Potential Impact of Global Climate Change on Malaria Risk

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The biological activity and geographic distribution of the malarial parasite and its vector are sensitive to climatic influences, especially temperature and precipitation. We have incorporated General Circulation Model-based scenarios of anthropogenic global climate change in an integrated linked-system model for predicting changes in malaria epidemic potential in the next century. The concept of the disability-adjusted life years is included to arrive at a single measure of the effect of anthropogenic climate change on the health impact of malaria. Assessment of the potential impact of global climate change on the incidence of malaria suggests a widespread increase of risk due to expansion of the areas suitable for malaria transmission. This predicted increase is most pronounced at the borders of endemic malaria areas and at higher altitudes within malarial areas. The incidence of infection is sensitive to climate changes in areas of Southeast Asia, South America, and parts of Africa where the disease is less endemic; in these regions the numbers of years of healthy life lost may increase significantly. However, the simulated changes in malaria risk must be interpreted on the basis of local environmental conditions, the effects of socioeconomic developments, and malaria control programs or capabilities. *Key words*: climate change, disability-adjusted life years, integrated modeling approach, malaria. *Environ Health Perspect* 103:458–464 (1995)

A potential consequence of anthropogenic climate change, foreseen for the coming century, is a change in the distribution and incidence of malaria (*1–7*). Although malaria eradication campaigns and socioeconomic development have caused malaria to disappear from many areas in which it had previously been endemic, in many tropical countries malaria remains a major cause of illness and death. Approximately 110 million clinical cases occur annually, and more than 1 million people, mostly children, die from malaria in tropical Africa (*8*).

Malaria incidence is determined by a variety of factors, particularly the abundance of anopheline mosquito species, human behavior, and the presence of malaria parasites. Anthropogenic climate change may directly affect the behavior and geographical distribution of the malaria mosquitoes and the life cycle of the parasite, and thus change the incidence of the disease. Indirectly, climate change could also have an effect by influencing environmental factors such as vegetation and the availability of breeding sites.

This study assesses, by integrated mathematical modeling, the effects of projected changes in temperature and precipitation on mosquito and parasite characteristics and their potential impact on malaria risk, and has followed two complementary approaches (*9*). One approach has sought to estimate the possible spatial shift in areas suitable for malaria transmission, using the critical vector density threshold as a comparative index. The other has considered possible changes in world malaria disease burden due to climate changes. Although the model only generates broad estimates of future trends and does not include all relevant factors which would influence the distribution of malaria (e.g., vaccination, pesticide use, and the emergence of drug resistance by the *Plasmodium* parasite), it addresses the question: If other things were held constant in the world, what would be the impact of climate change per se on the distribution and incidence of malaria?

Methods

Integrated Systems Approach

If the impact of a human-induced climate change on malaria risk is to be understood, the entire cause–effect chain must be described and analyzed comprehensively. The systems approach seems to be the only approach capable of adequately reflecting the complexity of the interrelationships between the climate system and mosquito and human population dynamics. The systems analysis not only studies the components of the various (sub)systems, but also the interactions and processes between them, rather than focusing on each subsystem in isolation. Given the complexity of the systems under consideration and the relative ignorance about the basic processes and interactions that determine their dynamics, the systems approach can help to foster understanding of the causal relationships between a human-induced climate change and changing malaria risks.

The model to assess the effects of climate change on malaria consists of several linked modules (i.e., systems): the climate system, the malaria system (divided into a human subsystem and a mosquito subsystem), and the impact system. The systems are linked in a straightforward manner; the output of one system serves as input to the next. The main climate factors that have a bearing on the malarial transmission potential of the mosquito population; are temperature and precipitation; i.e., factors derived from the climate system (Fig. 1). The interaction between the human system and the mosquito system determines the transition rates among the susceptible, the infected, and the immune. The impact system yields rough estimates of the health impact of climate change on malaria. This health impact is described by the disease burden due to malaria morbidity and mortality.

Climate Scenarios

To generate climate scenarios, we used the Integrated Model to Assess the Greenhouse Effect (IMAGE; Rotmans and Den Elzen, Bilthoven, The Netherlands). IMAGE (version 1.6) is a climate assessment model designed to simulate the entire cause–effect chain with respect to climate change and to develop scenarios of greenhouse gas emissions and their effect on global mean temperature. The model consists of a number of independent, but interlinked and integrated, submodels, each representing a separate component of the climate system (e.g., a world energy/economy model, land-use change model, atmospheric chemistry model, halocarbon model, carbon

