Foresight

Infectious Diseases: preparing for the future

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T7.4: Climate Change and Infectious Disease in Africa and the UK

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1 Introduction

The recent World Health Organization (WHO) initiative on the global burden of disease (GBD, see Box 1) underlines the central importance of infectious disease as a cause of human mortality and morbidity. Nowhere is this truer than in Africa. Diarrhoeal illnesses related to poor access to clean water and inadequate sanitation, childhood respiratory diseases, HIV/AIDS and vector-borne diseases such as malaria, remain major public health threats with substantial burdens on human populations.

In the UK, as elsewhere in western Europe, infectious disease makes a smaller contribution to disease burdens, thanks largely to good environmental services, immunisation programmes, effective healthcare and well-developed public health infrastructure. Nonetheless, even here there are concerns about new and re-emergent infections, multi-drug-resistant pathogens, and the possibility that major epidemics may spread with accelerated speed because of the rapid expansion of international travel and migration.

How infectious disease may be altered by climate change is an area of continuing enquiry and scientific debate[1]. In this chapter, we summarise some of the evidence relating to the selected infectious diseases of Africa and UK/Europe.

Box 1 Global burden of disease assessment[2]

The WHO has conducted a number of global assessments of human mortality and morbidity, and in their most recent GBD assessment, they estimated that, on a global basis, there are almost 56 million deaths per annum. Approximately 26.1% of these deaths are due to infectious disease (e.g. HIV/AIDS, tuberculosis, malaria, and respiratory infections). The WHO has developed a composite measure – the disability-adjusted life year (DALY) – which is an indicator of life expectancy that combines mortality and morbidity. The GBD estimates that the total global burden of DALYs is over 1,455 million per annum, and communicable diseases are responsible for approximately 30.59%. All data in the GBD assessment are stratified by WHO region, and divided into three broad categories of health outcomes: communicable diseases, maternal and perinatal conditions and nutritional deficiencies; non-communicable conditions; and injuries.

We have already provided data for communicable diseases above. Maternal and perinatal conditions and nutritional deficiencies are responsible for 6.5% of mortality and 11.4% of DALYs respectively. Non-communicable diseases (e.g. malignant neoplasms, and cardiovascular disease) are responsible for 58.3% of the global burden of mortality, and 45.7% of DALYs. Injuries are responsible for 9.1% and 12.3% of mortality and DALYs respectively.

2 Characterising sensitivity to climate change

The characterisation of sensitivity of infectious disease to climate change is complex. Many diseases and markers of health show seasonal and inter-annual fluctuation, but the demonstration of this is not direct evidence that disease will alter as a result of climate change – merely that these diseases exhibit a form of seasonal or meteorological dependence. It is, however, reasonable to conclude that if dependence can be demonstrated on temperature or other meteorological variables, there is at least the potential for disease to be altered as a result of climate change. We are primarily concerned with evidence that the geographical distribution of disease may change, or that the seasonality and/or intensity of infection may be affected by weather conditions. Much of the most relevant evidence is based on spatial or temporal comparisons between the distribution of disease and meteorological factors, but the significance of these correlations can be uncertain.

It is also important to note that the climate is only one factor among many that can influence the occurrence of infectious disease. Climate change is singled out because of the interest in it as arguably the foremost environmental challenge of the 21st century. But other social, environmental and healthcare changes may influence disease occurrence at least as much, if not more, and it is in many ways artificial to examine climate change on its own. It should also be noted that many of the diseases discussed in this report are major public health threats, regardless of any considerations of climate change, and hence they are already the focus of international efforts aimed at combating them.

We do not attempt to review the evidence for every group of infectious diseases but rather to pick out those for which there are at least good theoretical arguments to suppose climate may be a significant determinant of disease distribution and/or seasonality. We have also tended to concentrate on diseases of highest burden in terms of mortality and morbidity. For each disease, we adopt a common approach – firstly providing brief details on the clinical and epidemiological features of the disease, and then discussing the sensitivity of the disease to climatic factors.

3 Disease-specific evidence

In this section, we examine the evidence for specific diseases. Prominent in this list are the vector-borne diseases which are among those of greatest potential sensitivity to climate change because weather conditions, in particular temperature and rainfall, may influence the reproduction and survival of the vector and/or the pathogen. Among those of greatest importance for low-income countries are malaria and dengue, both transmitted by various species of mosquito, as well as diseases transmitted by flies and ticks. In a European context, tick-borne infections are considered to be the most frequent vector-borne infection[3], and we consider two tick-borne diseases (Lyme disease and tick-borne encephalitis).

3.1 Malaria

Malaria is a parasitic disease that occurs in humans when one of four infectious agents – *Plasmodium vivax*, *P. malariae*, *P. falciparum*, and *P. ovale* – is transmitted into the blood stream through the bite of a female mosquito[4]. *P. falciparum* is the most serious form of the disease as it often leads to death if left untreated, and it is responsible for the majority of infections in Africa[4, 5]. Although the total global area of human malaria risk has been reduced by about half in the 20th century[6] the disease is still endemic in over 100 countries throughout the tropics and subtropics[7], and the greatest burden of malaria cases and deaths occur in Africa[7].

In Africa, malaria is the third most important infectious disease (after HIV/AIDS and acute respiratory infections) in terms of number of deaths, where it leads to over 950,000 deaths per annum, and has the second highest burden of DALYs on the continent. The disease is also a significant indirect cause of death: malaria-related maternal anaemia in pregnancy, low birth weight and premature delivery are estimated to cause 75,000–200,000 infant deaths per year in Africa south of the Sahara. Although malaria caused high levels of mortality in the British marshlands and fens from the 15th to the 19th century, the disease is no longer endemic in the UK. The burden of disease for malaria in the UK arises from imported cases.

