks, people migrated from rural endemic areas to the cities in search for jobs or government aid, owing to ruined crops, while in the case of the increase in imported malaria cases, immigrants seem to have moved to the neighbouring Amazon, an endemic area, to find temporary work and then, with the end of the drought, took new cases of the disease to their homelands (U. Confalonieri, unpublished data, 1999).

There is little information about the possible impacts of climate change on the tropical forest of the Amazon, a natural source of dozens of known sylvatic arboviral infections, restricted mostly to the rainforest, with many more probably remaining to be discovered. Recent models of climate–land cover interactions have shown that deforestation in the Amazon region could have significant impacts on regional climate dynamics (*68–70*). Temperature increases on a local level due to deforestation in the Amazon can be even higher than those predicted by global climate change models under a doubling of carbon dioxide emissions. With continued deforestation, drier conditions are expected that will have an impact on the dynamics of infectious diseases, especially those associated with forest vectors and reservoirs, such as malaria, leishmaniasis and arboviral infections. Possible mechanisms for this interference are changes in the physical conditions for the survival of the vectors (humidity, breeding sites), and influences upon insect predators and vertebrate reservoirs (*71*).

Climate oscillations can affect the dynamics of dengue fever (*72*), which is transmitted by the predominantly urban mosquito *Aedes aegypti*. In Latin America, about 78% of the population — around 81 million people — live in urban settlements and the disease has been on the increase in the past decade (*51*). The influence of rising temperatures on the intensity and distribution of dengue fever transmission in the different continents has been estimated (*73*). With a rise of 2 °C by the end of the next century (*2*), the mean potential of transmission intensity could be expected to increase by a factor of 2–5 in most of South America. New areas of transmission areas are also expected to develop in the southern part of the continent.

In summary, the strong effects of El Niño on equatorial South America are likely to intensify the transmission of malaria and dengue fever. Human migration resulting from drought, environmental degradation and economic reasons may spread disease in unexpected ways, and new breeding sites for vectors may arise due to increasing poverty in urban areas and deforestation and environmental degradation in rural areas. Climate change will exacerbate these effects.

North America

Since 1900, average daily temperatures in the contiguous USA have increased by approximately 0.4 °C, with most of this increase occurring over the past 30 years (*74*). Recent studies have shown that the hydrological cycle is changing, with increases in cloud cover and precipitation (*75*). Extremes in precipitation have also changed with more frequent heavy precipitation events and fewer lighter precipitation events (*74, 76*). It is becoming increasingly apparent that measurable changes in climate trends are occurring (*77*).

The health risks arising from such climatic changes will differ between countries depending on health infrastructures. In Canada and the USA, good surveillance and vector-control programmes limit endemic transmission of diseases such as malaria and dengue fever. The health infrastructures of Mexico and other less developed nations are not so effective. Even in developed countries, increasing international travel and documented underreporting demonstrate a continued risk and need for strong surveillance (*78*).

The recent importation of West Nile viral encephalitis into the New York area in 1999 marked the first time West Nile virus had been found in North America (*79*). It is not yet known whether the extreme record-breaking summer drought along the east coast affected the *Culex* mosquito populations that can carry the virus. Birds are the natural hosts for West Nile virus.

The hard tick, *Ixodes scapularis*, transmits *Borrelia burgdorferis,* a spirochaete, and the causative agent for Lyme disease, the most common vector-borne disease in the USA, with 15 934 cases in 1998. Other tick-borne diseases are Rocky Mountain spotted fever and ehrlichiosis, the latter having first being recognized in the mid-1980s. The tick and host mammal populations involved are influenced by land use/land cover, soil type, elevation, and the timing, duration, and rate of change of temperature and moisture regimes (*80, 81*). The relationships between vector life stage parameters and climatic conditions have been verified experimentally in both field and laboratory studies (*80*). According to one modelling study, Rocky Mountain spotted fever may decline in the southern USA owing to tick intolerance of high temperatures and diminished humidity (*82*).

A temperature relationship for sporadic local malaria transmission was observed in New York and New Jersey during the 1990s; common to these outbreaks was exceptionally hot and humid weather that reduced the development time of malaria sporozoites sufficiently to render these northern anopheline mosquitoes infectious (*83, 84*). However, even when climate conditions have favoured local transmission, the size of outbreaks has so far remained small.

