1 Could global warming bring mosquito-borne disease to Europe?

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Introduction

In the 1980s, public attention on environmental issues shifted from issues of acid rain, asbestos and the ozone hole to a new concern: global warming. In the years following the negotiation of the Kyoto Protocol, numerous articles appeared in the scientific and popular press which stated that mosquito-borne diseases such as malaria, yellow fever and dengue would threaten Europe and North America if the climate continued to warm.

By the mid-1990s, the menace of these 'tropical' diseases was top of the list of nearly every account of the dangers of global warming. Interest groups used such claims to bolster their calls for urgent political actions to stop climate change:

> Global warming and the expected climate instability that accompanies it can have grave consequences for our health and well-being … Climate restricts the range of vector-borne diseases (those with animal carriers), while weather affects the timing and intensity of outbreaks. There are strong indications that a disturbing change in disease patterns has begun, and that the global warming trend identified by the more than 2,500 scientists of the Intergovernmental Panel on Climate Change (IPCC) is contributing to these changes.[1]

This chapter explains why such pronouncements are ill-informed and misleading. The discussion is limited to malaria, but similar concepts apply to other mosquito-borne diseases.

Climate and health

The belief that hot climates are harmful to health is very old. Hippocrates described climate, seasonality and meteorological events as determinants of human illness. Deviations from the ethnic norm, as defined by the ideal of the Greek mind and body, were also attributed to excessive heat and humidity. In essence, his treatise *On Airs, Waters and Places* was an environmentalist attempt to interpret disease and race in terms of climate.

From the seventeenth century onwards, Europeans revived this notion with graphic descriptions of the 'fevers' they encountered in the tropics, often reasoning that the febrile symptoms were directly attributable to the hot climate.

In the same period, public thirst for knowledge of the newly 'discovered' lands created a major demand for travel books. Many of these were written by explorer-naturalists to fund their expeditions. To achieve sales, they fuelled the imagination of their readers with sensationalist accounts of their travels.

As a result, popular representations of the tropics became replete with accounts of the dark, the mystical, the primitive and the shocking. Illustrations of 'tropical' diseases in medical texts, often with negative connotations towards the darker races, became a significant component of this imagery. At the end of the nineteenth century, the discovery that annoying insects – mosquitoes – transmit malaria fitted well into this fear-inspiring picture.

I believe that such imagery survives today – it is reflected in the news media's coverage of disease issues, and illustrates that in our modern psyche, concepts of the *Tristes Tropiques*[2] underlie popular attitudes to 'things tropical'.

Change is a fundamental feature of climate

Climate is commonly understood to mean the 'average weather' in a given region or zone. This definition is unsatisfactory, as it implies that unlike the obvious year-to-year variations of daily weather, long-term climate is a constant. Modern climatology recognises that change is an inherent and fundamental feature of climate.[3] Just as the yearly averages of climatic elements – e.g. temperature, humidity, rainfall, wind and airborne particles – differ from one another, so too do the averages for decades, centuries, millennia and millions of years. Therefore, climatic values cannot be referred to without specifying the time span to which they refer.

For nearly three centuries the earth's climate has been in warming phase, punctuated by several periods of cooling. This was preceded by a particularly cold period, the Little Ice Age, which was itself preceded by several centuries known as the Medieval Warm Period or Little Climatic Optimum. Such changes are entirely natural, but it is widely held that, in recent years, a portion of the current warming may be attributable to human activities, particularly the burning of fossil fuels.[4]

Climate is a major parameter in all ecosystems, and has always been a fundamental factor in human settlement, economy and culture. Episodes of climate change – such as the end of the Ice Age, the drying of the Sahara, the waning of the Medieval Warm Period and the onset of the Little Ice Age – have had an important impact on human history.[5]

However, awareness of such change has remained shadowy at best, probably because the inherent time scales are beyond the span of individual human experience. By contrast, weather – the short-term condition of climate – has a much more direct and tangible impact on daily life.

Since earliest times, weather was fundamental to the success of human activities, from agriculture to seafaring, from warfare to leisure. Feast and famine, drought and flood, health and disease – all were attributable to weather events. The universal belief in weather deities, the prominence of weather events in folklore, and the ubiquitous preoccupation with weather signs and portents are evidence that an awareness of weather – particularly a fear of inclement events – has been a major feature of the human psyche throughout history.

The significance of weather has not diminished in modern society. Indeed, in the past few decades, weather awareness, particularly in the global context, has reached unprecedented levels. Weather forecasting has become an important science, fundamental to the success of agriculture, transportation, trade, tourism and virtually every other aspect of human enterprise. Weather data are collected from every corner of the globe and disseminated in digested form by government and private agencies as an aid to decision making in all walks of life. Continually updated forecasts and other information are available to the public via the popular media. Disastrous weather events from around the world are a major news feature, with detailed descriptions and graphic illustration. With this weather awareness, a new realisation of the *changeability* of climate has emerged.