Transmission of malaria is closely linked with local environmental conditions, and stagnant bodies of water provide ideal habitats for mosquito breeding. Increased transmission is often associated with increased precipitation, although reduced precipitation (drought) can also increase transmission, as pools of water provide ideal habitats.

Climate sensitivity. Several important diseases (e.g. malaria, dengue, West Nile virus) are transmitted by arthropod vectors (mosquitoes, ticks), and the survival and development of these vectors is closely associated with climatic factors (temperature, precipitation, humidity); any changes in these climatic factors will affect not only the survival and development of the vector, but is also likely to affect the spatial and temporal distribution of vector-borne disease[1]. There has much been much debate about the potential impacts of climate change on human health, and in the context of infectious diseases much of this debate has focused on the spatial and temporal distribution of vector-borne disease (especially malaria and dengue)[8]. For malaria, much of the debate has focused on supposed changes in both latitudinal and altitudinal distribution of the disease. For instance, the highlands of east Africa have been frequently affected by malaria epidemics, often with devastating morbidity and mortality among populations with no immunity to the disease. These areas have experienced a resurgence of malaria in recent decades, and this has led to a great deal of scientific debate about the role of climatic variables in this increase.

Recent studies in the east African highlands have suggested that climate variability has played an important role in the recent re-emergence of malaria[9–11], although, controversially, some authors contest that the importance of climatic variables has been overestimated[12]. A number of other studies have also reviewed historical data both for malaria hospital admissions and meteorological variables, and argue that non-climatic factors are more likely to have played a role in this increased transmission[13–17]. These non-climatic factors include: increasing antimalarial drug resistance by the malaria parasite; migration of asymptomatic workers from endemic areas to the non-endemic highlands; and weakened malaria control programmes. Nonetheless, it is clear that temperature and rainfall patterns are at least important potential parameters of disease distribution, and in conditions of poor public health infrastructure, climatic changes may well lead to important alterations in the distribution of disease.

Given the uncertainties over the relative importance of climatic and non-climatic factors in different settings, the modelling of the impact that future climate change on malaria (and other infectious disease) is challenging. To date, several types of model have been used and these have produced varying results. On a global scale, biological (process-based) models have projected that by 2080 there will be a 2–4% increase in the number of people at risk of malaria[18], while models that use a statistical-empirical approach estimate no significant net change by 2080 in the portion of the world's population living in actual malaria transmission zones. However, the models that have been developed to date have methodological weaknesses, and concentrate only on the influence of climatic parameters, and none has been adequately validated at global or regional levels. More recently, Tanser and colleagues modelled the likely effects of climate change on malaria in Africa, and estimated a 5–7% increase in malaria distribution by 2100[19]. Much of this projected increase would be altitudinal rather than latitudinal. Like other modelling exercises, the projections by Tanser et al. are seen as indicative and do not include some important variables, such as population growth and the future effectiveness of vector-control programmes[17]. As with so much of the academic discussion on the likely impact of climate change on health, this more recent work has also led to fervent debate[19–22].

In terms of the UK, the current evidence is that indigenous malaria is unlikely to become re-established because of the over-riding importance of non-climatic factors: since the nineteenth century, land-use changes that have reduced mosquito breeding sites, improvement in health care, the quality of housing and urbanisation of the population have all contributed to the eradication of disease[23].

3.2 Dengue

Dengue fever is an acute febrile viral disease transmitted to humans by the *Aedes aegypti* mosquito, and is endemic in most countries in the tropics[4]. There are four serotypes of the dengue virus, and co-circulation of multiple serotypes and/or virulent viral strains may result in a greater risk of dengue haemorrhagic fever – a severe clinical presentation with a high case fatality rate. Currently there are 2.5 billion people at risk of dengue fever in more than 100 countries worldwide, with 50 million new cases and 21,000 deaths reported each year. The highest disease burden falls on developing countries, particularly in Asia and the Americas, but even economically advanced settings, such as Australia and USA, are affected.

Dengue is primarily an urban disease, and over the past several decades, there has been an unprecedented increase in the global incidence and geographical range of dengue fever and the primary mosquito vector, *Ae. aegypti*. The *Ae. aegypti* mosquito thrives in man-made urban environments and has been spread around the globe with the movement of man and his products (particularly the global trade in used car tyres). As well as spreading the vector, changes in the pattern of human movement, particularly the growth in international air travel, has resulted in the spread of the viruses that cause dengue fever. There are a number of important factors that may influence the geographical range and burden of dengue, particularly in Africa, but also in currently non-endemic regions (such as Europe). There are four major factors:

Lack of effective dengue control strategies: Currently, there are no effective means of controlling dengue either by targeting the mosquito (insecticides against the adult or clearance of breeding sites are costly, logistically demanding and ultimately ineffective) or the virus (there are no vaccine or specific drug therapies, nor likely to be within the next 10 years).

Global increase in urbanisation: The *Ae. aegypti* mosquito is ideally suited to urban environments, and breeds prolifically in rainwater that collects in man-made receptacles. Controlling these breeding sites over large tracts of urban landscape, particularly in poor settings, is an impossible task. The pace of change in urbanisation is likely to be greater in Africa than many other regions, and the implications for *Aedes* populations and dengue transmission potential are immense.

Global increase in the volume and frequency of international air travel: People infected with dengue will on average remain infectious to the mosquito vector for only a few days. However, the rapid growth in international air travel increases the probability that an infected person may carry a novel viral strain to a new setting with important epidemiological consequences.

Climate change: As with all vector-borne diseases, climate affects many aspects of the transmission cycle, and the implications for altering the transmission potential in a setting may be profound.

Climate sensitivity. Like malaria, the dengue vector (*Ae. aegypti*) is sensitive to meteorological conditions. In most tropical zones, the disease occurs year-round, but has a seasonal peak that occurs in the months of high rainfall and humidity[18]. As with malaria, some modelling studies have projected a net increase in the potential latitudinal and altitudinal range of dengue and an increase in the duration of the transmission season in temperate locations[18].