Dengue and dengue haemorrhagic fever are on the rise in the Americas (*85, 86*). Puerto Rico averages 10 000 dengue fever cases annually, and the condition now occurs in nearly all Caribbean countries and Mexico, and has been periodically endemic in Texas in the past two decades. Dengue viruses predominantly occur in the tropics between 30° N and 20° S (*87*), since frosts or sustained cold weather kill adult mosquitoes, over-wintering eggs, and larvae (*88, 89*). As mentioned above, global modelling studies have addressed transmission potential under climate change scenarios (*73, 90*). However, dengue fever is highly dependent on local environmental factors. The potential change in risk for three sites, Brownsville (TX), New Orleans, Louisiana, and sites in Puerto Rico has been analysed as part of the US National Assessment on Climate Variability and Change (Dana Focks et al., unpublished data, 2000). Thus far, only the analysis for Brownsville is complete. Use of a transient climate change scenario, based on the Hadley Centre's coupled atmosphere–ocean general circulation model (HadCM2), indicates that humidity falls dramatically in southern Texas as temperatures rise. The modelled transmission potential for dengue fever decreased for this site. This may not be the case, however, for the island situation of Puerto Rico.

Of reported encephalitis cases in the USA, most are mosquito-borne. Saint Louis encephalitis is the most prevalent (*91*); La Crosse encephalitis, and western, eastern, and Venezuelan equine encephalomyelitis also occur. Although mosquito longevity diminishes as temperatures rise, viral transmission rates (similar to dengue fever) rise sharply at higher temperatures (*92–94*). From field studies in California, researchers predict that a 3–5 °C temperature increase will cause a significant northern shift in both western equine and Saint Louis encephalitis outbreaks, with disappearance of western Venezuelan equine encephalitis in southern endemic regions (*94*). Human outbreaks of Saint Louis encephalitis are correlated with periods of several days when the temperature exceeds 30 °C (*95*) as was the case in the 1984 California epidemic. Computer analysis of monthly climate data has demonstrated that excessive rainfall in January and February, in combination with drought in July, most often precedes outbreaks (*96*). Such a pattern of warm, wet winters followed by hot, dry summers resembles some of the general circulation model projections for climate change over much of the USA (*97, 98*). Eastern equine encephalitis has been associated with warm wet summers along the east coast of the USA (*99*).

The pulmonary hantavirus epidemic in the south-west of the USA was believed to be due to an upsurge in rodent populations related to climate and ecological conditions (*100, 101*); six years of drought followed by extremely heavy spring rains in 1993 resulted in a 10-fold increase in the population of deer mice, which can carry hantavirus. Clusters of the disease have been spatially linked to areas with higher rainfall and vegetation following El Niño events (*102*). Similarly, the incidence flea-borne plague has been positively associated with preceding periods of heavy precipitation in the region (*103*).

Leptospirosis, carried by rodents, has been associated with flooding in Central America. For instance, in Nicaragua a case-control study of the 1995 epidemic found a 15-fold risk of the disease associated with walking through floodwaters (*104*). Leptospirosis is rarely reported in the USA. However, the disease is under-diagnosed (*105*).

Lyme disease and encephalitis will increasingly become public health threats in the USA, as suitable conditions for transmission increase. However, as understanding of the links between climate and these diseases increases, and climate predictions become better, methods of preventing outbreaks, e.g. through public health information, will improve. Although Lyme disease is treatable, it remains difficult to diagnose. Currently available standard laboratory tests are not fully satisfactory in that they lack sensitivity and specificity and are not well standardized. Under-diagnosis is a problem in parts of the USA where the disease is not endemic or is relatively uncommon. The number of mice and deer in a region influences the number of ticks found there. The recent resurgence of the deer population in the north-east USA and the incursion of suburban developments into rural areas where deer ticks are commonly found have probably been major contributors to rising prevalence.

Asia, Australia and the islands of the western Pacific

Asia spans tropical and temperate regions. *Plasmodium falciparum* and *P. vivax* malaria, dengue fever, dengue haemorrhagic fever, and schistosomiasis are endemic in parts of tropical Asia. In the past 100 years, mean surface temperatures have increased by 0.3–0.8 °C across the continent and are projected to rise by 0.4–4.5 °C by 2070 (*3*).

An increase in temperature, rainfall and humidity in some months in the Northwest Frontier Province of Pakistan has been associated with an increase in the incidence of *P. falciparum* malaria (*106*). In north-east Punjab, malaria epidemics increase five-fold in the year following an El Niño event, while in Sri Lanka the risk of malaria epidemics increases four-fold during an El Niño year. In Punjab, epidemics are associated with above-normal precipitation, and in Sri Lanka, with below-normal precipitation (*107*).