The concept of 'global warming'

Current temperatures, at least in the northern hemisphere, are broadly similar to those of the Middle Ages, in the centuries before the Little Ice Age.[6] However, from the 1940s to the late 1970s, global temperatures were in decline. This gave rise to concern that particulate industrial pollutants might be exerting a global cooling effect.[7]

Since then, as climates returned to a warming mode, interest has switched to consideration of the 'greenhouse effect', a natural phenomenon by which a range of atmospheric gases trap solar radiation in the form of heat. The principal greenhouse gas is water vapour – about 2% by volume – but public attention is mainly focused on carbon dioxide (CO_2), a gas that is essential as the ultimate source of carbon for nearly all life on the planet. From the mid-nineteenth century onwards, massive clearance of forests for agriculture, followed by an exponential rise in the combustion of fossil fuels (coal, oil and gas), has resulted in a measurable increase in atmospheric CO_2, from around 0.029% in 1890 to 0.037% today.

Many climatologists agree that this 28% increase in atmospheric CO_2, together with an increase in other 'anthropogenic greenhouse gases', may be contributing to the warming trend of recent decades.[8] The extent of this contribution remains far from clear, but the mere possibility, which implies that the trend could be reversible, has given rise to spirited scientific[9] and public[10] discussion.

Human health – and mosquito-borne disease in particular – is a prominent topic in this debate.[11]

Climate and mosquito-borne disease

In nearly all mosquito species, the female obtains the protein she needs for the development of her eggs by feeding on vertebrate blood. A complex salivary secretion facilitates feeding. It is the direct injection of this fluid into the capillaries that enables several life forms – viruses, protozoa and nematode worms – to exploit mosquitoes as a means of transfer between vertebrate hosts. They do this by infecting the mosquito after they have been ingested in a blood meal, and eventually multiplying in the salivary glands, from which they can be inoculated into a new host during a later blood meal. The majority of such organisms do not appear to affect either the mosquitoes or their vertebrate hosts, but a small number are pathogens of important human and animal diseases.

The ecology, development, behaviour and survival of mosquitoes, and the transmission dynamics of the diseases they transmit, are strongly influenced by climatic factors. Temperature, rainfall and humidity are especially important, but others, such as wind and the duration of daylight, can also be significant. The same factors also play a crucial role in the survival and transmission rate of mosquito-borne pathogens.

In particular, temperature affects the pathogens' rate of multiplication in the insect. In turn, this affects the rate at which the salivary secretions become infected, and thus the likelihood of successful transmission to another host. Of course, if the development time of the pathogen exceeds the life span of the insect, transmission cannot occur. The complex interplay of all these factors determines the overall effect of climate on the local prevalence of mosquito-borne diseases.[12]

Seasonality is a key component of climate. Summer temperatures in many temperate regions are at least as high as in the warmest seasons of much of the tropics. The crucial difference is that the tropics do not have cold winters. If tropical mosquito-borne pathogens are introduced to temperate regions in the right season they can be transmitted if suitable vectors are present; in most cases they are eliminated when winter sets in.

Mosquitoes native to temperate regions have evolved strategies to survive the winter, as have the pathogens that they transmit. In the tropics, comparable adaptations are necessary for surviving in unfavourable dry periods, which can last for several years. In both cases, such adaptations impose a seasonality on transmission. For example, before eradication, the transmission season for *Plasmodium falciparum* in Italy was July to September.[13] The same three months constitute the malaria season in Mali, where the disease is still endemic.[14]

Disease models

Much of the recent speculation on the possible impacts of climate change on mosquito-borne disease has focused on rudimentary mathematical models of transmission dynamics.[15]

However, these models have a limited value for assessing the impact of long-term climate change on disease transmission.[16] They cannot predict the presence or absence of the disease, nor its prevalence in any situation, because they do not account for the parasite-rate in humans or mosquitoes, nor any of the many ecological and behavioural factors that affect the interaction of mosquitoes and humans. For example, human behaviour and cultural traits can be crucial to the transmission of the parasite. Daily activity patterns – work, rest and recreation – the location of homes in relation to mosquito breeding sites, the design of buildings, the materials used to build them, the use of screens and bed-nets, the presence of cattle as alternate hosts for the mosquitoes, and many other factors are all highly significant.

An alternative approach is to look at the past: the history of mosquito-borne diseases at different latitudes and in different climatic eras can help us to assess how climate variables relate to many other factors that affect transmission.

