Malaria in the African highlands: past, present and future

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Many of the first European settlers in Africa sought refuge from the heat and diseases of the plains by moving to the cool and salubrious highlands. Although many of the highlands were originally malaria free, there has been a progressive rise in the incidence of the disease over the last 50 years, largely as a consequence of agroforestry development, and it has been exacerbated by scarce health resources. In these areas of fringe transmission where the malaria pattern is unstable, epidemics may be precipitated by relatively subtle climatic changes. Since there is little immunity against the disease in these communities, outbreaks can be devastating, resulting in a substantial increase in morbidity and death among both children and adults. We present here the results obtained using a mathematical model designed to identify these epidemic-prone regions in the African highlands and the differences expected to occur as a result of projected global climate change. These highlands should be recognized as an area of special concern. We further recommend that a regional modelling approach should be adopted to assess the extent and severity of this problem and help improve disease surveillance and the quality of health care delivered in this unstable ecosystem.

Introduction

Altitude is one of the oldest defences against malaria. As early as the sixteenth century the Spanish recognized there was little or no malaria at high altitudes in the New World (*1*). The protection afforded by elevation was also described in many early textbooks on tropical medicine, including that of the pioneer James Lind (*2*). Even before the mechanism of malaria transmission had been elucidated, Hirsch recognized that protection against the disease was related to low temperatures and high altitudes (*3*). He noticed that epidemics in the highlands were always located in a valley with a small declivity or a basin-like depression in a plateau — places where water collects and malaria mosquitos breed. The salubrious effects of higher altitude were well recognized by early European settlers, and hill stations became a common feature of expatriate life in various parts of the tropics. Even today in Ethiopia many lowland farmers shelter in the highlands until the malaria season has ended (T. Ghebreyesus, personal communication, 1997). Hills and mountains have therefore been recognized as a natural shelter against the heat and diseases of the lowlands for at least several centuries.

The current upper height limit for malaria in the African highlands is difficult to define precisely, and is likely to rise, as discussed below. In many countries this boundary was thought to occur around 2000 m; for example, in Burundi (*4*), Ethiopia (*5, 6*), Kenya (*7*), Morocco (*8*), and Rwanda (*4*). Malaria epidemics have occasionally been reported at higher altitudes (up to 2550 m (*7*)) but are rare. In other parts of Africa the upper limit is slightly lower: at around 1700–1800 m in Zaire (*9*) and at 1200 m in Zimbabwe (*10*). Generally we considered that areas higher than 1500 m (Fig. 1) have little or no malaria.

Most malaria epidemics in the African highlands are due to *Plasmodium falciparum*, the most lethal and dominant species found in the continent. While epidemics of vivax malaria have also been reported, for example, in the Atlas Mountains in the 1930s (*8*), they are unusual. In most highland areas, local communities have little or no immunity against malarial parasites and thus the disease affects both adults and children. This contrasts with the lowlands where immunity is high among most adults and malaria morbidity is confined largely to young children and primigravidae. As a consequence of the low immunity in highland communities, epidemics in the mountains are characterized by high morbidity and mortality among both children and adults, as illustrated by the outbreaks experienced in the Ethiopian highlands, where there were approximately 7000 deaths in 1953 (*12*) and 150000 in 1958 (*13*). The highlands are thus areas of unstable malaria patterns primarily because of the low and fluctuating levels

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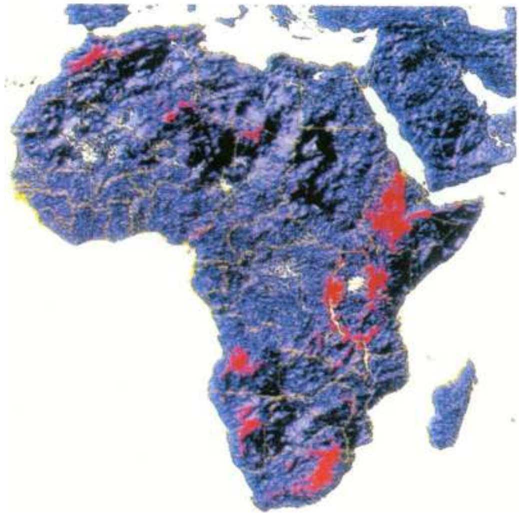


Fig. 1. **Highlands of Africa.** Areas over 1500 m are shown in red (excluding Madagascar). Produced using Data Exploration Tool Software (*11*).

of transmission experienced by local communities. Consequently many of these semi-immune populations experience severe outbreaks every few years.

Introduction of malaria into the African highlands

How malaria became established in the African highlands can be illustrated using the example of Nandi Plateau in Kenya. This plateau lies to the north-east of Lake Victoria at an altitude of over 1500 m. At the turn of the last century there were few mosquitos in the area and, according to local residents, there was no malaria in the hills (*14*). Sir Harry Johnston, a local resident, believed that malaria did not exist on the plateau in 1901, and the principal medical officer at that time wrote that Nandi was "one of the healthiest stations in the Protectorate". Also, malaria was not mentioned by the many officials, traders, soldiers or doctors who lived there. According to Nandi elders, malaria was introduced into the highlands by soldiers returning from the First World War in 1918 and 1919, which resulted in around 25% of the indigenous population contracting the disease. Since that time there has been a progressive increase in malaria cases reported in Nandi Hospital and other highland hospitals nearby (*15*).