According to WHO, many countries in Asia experienced unusually high levels of dengue and/or dengue haemorrhagic fever in 1998, the activity being higher than in any other year. Changes in weather patterns, such as El Niño events, may be major contributing factors (*108*), since laboratory experiments have demonstrated that the incubation period of dengue 2 virus could be reduced from 12 days at 30 °C to 7 days at 32–35 °C in *Aedes aegypti* (*5*). Dengue fever has been reported in several small island states in the Pacific where rainfall and local temperatures correlate with the southern oscillation index, a component of the El Niño–Southern Oscillation phenomenon. Furthermore, a positive correlation was found between the index and dengue fever in 10 out of 14 such island states (*109*).

In east Asia and the Pacific, 41–79% of the national domestic product comes principally from urban areas. Urbanization levels range from 16% and 19% for Papua New Guinea and Viet Nam, respectively, to 82% in the Republic of Korea, and the rate of urbanization in this region over the period 2000–2005 is expected to be about 3.5%. This trend will increase still further the risks of disease transmission (A.K. Githeko, unpublished data, 1999).

In Australia, the major vector-borne diseases are caused by the arthritides Ross River and Barmah Forest viruses as well as the encephalitic Murray Valley virus. Transmission of these viruses is associated with the availability of mosquito breeding sites and suitable environmental conditions (*110*). Flooding has been associated with viral outbreaks.

Climate scenarios for Australia for 2030 indicate that temperatures will rise by 0.3–1.4 °C, with an overall tendency for rainfall to decrease. However, in recent decades average rainfall appears to have increased by 14% and heavy rainfall by 10–20%. The Australian climate exhibits high variability (*3*).

In New Zealand, there have been concerns that the changing environmental conditions, such as global warming, with concomitant effects on vector distribution, increasingly rapid air travel by viraemic persons, and the accidental introduction of new vector mosquitoes, particularly *Aedes albopictus*, could pose a threat in view of the high proportion of residents with no protective antibodies (*111*).

In Asia, dengue fever (*5*) and malaria (*106, 107*) have been associated with positive temperature and rainfall anomalies, while in Australia arboviral disease outbreaks are most frequently associated with flooding (*110*). Urban developments in Asia and the surrounding regions may have a substantial impact on trends in the transmission of dengue fever. In some areas, such as Viet Nam, effects of past civil instability and slow economic growth may also be implicated.

Conclusions

In addition to the existing drivers of vector-borne diseases, such as seasonal weather variation, socio-economic status, vector control programmes, environmental changes and drug resistance, climate change and variability are highly likely to influence current vector-borne disease epidemiology. The effects are likely to be expressed in many ways, from short-term epidemics to long-term gradual changes in disease trends. There is some epidemiological evidence to support this view. For example, recent results in Kenya suggest that anomalies in climate variability account for up to 26% of the anomalies in hospital-based highland malaria cases (A. K. Githeko, unpublished data, 2000). However, the contribution of all the factors affecting disease transmission and clinical outcomes needs to be taken into account (multivariate analysis). Currently there are few if any published data that provide such information, partly because the science of climate and health is not well developed. The fraction of changes in vector-borne diseases attributable to climate change is therefore still unknown. This is a serious obstacle to evidence-based health policy change. Although the impacts of climate variability on vector-borne diseases are relatively easy to detect, the same cannot be said of climate change because of the slow rate of change. Furthermore, it is possible that human populations may adapt to climate change thus minimizing the impacts. For example, in the African highlands malaria could gradually become stable and this would lead to a reduction in epidemics.

Adaptation to climate change and variability will depend to a certain extent on the level of health infrastructure in the affected regions. Moreover, the cost and efficacy of prevention and cure will be critical to disease management. Some regions, such as Africa and South America, have a great diversity of disease vectors that are sensitive to climate change and greater efforts and resources will be required to contain the expected change in disease epidemiology. Furthermore, climate variability, unlike any other epidemiological factor, has the potential to precipitate simultaneously multiple disease epidemics and other types of disasters. Climate change has far-reaching consequences that go beyond health and touch on all life-support systems. It is therefore a factor that should be rated high among those that affect human health and survival. ■

Résumé

Changement climatique et maladies à transmission vectorielle : une analyse régionale

La vie de l'homme est tributaire de la dynamique du système climatique de la planète. Ce sont les interactions de l'atmosphère, des océans, de la biosphère terrestre et de la biosphère marine, de la cryosphère et de la surface de la terre qui déterminent le climat en surface. La concentration des gaz à effet de serre dans l'atmosphère augmente principalement du fait de l'activité humaine et conduit à un réchauffement accru à la surface de la terre. On estime que la température mondiale augmentera en moyenne de 1,0 à 3,5 °C d'ici 2100, ce qui accroîtra la probabilité de nombreuses maladies à transmission vectorielle. L'effet le plus important du changement climatique sur la transmission devrait être observé aux extrêmes des fourchettes de température nécessaires à la transmission (14 à 18 °C au niveau inférieur et environ 35 à 40 °C au niveau supérieur).