Although there has been limited work on projecting the future burden of dengue under climate change, one study has taken into account some of the variables (e.g. population growth) that were omitted in earlier modelling exercises[24]. Using projections for population growth and future climate change, Hales et al. have estimated the number of people likely to be at risk from dengue in 2085, and suggest that around 5–6 billion people (50–60% of the projected global population) are likely to be at risk[24]. This compares with a figure of 3.5 billion, or 35% of the population, if climate change did not occur. Separate estimates of changes in disease burden were not provided for Africa (or Europe), but the global model suggests appreciable expansions in the geographical distribution of the at-risk population in Africa.

3.3 Rift Valley fever

Rift Valley fever (RVF) is transmitted by female *Culex* mosquitoes and has only been identified in Africa. The disease is primarily associated with rural settings, but occasional outbreaks in urban and suburban areas have also been recorded[4]. Although precise data for the overall burden of mortality and morbidity due to the disease was not readily available for this report, the burden is likely to be extremely low, relative to the other infectious diseases highlighted here.

In terms of meteorological variables, a number of epidemics of RVF have been associated with above-average rainfall and temperatures. However, until the late 1980s, this link was mainly based on observations and anecdotal evidence[25]. Significant increases in rainfall and associated flooding have been linked to RVF outbreaks, and RVF outbreaks are positively associated with warm El Niño Southern Oscillation (ENSO) events and above-normal precipitation (indicated by remotely sensed vegetation patterns)[26]. A quantitative analysis of Kenya data from 1950 to 1998 suggested that RVF activity was significantly correlated with sea-surface temperature and normalised difference vegetation index obtained from satellite images[27].

3.4 West Nile virus

West Nile virus (WNV) is transmitted by female *Culex* mosquitoes and is found throughout Africa, the Middle East, parts of Europe (mostly central and southern), the former Soviet Union, south and central Asia and Australia [4, 28]. WNV is not present in the UK, and the risk of the disease becoming established is considered to be low.[29]

Climate sensitivity. Prior to 1999, WNV was not found in North America, but since a major outbreak in New York in the same year, the disease has spread to Mexico and the Caribbean.[28] This increase in the spatial distribution of the disease has raised concerns about further spread, but any predictions are difficult as the mechanism(s) that led to this increase are not understood; international passenger travel, and transmission via migratory birds have been cited as possible explanations.[28] Equally, the role that climatic factors may play in the transmission of the disease is not well understood, and there are no studies that have attempted to quantify the link between climate and outbreaks of WNV.[23] However, amplification of the virus is thought to occur under the climatic conditions of warm winters followed by hot dry summers.[1]

Several studies in Europe have reported that environmental factors, such as flooding, can facilitate the re-emergence of WNV,[30–32] although a more recent study did not find WNV infections following the 2002 floods in central Europe.[33] Under future climate change, the intensity and frequency of extreme weather events (such as floods) are likely to increase, and this could in turn facilitate increased transmission of the disease. Evidence relating to spread to the US and southern Europe from the original endemic area does not clearly implicate climatic factors, though some have suggested a link to hot dry weather[29, 31, 33–35].

3.5 Leishmaniasis

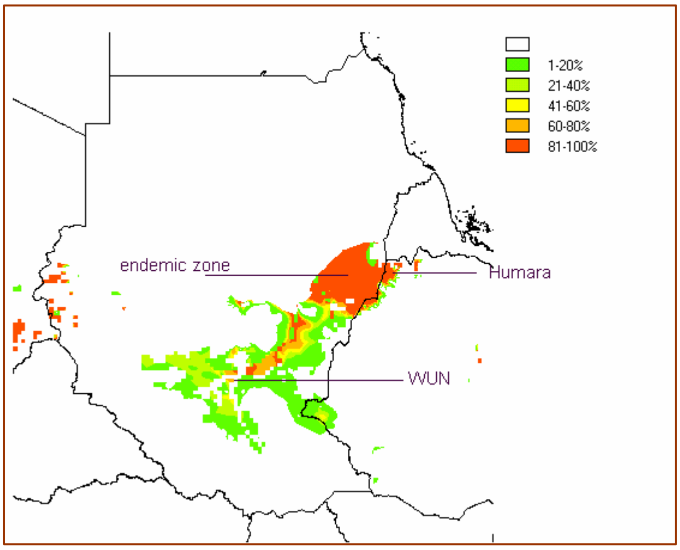
There are three types of leishmaniasis and each has its own set of clinical symptoms. *Cutaneous leishmaniasis* results in skin ulcers on exposed parts of the body, including the face, arms and legs; *Mucosal leishmaniasis* results in lesions that can lead to partial or total destruction of the mucous membranes of the nose, mouth and throat cavities and surrounding tissues; *Visceral leishmaniasis* – also known as kala-azar – is characterised by irregular bouts of fever, substantial weight loss, swelling of the spleen and liver, and anaemia[4, 7]. These various forms of the disease result from infection by the pathogenic protozoa *Leishmania*, which is transmitted via the bite of an infective female phlebotamine (sandfly)[4]. The sandfly vector is commonly found in intertropical and temperate regions[7].

Some 350 million people are at risk of contracting leishmaniasis, and the disease is prevalent in 88 countries[7]. In Africa all forms of the disease are found in Ethiopia, Kenya, Sudan, and the sub-Saharan savannah; cutaneous and mucosal leishmaniasis are also found in Namibia[4]. The most recent GBD assessment estimated that in Africa there are 9,000 deaths per annum, and 395,000 DALYs (see Table 1). The greatest burden of kala-azar in east Africa is experienced by the Sudan: both in western Upper Nile in southern Sudan, where an estimated 100,000 deaths is attributed to a visceral leishmaniasis epidemic in the 1980s and in eastern Upper Nile and Gedaref State since the mid-1990s.