Many factors govern highland malaria incidence and most of them are inter-related. Although grouping these factors is somewhat artificial and there may be overlap, they can be classified into environmental (including climate factors), biological, and socioeconomic factors (Fig. 2). We will illustrate the importance of some of these factors, first by reviewing how climate can affect transmission and then by examining how human-made changes in the highlands have created ideal conditions for the spread of this disease.

Climate factors

Malaria and temperature. As altitude increases temperature declines and both the development and survival of the mosquito vector and parasite are critically dependent on the ambient temperature. As the temperature drops so does the risk of infection, and there is a typical threshold below which transmission ceases. Below 16 °C the aquatic stages of tropical anophelines fail to develop (*16*) or breed (*17*), while *P. falciparum* fails to develop between 16 °C and 19 °C (*18*). However, the major vectors of malaria can avoid these extreme temperatures by resting in more favourable microclimates; for example, inside occupied houses the temperatures can be 3–5 °C warmer than outside (*7*). Importantly, inhabited houses can be warm enough to allow the parasite to develop, even if it is too cold for development in an unoccupied house or outside. Moreover, in an occupied house the relative humidity may stabilize at

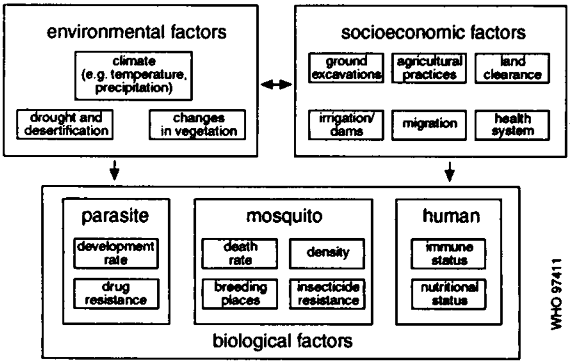
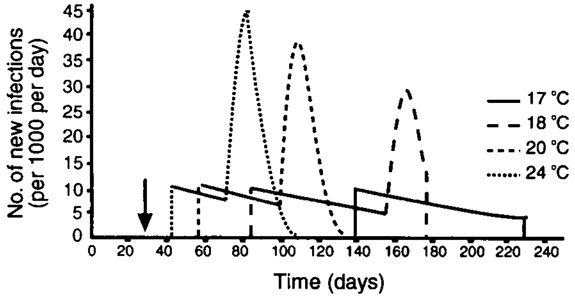


Fig. 2. **Schematic diagram of important factors affecting malaria incidence in the African highlands.**

Fig. 3. **Development of a malaria epidemic at different temperatures, as simulated using a basic epidemiological model** (*19*, *20*). The arrow indicates when conditions become favourable for transmission (vectorial capacity set to 1–3 months (day 30–120) and assuming the initial proportion infected was 1%). The only difference between the curves is that the incubation time inside the mosquito is 111 days at 17 °C, 56 days at 18 °C, 28 days at 20 °C, and 14 days at 24 °C. The parasite incubation time in humans is assumed to be 15 days (*21*).



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around 60%, which favours mosquito survival; outside relative humidities may vary considerably (12–80%).

Fig. 3 illustrates the importance of temperature on the development time of *P. falciparum* inside the mosquito and on the rise of an epidemic. At 17 °C parasites develop but not rapidly enough to cause an epidemic. On the other hand, temperatures ≥20 °C are sufficient to catalyse an epidemic. External ambient air temperatures of 17 °C may correspond to indoor temperatures of around 20 °C, i.e. those experienced by the parasite within the indoor-resting vector.

One further factor to consider is that the altitude limit of transmission in an area may be due to a lack of breeding sites, rather than unfavourable climatic conditions, as appeared to be the case in the Highlands of Kigezi, Uganda (*22*).

Malaria and rainfall. Rainfall in the African highlands can vary greatly from year to year. The catastrophic malaria epidemic in Ethiopia in 1958 was associated with unusually high rainfall over an extended period as well as with elevated temperatures and relative humidity (*13*). Also, the 1940 outbreak in Nairobi, Kenya, resulted from heavy rains, which followed 2 years of low rainfall (*23*). One of the major causes of the variation in annual rainfall in Africa is the El Niño–Southern Oscillation (ENSO), a meteorological phenomenon that occurs every 2–10 years and tends to exaggerate the extremes of climate in specific regions of the world (*24*). During the ENSO, the region around Lake Victoria, extending to the southern fringes of the Ethiopian highlands experiences periods of dryness, while highlands to the south tend to receive excessive rainfall. Bouma et al. illustrated that many areas which experienced periodic epidemics occurred in ENSO-affected areas (*25*, *26*), and suggested that the ENSO is the driving force behind these outbreaks. However, both the epidemics in Ethiopia did not take place during ENSO years, suggesting that there are other more subtle influences on the transmission of malaria. Although sharp increases in inter-annual rainfall and temperature, or both, may precipitate epidemics, they can also erupt in years that appear climatically similar to previous years (Mapping Malaria Risk in Africa (MARA)/Atlas du Risque de la Malaria en Afrique (ARMA), unpublished data, 1997). Thus while it may be possible to predict the physical location of epidemic-prone areas, identifying when an epidemic is likely to occur may be more problematic.

