

# Human Ecology and Human Behavior

Climate change and health in perspective

Paul Reiter



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The Civil Society Coalition on Climate Change seeks to educate the public about the science and economics of climate change in an impartial manner. It was established as a response to the many biased and alarmist claims about human-induced climate change, which are being used to justify calls for intervention and regulation.

The Coalition comprises over forty independent civil society organisations who share a commitment to improving public understanding about a range of public policy issues. All are non-profit organizations that are independent of political parties and government.

### About the author

**Paul Reiter** is a British scientist whose entire career has been devoted to the biology, ecology and behaviour of mosquitoes, the transmission dynamics and epidemiology of the diseases they transmit, and methods for their control. He worked for 22 years as a researcher in the Division of Vector-borne Infectious Diseases of the US Centers for Disease Control and Prevention (CDC). In 2003 he was appointed Professor at the Institut Pasteur, Paris, where he established a new unit of Insects and Infectious Disease.

He has led the entomological component of numerous field investigations of outbreaks of vector-borne disease on behalf of the US Government, the World Health Organization (WHO), and the Pan American Health Organization. He is a member of the WHO Expert Advisory Committee on Vector Biology and Control, and has served as a consultant to governments worldwide.

He has been actively involved in the international debate on climate change for more than a decade. He served as a lead author for the US National Assessment of Potential Consequences of Climate Variability and Change, and an Expert Reviewer for the Intergovernmental Panel on Climate Change Fourth Assessment Report. He is a frequent commentator in the news media on this and other issues that concern vector-borne disease.

# Human Ecology and Human Behavior

## Climate change and health in perspective

### Executive summary

Human ecology and human behavior are the two key factors that determine the transmission of human infectious diseases. When the cycle of transmission includes mosquitoes, ticks, rodents or other intermediaries, their ecology and behavior are also critical. When multiple species are involved, the levels of complexity are even greater. Lastly, the virulence of the pathogen, the susceptibility of its vectors and hosts, the immunity of those hosts and the collective immunity of the host populations all contribute to the force of transmission. The significance of climate factors can only be assessed in the perspective of this daunting complexity.

- **Enteric infections:** In the developing world, scarcity of basic needs such as shelter, food, clothing, electricity, clean water, education, and healthcare is the dominant factor in disease transmission. In wealthier countries, new and challenging problems have arisen as a result of economic success. Straightforward strategies are available to prevent infections in all these scenarios, given suitable economic resources. In nearly all cases, climate is at most a minor, often irrelevant parameter.
- **Mosquito-borne diseases:** Mosquitoes are found throughout the world in all climates. Meteorological variables are of limited value as a guide to the population densities, behavior and geographic range of vector species. The same is true for the pathogens they transmit. Future changes in climate may result in minor changes in prevalence and incidence of mosquito-borne diseases, but the critical factors will remain human ecology and human behavior.

- **Tick-borne diseases:** As with mosquito-borne diseases, the prevalence and incidence of tick-borne infections is affected by an incredible range of parameters. In northern temperate regions, for example, Tick-borne Encephalitis is influenced by agricultural practices, land-cover, populations of small mammals and their predators, small mammal immunology, population and behavior of large mammals, hunting, wild-life conservation, industrial activity, income levels, leisure activities, depth of winter snow, the micro timing of springtime temperatures, and summer rainfall and humidity. Moreover, the interaction of these variables is distributed over a two to three-year period. In the context of this complexity, it is ludicrous to claim a direct cause and effect relation between climate and infection.

In conclusion, it cannot be over-stressed that the ecology and natural history of disease transmission, particularly transmission by arthropods, involves the interplay of a daunting multitude of interacting factors that defy simplistic analysis. The rapid increase in the incidence of many diseases worldwide is a major cause for concern, but the principal determinants are politics, economics, human ecology and human behavior. A creative and organized application of resources to reverse this increase is urgently required, irrespective of any changes of climate.

### Introduction

There is a remarkable constancy in the majority of articles that have been published on climate change and infectious diseases. They name a disease, describe where

it occurs and how it is transmitted, and then make a succession of statements on the action of temperature and rainfall on specific components of its transmission cycle. These statements lead to conclusions that are persuasive because they are intuitive: tropical diseases will claim ever more victims in the (poorer) tropical countries and will move into temperate regions, those of temperate regions will move towards the poles, all will move to higher altitudes, and so on. Many of these predictions are backed by credible “evidence” that the process has already begun. Most are focused on arthropod-borne diseases<sup>1</sup>: there is a tragic increase in the death toll from malaria in the tropics, the disease is moving to higher altitudes, cases are occurring in Europe, ticks and tick-borne diseases are increasingly common and are moving northwards, chikungunya fever has appeared in Italy and the mosquito that transmits it is native to Asia. Enteric diseases also feature high on the list: epidemic cholera has appeared on the western seaboard of Latin America and epidemics of meningococcal meningitis are becoming more frequent in the Sahel. Many such articles focus on the vulnerability of people in poorer countries, and place the blame squarely on the activities of the industrial nations.

Articles structured in the same way, and with a similar message, are also common in the professional scientific press (WHO 1996, Lindgren and Gustafson 2001, McCarthy et al. 2001, Epstein 2005, Haines et al. 2006, McMichael et al. 2006, Menne and Ebi 2006). Some are based on mathematical models that select a climate variable (usually temperature), propose a direct interaction with a transmission parameter (i.e. multiplication of pathogen, survival of vector), and inevitably arrive at the same conclusions. In many cases it is clear that such articles have been written by persons with little or no background in the relevant field. A deplorable trend is the inclusion of a political message, much as in the popular media.

## Multiple depths of complexity

Two factors are key to the transmission of infectious diseases of humans: human ecology and human behavior. When the cycle of transmission includes mosquitoes, ticks, rodents or other intermediaries, their

ecology and behavior are also critical. When multiple species are involved, the levels of complexity are even greater. Lastly, the virulence<sup>2</sup> of the pathogen, the susceptibility of its hosts<sup>3</sup> and the immunity of the host populations can be critical at all levels.

Climate and weather<sup>4</sup> are often invoked as the dominant parameters in transmission, but their true significance can only be assessed in the perspective of this daunting complexity. Moreover, the key parameters – temperature, rainfall and humidity – cannot be viewed independently. The effects of temperature are modified by humidity. The daily range of each may be more significant than the daily mean. Brief periods of atypical heat or cold can be more significant than long-term averages. Heavy storms can have a different impact than light prolonged rainfall. One year’s events may have a significant impact on subsequent years.

There are several approaches to assess the significance of such parameters:

- The history of prevalence, incidence and geographic distribution in the context of the prevailing climate;
- Current prevalence, incidence and geographic distribution of disease under current climatic conditions;
- Targeted studies of incidence and prevalence, climate and weather;
- Empirical studies of climate parameters, pathogens and vectors in the laboratory
- Models that seek to describe transmission in mathematical terms.

### *History*

Systematic records of climate, mainly from a small number of land-based stations in the Northern Hemisphere, are only available for the past century or so. Global data, obtained by weather balloons and weather satellites, are only available for the past few decades. Nevertheless, a large amount of proxy information is available (Grove 1988, Lamb 1995, Le Roy Ladurie 1971). Archival materials are a rich source of indirect information, particularly on the timing and occurrence of drought, flood, unusual heat, cold or other extreme weather events. A wide range of evidence is also

available from archaeological, geological, fossil and other sources.

Literate, scholarly systems of medicine dating back more than 3,000 years are available for many parts of the world. Pathological signs in bones, fossil excreta and other items can be studied in archaeological material. Molecular techniques can yield additional information from such remains. In Europe, parish records, the diaries and publications of physicians and other archival material are a rich source of information. Thus, as with climatology, we can turn to a variety of sources for evidence of diseases in past climates.

### *Climate and current distributions of disease*

The distribution of many diseases coincides with certain climate patterns, but in many cases the reverse does not hold true. For example, malaria disappeared “spontaneously” from large areas of Western Europe and North America after the mid-1800s, precisely the period when the current warming trend began (Reiter 2001).

### *Short-term climate variations (weather) and disease transmission*

Favorable weather incidents may result in increased transmission, but here again, caution is needed when extrapolating to future incidence. For example, short periods of drought may reduce malaria transmission, whereas longer periods can initiate epidemics (Macdonald 1973).

### *Laboratory studies*

Some parameters can be measured in the laboratory (Christophers 1960, Monath 1998). Thus, the duration of the extrinsic incubation period – the time required for a vector to become infective after it takes an infected blood meal – is inversely proportional to temperature. In most parts of the tropics, however, temperatures are more than adequate for rapid incubation, so higher temperatures are unlikely to result in a significant increase in transmission. Indeed, higher temperatures, particularly at low humidity, may reduce the life-span of the vector, which is by far the most significant parameter in the dynamics of transmission (see page 20).