Le climat tropical africain est favorable à la transmission de la plupart des principales maladies à transmission vectorielle, et notamment du paludisme, de la schistosomiase, de l'onchocercose, de la trypanosomiase, de la filariose, de la leishmaniose, de la peste, de la fièvre de la Vallée du Rift, de la fièvre jaune et des fièvres hémorragiques à tiques. On estime que, d'ici 2050, la température du Sahara et des zones semi-arides d'Afrique australe risque d'augmenter en moyenne de 1,6 °C, alors que des pays équatoriaux comme le Cameroun, le Kenya et l'Ouganda pourraient enregistrer une augmentation moyenne de 1,4 °C.

La température en Europe a augmenté de 0,8 °C au cours des 100 dernières années. Des flambées de paludisme ont récemment été observées en Arménie, en Azerbaïdjan, au Tadjikistan et en Turquie. Le changement climatique va probablement favoriser l'extension de la maladie vers le Nord, en particulier dans les pays de l'ex-Union soviétique où les ressources consacrées à la santé sont limitées.

La répartition des tiques est liée au climat et l'on craint que les maladies à tiques comme la maladie de Lyme et l'encéphalite à tiques ne se répandent en Europe septentrionale. Avec le réchauffement, les phlébotomes vecteurs de la leishmaniose risquent de devenir plus nombreux et de s'étendre vers le Nord.

En Amérique du Sud, le paludisme, la leishmaniose, la dengue, la maladie de Chagas et la schistosomiase sont les principales maladies à transmission vectorielle sensibles au climat. On peut en mentionner d'autres, comme la fièvre jaune, la peste, l'encéphalite équine vénézuélienne et plusieurs arboviroses de la région amazonienne, comme la fièvre d'Oropouche. La sécheresse, consécutive au phénomène El Niño, a poussé des populations du Brésil à quitter les zones rurales pour se rendre dans les villes à la recherche d'un emploi, ce qui a eu pour conséquence d'accroître la transmission du paludisme et de la leishmaniose en milieu urbain. On a également constaté une aggravation du paludisme à la suite de certaines inondations associées à El Niño.

Des modifications des tendances climatiques sont également observées de plus en plus aux Etats-Unis d'Amérique. C'est à des tiques ixodides que l'on doit la transmission de l'agent étiologique de la maladie de Lyme, la maladie à transmission vectorielle la plus courante dans ce pays. Le lien entre les paramètres des stades évolutifs du vecteur et les conditions climatiques a été vérifié expérimentalement, aussi bien sur le terrain qu'au laboratoire. Des études de terrain en Californie ont permis à des chercheurs de conclure qu'une augmentation de la température de 3 à 5 °C entraînera un déplacement significatif vers le Nord des poussées de fièvre équine vénézuélienne occidentale et d'encéphalite de Saint-Louis, avec une disparition de l'encéphalite équine occidentale dans les régions d'endémie australe.

Au cours des 100 dernières années, la température moyenne à la surface du globe a augmenté de 0,3 à 0,8 °C dans l'ensemble de l'Asie et devrait augmenter de 0,4 à 4,5 °C d'ici 2070. Au nord-est du Pendjab, les épidémies de paludisme ont quintuplé dans l'année suivant un phénomène El Niño, et à Sri Lanka le risque

d'épidémie de paludisme a quadruplé au cours d'une année El Niño. Des expériences au laboratoire ont démontré que la période d'incubation du virus de la dengue 2 peut être ramené de 12 jours à 30 °C à 7 jours à 32-35 °C chez *Aedes aegypti*. En Australie, les principales maladies à transmission vectorielle sont provoquées par les virus de la Ross River et Barmah Forest responsables de manifestations articulaires et par le virus de l'encéphale de la vallée de la Murray. La transmission de ces virus est associée à la présence de gîtes larvaires de moustiques et d'un environnement favorable.