Global temperature change. More recently there has been growing concern that global warming will increase malaria in the highlands (*27–32*). In its second assessment report, the Intergovernmental Panel on Climate Change (IPCC) concluded that the Earth's mean surface temperature will increase by around 1–3.5 °C over the coming century (*33*). However, larger local increases on a shorter time-span can result from deforestation, with surface temperatures rising by as much as 3–4 °C (*34*), or simply from inter-annual variation in temperature (*35*). A progressive rise in annual temperatures has been linked to increasing malaria in the Usamabara Mountains in the United Republic of Tanzania (*36*). Also, a study in Rwanda found that recent increases in temperature and rainfall were associated with a steep rise in malaria cases (*37*), with the rise being greater among people with little immunity living at higher altitudes compared with those at lower altitudes where immunity to malaria was greater. What is surprising about this study is that the difference in altitude between the high and low villages was only 100 m, which may reflect a temperature difference of only 0.6 °C between the two sites (*38*). Such a small difference might suggest that in this case factors other than temperature were favouring transmission.

Biological factors

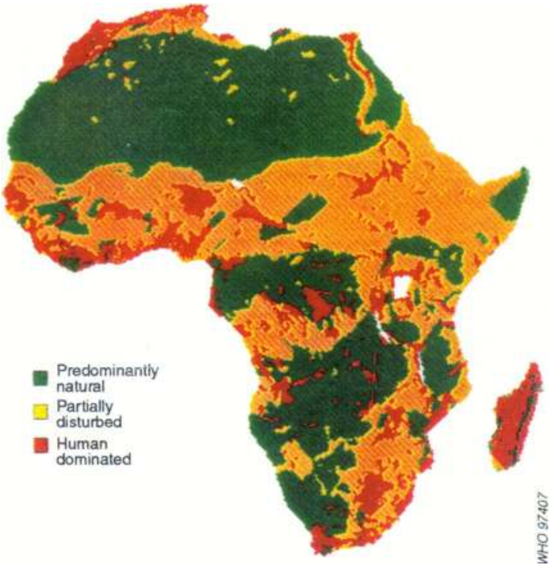
Highland vectors. Although there is a great diversity of anopheline species in the highland areas of Africa, members of the *Anopheles gambiae* complex are the principal vectors of malaria, as is true for most of the continent. These mosquitos have been identified as the major vectors at high altitudes in Ethiopia (*13*) and Kenya (*7*), and sporozoites from them have been recorded from specimens collected at altitudes >2000 m (Division of Insect-borne Diseases (DIBD), 1948). In this species complex only *A. arabiensis* (e.g. Madagascar (*40*)) and *A. gambiae* sensu stricto (e.g. Kenyan Highlands (*41*)) have been implicated as upland vectors. The other major highland vector is *A. funestus*, which has been associated with epidemics in Kenya (*42*) and Madagascar (*43*). Occasionally both *A. gambiae* sensu lato and *A. funestus* occur together as reported in Madagascar (*44*), United Republic of Tanzania (*36*), and Uganda (*22*). However, as a general rule, because *A. funestus* breeds in relatively permanent water bodies, its populations are relatively stable, and while they may contribute to an increase in malaria endemicity they rarely give rise to epidemics. The only other relevant species is *A. christyi*, which was reported to be a vector in the Kigezi Highlands in Uganda (*45*); however, later studies in the same area failed to find any infective specimens (*22*) (J. Mouchet, personal communication, 1997). A number of other anophelines have been identified as secondary vectors, including the following: *A. coustani* (United Republic of Tanzania) (*46*), *A. marshalli* (Uganda) (*45*), *A. mascarensis* (Madagascar) (*47*), *A. rivulorum* (*48*), and *A. squamosus* (United Republic of Tanzania) (*46*), but these are of minor importance. *A. clavinger* and *A. hispaniola* were identified as vectors in the vivax epidemic in the Atlas Mountains in the 1930s (*8*), but this finding has not been reported since, emphasizing their minor overall role as vectors.

In the African highlands, malaria transmission is probably much more focal in its distribution than in many lowland areas. Breeding sites are more common on the valley floor than the steep valley slopes, while the colder nights at higher altitudes restrict the dispersal of adult mosquitos from these sites. There is evidence that *A. gambiae* s.l. may fly only a few hundred metres in altitude up the hills (*49*) (R. Bødker, personal communication, 1997), although lateral movement along upland valley floors may be substantially greater. An elegant illustration of this uphill movement was reported by Smith for the Pare area of the United Republic of Tanzania, who found that when lowland houses were sprayed with insecticide *A. funestus* disappeared from villages at altitudes of 600 m (*50*). As a general rule there are fewer mosquitos at higher altitudes. Also, a recent study in the highlands of Madagascar found that 57% of *A. gambiae* s.l. (probably *A. arabiensis*) fed before 22:00 (*51*), whereas in warmer climates most feed after midnight (*52*). Thus the patchiness of the breeding sites and reduced flight activity of adults probably account for the often clustered nature of malaria outbreaks in upland areas of Africa.

Human activities

Once malaria is introduced into a highland area, it tends to become a growing problem largely as a consequence of agroforestry development (see Fig. 4), as suggested by Garnham (*15*) and Matson (*14*). The scale of change has been enormous, and to date only 10.4% of the mountains of east and central Africa remain undisturbed (data from ref. (*53*)). The principal reason for the link between such developments in the highlands and malaria is related to the ecology of *A. gambiae* s.l., which is intimately related to human activity, as discussed below.