Kala-azar is also endemic in Uganda (Pokot County), Kenya, Somalia and Ethiopia (where the growing AIDS epidemic is causing further complications for kala-azar case management as standard visceral leishmaniasis treatment for patients co-infected with HIV is relatively ineffective.

Climate sensitivity. The current distribution and pattern of kala-azar in east Africa is clearly dependent on the distribution of the principal sandfly vectors – *Phlebotomus martini* and *P. orientalis*. These are in turn determined by climatic and environmental parameters whose geographical patterns are likely to change during the 21st century due to changes in both land use and climate. For example, *P. martini* distributions are associated with the distribution of termite mounds (where they rest and possibly breed) and livestock (from which they feed). In contrast, *P. orientalis* distribution is associated with acacia woodlands and black cotton clay soil. Statistical associations with climate have been determined for the distribution of both species.

***Figure 1:** Risk map of kala-azar in Sudan, based on the probability of the presence of P. orientalis on the basis of type, mean annual daily maximum temperature and rainfall*



Humara = area of current epidemic in western Tigray, WUN = major epidemic area (1988 to present) in southern Sudan. *Courtesy of M. Thomson.*

In addition to the distribution of sandflies, risk of kala-azar is also determined by socio-economic factors – such as nomadic behaviour, associations with livestock, house design, sleeping indoors or outdoors. Clinical outcome is also affected by malnutrition and immunosuppression due to co-infections – notably HIV. Epidemics in this region are also typically associated with the displacement of people – as large numbers of susceptible people enter an endemic zone. In particular, as the peace process progresses, the expected return of hundreds of thousands of Sudanese from Khartoum to the south is widely expected to be associated with a new and potentially catastrophic kala-azar epidemic.

Hence, there is a range of ‘drivers’ that could influence future changes in the burden of kala-azar in Africa. These include the direct impact of climate change on sandfly distributions, but also the indirect impacts of climate change, e.g. on land use and livestock ownership patterns, as well as the expected socio-economic changes predicted in the various future ‘scenarios’.

The effects of changes in temperature and temperature variability are more obvious along altitudinal gradients than across latitudinal ranges, as communities separated by only a few kilometres, with similar socio-economic conditions and lifestyles, may be exposed to very different climatic regimes. Most previous investigations have attempted to either test whether long-term trends of individual climate variables in specific sites have reached statistical significance, or whether other non-climatic influences (e.g. land-use patterns, demographic change and breakdown of control programmes) have exerted a greater effect than climate in the past, or may do in the future.

3.6 African trypanosomiasis

Trypanosomiasis is a protozoan infection of humans and animals. In Africa, two forms of sleeping sickness are caused by *T brucei*: an acute form (east Africa) from infection with *T b rhodesiense*, and a more chronic form of the disease caused by *T b gambiense* (west Africa). The disease is transmitted by the tsetse fly (Glossina species), which is widely distributed in sub-Saharan Africa north of the Kalahari desert. Untreated, both east and west African forms of trypanosomiasis are fatal. The number of infected people in Africa is estimated to be 300,000–500,000, and the annual burden is around 50,000 deaths and 1.5 DALYs.

Climate sensitivity. As yet, there is no strong evidence to suggest that outbreaks of African trypanosomiasis are linked to climatic factors[23]. However, there have been a number of initiatives to develop models of disease distribution on the basis of geographical parameters, including climatic variables[36, 37]. Satellite-derived index of land-surface temperature has been shown to correlate with monthly mortality rates in some areas[36], but different seasonal cycles may occur relating to differing vectorial roles[36]. Cattle are an importance reservoir of the human disease, and so factors that determine variations in animal disease are likely also to influence the incidence of human infection.

3.7 Schistosomiasis

Schistosomiasis (bilharzias) is a disease caused by a trematode flatworm, which requires a freshwater snail as an intermediate host. Worldwide, around 200 million people are affected by schistosomiasis, and there are around 200,000 deaths. The main causes of death are renal failure and haematemesis. Most infection occurs in childhood. In Africa, the main schistosomes are *S Haematobium* and *S mansoni*, which are quite widely distributed in sub-Saharan Africa, the Nile river and basin, and Madagascar.

Climate sensitivity. Evidence that the distribution of schistosomiasis is in part determined by climatic conditions is reasonably clear[11, 38–40]. In China, the distribution of *Oncomelania hupensis*, the intermediate host snail of *S japonicum*, appears to be influenced by the temperature of the coldest months of the year[11]. The snail appears not to survive in conditions of sub-zero winter temperatures, and evidence that the historical 0–1°C January isotherm, considered to be the approximate northern limit of *S. japonicum* transmission, has shifted northwards over the last 30 years, has meant an expansion in the potential transmission area and population at risk. The problem may be exacerbated in this setting by proposed water resource developments, specifically the planned south–north water diversion.

In Africa too, the distribution of schistosomiasis and the intermediate hosts appear to be determined temperatures and land use[41–43]. For example, composite models suggest low night time temperature as one of the significant factors inhibiting *S mansoni* transmission in the south-western highland areas of Uganda[41]. Such models suggest that temperature and other meteorological changes associated with climate change may increase the distribution of disease in some areas. However, the distribution and prevalence of infection may already be increasing, mainly because of the expansion of irrigation projects and population movements. Clearly, these factors and specific control measures are likely to be at least as important as climate change in determining the overall distribution of disease in future.

3.8 Filariasis: onchocerciasis

Filarial infections are caused by filarial nematode worms transmitted by biting insects. The three main forms of human disease are:

i mosquito-transmitted lymphatic filariasis (common infecting parasite *Wuchereria bancrofti*), which affects 120 million people worldwide, a third of them in Africa

ii onchocerciasis (river blindness) caused by *Onchocerca volvulus*, and transmitted by the *Simulium* blackflies, mainly in sub-Saharan Africa, and causing blindness in 0.7 million of the estimated 17 million infected people worldwide (and accounting for an estimated 913,000 DALYs per annum in Africa)

iii loaisis, transmitted by tabanid mango flies in the rainforest belt of west Africa.