History of malaria in Europe

Ancient Greece and Rome

The introduction of agriculture in Europe, around 7000 BC, led to increased populations of relatively settled people, and increasingly favourable conditions for malaria transmission.[17] The extensive deforestation that began at this time may also have contributed to its prevalence, by creating additional habitat for malaria-carrying mosquitoes. Similar ecological changes in modern times have caused major increases in the prevalence of the disease.

Contemporary accounts, together with fossil and other evidence, suggest that a gradual warming and drying occurred in the Mediterranean region throughout classical times, until about AD 400.[18] Landscape studies suggest a gradual rise in sea level over this period. Around 300 BC, beech trees (genus *Fagus*) grew in Rome, the Tiber froze in winter, and snow lay for many days. However, by the first century AD the Romans considered the beech a mountain tree, and winters were definitely less severe. Over these centuries, the cultivation of the vine and olive moved gradually northwards along the Italian peninsula. The Romans were even able to introduce wine growing to Germany and Britain, and data from imports and exports suggest that Britain became self-sufficient in wine production by around AD 300. The warming trend is clearly indicated by tree-ring studies in California, so it may have been a worldwide or at least a hemispheric phenomenon.

Literary texts from that era, such as Homer's *Iliad*, include references to killing fevers at harvest time.[19] We cannot be certain that this was malaria, but later texts confirm that the disease was a significant feature in Greek life. Indeed, there is evidence that a major wave of malaria began with the flowering of Greek civilisation and transmission rates continued its increase throughout the period of the Roman Empire.[20]

Hippocrates (460–377 BC) gave exquisitely detailed descriptions of the course and relative severity of tertian vs quartan infections.[21] He also noted their association with wetlands, and even observed that enlarged spleen (often a symptom of chronic malaria infection) was particularly prevalent in people living in marshy areas. There is a wealth of evidence that malaria was common in imperial Rome.[22] Horace, Lucretius, Martial and Tacitus were among many Latin authors who mentioned the disease. The Pontine Marshes, close to the city, were notorious as a source of infection. In the second century AD, the detailed writings of Galen and Celsus on the symptoms and treatment of 'intermittent fevers' give clear evidence that three species of parasite – *P. falciparum, P. ovale* and *P. vivax* – were commonly present.[23]

The Dark Ages

Relatively little is known about climate after the Roman era during the 'Dark Ages', but there seems to have been a cooling trend from the fifth century onwards, with some severely cold winters. In AD 763–64 there was ice on the sea in the Dardanelles, and in 859–60 the sea ice on the Adriatic was strong enough to support heavy wagons. In 1010–11 it was even cold enough for ice to form on the Nile. Again, tree-ring data from California indicate that this cooling was not restricted to Europe.

Nevertheless, 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. Around the turn of the millennium, the armies of Otto the Great, Otto II and Henry II suffered severely from the 'Roman Fever' during their sieges of the Holy City.

The Middle Ages

The Medieval Warm Period, which reached its peak around the year 1200, coincided with major advances in technology and agriculture, and a significant increase in population throughout most of Europe. The Vikings established self-sufficient colonies, cultivating oats and barley, in northern Scandinavia, Iceland and Greenland. In the British Isles, tillage was extended to much higher altitudes than is possible today, so high that there were complaints from sheep farmers that there was too little land left for grazing. English vintners were able to maintain a flourishing production of high-quality wine, despite efforts by Bordeaux traders to restrict English exports by treaty.

The explosion of economies and culture that occurred during this warming period has been attributed, at least in part, to the beneficial impact of the warming climate. From caliphate Spain to Christian Russia, numerous medieval writers, including Dante and Chaucer, mentioned 'agues', 'intermittent fevers', 'tertians', 'quartans' and the like.[24]

Favourable temperatures and rainfall may have enhanced malaria transmission in earlier years, but Chaucer's lifetime coincided with a cooling trend that culminated in a series of severely cold winters in the first decades of the fifteenth century.[25] Much of the earlier agricultural expansion was reversed. There were many years of famine, and a large-scale abandonment of farms. Despite this cooling, malaria persisted, even in northern regions.[26]

The Little Ice Age

The first half of the sixteenth century was warm again. Temperatures were probably quite similar to those of the period 1900 to 1950. In the middle of the century, however, a remarkably sharp change occurred. After a decade or so of particularly warm years – warm enough for young people to bathe in the Rhine in January – the winter of 1564–65 was bitterly cold.[27] The next 150–200 years – dubbed the Little Ice Age – were probably the coldest era of any time since the end of the last major ice age, some 10,000 years ago.[28] Yet despite this spectacular cooling, malaria persisted throughout Europe.[29]

William Shakespeare (1564–1616) was born in the year of that first fierce winter, yet there are twelve mentions of ague in his writings. He also made several allusions to the association between swampy land and disease, and the name Sir Andrew Aguecheek presumably referred to the trembling cheeks of this ineffectual hero.