Fig. 4. **Areas of human disturbance in Africa** (© Lee Hannah, Conservation International, 1993). Predominantly natural areas are those with primary vegetation, no evidence of disturbance, and a population density <10 people/km^2 or <1 person/km^2 in arid or semi-arid areas; partially disturbed areas are those with shifting or extensive agriculture, evidence of secondary vegetation, livestock density greater than the carrying capacity or other evidence of human disturbance; human-dominated areas are those with permanent agriculture or urban settlements, lack of primary vegetation, or areas experiencing desertification or other permanent degradation (*53*, *54*).



Transportation and housing. In the pioneering highland settlements the activities of the growing human and animal populations created many new opportunities for *A. gambiae* s.l. to breed. This mosquito typically breeds in small sunlit puddles, such as those formed by feet, hoofs, and wheels (*52*) — all of which flourished around the expanding communities. Making bricks for new homes and collecting material for road construction produced numerous borrow pits which filled rapidly with water, creating yet more mosquito breeding sites. Most of these pits were close to human habitation, increasing the ease with which female mosquitos could locate a human blood meal and transmit parasites.

Furthermore, *A. gambiae* s.l. probably colonized the highlands through a process of passive dispersal, being transported there by car, truck, train or ox wagon. This threat was well recognized in the past, and in many parts of Africa vehicles travelling to the hills were sprayed with insecticide to prevent the importation of anophelines into malaria-free areas.

Land clearance. Many of the African highlands were originally heavily forested, providing an environment inimical to *A. gambiae*. However, deforestation of the highlands has occurred at an alarming rate, with 2.9 million hectares being cleared between 1981 and 1990, representing a 8% reduction in forest cover in one decade (*55*). Clearance of the forest to grow crops or create pastures led to open landscapes, which when puddled, provided ideal mosquito breeding sites. Thus, deforestation was thought to have been one of the reasons for the increased malaria in the Usambara Mountains in the United Republic of Tanzania (*36*). The floors of many highland valleys are often choked with dense beds of papyrus and other vegetation which restricts the breeding of *A. gambiae*. Also, oils produced by the papyrus form a thin layer on the water surface, which may prevent mosquito larvae from breathing (J. Mouchet, personal communication, 1997). Thus, when swamps are cleared for cultivation of crops any surface water will provide suitable breeding sites for *A. gambiae* s.l., leading to increased incidence of malaria in a number of places, including Burundi (*56*) and the Kigezi Highlands of south-western Uganda (*45, 57*).

Irrigation and dams. Large-scale irrigation schemes for cultivating crops can also sharply increase malaria transmission. The building of dams in the Uasin Gishu Highlands in Kenya (*58*) and the irrigation of fields (e.g. in Burundi and Rwanda (*4, 59*)), particularly ricefields (e.g. Madagascar (*60*)) created a profusion of breeding sites for malaria vectors. A recent malaria epidemic in Burundi was linked to the expansion of local ricefields and the creation of fish ponds (*61*). In this example, ricefields may have been a more important source of vectors, since it is well known that they can generate large numbers of *A. gambiae* s.l., while fish ponds are not, since mosquito larvae are usually rapidly eaten by the fish. Excavations created during mining can also become important mosquito breeding sites, as exemplified by those in the Kigezi Highlands which resulted from gold mining activities (*45*).

Human migration. As farming increased in the African highlands, many immigrants attracted to the area brought their parasites with them. There are a number of accounts of travellers from the lowlands with vivax or falciparum malaria experiencing relapses or recrudescences in the highlands (*15, 62, 63*). Whether these were caused by the cooler temperatures in the mountains, a drop in air pressure, or the stress of travelling remains unknown. As the human highland populations grew there was an inevitable increase in human–vector contact and a consequent increase in malaria transmission; moreover, it became harder to find productive land as the pressure on land increased (Fig. 4). Thus in areas such as the Usamabara Mountains in United Republic of Tanzania, people living in the highlands may farm in the lowlands, often staying overnight in their lowland fields, where transmission is high, and returning to their highland homes harbouring an infection. Indeed studies carried out in Rwanda (*64*) and Burundi (*65*) confirmed that adult males were at greatest risk from malaria because they travelled most often to endemic areas. Outbreaks of malaria may also be exacerbated by famine, as reported in Ethiopia (*13*) and Uganda (*45*). Recent epidemics in the highlands may have been precipitated by immune populations harbouring gametocytes from earlier outbreaks or by travellers from endemic areas (*66*).

Deteriorating health systems. Many of the highland areas in Africa have experienced a decline in basic health services as a result of war, civil conflicts, and declining resources. This has been compounded by growing resistance to antimalarials, most notably to chloroquine. Chloroquine-resistant parasite strains are likely to pose a greater threat in the highlands, where immunity to malaria is low or absent, than in the lowlands, where exposure to the disease is generally greater. It seems likely that chloroquine-resistant strains of falciparum malaria found in the hills (*67–69*) have spread there from the lowlands, indicating that parasite strains are similar in both biotopes.

In the 1950s vector control programmes in Madagascar led to the eradication of *A. funestus* in the central highland plateau and almost total eradication of malaria (*43*). Since then there has been a progressive increase in malaria due to the collapse of the spraying programme (*44*). Indoor spraying campaigns with DDT were effective at reducing both morbidity and mortality in Ethiopia (*13*) but over the last 20 years there has been an increase in cases partly because of a breakdown in the health service as a result of civil war and forced movement of people. Similarly, towns in the highlands of Zambia where malaria was once rare now experience a substantial number of cases as a result of the cessation of vector control activities (*70*). It therefore appears likely that the increase of malaria in many parts of the highlands is largely a result of inadequate control measures.