Although onchocerciasis is one of the most important fly-related diseases in Africa, highly successful control programmes have substantially reduced the level of morbidity caused by this disease.

Climate sensitivity. The transmission pathways of filarial diseases would suggest that they should exhibit at least partial sensitivity to climatic conditions and other environmental changes. For onchocerciasis, GIS-based statistical models have attempted to explain the distribution of disease on the basis of a combination of environmental and climatic variables, including, for example, land-surface temperature, rainfall and evapo-transpiration[44]. For lymphatic filariasis, a study in the Nile Delta found correlations between microfilarial prevalence on the one hand and weather variables (including temperature, rainfall and humidity) on the other[45]. In settings outside Africa, the extrinsic incubation period of *Wuchereria bancrofti* and the biting density of the vector mosquitoes have, for example, been related to ambient temperatures and other weather parameters[46–48]. However, it is also important to recognise that changes in disease in parts of Africa in recent decades have been driven not by climatic variables but by large-scale agricultural development projects that have shifted the nature and quantity of water sources and potential mosquito breeding sites[49]. No studies appear to have attempted to quantify the link between filarial disease and climate directly.

3.9 Lyme disease

Lyme borreliosis (Lyme disease) is a tick-borne spirochetal, zoonotic disease and there have been cases in parts of North America, Europe, former Soviet Union, China and Japan[4]. In Europe, the pathogenic agent (*Borrelia* *burgdorferi*) is transmitted to the tick species *Ixodes ricinus* after feeding on deer and small mammals, and the distribution of the majority of human cases of the disease coincides with the distribution of the tick[4].

Recent evidence from Germany found the prevalence of *B. burgdorferi* infection in *I. ricinus* ticks increased over a 10-year period, and suggested that this increase could be a result of increased contact between the vector and the reservoir host[50]. There is a remote possibility that this increase may be linked to changes in climatic variables. However, any such linkage has yet to be analysed. There is also evidence from Sweden which suggests that the relatively mild climate of the 1990s was probably one of the primary reasons for the observed increase of density and geographic range of *I. ricinus* ticks[51, 52].

3.10 Tick-borne encephalitis

Tick-borne encephalitis (TBE) is a disease of the central nervous system, and the geographical distribution of the disease includes the former Soviet Union, other parts of central and eastern Europe, Scandinavia and the UK[4]. The *Ixodes ricinus* tick is the primary vector in western Europe. Humans may be at increased risk of contracting infection when:

- improved conditions for natural transmission cycles result in higher densities of infected ticks
- changed human behaviour result in greater exposure to ticks
- changed agricultural practices result in a higher consumption of raw milk.

The first two factors are climate-dependent, and there is therefore potential for changes in climate to affect the distribution of TBE[52]. In terms of observed changes in the distribution of TBE in parts of Europe, changes in climate have not been found to be a causal factor and several explanations have been offered, including changes in habitat structure and increases in deer abundance; and socio-political changes following the collapse of the communist system[52]. As with other vector-borne diseases (such as malaria), there are alternative explanations for recently observed increases in disease.

3.11 Faeco-oral disease: diarrhoea, including cholera

Many infectious pathogens are transmitted through ingestion of contaminated water or food. Faeco-oral disease results when faecal material is permitted to pass into the mouth (the ‘faecal–oral’ route) and includes many of the common diarrhoeal diseases. These diseases are often associated with conditions where there is inadequate water and sanitation infrastructure, or poor personal hygiene[53, 54]. This is especially the case in many low-income countries where large populations do not have access to a water supply of sufficient quantity and quality, rely on inadequate facilities for disposal of faecal material, or engage in inappropriate personal hygiene practices. In this section, we consider diarrhoeal diseases generally, and give specific mention to cholera.

Diarrhoeal illness is already of major importance for tropical developing countries because of its large contribution to the burden of ill health[55]. Although that burden is much more a consequence of poor sanitation and nutrition than a consequence of climatic conditions, the demonstration of climate sensitivity suggests that climate change is likely to contribute to an increase in morbidity unless counteracted by increasing standards of living and improved public health.

3.11.1 Diarrhoeal illness

Diarrhoeal disease can be caused by both viral and bacterial pathogens[4], and is a major cause of childhood mortality and morbidity in low-income countries[56]. In Africa, diarrhoeal illness is the fourth most important infectious disease both in terms of mortality and morbidity (see Table 1).

Climate sensitivity. The transmission of many diarrhoeal diseases shows seasonal variation that may be associated with seasonal rains and flooding, although the evidence for this is not well established[57]. Nevertheless, the transmission of most infectious diseases is influenced to some extent by the weather. The most important influences are on those diseases where either the pathogen itself, or its vector, replicates outside of the stable environment of the human host. For example, environmental temperature and humidity may affect the survival and replication rates of bacteria and other enteric pathogens on water or food, as well as the survival of enteroviruses in the environment[58].

This is the most likely explanation for the strong seasonality of diarrhoeal disease in numerous regions[59] and for the observation that populations without access to adequate clean water and sanitation have higher rates of diarrhoea during summer months[60], particularly on hotter days and during strong ENSO events[61]. Climate also affects the rate at which water-borne pathogens come into contact with humans, rates often being higher when rainfall is either unusually high (leading to flooding), or unusually low (leading to prolonged water storage and concentration of pathogens)[62].