The years 1594–97 were so cold and wet that wheat harvests were a disaster, yet William Harvey (1578–1657), who wrote the first descriptions of the circulation of the blood, missed much of his final year at the University of Cambridge in 1597 because of malaria. In later years he made careful observations of malaria cases in London. The marshes in the Borough of Westminster, where the Houses of Parliament now stand, were notoriously malarial. In his treatise *On the Motion of the Heart and Blood in Animals* (1628), he described the clinical pathology of the febrile episodes, including the changes in the consistency of blood that occur in serious cases:[30]

> In tertian fever … in the first instance … the patient [is] short-winded, disposed to sighing, and indisposed to exertion, … the blood [is] forced into the lungs and rendered thick. It does not pass through them (as I have myself seen in opening the bodies of those who had died in the beginning of the attack), when the pulse is always frequent, small, and occasionally irregular; but the heat increasing … and the transit made, the whole body begins to rise in temperature, and the pulse becomes fuller and stronger. The febrile paroxysm is fully formed …

Thomas Sydenham (1624–89), a notable physician, also lived through some of the coldest years of the era, yet made frequent reference to tertians and quartans.[31] He even remarked, ‘When insects do swarm extraordinarily and when … agues (especially quartans) appear early as about midsummer, then autumn proves very sickly.’[32]

Not all the summers of the Little Ice Age were cool. The overall mean temperature was probably at least 1°C cooler than in the twentieth century, but there also seems to have been an enhanced variability of the climate, with wide differences between clusters of up to six to eight years.

Warm summers may have contributed to this and other outbreaks, but transmission was not restricted to such years. In 1657–58, snow lay on the ground for 102 days – exceptionally cold, even with respect to the climate of the times – yet Oliver Cromwell (1599–1658) died of malaria in September 1658, just as another severe winter was setting in.

Temperatures were probably at their lowest in the period 1670 to 1700, yet it was during this very period that Robert Talbor (c.1642–81) persuaded the aristocracy of England and Europe to buy prescriptions for curing malaria that he had developed in the marshlands of Essex.[33] These were based on cinchona bark, the source of natural quinine, and earned him wealth and fame throughout Europe. In the same period, Daniel Defoe (1660–1731) described life in the Dengie marshes of Essex:[34]

> a strange decay of the [female] sex here … it was very frequent to meet with men that had had from five to six, to fourteen or fifteen wives … the reason … was this: that they (the men) being bred in the marshes themselves, and seasoned to the place, did pretty well with it; but that they always went into the hilly country … for a wife: that when they took the young lasses out of the wholesome and fresh air, they were healthy, fresh and clear, and well; but when they came out of their native aire into the marshes … they presently changed their complexion, got an ague or two, and seldom held it above half a year, or a year at most; and then … [the men] would go to the uplands again, and fetch another; so that marrying of wives was reckoned a kind of good farm to them.[35]

Dr Mary Dobson masterfully researched the demography, epidemiology and social impact of malaria in England in this period.[36] She found that the disease was especially prevalent in areas of brackish marshland, the preferred habitat of an effective vector, *An. atroparvus*. Data from burial records show mortality rates in 'marsh parishes' were much higher than those in upland areas, and were comparable to those in areas of stable malaria transmission in sub-Saharan Africa today.[37]

After the Little Ice Age

From the early eighteenth century until the present, temperatures have gradually returned to levels that prevailed before the mid-sixteenth century. However, the marked variability of the Little Ice Age persisted for at least 150 years. Indeed, in the 1770s, much as is happening today, there was alarm that the climate was becoming increasingly erratic, and this prompted a new emphasis on the recording of weather variables. Some of the cold periods, particularly those between 1752 and the 1840s, were probably due to major volcanic eruptions. Whatever their causation, such episodes – accompanied by major advances of the Alpine glaciers from 1820 to 1850 – persisted until a more lasting warmth was established in the late nineteenth century.[38]

A wealth of records in the eighteenth and nineteenth centuries reveals the northern limits of malaria transmission. In the British Isles, the disease was common in most of England and in many parts of Scotland, with occasional transmission as far north as Inverness. It was endemic throughout Denmark, coastal areas of southern Norway, and much of southern Sweden[39] and Finland.[40] In Russia it was common in the Baltic provinces and eastward at similar latitudes throughout Siberia. The current average January temperature in some of these regions is less than -20°C (-4°F). Clearly, the distribution of the disease was determined by the warmth of the summers, not the coldness of the winters. The northern limit of transmission[41] was roughly defined by the present 15°C July isotherm – not the 15°C *winter* isotherm, as stated in several widely cited articles on climate change.[42]

The decline of malaria in Europe

In the second half of the nineteenth 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 had essentially disappeared around the turn of the century.[43] The picture was similar in Sweden, although isolated cases were still being reported until 1939.[44]

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.[45] In Germany, transmission also diminished rapidly after the 1880s; after World War I it was mainly confined to a few marshy localities.[46] The last outbreak of locally transmitted malaria in Paris was in 1865, during the construction of the *grands boulevards*, and the disease had largely disappeared from the rest of France by the turn of the century.[47] In Switzerland, the majority of foci had disappeared by the 1890s.[48]

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. However, a host of other factors can be identified:

Ecology of the landscape
'Malaria flees before the plough' is an old Italian saying, and indeed in much of Europe, improved drainage, reclamation of swampy land for cultivation and the adoption of new farming methods 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.