### *Mathematical models*

At the start of the 20th Century, Sir Ronald Ross stepped beyond intuition by building simple mathematical models to describe the cycle of malaria transmission. The advent of low-cost computers has propelled mathematical modeling into a major role in the description of complex systems, including ecology, epidemiology and public health (Murray 2002). Most models are constructed from variables, and the interactions between these variables are driven by sets of equations that are termed operators. The approach involves many new and rapidly evolving techniques but is often too abstract and esoteric to be understood by non-mathematicians.

Complex systems imply the need for a large number of variables and operators, but as this number increases, so does the variance – and the uncertainty – of the models.

In a sense, therefore, models are an extension of the intuitive approach because the ultimate selection of variables, the mathematical descriptors of the operators, and the constraints on both are made by the modeler. This is not to say that such models are inappropriate. On the contrary, they represent an important and exciting advance in epidemiology and related fields. Nevertheless, the selection of variables is a critical, but often unmentioned, constraint in forecasts of the impacts of future climate change on human health, not to mention on the forecasts of the climates on which they are based.

In conclusion, a holistic view of the role of human behavior and human ecology in the natural history and dynamics of an infectious disease is the only valid starting point for a study of the significance of climate parameters in its transmission. Having established what we understand and don't understand about the system as a whole, we can begin to speculate on future scenarios in the context of changing climates.

## First level of complexity: enteric diseases

Enteric infections kill nearly 2 million people per year. According to the World Health Organization, they are the second highest cause of death from infectious disease (WHO 2003). Transmission is from person to

person, either directly or through contaminated food and water. They are an outstanding illustration of the dominant role of human ecology and human behavior in the dynamics of transmission (Levine and Levine 1995). It is informative to examine the natural history of these diseases in detail and in the context of repeated claims that their incidence is likely to change as a result of climate change.

## Background

In much of the developing world, particularly in the crowded conditions of rapidly urbanizing populations, pervasive faecal contamination of food and water presents ideal conditions for transmission of a host of bacterial, protozoal, parasitic and viral diseases. By contrast, in the industrialized regions of the world, distinct patterns of diarrhoeal disease are occurring with increasing frequency, despite piped water, flush toilets, wastewater treatment, microbiologically monitored drinking water, adequate housing and widespread awareness of the importance of faecal-oral hygiene.

### *Enteric disease and industrialization*

The filth and festering poverty of 19th Century London described by Charles Dickens – crowded conditions, open sewers, offal and garbage in the streets, rag-pickers, “swill children” and other scavengers – were as typical of the great cities of Europe and North America as they are of urban populations in much of the developing world today. The only difference is one of degree; 19th Century cities were tiny compared to today’s burgeoning mega cities.

Cholera (Sack et al. 2004) and typhoid (WHO 2007a) were the dreaded diseases of Dickens’ era, killing tens of thousands in pandemics that swept around the world. These pandemics were a classic example of the role of transportation and human mobility in the dissemination of pathogens. In the modern world, this factor is ever more prevalent. The only major difference is in the mode, speed of transport, and sheer volume of traffic.

Ten global pandemics of cholera are recognized from the start of the 19th Century until recent times. The bacterial pathogen *Vibrio cholera* sailed from port to port in contaminated kegs of water and in the excrement of

shipboard victims. Progression by land was somewhat slower, but remorseless. The first cases to reach Western Europe were in the 1820s. Sunderland, an industrial town in northeast England, was hit in the winter of 1831. Other British cities were rapidly affected, as well as many in Western Europe and North America. In one month, for example, 1,220 immigrants to Montreal, Canada, were dead on arrival, and the disease spread rapidly to Quebec and other cities, killing tens of thousands. In many cases, the wealthier classes were the least affected. Indeed, when the first epidemic hit Paris in 1832, the contrast was so obvious that some believed it was a plot by the aristocracy to weed out the poor.

A second pandemic reached England in 1854 and raged for more than two years. John Snow’s classic epidemiological study, in which he pin-pointed a water pump as the source of local infections by mapping the distribution of cases (McLeod 2000), led to the creation of public health agencies, the introduction of sand filtration, chlorination of water, an extensive system of water-mains, sanitary disposal of sewage, and public education in basic concepts of hygiene. By the turn of the 20th Century, cholera and typhoid were relatively rare in London and in most of the economically advanced cities of Western Europe and North America.

## Enteric diseases in developing countries

### *Urban ecology*

In most economically advanced countries, public sanitation, enforced by strict legislation, is so much a part of urban infrastructure that many inhabitants are hardly aware of its existence. Such measures are non-existent, or at best inadequate, in much of the rest of the world. Rapid urbanization and high birth rates are dominant factors in the ever-increasing toll of viral, bacterial and protozoal diseases. In much of the world, it is not uncommon for children less than two years old to suffer severe diarrhoeal illness for four to six months in the first two years of life, with more than one-third of all deaths in this age group attributable to such infections (WHO 2007b).

### *Changing patterns of agriculture*

Human and animal faeces are used as fertilizer to boost food production in many countries, with obvious

dangers. In some countries, farmers who switch to a single cash crop (sugar, coffee, cocoa) may do so at the expense of staple food crops (Levine and Levine 1995). This may render children prey to malnutrition and infection if substitute diets are deficient in essential nutrients. In some countries, population pressures and other factors have forced rural people from relatively isolated hamlets and villages to larger agricultural communities, with attendant problems of sanitation and disease transmission (Kennedy et al. 1992).

### *War and civil strife*

Throughout history, war has been a major, often dominant human behavioral factor in public health. Today, as never before, conflicts in dozens of countries are responsible for mass displacement of populations, with accompanying malnutrition and disease. The ecology of enormous refugee camps provides an optimum environment for enteric disease and many other types of infection. Death rates are frequently measured in days, rather than years. This scenario is not restricted to the developing world. For example, disruption of public health infrastructure resulted in a high incidence of diarrhoeal disease in Europe during the Balkan wars in the 1980s (Weiss and McMichael 2004).

### *Maternal behavior*

In many developing countries, the incorporation of women into the workforce has led to a major decline in breast-feeding. Breast milk is bacteriologically sterile, and contains antibodies and non-immunological anti-bacterial systems that are highly effective against enteric infections (Reiter 1985). Infants deprived of this protective nutrition are particularly prone to intestinal infection (Qureshi et al. 2006).

Early weaning of infants is encouraged by availability of manufactured substitutes, often backed by persuasive advertising. Apart from the absence of anti-bacterial components, the dilution of such formulae with contaminated water is a dangerous route to severe infection (Horton et al. 1996).

## **Enteric disease in wealthy industrialized countries**

### *Imports of food from developing countries*

The advent of cheap transport by air and sea has provided poor countries with a valuable source of foreign currency through exports of agricultural products. In a number of instances, unexpected outbreaks of bacterial and protozoal disease have been traced to these exports. In 2000, for example, widespread infections by *Cyclospora cayentanensis*, an intestinal protozoan, occurred in the United States as a result of imports of faecally contaminated raspberries from Guatemala (Ho et al. 2002). In another instance an outbreak of cholera in Maryland, USA, was traced to contaminated frozen coconut milk imported from Thailand (Taylor et al. 1993).

### *Mass production and consumption of food*

Economies of scale have led to a revolution in food production and food consumption, particularly in industrialized countries. Intensive farming of chickens and eggs in densely packed indoor colonies numbering hundreds of thousands of birds provides an ideal environment for enteric pathogens, particularly *Salmonella* and *Campylobacter*. Consumption of uncooked or partly cooked products of such "farms" has resulted in several major epidemics in northern Europe and North America.

Fast food chains are a major component in food consumption in wealthy countries, and, to an increasing extent, in those with emerging economies. These chains rely on a brand identity that requires strict standardization of the end product on a national and even international scale. Here again, economies of scale require centralized, mass-production and mass-preparation of the basic ingredients, followed by dissemination over long distances.

Unsanitary preparation and cooking practices can lead to huge and widely disseminated outbreaks of enteric infection (Tuttle et al. 1999). A classic example was the entero-haemorrhagic strain of *E. coli* that emerged in Europe and the United States in the 1980s, infecting tens of thousands of people, with a significant proportion of severe, sometimes fatal illness (Jay et al. 2004). These epidemics were traced to intensive cattle

rearing and insufficient cooking of meat processed as hamburgers. Interestingly, this pathogen is uncommon in poorer countries, where intensive livestock rearing and fast-food chains are less common.

### *Day-care centres*

Just as in poorer countries, the children of working women in industrialized countries are weaned early in order for their mothers to return to work. Problems of infected food are reduced by sterile prepared foods, availability of clean water, and attention to personal hygiene, but the crowded conditions of nursery schools, particularly in low income neighbourhoods, have led to a high prevalence of enteric pathogens such as *Giardia* and *Shigella* (O'Donnell et al. 2002).