Identifying epidemic-prone areas

Although it is always difficult to make reliable estimates about the areas that are vulnerable to epidemic outbreaks of malaria, several techniques may be useful in making such risk assessments. Much of this analysis requires the collection of data on disease incidence, mosquito populations, basic demography, and climate linked to specific geographical locations. Geographic information systems (GIS) (computerized mapping systems) are increasingly being used to assist in the organization and analysis of these complex data sets (*71*). Remotely sensed (RS) imagery data from earth-orbiting satellites together with digital terrain models may prove useful in studying malaria in the highlands, where data on population distribution, land use patterns, or transportation patterns are often lacking (*71*, *72*). Thus, RS data coupled to GISs can be used to analyse malaria since its distribution and intensity depend on climate and landscape features. Malaria is particularly influenced by spatial and temporal changes in vector populations. Vegetation can act as a proxy marker for mosquito breeding sites (Thomas CJ, Lindsay SW, unpublished data, 1997) since plant communities reflect an aggregate effect of temperature, wetness, and soil composition. The use of RS data to map malaria in Africa is still in its infancy, although two recent studies have produced some encouraging results. The seasonal abundance of *A. gambiae* s.l. in one Gambian village was shown to be related to the normalized difference vegetation index, a measure of vegetation greenness derived from satellite imagery (*73*). Moreover, the risk of malaria transmission and the prevalence of infection in individual Gambian villages was correlated with surrounding mosquito breeding sites derived from satellite imagery data (Thomas CJ, Lindsay SW, unpublished data, 1997). However, most GIS and RS analyses are based on statistical patterns; correlation does not imply causation and these models need to be validated with historical, or better still, contemporary data from the field.

Modelling highland malaria in relation to global climate change

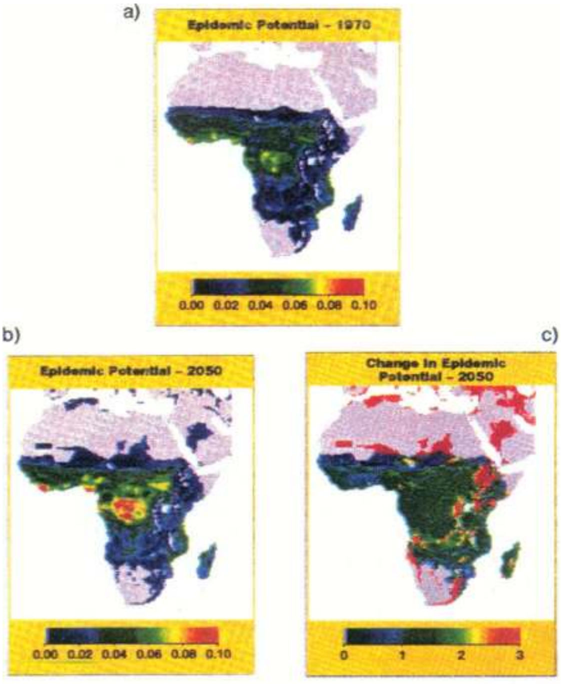
The complex task of estimating *future* trends in highland malaria incidence requires the use of integrated mathematical models based on variables describing climate, vectors, parasites, human populations, and health impact (*31*, *74*). We have modelled the spread of malaria as a consequence of global climate change at a regional level for Africa as a whole and at a local level for Zimbabwe using an approach recently developed by Martens et al. (*29*, *30*, *74*). No claim is made that climate is the most important determinant of malaria transmission; rather, we illustrate the substantial influence that the direct effects of climate change may contribute to malaria risk. The results presented here, rather than being predictive, should be interpreted as an indication of the sensitivity of malaria to global climatic changes, in particular temperature. Future risk assessments of climate change will ultimately need to integrate the (global) climate-based analysis, with local socioeconomic and environmental factors to guide comprehensive and sustainable preventive health strategies.

Epidemic (or transmission) potential is the reciprocal of the critical mosquito density threshold, and summarizes how climate change might affect the mosquito population directly. This is done by calculating the effect of temperature on mosquito development, feeding frequency, and longevity, as well as the incubation period of the parasite in the vector (*74*). This model has been linked to baseline climatology data (from 1931 to 1960 (*75*); with monthly mean temperature and precipitation data (on a grid size of 0.5° × 0.5° — approximately 3000 km^2 at the equator)). Scenarios were generated using IMAGE2.0 (*76*), a multi-disciplinary integrated model designed to simulate the dynamics of climate change. The scenarios were overlaid on the baseline climatology.