Mechanisation
Rural populations declined as manual labour 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 reduced the survival rate of the malaria parasite in its human host.

Much of the decline in malaria came before recognition of the role of mosquitoes in its transmission. Thus, for most of the region, deliberate mosquito control played little or no role in its eventual elimination.

The persistence of malaria in the USSR

In countries where profound changes in crop production and stock rearing were absent, malaria did not decline.

In Russia, from the Black Sea to Siberia, major epidemics occurred throughout the nineteenth century, and the disease remained one of the principal public health problems for the entire first half of the twentieth century.[49] In 1900, annual incidence in military garrisons was 6.6 per 1,000 in St Petersburg, 31.0 per 1,000 in Moscow, and several hundred per 1,000 in the more southerly provinces. Mean annual incidence from 1900 to 1904 was 3,285,820, but by the period 1933 to 1937, it had risen to 7,567,348.

Some of this increase can be attributed to more effective reporting, but there is no doubt that the disease became much more prevalent after World War I and the Revolution. In the 1920s – in the wake of massive social and economic disruption, two years of severe drought, and a year of widespread flooding – a pandemic swept through the entire Soviet Union.[50] Official figures for 1923–25 listed 16.5 million cases, of which not less than 600,000 were fatal. Tens of thousands of infections, many caused by *P. falciparum*, occurred as far north as the Arctic seaport of Archangel (61° 30'N).

The Soviet government appeared to make some headway against the disease in the 1930s, mainly by drainage schemes, afforestation, and naturalistic methods such as the use of mosquito-eating fish. World War II interrupted these efforts, and transmission soared, particularly in the Ukraine, Byelorussia and other occupied areas. Finally, in 1951, a huge multi-faceted anti-malaria campaign was initiated. It involved widespread use of DDT and other residual insecticides, antimalarial therapy, land reclamation, water management, public health education and many other approaches. This mammoth effort finally brought about a dramatic reduction of transmission, so that by the mid-1950s the national annual incidence was below 1 per 10,000.[51]

Until the collectivisation of farmland that began in the winter of 1929–30, the Soviet Union was largely unaffected by the agricultural revolution. By 1936, all farming was essentially in government hands, but in protest, many peasants had 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. In neighbouring Poland and Finland, farming was also less advanced than in much of the rest of northern Europe, and malaria continued to be a problem, but slow modernisation probably contributed to the steady downward trend in cases.

The contrast between the devastation caused by malaria in the Soviet Union until the 1950s and its quiet withdrawal from other countries at similar latitudes in the previous century is a vivid illustration of the importance of non-climatic factors in transmission.

The persistence of malaria in southern Europe

Malaria remained highly prevalent in much of Mediterranean Europe, the Balkans and the countries bordering the Black Sea until after World War II.[52] A number of effective vector species, an abundance of prolific mosquito breeding sites, the warm climate and the long summer season were all highly conducive to transmission.

In addition, much of the region was 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 characterised 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.[53]

The final elimination of malaria from Europe

Until the end of World War II, the only effective approach to mosquito control was to target the breeding sites – by environmental modifications such as drainage and landfill, and by the application of insecticidal oils or chemicals. These methods were costly, so they were mainly applied to urban centres and other areas of high economic importance. The advent of DDT revolutionised malaria control.[54] It enabled cheap, safe, effective treatments to be targeted at the site where most infections occur – in the home.

The principal treatment method was to apply 2 gm/m^2 to indoor surfaces once every six months. Mosquitoes were killed by contact when they alighted on the treated surfaces. Initial efforts in Italy, Cyprus and Greece were so successful that a decision was made to eradicate the disease from all of Europe.[55]

The campaign was based on a careful application of scientific principles, meticulous planning, efficient administration, generous financing and continuous emphasis on evaluation. It was orchestrated by several international agencies, particularly the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), as well as numerous national bodies, including the US Public Health Service. The International Health Division of the Rockefeller Foundation also provided generous financial and technical support. By 1961, eradication had already been achieved in many countries. The entire continent was finally declared free of endemic malaria in 1975.[56] One of the last countries to be declared free of malaria was Holland.