### *Hospitals*

Hospitals are close-packed communities of people under the care of staff who are in close contact with multiple patients, many of whom arrive with low defense against infection. For this and other reasons, diarrhoeal disease among hospital patients is an increasingly serious problem in many technically advanced countries (O'Brien et al. 2007). In the UK, for example, hospital deaths as a result of infection by the spore-forming bacillus *Clostridium difficile* account for nearly as many deaths as those from road accidents. Control of *C. difficile* is difficult because of rapidly increasing resistance to a wide range of antibiotics, and because normal alcohol scrubs and other sanitary measures are ineffective (McMaster-Baxter and Musher 2007).

### *Geriatric wards and homes for the elderly*

A similar ecological niche exists in colonies of elderly persons. In many cases, low stomach acidity allows living pathogens to pass easily through the stomach (Morley 2007). Other factors include chronic disease and poor personal hygiene. Breakdowns in food-hygiene in such institutions can result in outbreaks of enteric disease with high fatality.

### *International travel*

Traveler's diarrhoea is a familiar term for a condition that affects persons from affluent countries when they visit countries with relatively unhygienic conditions and a higher incidence of enteric disease. Cheap air travel

exposes millions of people to such infections during holidays abroad. Outbreaks of similar infections on cruise ships are another example of recreational exposure.

## Summary

The dominant theme of the examples above, and of those that follow, is that human health is determined by a constellation of events and circumstances. In the developing world, the main defects are in the social matrix: a scarcity of basic needs: shelter, food, clothing, electricity, clean water, a safe living environment, education and access to healthcare. In wealthier countries, new and challenging problems have arisen as a direct result of economic success. In both cases, straightforward strategies are available to correct the problems, given suitable economic circumstances. New technologies, such as the development of genetically modified food-crops and novel methods for control of pathogens, will also become available. In nearly all cases, climate is at most a minor, often irrelevant parameter. A continued, obsessive emphasis on climate change is unwarranted, and will misdirect efforts to implement these strategies.

## Second level of complexity: mosquito-borne diseases

Speculations on the potential impact of global warming on human health often focus on the mosquito-borne diseases. Predictions are common that malaria will move into Europe, that dengue is increasing its range in the tropics, that mild winters enabled West Nile virus to become enzootic in the United States, and so on. A search of the electronic catalogue of the National Library of Medicine (PubMed) listed more than 200 articles on climate change and health, the majority citing vector-borne diseases, particularly malaria. Many are simply speculative reviews with liberal quotation from other reviews, frequently written by the same authors (Haines et al. 1993, Martens et al. 1995a, Martens 1995, Martens et al. 1995b, Patz et al. 1996, Epstein 1997, Epstein et al. 1998, Haines 1998, Lindsay and Martens 1998, McMichael et al. 1998, Patz et al. 1998, Kovats et al. 1999, Patz and Lindsay 1999, Epstein 2000, Githeko et al. 2000, Haines et al. 2000, Kovats 2000, Patz et al.

2000, Haines 2001, Kovats et al. 2001, Patz and Reisen 2001, Patz et al. 2002, Patz and Kovats 2002, Bunyavanich et al. 2003, Hales and Woodward 2003, 2005, Casimiro et al. 2006, Patz and Olson 2006)<sup>5</sup>.

These authors, their deluge of publications, and the enormous media attention that they generate, have had a major impact on public perceptions of climate and malaria. Moreover, eight of them have had important input in the health chapters of the reports of the Intergovernmental Panel on Climate Change (IPCC), and one (Paul Epstein) is one of “a small group” of twelve persons that former US Vice-President Al Gore cites as having “played a particular role in advising me” in his highly successful books and Oscar winning film (Gore 2006). In 2007, Gore and the IPCC were jointly awarded the Nobel Peace Prize for their efforts.

## Background

Many people are unaware that there are more than 3,500 species of mosquitoes, that they are found throughout the world in all climates, and that colossal numbers breed in snowmelt pools that overlie the permafrost in the Arctic tundra.

In nearly all species, the female obtains the protein she needs to develop her eggs by feeding on vertebrate blood. Some species are highly selective, restricting themselves to one, or at most a few closely related host species. Others have a less clearly defined diet, and may alternate between birds, mammals and even reptiles.

If the blood meal contains a pathogen, the mosquito herself must become infected before she transmits to the next host. More specifically, the pathogen must infect her salivary glands, because transmission occurs by injection of salivary secretions during a subsequent blood meal. The period from ingestion to infection of the salivary glands is termed the extrinsic incubation period, and is shorter at higher temperatures (Gilles and Warrell 1993).

There is a widespread misconception that mosquito-borne diseases require tropical temperatures, or at least the temperatures of the warmer regions of temperate regions. A glance at a map of global isotherms reveals that summer temperatures in many temperate regions are at least as high as in the warmest seasons of many

regions in the tropics. The crucial difference is that the tropics do not have cold winters. Moreover, if tropical mosquito-borne pathogens are introduced to temperate regions in the right season, they can be transmitted if suitable vectors are present (Reiter 2001).

There is also a misconception that mosquitoes die in winter, and that more die in colder winters, but it is obvious that mosquitoes native to temperate regions have evolved strategies to survive low temperatures. In the tropics, comparable adaptations are necessary for surviving unfavorable dry periods, which may last for several years. In both cases, such adaptations merely impose a seasonality on transmission. In southern Europe, for example, *Plasmodium falciparum* (the most dangerous species of malarial pathogen) was transmitted from July to September (Bruce-Chwatt and de Zulueta 1980). In Mali, where the disease is still endemic, it is limited to the same three months by the dry season (Craig et al. 1999).

The physical environment is an important modifier of local climate. *Anopheles arabiensis*, an important vector of malaria in Africa<sup>6</sup>, can survive in the Sudan when outdoor temperatures are above 55°C by hiding in the thatch of buildings in the daytime, feeding after midnight, and laying eggs at dawn or dusk (Omer and Cloudsley-Thompson 1970). In Lapland, *Anopheles maculipennis* can survive the winter in houses and stables, feeding occasionally, and even (in the past) transmitting malaria when outdoor temperatures were below –40°C (Hulden et al. 2005).

*Culex pipiens*, a vector of West Nile virus in the northern hemisphere, is common as far north as Nova Scotia and Finland. It overwinters in the adult stage; I have collected live specimens in Tennessee that were sheltering at –20°C. *Aedes aegypti*, the principal urban vector of dengue and yellow fever, is a tropical species for which temperatures below 0°C are fatal, but its range extends in 11 states from Texas to South Carolina, surviving the sub-zero winter temperatures in niches protected from the cold (Carpenter and LaCasse 1955). Thus, meteorological variables alone are of limited value as a guide to the development times, behavior and geographic range of vector species, and the same is true for the pathogens they transmit.

## Malaria in temperate climates

*“Everything about malaria is so moulded and altered by local conditions that it becomes a thousand different diseases and epidemiological puzzles. Like chess, it is played with a few pieces, but is capable of an infinite variety of situations”*

*Malaria in Europe, An Ecological Study (Hackett 1937)*

Malaria is the most important of all mosquito-borne diseases. Each year, 350–500 million cases of malaria occur worldwide, and over a million people die, most of them young children in sub-Saharan Africa (WHO 2003). This appalling toll is mainly restricted to the tropics, but less than forty years have passed since the final eradication of the disease from Europe. It is instructive to review the history of the disease in Europe in the context of the continuous natural variation of climate, both in temperate and tropical climates.

More than sixty species of *Anopheles* mosquitoes are capable of transmitting human malaria. Those that exist in Europe probably began colonizing the region as the icecaps retreated, at the end of the Pleistocene (approximately 11,550 years before present). Human populations, also moving northward, almost certainly brought malaria parasites along with them. The introduction of agriculture around 7,000 BC led to larger populations of relatively settled people, and increasingly favorable conditions for malaria transmission. Extensive deforestation may have also contributed to prevalence, by creating additional habitat for anopheline mosquitoes. Similar ecological changes in modern times have caused major increases in the prevalence of the disease in the tropics.

Malaria was common in ancient Greece and imperial Rome. Hippocrates (460–377 BC) gave detailed descriptions of the course of infections and their association with wetlands. He even noted that splenomegaly (enlarged spleen, often a symptom of chronic malaria infection) was particularly prevalent in people living in marshy areas. The Pontine Marshes, close to Rome, were notorious as a source of infection, and it is clear from descriptions of the symptoms and treatment of ‘intermittent fevers’ that three species of

parasite – *P. falciparum*, *P. ovale* and *P. vivax* – were common (Bruce-Chwatt and de Zulueta 1980).

After the fall of the Roman Empire, the armies of Visigoths, Vandals, Ostrogoths and other ‘barbarians’ that swept the continent had to contend with malaria, often as a major setback to their campaigns. Several popes and churchmen, including St Augustine, the first Archbishop of Canterbury, died of malaria during their journeys to Rome.

During the “Medieval Warm Period”, which reached its peak around the year 1200 AD, ‘agues’, ‘intermittent fevers’ ‘tertians’, ‘quartans’ were described from caliphate Spain to Christian Russia. In the first decades of the 15th Century, a rapid cooling trend caused many years of famine and a large-scale abandonment of farms, but malaria persisted, even in northern regions.