Within the model, the relation between ambient temperature and latent period is calculated using a temperature sum as described by MacDonald (*77*), with the assumption that the threshold temperature for parasite development is 16 °C (*18*). The number of blood meals a mosquito makes on human beings is the product of the frequency with which the vector takes a blood meal and the proportion of such meals that are taken from humans (the human blood index). The frequency of feeding depends mainly on the rapidity with which a blood meal is digested, which increases with the ambient temperature, and can be calculated by means of a thermal temperature sum (*78*). The female mosquito has to live long enough for the malaria parasite to complete its development if transmission is to occur. Between certain temperature limits, the longevity of a mosquito decreases with rising temperature (*18*), with the optimal temperature for mosquito survival being 20–25 °C. Temperatures in excess of this range increase mosquito mortality, and there is a threshold temperature above which rapid death is inevitable. There is also a minimum temperature (assumed to be 9 °C) below which the mosquito cannot become active. Based upon data reported by Boyd (*79*) and Horsfall (*80*), we assumed an adult daily survival probability of 0.82, 0.90, and 0.04, respectively, at 9 °C, 20 °C and 40 °C.

Rainfall, or the lack of it, plays a crucial role in malaria epidemiology; it not only provides the medium for the aquatic stages of the malarial mosquito's life cycle, but also may increase the relative humidity and hence the longevity of the adult mosquito. Because the relationship between rainfall and malaria is poorly defined, the model takes a simplistic approach by assuming that rainfall occurs concurrently with the window of suitable temperature; the rainfall criterion used (>80 mm per month necessary for transmission) is therefore rather conservative. Refinement of this parameter is currently being investigated within the MARA/ARMA project.

Fig. 5. a). **Potential malaria risk areas for baseline climate (1931–1960).** b) **Climate change scenario (the IMAGE2.0 "conventional wisdom" scenario (*76*)).** c) **Relative changes in risk between "current" (1970) and future (2050) conditions.**



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Potential malaria risk in Africa

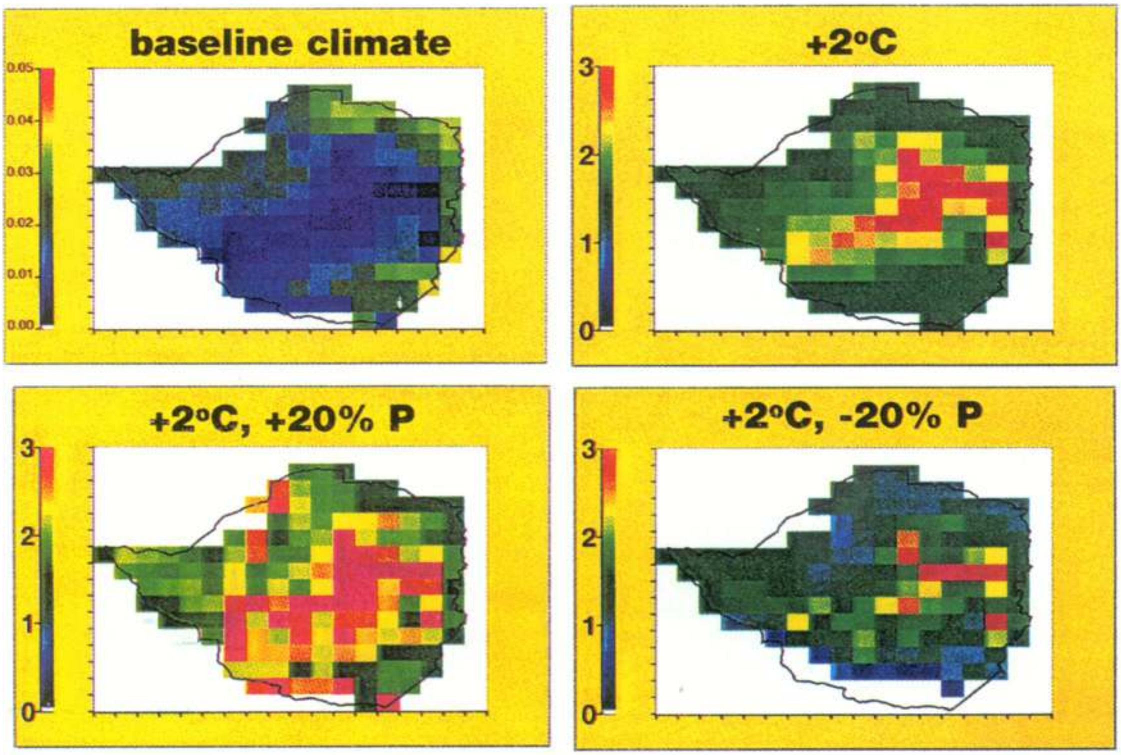
Fig. 5a–c illustrate the results of calculations of the epidemic potential for the African continent. No accurate information on the intensity and distribution of malaria on the continental scale is currently available (although there are plans to produce such maps (*81*)). However, the potential risk maps correspond well with the broad levels of endemicity described previously (*82*, *83*). Nevertheless, the model fails to demonstrate malaria transmission in the Horn of Africa; this may be explained by both the underlying climate database (which does not have adequate coverage in some regions) and specific ecoepidemiological circumstances not included in the model. Nevertheless, Fig. 5c shows clearly that the largest changes in transmission potential are to be expected at the fringes (both latitude and altitude), of the current risk areas. In the highlands, warming could push malaria transmission to higher altitudes, resulting in increased transmission in previously unexposed, and therefore immunologically naive, populations.

A case study in Zimbabwe

Zimbabwe lies at the southern limits of malaria transmission in Africa. The vast majority of the population live in the middle and highveld regions over 900 m altitude, and there are no defined migration patterns of direct relevance to malaria (*10*).