The relative importance of different pathogens and modes of transmission (e.g. via water, food, insects or human-to-human contact) varies between areas, and is influenced by level of sanitation[63]. As pathogens are known to vary in their response to climate (see for example, references[64, 65]), this is likely to cause geographical variation in temperature relationships, depending on level of development. While several studies describe climate effects on particular diarrhoea pathogens[66–68], these cannot be directly used to estimate effects on diarrhoeal disease overall. The quantitative relationship between climate and diarrhoea incidence has been explicitly quantified in few studies and in none from Africa. Evidence from other settings provides an indication of the nature of the relationships.

In 2000, Checkley et al.[61] reported a time-series study of the relationship between temperature and relative humidity and daily hospital admissions at a single paediatric diarrhoeal disease clinic in Lima, Peru. Analyses based on 57,331 admissions over a period of just under six years revealed a 4% (95%

CI 2 to 5%) increase in admissions for each degree Celsius increase in temperature during the hotter months, and a 12% (95% CI 10 to 14%) increase per degree Celsius in the cooler months. During the 1997–1998 ENSO period, there was an additional increase in admissions above that expected on the basis of pre-ENSO temperature relationships. The positive correlation with temperature is also biologically plausible, as a high proportion of diarrhoea cases in Peru, as in many tropical developing countries, are caused by bacteria, entamoeba and protozoa[63], which are favoured by high temperatures. Singh et al.[62] used similar methods to correlate monthly reported incidence of diarrhoea throughout Fiji, 1978–1998, against variations in temperature and rainfall, after allowing for the effects of seasonal variation and long-term trend. The reported incidence increased by approximately 3% (95% CI 1.2 to 5.0%) for each degree Celsius increase in temperature, by 2% (1.5 to 2.3%) per unit increase in rainfall above average rainfall conditions (5 x 10^{-5} kg/m^2/minute), and by 8% per unit decrease below average conditions. The pattern is supported by a positive geographical correlation between temperature and incidence in 18 Pacific Island countries.

3.11.2 Cholera

Cholera is an acute and severe form of diarrhoeal disease, caused by the infectious bacterium *Vibrio cholerae* 01 (a more recent strain, *V. cholerae* 0139, has also been identified). Although cholera vibrios can be found worldwide, the disease is endemic only in certain regions – mainly the tropics and subtropics[69], and the disease is largely concentrated in Africa, where more than 80% of the total cases worldwide are found[70]. The most recent global figures available from the WHO are for 2004, when there were 95,560 cases of cholera in Africa, and 2,331 deaths[7]. In the same year, European countries reported a total of 21 cases (all imported), and 62% (13) of these were in the UK; no deaths were reported. We do not have a full understanding as to why the disease is only endemic in certain regions, but environmental and socio-economic factors appear to be important. And where disease is endemic, there are distinct seasonal trends in the frequency of cases, and this frequency also tends to increase near coastlines[69].

The death rate from severe cholera is especially high, with almost half of those affected dying, and in endemic areas children between two and four years of age are worst affected[71]. Humans are the main reservoir, although in recent years, environmental reservoirs have been shown to exist, apparently in association with copepods or other zooplankton in brackish water or estuaries[4, 70, 72–74]. The main modes of transmission are through the ingestion of contaminated water or food.

Climate sensitivity. The occurrence of cholera appears to be influenced by temperature and flooding. Since the 1990s, there have been several reports of cholera following flood events. These include reports from Djibouti[75], the Horn of Africa[7], India[76], Indonesia[77], and Mozambique[70]. Epidemics of enteric infection commonly follow episodes of catastrophic flooding. This is partly because the floodwater is invariably heavily contaminated with faecal matter, and also because of the contamination of water supplies and damage to excreta disposal systems. After the 1998 floods in west Bengal, there was a severe outbreak of diarrhoeal disease, with 16,590 reported cases and 276 deaths. A quarter of the cases, and most of the deaths were in children under five. The main pathogen was identified as *V. cholerae* 01, biotype El Tor[76]. The epidemic, however, may have been caused by the inappropriate positioning of emergency tube wells in low-lying areas.

Cholera is commonly found in coastal areas, and research has shown in recent decades that the vibrio that causes it has an environmental reservoir in slightly saline coastal lagoons[69]. Indeed, Drasar (1998) has suggested that the new strains of cholera which have given rise to the various cholera pandemics have arisen from mutations occurring in the starved environmental forms of the bacterium. There is reason to believe that these new strains then enter the human population through coastal flooding. For example, there is anecdotal evidence that *V. cholerae* 0139 first occurred in human patients after the flooding of a coastal mangrove swamp. There is evidence that cholera epidemics are linked to sea-surface temperature and other climatic conditions[78]. Among physical factors, temperature perhaps has the most direct and significant effect on the ecology of most bacteria, and it's not any different for cholera. Cholera is considered to have marked seasonality which seems to be related to the ability of vibrios to grow rapidly in warm environmental temperatures. The population dynamics of *V. cholerae* in the environment are strongly controlled by environmental factors, such as water temperature, salinity, and the presence of copepods, which themselves are controlled by larger-scale climate variability. The association between plankton and *V. cholerae* has been documented over the last 20 years[69]. The growth of cholera vibrios is associated with plankton in coastal waters and riverine estuaries, and as global climate affects the growth of plankton, any future climate change is likely to also influence cholera[71].

3.12 Respiratory disease

Acute respiratory infections (both upper and lower) are major contributors to the GBD, and this is especially evident for Africa (see Table 1). In terms of the total burden of disease (DALYs) from infectious disease in Africa, acute lower respiratory infections are ranked third after HIV/AIDS and malaria, and result in over 1 million deaths per annum, many of which occur in the under-fives. While other childhood infections such as diphtheria, measles and whooping cough are responsible for over 600,000 deaths in Africa per annum, many of these infections are preventable with appropriate vaccination.

At present, it is difficult to draw clear conclusions about the significance of climate change for respiratory infections. Many show forms of seasonality, but as yet we lack the detailed evidence to make quantitative or even qualitative judgements about the net impacts of climate change.