The first half of the 16th Century was warm again, but the period from the 1550s to the early 18th Century – dubbed the Little Ice Age – was probably the coldest of any time since the end of the last major ice age. Despite this spectacular cooling, malaria persisted throughout Europe (Reiter 2000). Data from burial records around the Thames estuary reveal mortality in “marsh parishes” comparable to that in areas of transmission in sub-Saharan Africa today (Dobson 1989, 1997).

Temperatures were probably at their lowest from 1670 to 1700, yet during that period Robert Talbor (c.1642–1681) became an exceedingly wealthy man by selling an effective prescription for curing malaria to the European aristocracy. His concoction was based on cinchona bark, and he had developed it by experimenting on malarious patients in the marshlands of Essex.

In the 18th and 19th Centuries, malaria was common in most of England and in many parts of Scotland. It was endemic throughout Denmark, coastal areas of southern Norway, and much of southern Sweden and Finland. In Russia it was common in the Baltic provinces and eastward at similar latitudes throughout Siberia. The northern limit of transmission was roughly defined by the present 15°C July isotherm (not the 15°C *winter* isotherm cited by the Intergovernmental Panel on Climate Change)(IPCC 1996).

## Spontaneous decline

In the second half of the 19th Century, malaria began to decline in much of northern Europe. Denmark suffered devastating epidemics until the 1860s, particularly in the countryside around Copenhagen, but thereafter transmission diminished and essentially had disappeared around the turn of the 20th Century. The picture was similar in Sweden, although isolated cases were still being reported until 1939 (Renkonen 1944). In England, there was a gradual decrease in transmission until the 1880s, after which it dropped precipitously and became relatively rare except in a short period following World War I. In Germany, transmission also diminished rapidly; after World War I it was mainly confined to a few marshy localities (Bruce-Chwatt and de Zulueta 1980).

The decline of malaria in all these countries cannot be attributed to climate change, for it occurred during a warming phase, when temperatures were already much higher than in the Little Ice Age. Nor can it be attributed to deliberate mosquito control, for it came before recognition of the role played by the vector. A number of other factors, however, can be identified, all attributable to the ecology and behavior of both the vectors and its hosts:

### *Ecology of the landscape*

Improved drainage, reclamation of swampy land for cultivation and the adoption of new farming methods (there is an old Italian saying: “malaria flees before the plough”) all served to eliminate mosquito habitat.

### *New farm crops*

New root crops, such as turnips and mangel-wurzels were adopted as winter fodder. These enabled farmers to maintain larger numbers of animals throughout the year, thus diverting mosquitoes from feeding on humans.

### *New rearing practices*

Selective breeding of cattle, and new introductions (e.g. the Chinese domestic pig), in combination with the new fodder crops, enabled farmers to keep large populations of stock in farm buildings rather than in open fields and woodland. These buildings provided attractive sites for

adult mosquitoes to rest and feed, diverting them from human habitation.

### *Mechanization*

Rural populations declined as manual labor was replaced by machinery. This further reduced the availability of humans versus animals as hosts for the mosquitoes, and of humans as hosts for the parasite.

### *Human living conditions*

New building materials and improvements in construction methods made houses more mosquito-proof, especially in winter, another factor that reduced contact with the vector.

### *Medical care*

Greater access to medical care, and wider use of quinine (in part due to a major reduction in price) reduced the survival rate of the malaria parasite in its human host.

### *Control campaigns*

In countries where profound changes in crop production and stock rearing were absent, malaria did not decline “spontaneously” (Bruce-Chwatt and de Zulueta 1980). In Russia, for example, from the Black Sea to Siberia, major epidemics occurred throughout the 19th Century, and the disease remained one of the principal public health problems for the entire first half of the 20th Century.

In the 1920s, in the wake of massive social and economic disruption, a pandemic swept through the entire Soviet Union. Official figures for 1923–25 listed 16.5 million cases, of which no less than 600,000 were fatal (Bruce-Chwatt and de Zulueta 1980). Tens of thousands of infections, many caused by *P. falciparum*, occurred as far north as the Arctic seaport of Archangel (61° 30'N). A huge, multi-faceted anti-malaria campaign was initiated in 1951. It involved widespread use of DDT and other residual insecticides, antimalarial therapy, land reclamation, water management, public health education and other approaches. This mammoth effort finally brought about a dramatic reduction of transmission; by the mid-1950s the national annual incidence was below one per 10,000.

The contrast between the devastation caused by malaria

in the Soviet Union until the 1950s, and its quiet withdrawal from other European countries in the previous century, is a vivid illustration of the importance of non-climatic factors in transmission. Until the collectivization of farmland that began in the winter of 1929–30, the Soviet Union had been largely unaffected by the agricultural revolution. By 1936, all farming was essentially in government hands, but in protest, many peasants slaughtered their horses and livestock, and destroyed their equipment. These events ran counter to many of the changes that had reduced transmission in much of Europe (Reiter 2001).

Malaria remained highly prevalent in much of Mediterranean Europe, the Balkans, and the countries bordering the Black Sea until after World War II. Much of the region had been relatively unaffected by the environmental changes associated with modern agriculture. Part of this lack of change can be attributed to the disease itself, for poverty and lack of progress characterized many of the highly malarious regions. In northern Italy, for example, much of Piedmont and Lombardy was free of transmission. By contrast, large portions of the rest of the country, particularly in Sardinia, Calabria and Sicily, remained virtually uncultivated until the 1950s, at least in part because of the ravages of the disease. The same was true for major regions in Spain, Greece, Romania and Bulgaria.

The advent of DDT revolutionized malaria control. Cheap, safe, effective applications of the chemical could be targeted at the site where most infections occur – in the home. Initial efforts in Italy, Cyprus and Greece were so successful that a decision was made to eradicate the disease from all of Europe. The entire continent was finally declared free of endemic malaria in 1975. One of the last countries affected was Holland.

The history of the decline of malaria in North America is similar to that of Europe. In the 1880s, the disease was widespread in nearly all states east of the Rocky Mountains, from the semitropical Gulf Coast states to the northern border and into Canada (Fisk 1931, Faust 1941). It was also present west of the Rocky Mountains, particularly in areas where rainfall is abundant. As living conditions improved, and antimalarial drugs became more widely available, the incidence of the disease declined (Moulton 1941). In 1946 the United States

Congress established a new agency, the Communicable Disease Center. This was the forerunner of the U.S. Centers for Disease Control and Prevention (CDC), and its principal mission was to eradicate malaria from the entire country. Its headquarters were in Atlanta, Georgia, because the southern states were the main region still affected by the disease. The disease was finally eradicated in the late 1950's. Today, as in Europe, there are many parts of the country where anopheline vectors are abundant, but the transmission cycles have been disrupted and the pathogens are absent.

## **Malaria in the tropics**

Increases in the incidence of malaria in the tropics are frequently attributed to climate change but this claim ignores fundamental concepts in the dynamics of transmission. Among these, the concept of *stability* is critical.

In much of equatorial Africa, parts of northern India, Indonesia, South America and elsewhere, transmission is termed *stable* because it is fairly constant from year to year. The disease is endemic, but epidemics are uncommon. In other regions, including much of India, Southeast Asia, Central and South America, the disease is also endemic but is termed *unstable* because transmission can vary greatly from year to year, and the potential for epidemics is high.

These terms are, of course, a simplification; there is a wide range of degrees of stability, depending on complex factors in local circumstances. The examples below refer to sub-Saharan Africa, because it is the focus of much of the scientific and public debate, but the principles involved apply to many other parts of the world.

### *Stable endemic malaria*

In regions where the anophelines are anthropophilic (prefer to feed on humans) and have a high survival rate (see page 17), transmission is usually stable. The disease is hard to control because transmission is efficient and transmission rates are so high that most people experience many infective bites per year. Severe illness and mortality occurs mainly among “new arrivals,” i.e. children and non-immune immigrants. Older inhabitants have survived multiple infections and



maintain a degree of immunity by repeated re-infection. They can have bouts of illness that may be life-threatening, but are usually relatively mild.

*Unstable endemic malaria*

This generally occurs in regions where the anophelines are zoophilic (bite animals as well as humans), or their survival rates are low, or where both apply. Transmission can vary greatly from year to year, with epidemics separated by many years of relatively low activity.

**Behavioral and ecological factors that affect transmission**

As in temperate regions, the behavior and ecology of vector and host are the dominant factors in transmission, and as with enteric diseases, many can be attributed to explosive population growth and poverty.

*Birth rate*

The world's population has grown from 2.5 billion in 1950 to 6.2 billion in 2007. In sub-Saharan Africa, there are now nearly five times as many people (ca. 750 million) as there were in 1955. In some countries, more than half the population is under 15 years of age. A high

birth rate invokes a high incidence among “new arrivals”, and thus of new infections. Clinical studies in some parts of Africa quote 998 infections per 1000 infants (Snow et al. 1999).