For the purposes of characterizing malaria, Zimbabwe can be divided into seven clearly defined altitude zones. To the north, in areas <600 m, malaria is almost always perennial; in areas >1200 m it normally does not occur. In other areas of the country malaria is seasonal-to-epidemic in nature. The higher malaria transmission rates in the north and south at altitudes below 600 m produce a peak

Fig. 6. **Yearly averaged epidemic potential (EP), for Zimbabwe under "current" (1970) baseline climate, and relative change in EP under climate change scenarios, calculated from monthly temperatures and precipitation.** (+2 °C = 2 °C increase in temperature, +20% P = 20% increase in precipitation, –20% P = 20% reduction in precipitation). Ordinate on baseline climate plot shows epidemic potential, while that on the remaining plots shows change in epidemic potential.



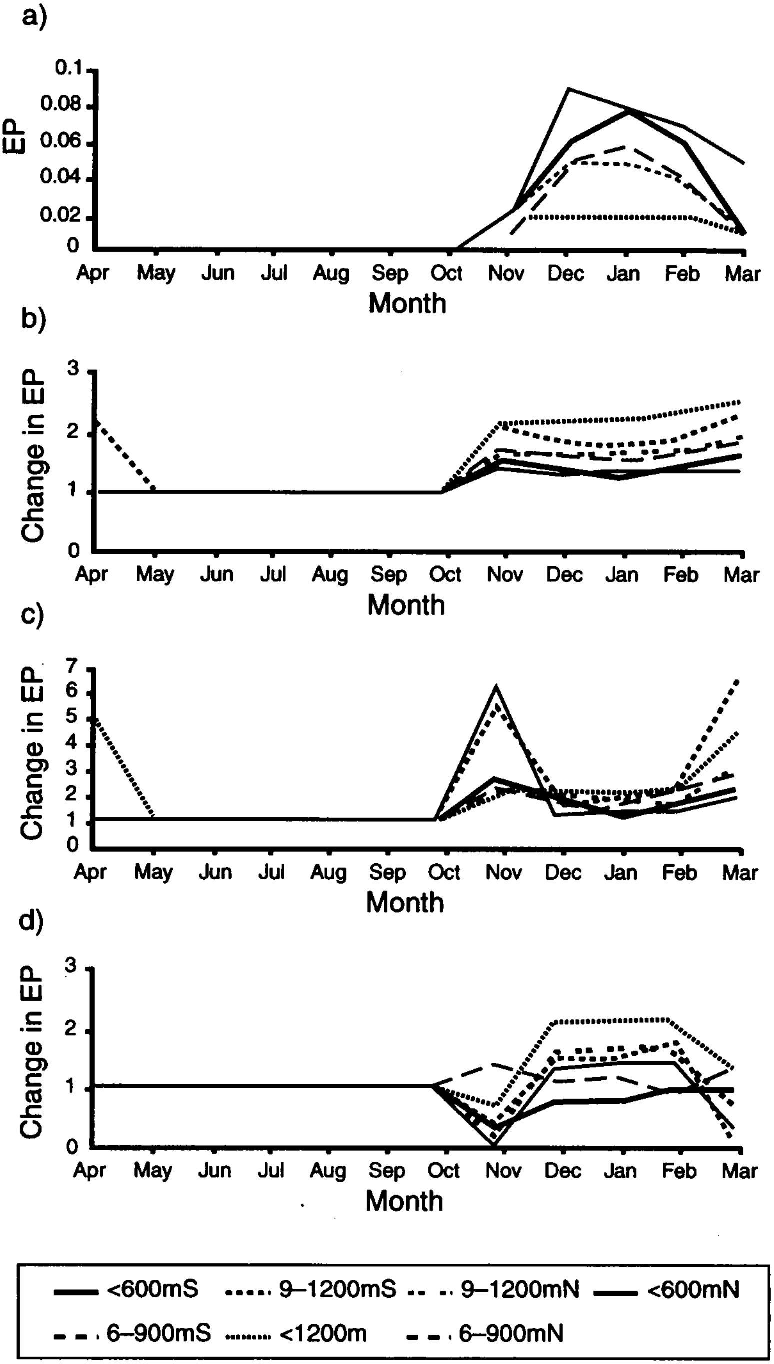
falciparum prevalence among 5–9-year-olds, which is lower than in other malarious areas (*10*).

Fig. 6 and 7 show the epidemic potential, as simulated for the baseline climate from 1931 to 1960 (*75*). For each altitude zone, corresponding grid cells (0.5° × 0.5°) are used to calculate the monthly epidemic potential. Malaria transmission occurs mainly during the rains which start in November, with most transmission occurring from February to May (*10*, *84*). From June to August, temperatures are at their coldest and transmission is extremely low or absent, whereas in the hot dry season from August to October much of the country is too dry (*85*).

This pattern is consistent with the model projections shown in Fig. 7, taking into account a lag period of approximately 1 month between the peak in mosquito transmission potential and the peak of malaria incidence. Shown clearly is the pattern of transmission intensity, which is highest at altitudes <900 m in both the north and south and decreases towards the central higher altitudes (*10*).