Resumen

El cambio climático y las enfermedades transmitidas por vectores: un análisis regional

La vida humana depende de la dinámica del sistema climático de la Tierra. Las interacciones entre la atmósfera, los océanos, las biosferas terrestre y marina, la criosfera y la superficie terrestre determinan el clima de la superficie del planeta. La concentración atmosférica de los gases de efecto invernadero está aumentando debido principalmente a la actividad humana, provocando un recalentamiento de la superficie terrestre.

Se estima que la temperatura mundial habrá aumentado como promedio 1,0-3,5 °C para 2100, con lo que aumentará también el riesgo de enfermedades transmitidas por vectores. El mayor efecto del cambio climático en ese sentido se observará probablemente en los extremos del intervalo de temperaturas requerido para la transmisión (14-18 °C como límite inferior, y 35-40 °C como límite superior).

El clima africano tropical favorece la transmisión de la mayoría de las principales enfermedades mediadas por vectores, entre ellas el paludismo, la esquistosomiasis, la oncocercosis, la tripanosomiasis, la filariasis, la leishmaniasis, la peste, la fiebre del Valle del Rift, la fiebre amarilla y las fiebres hemorrágicas transmitidas por garrapatas. Se calcula que para 2050 el Sáhara y las zonas semiáridas de África meridional podrían experimentar un aumento medio de 1,6 °C, y países ecuatoriales como el Camerún, Kenya y Uganda podrían experimentar incrementos de 1,4 °C.

Europa se ha recalentado 0,8 °C durante los últimos 100 años. Recientemente se han registrado brotes de paludismo en Armenia, Azerbaiyán, Tayikistán y Turquía. Es probable que el cambio climático amplíe la distribución actual de la enfermedad a latitudes septentrionales, sobre todo en los países de la antigua Unión Soviética, donde los recursos de salud son escasos.

La distribución de las garrapatas depende del clima, de ahí la creciente preocupación por la posibilidad de que las enfermedades transmitidas por esos arácnidos, como la enfermedad de Lyme y la encefalitis transmitida por garrapatas, estén aumentando en la Europa del norte. A medida que el clima se hace más cálido, los flebótomos transmisores de la leishmaniasis tienden a proliferar con más intensidad y a propagarse hacia el norte.

En América del Sur, el paludismo, la leishmaniasis, el dengue, la enfermedad de Chagas y la esquistosomiasis son las principales enfermedades de transmisión vectorial sensibles al clima. Otras son la fiebre amarilla, la peste, la encefalitis equina venezolana y varias enfermedades arbovirales detectadas en la región amazónica, por ejemplo la fiebre de Oropouche. Como consecuencia de la sequía provocada por El Niño, las poblaciones humanas del Brasil migran de las zonas rurales a las urbanas en busca de trabajo, favoreciendo así la transmisión del paludismo y de la leishmaniasis en las ciudades. Sin embargo, se ha observado que el paludismo aumenta también tras las inundaciones asociadas a El Niño.

Cada vez son más los indicios de que está cambiando el clima en los Estados Unidos. Las garrapatas transmiten el agente causante de la enfermedad de Lyme, la dolencia de transmisión vectorial más común en los Estados Unidos. Se ha comprobado experimentalmente, en estudios tanto de campo como de laboratorio, la existencia de una relación entre los parámetros de las fases de la vida del vector y las condiciones climáticas. A partir de estudios sobre el terreno realizados en California, los investigadores predicen que un aumento de 3-5 °C de la temperatura causará un importante desplazamiento hacia el norte de los brotes tanto de la fiebre equina del oeste de Venezuela como de la encefalitis de Saint Louis, así como la desaparición de la encefalitis equina occidental en las regiones endémicas del sur.

Durante los últimos cien años las temperaturas superficiales medias han aumentado en 0,3-0,8 °C en el conjunto de Asia, y se prevé que para 2070 habrán aumentado en 0,4-4,5 °C. En el Punjab nororiental, las epidemias de paludismo se quintuplicaron a causa del fenómeno de El Niño registrado el año anterior, y en Sri Lanka el riesgo de epidemias de paludismo se multiplicó por cuatro durante un año de actividad de El Niño. Experimentos de laboratorio han demostrado que el periodo de incubación del virus 2 del dengue en *Aedes aegypti* podría reducirse de 12 días a 30 °C a 7 días a 32-35 °C. En Australia, las principales enfermedades transmitidas por vectores son las causadas por los virus Ross River y Barmah Forest de la artritis y el virus Murray Valley de la encefalitis. La transmisión de esos virus se asocia a la existencia de criaderos de mosquitos y a unas condiciones ambientales propicias.

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