## *Forest clearance*

Many malaria vectors breed in open sunlit pools. Forest clearance provides abundant new habitat for these species, a classic cause of the emergence of malaria problems (Walsh et al. 1993).

## *Agriculture*

Irrigation creates an ideal habitat for mass-production of mosquitoes, as can construction of dams for hydroelectric power. Rice cultivation provides an environment for many of the most efficient malaria vectors. Conversely, the cultivation of ground depressions can suppress such vectors and thereby reduce transmission (Mouchet et al.).

## *Movement of people*

Infected people in pursuit of work can introduce malaria to areas where it is rare. Non-immune people are at high risk if they move to areas of transmission. Extensive road building and modern transportation have greatly exacerbated this factor.

## *Urbanization*

Water storage and inadequate water disposal can provide habitat for mosquitoes, particularly in rapidly expanding urban areas. The absence of cattle can promote stable transmission by forcing zoophilic species to feed on people. Moreover, many tropical cities are surrounded by densely populated satellite settlements that are essentially rural in nature.

## *Insecticide resistance*

*Physiological resistance* to insecticides is common in many regions. *Behavioral resistance* can also be a major problem: species that prefer to feed and rest indoors (*endophilic*) can switch to outdoor (*exophilic*) activity in response to treatment of indoor surfaces with insecticides.

## *Drug resistance*

In many parts of the world, the malaria parasite has

evolved resistance to commonly used anti-malarial drugs. Substitutes are available, but are much more expensive.

## *Degradation of the health infrastructure*

Lack of funding, institutional difficulties, rapid urbanization and other problems associated with rapid development have eroded the public health sector of many countries. In addition, the AIDS pandemic has overwhelmed the ability of authorities to deal with other diseases.

## *War and civil strife*

In times of conflict, mass movements of people, e.g. soldiers and refugees, often promote malaria transmission. The breakdown of public health services, damage to water distribution and drainage systems, and the destruction of homes often exacerbate the situation. High concentrations of people in camps for displaced persons can also be disastrous.

## **Climatic factors that affect transmission**

The distribution of climates suitable for endemic malaria transmission in sub-Saharan Africa is shown in Figure 1. It is clear that the vast majority of people in Africa live in regions of stable endemic transmission. In other words, throughout their lives, people living in the grey areas of the map are regularly exposed to multiple bites from infective mosquitoes; studies in some regions have shown that people experience up to 300 infective bites per year. Under such circumstances, just as it is impossible to pour more water into a glass that is already full, it is illogical to suggest that increased temperatures will result in an increased incidence of infections.

In regions of unstable, epidemic transmission, incidence may be affected by variations in climatic factors, but the relationships are often complex and counterintuitive, and in many cases the factors that precipitate transmission are unclear.

## *Temperature*

High temperatures should increase the likelihood of transmission because they reduce the extrinsic incubation period, but the frequency of biting, egg

laying and other behaviors are also likely to accelerate. These are high-risk activities, so survival – and thus transmission rate – may also be affected (see page 17).

#### Humidity

Survival may be reduced when hot weather is accompanied by low humidity, but in areas where such conditions are normal, local species are adapted to cope with them. For example, in the severe drought and extreme heat of the dry season in semi-arid parts of the Sudan, female *Anopheles arabiensis* survive for up to eleven months of the year by resting in dwelling huts, wells and other sheltered places (Omer and Cloudsley-Thompson 1970). Blood feeding continues, so transmission is not interrupted, but eggs do not develop until the rains return. This *gonotrophic dissociation* is remarkably similar to the winter survival of *An. atroparvus* in Holland and other parts of Europe in the past (Bruce-Chwatt and de Zulueta 1980). In both cases, inactivity leads to a high survival rate and continued transmission of malaria, even under adverse climatic conditions.

#### Rainfall

Rainfall can promote transmission by creating ground pools and other breeding sites, but heavy rains can have a flushing effect, cleansing such sites of their mosquitoes. Drought may eliminate standing water, but cause flowing water to stagnate. Thus, in arid areas, prolonged drought may cause malaria to decline, whereas in areas where rainfall is normally abundant, vast numbers of mosquitoes can be produced and “drought malaria” may follow. The same applies to artificial streams in irrigated regions and storm drains and sewers in urban areas. Drought may also stimulate people to store water in cisterns, drums and other man-made containers that serve as breeding sites.

The complexity of the influence of climate on malaria transmission in the tropics is well illustrated by the history of epidemics in Sri Lanka (Macdonald 1973). In the 1930s, the disease was common. In a “normal” year, 1.5 million cases – about a quarter of the total population – were treated in hospitals and dispensaries. However, in the years 1934–35 there was a catastrophic epidemic that is estimated to have killed 100,000 people. The country’s southwestern quadrant, a region with an

average annual rainfall of more than 250 cm, was worst hit.

The dominant vector in that part of the country is *An. culicifacies*, a species that breeds along the banks of rivers. In normal years, it was not abundant. Malaria was endemic, but the stability index was low; in most years the disease was relatively unimportant.

The monsoons in the preceding five years had been exceptionally favorable, with abundant heavy rainfall leading to excellent rice crops. Under such conditions, river-flow was high, *An. culicifacies* was rare, and the population was exceptionally healthy. However, when two successive monsoons failed, the rice crops were lost and there was widespread hunger. Colossal numbers of *An. culicifacies* were produced in the drying rivers and irrigation ditches.

The epidemic that followed was exacerbated by the weakened condition of the people. In addition, the immunity of the population was especially low because the previous five years had been wet and therefore relatively free of malaria. By contrast, in the drier parts of the island, where *An. culicifacies* was dominant but the stability index was higher, immunity protected the population from the worst ravages of the epidemic.

Malaria was almost eradicated from all of Sri Lanka in the 1960s, but in recent years, lack of effective control has allowed the disease to return as a public health problem.

#### Highland malaria

A topic that is repeatedly cited in the climate change debate, both in the scientific and the popular press, is that warmer temperatures will drive malaria transmission to higher altitudes in the Highlands of Africa, particularly East Africa. Indeed, environmental alarmists often state that this is already happening (Epstein 2000, Gore 2006).

It is certainly true that, just as in lowland regions, the incidence of malaria has increased in highland areas, and it is perfectly acceptable to cite temperature as a limiting factor at high altitude. Vectors such as *An. gambiae* are commonly found as high as 3,000 m above sea level, but endemic malaria disappears above

1,800–2,000 m. What is rarely mentioned is that less than two percent of the African continent (including North Africa) is above 2,000 m, and that much of this is so arid that it offers little opportunity for cultivation. Moreover, the history of malaria in highland areas is a compelling example of the dominant role of human behavior and human ecology, not climate, as the driving factors in the dynamics of transmission.

## Kenya Highlands

The city of Nairobi, capital of Kenya, was founded in 1899 during the construction of a railway from Mombassa, on the coast, to Lake Victoria. The site was chosen because it was on the last stretch of level ground before the steep descent into the Rift Valley. It was a swampy area, and had always been known as an unhealthy locality “swarming with mosquitoes” (Miller 1971).

Indeed, in 1904, when the town had already grown substantially, a committee of doctors petitioned the Colonial government that the entire municipality be relocated because it was a spawning ground for disease. At 1,680 m, it marked the upper limits of malaria transmission at that time, but the disease began to appear at higher altitudes after the clearance of forests for the development of tea estates and the importation of infected laborers (Garnham 1948). The first sizeable epidemic, shortly after World War I, was attributed to the return of local soldiers from Tanzania. A major epidemic in 1926 led to recognition that economic development was a key factor in the proliferation of mosquito breeding sites, and hence the source of the increasingly serious problem:

*That there have been no notable general alterations in the domestic environment of the natives of these reserves during recent years is true, but on the other hand it is to be remembered that in every direction roads, and to a lesser extent, railways, have been carried into and through these areas, and always where there are roads, artificial and undrained excavations are to be found* (Gilks 1926) quoted by (Snow et al. 1999)

The following year, the Municipal Corporation of Nairobi agreed to match a grant of £20,000 (the equivalent of nearly £400,000 in 2007)<sup>8</sup> from the Colonial government

for eradication of anopheline breeding sites in the Nairobi area. Nevertheless, there were six major epidemics in the city between the two World Wars, with serious rates of transmission extending to the Londiani district (2,250–2,490 m) and even at a farm near Mount Timboroa, at 2,490–2,550 m (Garnham 1945).

The fundamental cause of the upward advance of malaria was widespread deforestation and development, as the areas were opened up for large farming ventures. As already discussed, the construction of roads and railways generated innumerable flooded “borrow pits” (depressions left by excavation for materials) and also contributed to the dispersal of the mosquito. The introduction of the ox wagon caused a proliferation of rough cart roads; water in the wheel ruts provided a prolific breeding site for vectors. Milldams on rivers interfered with natural drainage (Garnham 1945).