Holland: an illustration of the complexity of malaria transmission

The persistence of malaria in Holland, a country that has held a central position in the economic life of Western Europe since the Middle Ages, is a good illustration of how local conditions make malaria transmission extremely complex.

In the nineteenth century, despite great progress in drainage and cultivation, the heavily populated 'Low Countries' were the most malarious region of northern Europe. During the Napoleonic Wars, the failure of the British Walcheren expedition (1809) was blamed on malaria, after 4,000 troops died of fever. Severe outbreaks, also attributed to the disease, occurred in 1826, 1834 and 1846, with many thousands of deaths.[57]

The dominant vector, *Anopheles maculipennis*, was present throughout the country. However, the disease was particularly prevalent in areas that had been reclaimed from the sea, especially in Noord Holland, a province that includes the cities of Haarlem and Amsterdam. Moreover, a major peak of incidence occurred in the springtime, rather than summer or autumn.

The unravelling of this puzzle was one of the classic triumphs of medical entomology.[58] Investigation revealed that *An. maculipennis* was not one, but several 'sibling' species:[59] *An. atroparvus*, which lays its eggs in brackish water; *An. messeae*, which prefers fresh water; and

*An. maculipenni*s *sensu strictu*, which occurred inland, in non-malarious areas.

In the laboratory, *An. messeae* and *An. atroparvus* were excellent malaria vectors. In the field, the picture was very different. Both species preferred to feed on domestic animals rather than humans, but whereas *An. atroparvus* rested in stables, *An. messeae* preferred uninhabited sheds and other unheated outhouses. In the autumn, *An. messeae* built up a fat body that allowed it to hibernate. By contrast, *An. atroparvus* remained semi-active, feeding at regular intervals throughout the winter. Although most of its meals were taken on farm animals, it occasionally wandered into adjacent human dwellings. If persons infected with the malaria pathogen were present, the mosquito acquired the infection.

Thus, as in many tropical countries, transmission in Holland occurred at all times of the year, despite winter temperatures that could dip below -20°C. However, the mosquito's ovaries did not develop eggs until the advent of spring, a condition known as *gonotrophic dissociation*. An additional twist to the story was that the local strain of *P. vivax* had a particularly long incubation period, so persons infected in the autumn and winter only showed symptoms of illness in the spring, after the first new brood of mosquitoes had emerged.[60]

In 1932 a dyke was built to enclose the Zuider Zee, a vast area of brackish water to the east of Noord Holland. The accumulation of river water behind this dyke caused a gradual decrease in the salinity of the surrounding land, greatly reducing the larval habitat of *An. atroparvus*.[61] In addition, there were major changes in the living conditions of humans. New farmhouses were less intimately associated with cattle sheds and stables, and their structure and heating technology made them much less hospitable to overwintering mosquitoes.[62]

Thus, although the disease was finally eradicated by routine DDT applications and the administration of anti-malarial drugs, the ecology, physiology, behaviour and survival of the vector, plus the interaction of the pathogen with both vector and host, all contributed to its demise.

Could malaria return to Europe?

In much of Europe, changes in lifestyles and living conditions were the most important factor in the elimination of malaria. Even in countries where these factors were less dominant, eradication of the disease did not require total elimination of the vector. Residual treatments were effective because they reduced the life span of the adult insect, reducing the probability of transmission and eventually leading to the elimination of the parasite. Thus, the malaria-carrying mosquitoes are still present in the brackish waters of England, the rice fields of Italy, the ponds of Poland, the forest pools of Finland and the riverine swamps of Russia.

Advances in agriculture and improvements in living standards have limited the mosquito populations and reduced their contact with humans in many regions, but this is not always the case. For example, recent surveys show that in large areas of Italy, *Anopheles* mosquito populations have returned to levels not seen since before the DDT era. In entomological terms, the infestations are comparable to those in areas of Africa that have extremely high transmission rates.

Nevertheless, the malariogenic potential of Italy is considered to be very low, and re-establishment of malaria is judged unlikely unless living standards deteriorate drastically.[63] Moreover, if the present warming trend continues, human strategies to avoid warmer temperatures – particularly indoor living and air conditioning – are likely to become more widespread.

Of course, this does not mean the disease will be entirely absent. International travel and population movement will facilitate introductions from other parts of the world. For example, in 1997 the WHO recorded 12,328 cases of imported malaria in the European region. Such cases occasionally lead to summertime transmission,[64] recently reported as far north as Toronto and Berlin. However, in all the wealthier countries, such outbreaks are likely to be small, easily contained and confined to a limited geographic area.

The same may not be true of less affluent regions. Rapid economic decline, combined with political instability, has already brought back epidemic typhus, diphtheria and other infectious diseases to several countries of the former Soviet Union.