3.13 Meningococcal meningitis

Meningococcal meningitis is an acute bacterial disease that is ubiquitous, and results from infection with the *Neisseria meningitides* bacterium[4]. In many countries, the disease often peaks in late winter to early spring[4], and in sub-

Saharan Africa, there is a highly seasonal epidemic pattern where outbreaks occur in the dry season, declining when the seasonal rains begin[79].

Climate sensitivity. In the Sahelian region of sub-Sahara Africa, the ‘meningitis belt’ represents a reasonably well-defined spatial and temporal distribution of the disease[79, 80]. However, the precise influence of climatic factors in the seasonal epidemics remains unclear. A set of theories has arisen about the role of dust clouds in the spread of infection[79].

4 Looking forward

Most climate change scenarios are broadly consistent in the predicted regional patterns of change in mean temperatures and rainfall over the course of the 21st century, though they differ in detail and in the magnitude of change given differences in greenhouse gas emissions, which are influenced by political, economic, technological and social developments. The maps provided for the UK Climate Impacts Programme suggest temperature increases, particularly in southern Britain and during summer and autumn, which are comparatively modest during the 2020s but larger by the 2080s. The degree of change is evidently greater under higher-emissions scenarios. The changes in precipitation patterns for the UK are more complex, with indication of higher winter precipitation in most areas but drier summers, again with the speed of change gaining pace from the middle of the century. For Africa, Hadley centre models and others, produced for the Intergovernmental Panel on Climate Change, also suggest varying degrees of temperature increases across the continent and generally lower precipitation, though there are variations by season and area. Given the uncertainties that exist, and the still-limited body of scientific evidence, it is difficult to provide a precise picture of the effects that such climate change will have on human infectious disease in Africa and the UK over the medium and longer term. The geographical distribution of most of the diseases referred to in this report is determined by a combination of factors, including land use, socio-economic development, population factors, public health infrastructure and disease control measures. The relationships between infectious disease and these multiple factors is complex and, in most cases, still not sufficiently well characterised for us to be able to provide specific predictive maps of the consequences of climate change. However, the science is advancing, and continuing research efforts are progressively improving understanding of the disease drivers.

Malaria is the human disease that has received most attention from a climate change perspective. As described above, for this disease, research efforts are now beginning to provide clearer insight into the likely future patterns of risk, though models remain limited by the paucity of data to reflect multiple social and environmental influences. Models such as those developed by Tanser and colleagues[19] suggest small increases in the geographical distribution of malaria over the course of this century (mainly through altitudinal shifts), but they also indicate important overall increases in the burden of disease (with decreases in some areas) because of changes in the length of the transmission cycle. Their broad estimate is for a 16–28% increase in the person months of exposure to malaria transmission (assuming a constant population), most of which occurs in areas of existing transmission.

Such evidence is useful because it suggests that the main concern with malaria under climate change is in areas where the disease is already established, rather than because of the potential for dramatic extension to new areas. Nonetheless, we must recognise that no models have yet adequately addressed such issues as the effect of control programmes, improvements in public health, and infrastructure development, which may be just as important, if not more so, than the effect of climate change. We can, however, conclude that, all other things being equal, climate change is likely to increase the demands of malaria control[17], particularly in sub-Saharan Africa, where it is already a major cause of mortality and morbidity, and where increases in disease burdens have occurred in recent years because of failures of control programmes, land-use changes and other non-climatic reasons.

It is consideration of the non-climate factors that also leads to the conclusion that global warming is unlikely to lead to the re-establishment of malaria in the UK, from where it disappeared around the time of the First World War. In the UK, as in much of Europe, changes in lifestyle and living conditions were the principal factors contributing to the elimination of disease in the past. Even though potential malaria vectors remain present in many areas of Europe, mosquito populations and their contact with humans have been reduced to such a degree that transmission potential is very low, and is likely to remain low even if, under climate change, temperature and rainfall patterns alter in favour of the malaria vector and parasite. In the UK, the main threats from malaria are likely to continue to be from international travel, though imported malaria might occasionally lead to small outbreaks of summertime transmission, as it has in other areas of Europe.

Similar complexities apply to the other infectious diseases that have potential climate sensitivity. There is potential for the geographical expansion of dengue in Africa, and evidence that high temperatures and heavy rainfall can increase transmission, but the determinants of human exposure are not well enough understood and modelled to make detailed predictions about future patterns under climate change. It is probable that climate change will have significant bearing on leishmaniasis, including its visceral form, because of changes in the distribution of sandfly vectors, but socio-economic and lifestyle factors are likely to be dominant determinants. Evidence of climate change in relation to filariasis and African trypanosomiasis remains extremely limited, though, again, theoretical considerations and some empirical evidence suggests the potential for altered distribution of disease. Warmer minimum temperatures, predicted for various parts of Africa, may extend the range of schistosomiasis in some settings; and it seems very probable that warmer temperatures and more irregular rainfall will add to the already high burden of disease from diarrhoeal illness and mortality in the African continent. However, with nearly all the main infectious diseases of concern, the *existing* burdens of disease are primarily functions of poverty and lifestyle, and this is likely to remain the case in future. From a public health perspective, the importance of climate change arises because it may add to those burdens, but in ways that are as yet difficult to predict at local level.

In the UK, infectious disease burdens are low, and at present it seems unlikely that climate change will have a critical influence in seeing the emergence of new human infectious disease. Climate change may have some adverse effects on such diseases as leptospirosis and Lyme disease, but for most diseases of concern, good infrastructure, hygiene and healthcare mean risks are low. The emergence of West Nile virus in the UK remains a theoretical possibility, but climate change is unlikely to be a primary reason for this, though warmer temperatures may make the environmental conditions more suitable for it. For the majority of infectious diseases, the effects of climate change are likely to have comparatively small direct impacts on public health in the UK.