These and many other factors were components of a drastic ecological change, and it was this change that brought transmission to the Highlands. The disease continued to be a serious public health problem until the 1950s, when the colonial government organized an extensive control program, mainly based on DDT, after which the area was essentially malaria free until the 1970s.

The tea-growing estates (1,780–2,225 m) in the Kericho district have an extensive medical service for employees and their dependents that was initiated in 1925. Health care at the central hospital of Brookebond Kenya Ltd. is extended to some 100,000 inhabitants of the region. However, there is no attempt at mosquito control, and malaria has re-emerged as a serious problem. Epidemics occurred almost every year from 1990 to 1997, with a mean annual attack rate of around 50 percent (Malakooti et al. 1998). Peak transmission was from May to July, after the principal rainy season and before mean monthly temperatures drop below 18 °C. A questionnaire survey (June 1997) indicated that only 8 percent of patients had traveled to areas with known malaria transmission in the previous 30 days.

The main factor in this recrudescence may be increased resistance to antimalarial drugs, as well as the unsupervised use of ineffective medications, but the

picture is not entirely clear (Shanks et al. 2000). Whatever the cause, the history of multiple epidemics in the earlier part of the century, including many at higher altitudes, makes it unnecessary to infer climate change as a contributory factor. Moreover, a set of well-maintained meteorological records shows no significant change in temperature over recent decades (Hay et al. 2002). Indeed, in a detailed report to the World Health Organization, a group of malaria specialists based in Nairobi dismissed those who claim a global warming link as “scientific Nostradamus’s” (Snow et al. 1999).

### New Guinea Highlands

In the early 1930s, a human population estimated at one million people and previously unknown to outsiders was contacted in the mountains of New Guinea. It appeared that these so-called “Stone Age people” were malaria-free, and this was attributed to their unique state of isolation. By contrast, the lowland coastal regions were highly malarious.

At first, the highlanders became a new source of labor for the coastal plantations, but after World War II, there was a rapid increase in the number of small landholders growing *Arabica* coffee and other crops in the mountains. In the late 1940s, government scientists warned that the increasing contact between the regions could bring disaster, for epidemic malaria had already appeared in several highland areas at around 1,500 m (Christian 1947–49). By the mid-1950s several alarming outbreaks led to the enforcement of a law that required employers of highlanders working on the coast to supply them with antimalarials, and to ensure that the medications were actually taken. On repatriation, highlanders were held by the government in compulsory quarantine for two weeks and given curative malaria therapy (Spencer et al. 1956, Peters et al. 1958).

These regulations failed to stop the emergence of the disease and its spread to many isolated valleys. The increase in prevalence was clearly attributable to a rapid increase of anopheline populations after forest clearance, and to the construction of roads, airstrips, plantations, mines, water impoundments, and other human artifacts. Several vectors were involved, including *An. farauti* and *An. punctulatus* (Peters and Christian 1960). These

species breed in open sunlit pools and are in many ways analogous to *An. gambiae* and *An. funestus* in sub-Saharan Africa.

Subsequent studies suggest that the parasite may have arrived in the highlands as early as the 1940s but did not become evident until forest clearance and development were more widespread. Whatever the chronology, the recent history of the disease is clearly attributable to the introduction of the parasite to non-immune populations and the proliferation of its vectors as a result of large-scale ecological change.

### Transmission models based on vectorial capacity

Much of the speculation about the impacts of climate change on mosquito-borne disease utilizes models based on *vectorial capacity*, a rudimentary expression of transmission risk:

$$c = \frac{ma^2p^n}{-\log_e p}$$

$m$  is the mosquito density per human,  $a$  is the average number of bites per day for each mosquito,  $p$  is the probability of a mosquito surviving through any one day, and  $n$  is the *extrinsic incubation period*, the time taken for the pathogen to develop in the mosquito until the insect becomes infective. The only factor directly affected by a climate variable is  $n$ , which is inversely related to temperature. Since  $p$  is less than unity,  $p^n$  will increase at higher temperatures, although  $p$  itself may increase or decrease as a result of other factors. The denominator is an exponential function, so  $p$ , survival rate, is by far the dominant parameter.

Caged mosquitoes can live for three to four months, but their median age in the field is a matter of weeks at most. Few die of senescence; most are killed by predators, disease, and other hazards. Feeding and the search for oviposition sites are probably the most hazardous activities. Exceptions are mosquitoes in the dormant phases mentioned above.

Vectorial capacity and similar elementary concepts were developed to describe the fundamental features of transmission, mainly in the context of control operations. With the exception of  $n$ , calculation of  $C$  is dependent on quantitative values that can only be

obtained in the field. It is difficult to make realistic estimates of these values, however, because their measurement is heavily dependent on a thorny range of assumptions. Moreover,  $C$  is limited to entomological parameters and the duration of extrinsic incubation period; it does not incorporate the parasite-rate in humans or mosquitoes, nor any ecological or behavioral factors. Thus, while helpful in our understanding of the interaction between selected variables, such models have little value for assessing the likely impact of long-term climate change.

## Summary

Simplistic reasoning on the future prevalence of malaria is close to irrelevant. Malaria is not limited by climate in most temperate regions<sup>9</sup>, nor in the tropics. In nearly all cases, “new” malaria at high altitudes is well below the maximum altitudinal limits for transmission, and in sub-Saharan Africa the altitudes above the present limits are so small as to be insignificant. Moreover, there is no evidence that climate has played any role in the burgeoning tragedy of this disease at any altitude; as with enteric diseases, most of the other significant variables are attributable to defects in the social matrix. Future changes in climate may result in minor changes in prevalence and incidence, but obsessive emphasis on climate change as the dominant parameter is unwarranted. There is a desperate need for cheap, effective control campaigns, as were implemented during the DDT era. The development of new strategies, such as the release of transgenic mosquitoes carrying lethal genes, should be a priority.

## Third level of complexity: mosquito-borne zoonoses

Nearly six hundred viruses (arboviruses) transmitted by arthropods – principally mosquitoes, sandflies, biting midges and ticks – have been described by scientists. Of these, about a hundred are known to produce clinical infection in humans, though infection is often asymptomatic. All are zoonoses; they circulate in nature without involving humans. In most cases, infections in humans are incidental, acquired by an arthropod that has been infected by feeding on a bird or mammal.

Thus, unlike malaria, infection of humans involves a third level of complexity.

## Yellow Fever, Dengue and Chikungunya

In their original habitat, these three viruses are transmitted between primates by forest-dwelling mosquitoes. They are among the few zoonoses that are regularly transmitted between humans. The majority are termed “dead end” because the level of virus in the blood during infection (viraemia) is insufficient to infect an arthropod and thus does not contribute to the chain of infection.

Humans are infected when they enter the forest to hunt, gather food (fruit, honey etc.), harvest timber, make charcoal, and other activities. In addition, in recent years, a number of unvaccinated tourists from developed countries have died of yellow fever after visiting the South American rainforest.

Unlike parasitic diseases such as malaria, viraemia for all three viruses – and indeed for most viral diseases – is short-lived, a matter of days. A viraemic person entering a village or town, however, can relay the virus to the community via mosquitoes living in the peridomestic environment. Chief among these is the Yellow Fever mosquito, *Aedes aegypti*, a highly effective vector of all three viruses because it feeds almost exclusively on humans.

A second species, the Asian Tiger mosquito, *Aedes albopictus*, has generally been regarded as less effective because it does not discriminate between hosts; blood meals taken from animals and birds that are not susceptible to the viruses do not contribute to the transmission cycle. Nevertheless, in recent years, the species has proved highly effective in urban transmission of chikungunya (Reiter et al. 2006), possibly because levels of this virus in the blood are very high, and because it has a high rate of infection and replication in the mosquito; all would contribute to a high vectorial capacity. Both species live in close contact with humans because they have adopted man-made containers such as water storage vessels, abandoned tyres, buckets and blocked gutters as a substitute for tree-holes and other natural containers in their original habitat.

*Aedes aegypti*, *Ae. albopictus*, and the three viruses share an important feature: all have been disseminated worldwide by human activities. *Aedes aegypti*, Yellow Fever and Dengue were introduced to the New World from Africa, transported in slave ships. Yellow Fever (and possibly dengue) is now enzootic in the forests of Latin America, and occasionally gives rise to urban transmission. In the past 30 years, *Ae. albopictus* has become widely established from Chicago to Buenos Aires in the Americas, in 12 countries in Europe, and at least three countries in Africa. Nearly all infestations are attributable to an international trade in used tyres (Reiter and Sprenger 1987, Reiter 1998). Dengue and Chikungunya viruses circulate freely around the world in aircraft, transported by infected passengers (Gubler 1997). The rate of this globalization of vectors and pathogens will continue to increase so long as the global economy continues to flourish.