In the 1990s, epidemic malaria has made a dramatic reappearance in Armenia, Azerbaijan, Tajikistan, Turkey and Turkmenistan. Cases have also been reported from Dagestan (Russian Federation), Georgia, Kazakhstan, Kyrgizstan and Uzbekistan.[65] It is quite possible that the disease could spread northward into Russia and westward around the Black Sea. The 1999 conflict in the Balkan states was in the same region where hundreds of thousands were infected with malaria during World War I. Endemic transmission in such areas could be significant if the parasite were to be reintroduced. Climate change might augment this possibility, particularly at high latitudes (e.g. in Siberia) although low stability should facilitate control.

Perspective on the global debate

The history of malaria in Europe, especially during periods when the climate was much colder than it is today, contradicts the popular notion that the disease is restricted to the tropics, yet the authors of many influential publications on the impacts of climate change evidently share this misconception.

For example, in 1995, the International Panel on Climate Change (IPCC) confidently forecasted that malaria and other mosquito-borne diseases would move from the tropics into temperate regions.[66] Similarly, in 1997, the Environmental Protection Agency (EPA) of the US government stated that in the 21st century there would be: 'an increase from approximately 45 percent to 60 percent in the proportion of the world's population living within the potential zone for malaria transmission.' In their estimate, this could result in 50–80 million additional cases annually.[67] Several other publications included maps that showed the future range of the disease extending into southern Europe.

In the past two years the subject has been treated more cautiously, but the intuitive assumptions and predictions of the 'spread' of malaria from the tropics into temperate regions still persist. Thus, in its *Third Assessment Report*, the IPCC repeats the assertion that, 'the geographic range of malaria is limited to the tropics and subtropics',[68] and the EPA continues to state that, 'global warming may also increase the risk of … infectious diseases … that only appear in warm areas. Diseases such as malaria could become more prevalent if warmer temperatures enabled [mosquitoes] to become established farther north.'[69]

Environmental activists quote these official statements and add warnings that are even more graphic. For example, the World Wildlife Fund quotes the IPCC, followed by a statement that 'malaria generally extends only to places where the minimum winter temperatures reach no lower than 16°C.' It even asserts that 'small outbreaks now occurring north and south of tropical regions are consistent with model projections' and supports this with claims of local transmission of malaria in the US and Canada 'during particularly hot, humid periods'.[70] The outbreaks it refers to are all associated with imported cases and occurred in regions where malaria was once common.

I believe that such misinformation should be treated seriously. There is much talk of efforts to improve the health of poorer nations. At the same time, erroneous concepts of mosquito-borne disease are used as an argument to spend colossal amounts of scarce resources to 'halt' global warming, even as climate experts confess that the true contribution of human activities to the present warming trend is uncertain.

History is replete with bizarre decisions based on superstition and misconception. There is a tendency to assume that modern science is proof against such error. While it is true that public policy is increasingly driven by science, it is also true that much of science is nurtured by public policy.

The story of malaria in Europe is widely known and readily accessible in any good library. Nevertheless, uninformed predictions on the spread of this and other vector-borne diseases to temperate areas are commonplace – even in the scientific literature – and are widely quoted in public discussion of national and international policy on global warming.

In my opinion, these predictions are sustained by (1) Hippocratic concepts of the association between climate and disease; (2) a fear of things tropical; (3) a disregard for the past; and (4) a necessity to simplify concepts for public consumption. The truth, as we have seen, is that the natural history of malaria is complex, and the interplay of climate, ecology, vector biology and many other factors defies simplistic analysis.

The sad fact is that there is little we scientists can do to challenge the campaign of misinformation. None of us denies that temperature *is* a factor in the transmission of mosquito-borne diseases, and that transmission *may* be affected if the world's climate continues to warm. But it is immoral for political activists to mislead the public by attributing the recent resurgence of these diseases to climate change, particularly in Africa. The true reasons are far more complex, and the principal determinants are politics, economics, and human activities. A creative and organised application of resources to correct the situation is urgently needed, regardless of future climate.