5 Conclusions

Infectious diseases are a major contributor to the burden of disease, especially in Africa. Many infectious diseases are sensitive to climatic variables or at least can be shown to be correlated in spatial distribution with climatic factors.

In this review, we have focused primarily on infectious diseases for which there is some evidence of a link with climatic variables, and where the underlying burden of disease is already high (e.g. malaria). We have also included a number of diseases where the current burden is relatively low, but where there is potential for this to increase (e.g. Rift Valley fever).

With all diseases of potential climate sensitivity, many uncertainties remain, particularly because non-climatic factors are important, sometimes critical, to the geographical and/or temporal pattern of disease. Modelling studies have provided interesting insights into the possible future burdens of some (especially vector-borne) diseases under climate change, but most have been limited by the omission of potentially important non-climatic determinants.

Nevertheless, there is sufficient evidence that diseases of current or potential high-population burdens may be altered by climate change with net adverse impacts. The nature of these climate change impacts and how they can be reduced is an important area for further enquiry.

Table 1: Summary of principal infectious diseases

Disease/disease group	**Current disease burden (deaths/DALYs)/thousands**		**Climate sensitivity**	**Effect on future burdens in Africa under climate change**
	Africa	**UK** [a]		
Acute respiratory infections (upper + lower)	9/336 + 1,011/28,711	3/26 + 169/621	Many of these infections exhibit seasonality but there is insufficient evidence to draw general conclusions about climate change impacts	Uncertain/mixed evidence
Cholera	95,560 cases and 2,331 deaths notified to WHO	13 cases notified to WHO	Increases in sea and air temperatures as well as ENSO events are associated with epidemics. Reported links to flood events	Climatic conditions may contribute to maintenance of disease and to epidemics, especially relating to coastal flooding
Diarrhoeal illness	690/21,104	2/109	Certain forms of food- and water-borne transmission increases with temperature and during periods of low or erratic rainfall. Sanitation and human behaviour are principal determinants of transmission risk	Probable increase in some forms of diarrhoeal illness, especially in lower-income countries
Dengue	0/6	0/0	Outbreaks of dengue and dengue haemorrhagic fever are associated with high rainfall and elevated temperatures and humidity[81]. Not currently a major burden for Africa. Population immunity more important than climate in epidemics	Projected expansion in the population at risk
Filariasis	0/1,884	0/0	For lymphatic filariasis, there have been correlations between microfilarial prevalence and weather variables (including temperature, rainfall and humidity). Outside Africa, the extrinsic incubation period of *Wuchereria bancrofti* and the biting density of the vector mosquitoes have been related to ambient temperatures and other weather parameters. However, changes in disease in parts of Africa in recent decades have not been driven by climatic variables	Probable net impacts remain uncharacterised

Disease/disease group	Current disease burden (deaths/DALYs)/thousands		Climate sensitivity	Effect on future burdens in Africa under climate change
	Africa	UK [a]		
HIV/AIDS	2,000/61,845	7/218	No published evidence for climate link. Principal significance may be that populations with high prevalence of HIV/AIDS may also be vulnerable to climate-change-related impacts	No established link
Leishmaniasis	9/395	0/0	The current distribution and pattern of kala-azar in east Africa is dependent on the distribution of the principal sandfly vectors which in turn are determined by climatic and environmental	Potential increases, but possible impacts remain uncharacterised
Malaria	957/35,738	0/2	There is good evidence, mainly from laboratory studies, that vector and parasite are sensitive to temperature and other meteorological parameters. Surface water, which is influenced by precipitation patterns, is potentially important for breeding of vector. The effects are more obvious along altitudinal gradients than across latitudinal ranges, as communities separated by only a few kilometres, with similar socio-economic conditions and lifestyles, may be exposed to very different climatic regimes	Alterations in the distribution of disease predicted: probably net adverse impacts
Meningococcal meningitis	22/938	2/66	There is a highly seasonal epidemic pattern in sub-Saharan Africa where outbreaks occur in the hot dry season, declining when the rains begin. Hypothesised link to dust clouds	Uncertain
Rift Valley fever	N/A	N/A	Epidemics have been associated with above-average rainfall and temperatures, but until the late 1980s, this link was based mainly on observations and anecdotal evidence. Significant increases in rainfall and associated flooding have been linked to RVF outbreaks, and RVF outbreaks are positively associated with warm ENSO events and above-normal precipitation (indicated by remotely sensed vegetation patterns)	Possible increase, but uncharacterised

Disease/disease group	Current disease burden (deaths/DALYs)/thousands		Climate sensitivity	Effect on future burdens in Africa under climate change
	Africa	UK [a]		
Schistosomiasis	5/1,385	0/0	Distribution of the intermediate host snail appears to be influenced by temperature, but the distribution and prevalence of infection may already be increasing mainly because of the expansion of irrigation projects and population movements	Some increase possible in areas with warmer cold-season temperatures, especially in the absence of disease controls
Trypanosomiasis (African)	49/1,543	0/0	At present, there is no clear link between climate and interannual variability of sleeping sickness, but reports suggest a correlation between monthly cases and meteorological variables in Uganda (land-surface temperature). Rainfall patterns may be related to temporal distribution of disease. However, because of the strong association between cattle and human infections, other non-climatic factors such as population movements, deforestation and drug resistance, the climate's exact role in sleeping sickness epidemics remains unclear	Apparent potential for increase in some settings, but overall evidence is unclear.
Tuberculosis	317/8,491	5/57	Climate link is not established. Predominant influences relate to overcrowding, low socio-economic status, poor nutrition	No established link
West Nile virus	N/A	N/A	Evidence relating to spread to US and southern Europe from original endemic area does not clearly implicate climatic factors, though authors have suggested link to hot dry weather	Potential for expansion of distribution, but not clearly characterised

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