#### *Yellow Fever*

In the 18th and 19th Centuries, devastating epidemics of Yellow Fever (“Yellow Jack”, “Vomito Negro” etc.) occurred in many countries, as far north as Dublin and Cardiff in Europe and New York and Boston in the United States. One of the greatest epidemics on record globally began in 1878 in Memphis, Tennessee and quickly spread as far north as Illinois and Michigan. An estimated 19,500 people were infected in Memphis, and more than 100,000 in the country at large. The vector, *Ae. aegypti*, persists in eleven states from Texas to South Carolina, but, for reasons unknown, disappeared from Europe about 50 years ago (Reiter 2001).

A safe, cheap and effective vaccine is available against Yellow Fever, but, apart from Brazil, very few countries routinely vaccinate populations at risk. The global pandemics of dengue that affect nearly all the cities in the tropics are a clear warning that an introduction of Yellow Fever virus into an urban population could have catastrophic consequences. In such an event, world stocks of vaccine would be totally inadequate to halt transmission.

#### *Dengue*

There are four serotypes of dengue; infection with any serotype results in lifetime immunity, but not to the other serotypes, so, theoretically, a person can be

infected four times. Like Yellow Fever, chikungunya and indeed many other viruses<sup>10</sup>, illness begins with a sudden onset of high fever and ‘flu-like’ symptoms. The disease is usually self-limiting – fever rarely lasts more than a week – but a small percent of cases require hospitalization, up to five percent of which can die of haemorrhage and other complications.

The first epidemic on record was in Philadelphia in 1780, and, as with yellow fever, numerous outbreaks followed in many temperate regions in Europe and the Americas. One of the largest epidemics on record occurred in 1927–28 in refugee camps in Greece, with an estimated 1,000,000 cases and 1,000 deaths. The global prevalence of the disease has grown dramatically in recent decades and it is now endemic in more than 100 countries throughout the tropics, with some 2.5 billion people – two-fifths of the world’s population – at risk (Gubler 1997). The only effective approach to control is to eliminate the breeding sites of the mosquito. This has been applied effectively in the past, but in the teeming cities of today’s tropics the task is next to impossible (Reiter and Gubler 1997).

#### *Chikungunya*

Symptoms of chikungunya are similar to those of dengue, but also involve arthritic complications that may last for many months. Pandemics of chikungunya have been known in Africa and Asia for many decades, but only garnered the world’s attention in 2005 when the disease appeared on the island of La Reunion, a *département* of France<sup>11</sup> in the Indian Ocean. Epidemic transmission was first reported on the East African coast, and introduction to other regions was by infected air passengers. The vector was *Ae. albopictus*, and more than 260,000 cases, a third of the population, was affected. The epidemic was highly publicized in Europe because the island is legally a part of France, and because neighboring Mauritius, a major tourist destination, was also affected. It ended in 2007, but remains rampant (as of November 2007) in India (an estimated 2,000,000 cases) and in South East Asia, though with relatively little publicity.

As already mentioned, modern transportation has enabled *Ae. albopictus* to extend its range worldwide. It is already established in Belgium and Holland, and there is

no reason to suppose it will not move northwards in Europe, perhaps into Scandinavia. Nor is there reason to believe that outbreaks of chikungunya could not occur at these latitudes, for the conditions suitable for transmission are the same as those for malaria.

Indeed, a small outbreak occurred in the autumn of 2007 in northern Italy, in the delta region of the river Po. The area was once notoriously malarious, but the disease disappeared when the marshes were drained at the beginning of the 20th Century. The outbreak, which began in two small villages, was traced to a traveler from India. The *Ae. albopictus* infestation had been traced to used tyres imported from Atlanta, Georgia, and the infestation in the United States traced to shipments of used tyres from Japan.

Thus, human activities had altered the local ecology and eliminated malaria. They also provided a new environment (human settlement) suitable for the establishment of an exotic species of mosquito that had been carried across the Pacific Ocean and subsequently the Atlantic Ocean by modern transportation. This was followed by an exotic virus that arrived in a passenger who was infected on yet another continent and was transported by a new and effective vector, the jet aircraft.

The significance of this series of events was lost in a declaration by the World Health Organization that “although it is not possible to say whether the outbreak was caused by climate change...conditions in Italy are now suitable for the Tiger mosquito” and in a short article by one of the most prolific climate change activists (Epstein 2007).

## West Nile encephalitis

West Nile virus is transmitted between birds by ornithophilic mosquitoes, many of which rarely bite mammals. It is an Old World virus with a huge range from southern Europe, to South Africa, the Indian subcontinent, Southeast Asia and even Australia. For the most part, the virus goes un-noticed though it is clear that incidence is high in many parts of the world. In temperate regions there is evidence that the virus survives winter in hibernating mosquitoes, but there is also repeated introduction from other continents by

migrating birds. Humans are incidental to transmission – dead end hosts. Infections are usually asymptomatic or mildly febrile, but a small portion involve inflammation of the brain and can be fatal, particularly in older people. In Europe, transmission is usually signaled by clusters of cases of encephalitis in horses.

Human clinical cases are rare and sporadic; the number of human cases confirmed in the whole of Europe rarely exceeds five in any year. Two exceptions stand out: a major epidemic involving at least a thousand cases in Bucharest, Romania, in 1996, and a similar outbreak in Volgograd (formerly Stalingrad), Russia, in 1999. In both cases, leaking water, heating and sewage pipes in the basements of Soviet-style “functionalist” apartment buildings created perfect breeding site for *Cx. pipiens*, an effective vector that breeds in organically polluted water. Inadequate refuse disposal encouraged high populations of House Sparrows to complete the zoonotic cycle. The problem is widespread in ex-Soviet bloc countries, and will undoubtedly get worse in coming years (Marina Sokolowa, personal communication).

In 1999, the virus was identified in a sudden outbreak of encephalitis in the Queens district of New York. It was probably imported in infected live birds; protection from local mosquitoes is not required by quarantine regulations. Once established, the speed of transcontinental spread was spectacular and totally unexpected. By 2003 it had reached the Pacific seaboard, and had been detected in every state except Washington and Oregon.

The virus is now enzootic from Canada to Venezuela, including Mexico, Central America and the Caribbean Islands. Dispersal clearly takes place through birds, both migrant and resident. Some 25,000 human cases – about 1% of the total number of infections – and just over 1,000 deaths have been reported in the United States. Viraemia in New World birds is very high, and lethal to at least 250 species. For this reason, the introduction of the virus has had a catastrophic impact on wildlife, a phenomenon typical of the introduction of an exotic virus into a new environment.

Environmental alarmists have ascribed the conquest of the Americas by West Nile virus to unusually warm winters and other climatic phenomena, and have

predicted future changes in range in many parts of the world (Epstein 2000, Parkinson and Butler 2005, Paz 2006). As with so many similar claims, there is no scientific basis for this. Temperatures can drop below  $-30^{\circ}\text{C}$  in the provinces of Canada where transmission is now an annual event, and in Bucharest and Volgograd (formerly Stalingrad), where the major urban outbreaks occurred.

Another claim is that the epidemiology of West Nile virus in Europe will follow that of the New World in a future, warmer climate. There is zero evidence to support this either. Summer temperatures in many parts of Europe are far warmer than required for epizootic transmission and suitable species of mosquitoes are abundant, yet the virus is rare, or at least transmission is rarely evident.

## Japanese encephalitis

This important human pathogen is taxonomically related to Yellow Fever, Dengue, and West Nile viruses. It was once the leading cause of viral encephalitis in a large part of Asia, from Japan to the Indian sub-continent to Borneo, Indonesia, the Philippines and New Guinea. A safe, effective vaccine is available, but there are still an estimated 50–100,000 cases per year, particularly in the poorer countries, 60% of which are fatal (Diagana et al. 2007, Schioler et al. 2007).

Like West Nile virus, the pathogen mainly infects birds and is transmitted by ornithophilic mosquitoes; humans and horses are dead end hosts. Domestic pigs, however, contribute a fourth level of complexity (the virus is included in this section because it is mosquito-borne). Infection is asymptomatic, but viraemia is high and sustained. Pigs are thus an important amplifying host because they live in close proximity to humans in many communities. Several species of mosquito are involved in transmission.

## Factors that affect the herd immunity

The key component of zoonotic human infections is contact with the natural cycle of transmission. This can only occur through activities in their natural habitat. The urban vectors, *Ae. aegypti*, *Ae. albopictus* and *Cx. pipiens*

have adopted the peridomestic environment because humans provide a suitable alternative to that habitat. In the case of the two *Aedes* species, humans are the perfect host: they offer safe shelter indoors, a freely available source of blood, and breeding sites in abundance, even in relatively affluent neighborhoods. *Cx. pipiens* is abundant in urban areas for the same reasons: it breeds prolifically in organically polluted water and human activities provide this in abundance, from faecally polluted ground water to sewage treatment plants.