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Notes

1 'Global warming: Health and Disease' WWF Fact Sheet. Available at http://www.panda.org/resources/publications/climate/health_factsheet/
2 Levi-Strauss (1992), p. 425.
3 Wigley (1981); Lamb (1995); Chorley and Barry (1998).
4 Houghton *et al.* (1996); Tett (1999); Wigley and Schimel (2000).
5 Wigley (1981); Lamb (1995); Rampino (1987).
6 Lamb (1995), p. 433.
7 Calder (1974), p.143; Ponte (1976), p.306; Halacy (1978), p. 212.
8 Houghton *et al.* (1996); Tett (1999); Wigley and Schimel (2000).
9 Tett *et al.* (1999), pp. 569–72; Karl *et al.* (1996). pp. 279–92; Michaels and Knappenberger (1996), pp. 522–23; Kerr (1997), pp. 1040–42; Lindzen (1997), pp. 8335–42.
10 Ross (1991), p. 277; Gelbspan (1997), p. 278; M8ichaels and Balling (2000), p. 236.
11 See, for instance, McMichael *et al.* (1996); Patz *et al.* (1996); Hay (2001); Hay *et al.* (2002); Mouchet, J. *et al.* (1998); Epstein *et al.* (1998); McMichael, Patz and Kovats (1998); Martens (1998); Epstein (1999); Kovats *et al.* (1999); Reiter (2000); Shanks *et al.* (2000); Reiter (2001).
12 Gilles and Warrell (1993); Cook (ed.) (1996).
13 Bruce-Chwatt and de Zulueta (1980), p. 240.
14 Craig, *et al.* (1999), pp. 105–11.
15 Martens (1998), p. 176; Lindsay and Birley (1996), pp. 573–88; Jetten and Focks (1997), pp. 285–97; Patz (1998), pp. 147–53.
16 Rogers and Randolph (2000), pp. 1763–66; Dye and Reiter (2000), pp. 1697–98.
17 Bruce-Chwatt and de Zulueta (1980), p. 240.
18 Lamb (1995), p. 433.
19 Homer (1990) Book 22, lines 31–37.
20 Lamb (1995), p. 433; Jones (1909).
21 Langholf (1990).
22 Bruce-Chwatt and de Zulueta (1980), p. 240.
23 Lamb (1995), p.433; Jones (1907).
24 Dante (1949) Cantica I: Hell (L'inferno). Canto XVII, lines 85–8; Chaucer (1977). 'The Nun's Priest's Tale', lines 134–140.
25 Campbell (1991), p. 232.
26 Bruce-Chwatt and de Zulueta (1980), p. 240.
27 Lamb (1995), p. 433.
28 Grove (1988).
29 Bruce-Chwatt and de Zulueta (1980), p. 240.
30 Harvey (1993), p. 91.
31 Bruce-Chwatt and de Zulueta (1980), p. 240.
32 *Quoted in* Bruce-Chwatt and de Zulueta (1980), p. 240.
33 Bruce-Chwatt and de Zulueta (1980), p.240; Dock (1927), pp. 241–47; Siegel and Poynter (1962), pp. 82–85; Dobson (1998), pp. 69–81; Poser and Bruyn (1999), p.165.

34 Defoe (1986).
35 Ekblom (1938), pp. 647–55.
36 Dobson (1980), pp. 357–89; Dobson (1989), pp. 3–7; Dobson (1994), pp. 35–60. Dobson (1997), p. 647.
37 Reiter (2000), pp. 1–11.
38 Lamb (1995), p. 433; Grove (1988).
39 Ekblom (1938), pp. 647–55.
40 Renkonen (1944), pp. 261–75.
41 Russell (1956), pp. 937–65.
42 Patz (1996), pp. 217–23; Epstein (1998), pp. 409–17.
43 Wesenberg-Lund (1921), pp. 383–86.
44 Ekblom (1938), pp. 647–55.
45 Bruce-Chwatt and de Zulueta (1980), p. 240; James (1920), pp. 71–85.
46 Bruce-Chwatt and de Zulueta (1980), p.240.
47 Crosnier (1953), pp. 1299–1388; Laigret (1953), pp.1308–12.
48 Galli-Valerio (1917), pp. 440–54.
49 Bruce-Chwatt and de Zulueta (1980), p. 240.
50 Hackett (1937), p. 336.
51 Bruce-Chwatt and de Zulueta (1980), p. 240.
52 Hackett (1937), p. 336.
53 Bruce-Chwatt and de Zulueta (1980), p. 240.
54 Brown, Haworth and Zahar (1976), pp. 1–25.
55 Gilles and Warrell (1993); Bruce-Chwatt (1987), pp. 75–110.
56 WHO (1978), pp. 9–17.
57 Lloyd and Coulter (1961).
58 Hackett (1937), p. 336.
59 Hackett and Missiroli (1935), pp. 45–109.
60 Bruce-Chwatt and de Zulueta (1980), p. 336.
61 de Jong, JCM (1952), pp. 206–9.
62 Bruce-Chwatt and de Zulueta (1980), p. 240.
63 Guido Sabatinelli, WHO, Regional Office for Europe, Copenhagen, Denmark.
64 Zucker (1996).
65 Sabatinelli (1998).
66 Watson, Zinyowera, and Moss (1996).
67 EPA (1997), pp. 1–4.
68 Manning and Nobre (2001), p. 74.
69 EPA (2002), pp. 1–4.
70 Epstein (2002).

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