The baseline transmission potential is compared with a range of possible changes in temperature and precipitation. Three scenarios are simulated: an increase of 2 °C; an increase of 2 °C with a 20% increase in precipitation; and an increase of 2 °C with a 20% decrease in precipitation. These changes are well within the range of the general circulation model scenarios for southern Africa by the end of the next century (*86*); however, it should be noted that mean monthly temperatures may vary naturally by several degrees from year to year (*35*). The results show that the effect of a temperature increase would be greatest on malaria transmission potential at high altitudes (>900 m). In the relatively drier lower altitudes, a temperature increase of 2 °C combined with

Fig. 7. **Monthly malarial epidemic potential (EP) for Zimbabwe, by altitude zone, under "current" (1970) climate and under various climate change scenarios.** a) Baseline. b) 2 °C increase in temperature. c) 2 °C increase in temperature and 20% increase in precipitation. d) 2 °C increase in temperature and 20% reduction in precipitation (S = south, N = north).



a 20% decrease of precipitation may result in areas becoming too dry for malaria transmission to take place and in a shortening of the transmission season; in contrast, the transmission potential increases with the amount of precipitation.

Precise predictions are difficult to make since there are many uncertainties about how land use changes; and improvements in health and social changes will influence transmission. Moreover, some of the assumptions on which the model is based are difficult to measure and we are uncertain about the simultaneous interaction of variables within the model. None the less we consider that this approach is an important first step to identifying vulnerable communities in the African highlands.

Conclusions

Although malaria outbreaks have occurred in the African highlands for at least the past 100 years, it is difficult to be confident that *epidemics* are becoming more common in this region as a whole since a comprehensive and reliable data set is not available (although one is being compiled (*81*)). Nevertheless, there is strong evidence that *endemic* malaria is a growing problem in the African highlands since there have been numerous reports of increased incidence in recent years down the East African highland chain, from Ethiopia in the north to South Africa in the south, including the highlands of Ethiopia (A.N. Tulu personal communication, 1996); Kenya (*58*, *87*); Uganda (A. Onapa, personal communication, 1996); Rwanda (*37*); Burundi (Fig. 7 and *88*), United Republic of Tanzania (*36*), Zambia (Fig. 6 and *88*), Zimbabwe (*84*, *85*), and Madagascar (*51*). However, it should be appreciated that this increase is not confined to the highlands, as illustrated by the rise in malaria cases in lowland Togo (*88*).

In this article we have discussed many reasons for a rise in malaria incidence in Africa, mostly in relation to environmental changes, but we introduce a caveat. In the ecological studies we have described it is not possible to *prove* that any one factor has resulted in this increase, since correlation does not prove causality. Moreover, the risks of increasing endemicity and of more epidemics are dependent not only on environmental factors but also upon the vulnerability of highland communities and the capacity and capability of local health services (*89*). One of the major reasons for increases in malaria incidence in recent years has probably been a decline in the control and treatment of the disease. While inadequate health care makes communities vulnerable to malaria, the factors that precipitate epidemics are often climatic in origin — including sharp increases in rainfall, temperature, and humidity. Rainfall provides the breeding sites for mosquitos, and higher temperature and relative humidity increase mosquito survival and parasite development. It seems likely that epidemic-prone areas are those which experience marked differences in inter-annual climate and where the thresholds required for malaria transmission are exceeded every few years (M. Hulme, personal communication, 1996). Outbreaks can, however, occur in years that have a similar climate to others when epidemics did not occur. In this article we have shown how mathematical models can be used to explore the ways in which global warming could change future malaria patterns in Africa. These projections demonstrate that rises in temperature are likely to increase the risk of epidemics in the highlands both on continental and national scales — a finding supported by other recent studies (*27–30*, *32*). Clearly there is a need to confirm these projections in the field and to refine the model to improve its predictive capacity.

The African highlands are a fragile ecosystem under great pressure from rising populations, deforestation, and increased farming. The upland communities are often remote from regional health centres and the health services that are available are patchy, making the surveillance and control of malaria difficult. In view of recent reports of increased malaria in the African highlands an international workshop organized by the UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases and the International Development Research Centre of Canada was recently held to discuss this problem. It was concluded that malaria in the African highlands should be recognized as a distinct entity and a regional initiative is being launched to define epidemic-prone areas, identify the reasons for increased malaria, and help develop solutions to protect these vulnerable communities from this growing problem.

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Résumé

Le paludisme sur les hauts plateaux africains: situation passée, actuelle et future

Beaucoup des premiers colons européens arrivés en Afrique ont fui le climat chaud et insalubre des plaines pour s'installer sur les hauts plateaux. Alors que beaucoup étaient à l'origine exempts de paludisme, l'incidence de la maladie y a progressivement augmenté au cours des cinquante dernières années en grande partie à la suite du développement de l'agriculture et la sylviculture et, à ce problème est venu s'ajouter l'insuffisance des ressources sanitaires. Dans ces régions de transmission limite où le tableau du paludisme est instable, des épidémies peuvent être provoquées par des changements climatiques relativement subtils. Comme l'immunité au sein de ces communautés est faible, ces épidémies peuvent être très graves et entraîner une augmentation sensible de la morbidité et de la mortalité chez les enfants comme chez les adultes. Nous présentons ici les résultats obtenus à l'aide d'un modèle mathématique conçu pour déterminer ces régions des hauts plateaux africains exposées à des épidémies et les tendances qui pourraient être observées à la suite des changements climatiques mondiaux. Ces régious de hauts plateaux devraient être considérées comme un sujet de préoccupation particulière.Nous recommandons en outre que soit appliquic une méthode de modélisation régionale pour apprécier l'étendue et la gravité du problème et aider à améliorer la surveillance de la maladie et la qualité des prestations de santé dans cet écosystème instable.

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