Immunity is a critical feature of virus transmission, both in nature and in the urban environment. Immunity to malaria and other parasitic diseases is only partial. Parasites can circulate in the blood of infected persons, and can be re-introduced by infective bites. In contrast, immunity to viruses is generally life-long. Therefore, whereas a population can support chronic infection with malaria, the circulation of viruses is regulated by the “herd immunity”, the common immunity of the inhabitants. As a result, transmission occurs in peaks, with intervening periods of little or no activity. In a sense, viral epidemics are like forest fires; they burn furiously until available fuel has been consumed, after which there is a recovery period in which fuel accumulates once more.

Sylvatic transmission of primate viruses follows this pattern; epizootic waves followed by periods of relatively low transmission. The inhabitants of the South American rain forest have learned that when the forest goes silent (i.e. when there is high mortality of the Howler monkeys), Yellow Fever is circulating. The same is true for people in North America; a high mortality in wild birds and animals indicates circulation of West Nile virus in the vicinity. In both cases, importation of an exotic virus has had a disastrous impact on indigenous species.

The “forest fire” phenomenon is particularly evident in isolated communities. For example, dengue is repeatedly introduced to islands in the Pacific Ocean and the Caribbean, and explosive epidemics generally occur when a particular serotype has been absent for some time. This activity may last two or sometimes three years, after which the virus circulates at low levels or becomes extinct. Yet again, the key factors for transmission are human behaviour and human ecology:

the size of the human population, the introduction of a new serotype, the herd immunity to the relevant serotype, the abundance of artificial containers that are the principal mosquito breeding sites, and contact with the vector (Reiter and Gubler 1997, Reiter et al. 2003).

In most of the tropics, the climate is suitable for transmission for at least part of the year, so transmission will occur if the virus is introduced. Yet there is definitely a marked seasonality of transmission of dengue in many parts of the world. The causes of this peak are not always evident, but immunity remains the dominant parameter, so even if the climate were to become more favorable for transmission, the effect would be to shorten the duration of epidemics without increasing the overall incidence of cases. In temperate regions, as already mentioned, epidemic transmission has occurred in the past, even in an era when temperatures were considerably lower. Warmer conditions might increase the duration of the transmission season, but the critical factors will remain human ecology and human behavior.

## Fourth level of complexity: tick-borne encephalitis

Ticks are second only to mosquitoes in the human diseases that they transmit. Tick-borne encephalitis (sometimes called Central European encephalitis, Russian Spring-Summer encephalitis, Far Eastern Tick-borne encephalitis) is chosen as an example, because there has been a rapid increase in incidence in Europe in the past two decades, and climate change is frequently invoked as the causative factor. In truth, the factors that influence transmission are so complex that they present an outstanding example of how intuitive thinking from a starting point of changing climate can offer an explanation that is simple, persuasive, and wrong.

The life cycle of ticks is very different from that of mosquitoes. In mosquitoes, the pre-adult stages are aquatic, so only the adult feeds on blood and is thus a potential vector (although in some cases, the virus can be transmitted to the next generation via the egg stage). The vector of Tick-borne encephalitis – classed as a “Hard Tick” – goes through three stages after the egg hatches: larva, nymph and adult. Each stage takes a

single blood meal. In temperate regions, the entire cycle can take three years.

Tick-borne encephalitis is a typical zoonosis. The virus is closely related to all the viruses mentioned above except Chikungunya, and is exclusively a disease of rodents; here again, humans and other animals are dead end hosts. More than 10,000 human cases are reported in Europe and Russia each year, mostly at higher latitudes. About one percent of cases are fatal, although mortality rates as high as 40 percent have been reported in outbreaks of a sub-type of the virus in Siberia and the Far East.

Adult female ticks lay as many as 100,000 eggs in their lifetime, an indication of the enormous mortality in the immature stages. Only the larvae and nymphs feed on rodents; the adults feed on other animals, including humans. As with most other viruses, viraemia in the rodent host only lasts a few days, so there is a limited window of opportunity for direct infection of the larvae. However, the virus can also pass from infected nymphs to larvae if both are feeding in close proximity on the same host. This feedback mechanism (called co-feeding) enables relatively few infected nymphs to infect the much more abundant larvae even on a non-viraemic host, an amplification system that is critical for continued transmission.

Larval ticks moult to nymphs up to a year after feeding. Survival between the three developmental stages depends on a habitat that provides suitable moisture conditions for the tick and suitable habitat for the host over the years of their development. Adult ticks “quest” for hosts by stationing themselves at elevated points on grasses or other ground vegetation and waiting for a passing animal. In woodland, their principal hosts are deer, though they will attach to other species, including humans. Questing behaviour and survival are also determined by moisture, as well, of course, as the chances of contact with a suitable host.

Ticks survive winter at soil level, where snow cover insulates them from extreme cold. Springtime activity begins when temperatures rise above a critical threshold, which is lower for nymphs (a mean daily temperature of about 7°C) than for larvae (about 10°C). These differences are critical, because earlier activation of

nymphs can prevent synchrony with larvae. Rainfall is critical for adult survival; activity is suppressed during rainy periods, but mortality is high when humidity is low (Sumilo et al. 2006).

The incidence of tick-borne diseases has increased dramatically in Europe in the past two to three decades. The increase has been particularly high in the ex-Soviet Bloc countries, and has been widely attributed to a warming trend in the climate (Lindgren and Gustafson 2001, Danileová et al. 2003).

Careful study, however, has revealed that although climate may have contributed to the change in incidence, other factors are clearly involved (Sumilo et al. 2006). Activities of humans in tick habitat are particularly important.

In Latvia and Lithuania, for example, the collapse of agriculture and industry after the economic transition led to increased activity in woodland for a large portion of the population, particularly among female, older, poorer and rural people.

By contrast, in Estonia, where economic conditions improved rapidly after the change, visits to woodland were less frequent, and were associated with recreational walking and gathering berries and mushrooms. In this cohort, tick-bites were most frequent when rain-free summer weekends followed a week of heavy rainfall. There is evidence that the incidence of tick-borne infections is correlated to these variations in behavior (Randolph and Sumilo 2007).

Abundance of deer is another important factor. The rapid increase in the incidence of tick-borne infections has coincided with an enormous increase of deer populations in large areas of Europe and North America. Much of this is due to re-forestation in regions where agriculture has been abandoned, or where conservation efforts have reduced hunting activities. Reforestation has also provided ideal habitat for rodents, particularly mice of the genus *Apodemus*, which are the principal host of the virus. Populations of these small rodents undergo regular asynchronous cycles with those of their predators, although the amplitude of recurrent peaks is affected by masting (seed production) of trees such as oak and beech.

In summary, the list of putative parameters affecting transmission of tick-borne encephalitis to humans includes agricultural practices, land-cover, small mammals and their predators, small mammal immunology, large mammals, hunting, wild-life conservation, industrial activities, income levels, leisure activities, and of course, climate variables. These include the depth of winter snow, the micro timing of the onset of springtime temperatures, and summer rainfall and humidity. And, of course, the interaction of these variables is distributed over a three-year period.

## Final comment

The ecology and natural history of disease transmission, particularly transmission by arthropods, involves the interplay of a multitude of interacting factors that defy simplistic analysis. The rapid increase in the incidence of many diseases worldwide is a major cause for concern, but the principal determinants are politics, economics, human ecology and human behaviour. A creative and organized application of resources to reverse this increase is urgently required, irrespective of any changes of climate.

## Notes

1. Insects, ticks, spiders, crustaceans etc.
2. Strains of many pathogens show distinct differences in their infectivity towards a particular host. In this chapter, this degree of infectivity is defined as virulence.
3. In this context, host refers to any organism that is infected by the pathogen. In the case of arthropod-borne pathogens, the arthropod is generally referred to as the vector, and the organism that it infects as its host.
4. Climate is always varying, so climatologists define it as the mean of a set of climate variables over a specific period, usually not less than 30 years. Weather is the short-term variation of climate.
5. These articles all refer to malaria, and all propose that incidence and prevalence will increase as a direct result of climate change

6. In all parts of the world, malaria is transmitted by a group (genus) of mosquito species called *Anopheles*.
7. Funded at various stages by the International Development Research Centre of Canada (IDRC); South African Medical Research Council (SAMRC); Wellcome Trust, UK; Swiss Tropical Institute; UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases (TDR); Multilateral Initiative on Malaria (MIM) of the UNDP/World Bank/WHO Special Programme for Research & Training in Tropical Diseases (TDR).
8. Based on retail price index, <http://www.measuringworth.com/ppoweruk/>
9. Effective vector species are still present, sometimes common, in many of the regions that were previously malarious, and transmission can occur if the parasite is introduced by the arrival of infected people. Such local cases, however, are easily eliminated by treatment with antimalarial drugs. Unfortunately, these incidents are exploited by environmental alarmists as evidence of the impact of climate change.
10. Many non-viral diseases also start with these symptoms. The author has had typhus, malaria and dengue. In the first days of illness, he diagnosed his typhus infection as malaria, his malaria as dengue, and his dengue as malaria. Apart from other considerations, it is not a good idea to consult a medical entomologist to diagnose a fever.
11. Equivalent to a county in the USA and the UK

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