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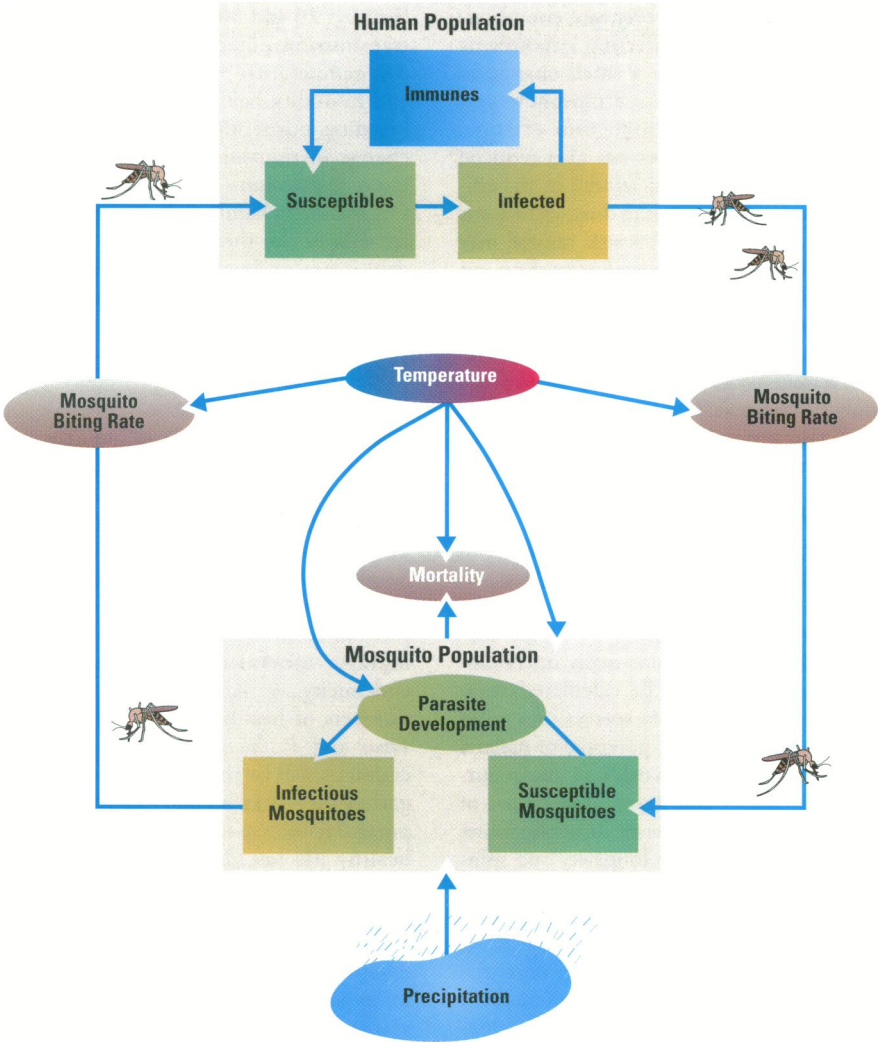

Figure 1. Diagram of the main population and rate processes involved in the life cycle of the malaria parasite.

cycle model, and climate model). A thorough description of the IMAGE model can be found elsewhere (*10,11*). Using the method of Santer et al. (*12*), the simulated global mean temperature changes are converted in time-dependent series of changes in regional seasonal temperature and precipitation by standardizing the output of a General Circulation Model (GCM). GCMs have been shown to simulate current temperature reasonably well, but they do not reproduce precipitation very accurately. They also cannot reliably project changes in climate variability, such as changes in the frequencies of droughts, which also could have a significant effect on vector-borne disease transmission. Nevertheless, GCMs currently provide the most advanced means of predicting the potential future climate consequences on a grid base (*13*).

The GCM used in this study is that of the UK Meteorological Office (*14*), using a grid resolution of 5° latitude by 7.5° longitude, with a climate sensitivity of 5.2. This equilibrium mean global temperature change of 5.2°C that would eventually occur if the CO_2 level were doubled falls beyond the current uncertainty range (1.5–4.5) projected by the Intergovernmental Panel on Climate Change (IPCC) (*11,15*). Although our projected changes in malaria transmission will be more pronounced compared to experiments using less sensitive GCMs, the direction of these changes will not be influenced significantly. The baseline climatology relies on precipitation and temperature data for the period 1951–1980.

New regional climate conditions are calculated using two widely used greenhouse gas standard scenarios: the business-as-usual (BaU) scenario and the accelerated policies (AP) scenario of the IPCC (*16*). BaU represents an ongoing trend of increasing fossil fuel-based energy use, agricultural use, and industrial growth, while AP entails increasing usage of renewable energy.

Epidemic Potential

Malaria is caused by species of the genus *Plasmodium* (of which *P. vivax* has the broadest geographic range and *P. falciparum* is the most dangerous clinically), and the vector responsible for malaria transmission is the mosquito of the genus *Anopheles*. The life cycle of the malaria parasite involves transmission both from mosquito to man and from man to mosquito, effected by the bite of a female mosquito. Inside the mosquito, the extrinsic development of the parasites takes several days.

A measure that summarizes many important processes in transmission of infectious diseases is the basic reproduction rate (R_0). For the malaria microparasite, R_0 is more precisely defined as the average number of secondary infections produced when one infected individual is introduced into a host population where everyone is susceptible (*17*). The basic reproduction rate is measure of an individual parasite's reproductive potential, and enables us to simplify the epidemiology of malaria. Basically, if $R_0 > 1$, the disease will spread indefinitely; if $R_0 < 1$, the disease will die out.

The vector density is one parameter in the basic reproduction rate that is strongly related to local environmental conditions. Change in the number of existing malaria vectors with time varies greatly between species, being determined by numerous biological and physical factors such as the availability of species-specific breeding sites, the presence of predacious fish or other natural enemies, the hydraulics of bodies of water, and the type of vegetation present. It is impossible to estimate the change in vector abundance over large areas as a result of temperature, precipitation, and humidity changes using an aggregated model such as ours (*18*). However, the basic reproduction rate allows calculation of the critical density threshold of hosts necessary to maintain parasite transmission. The critical density for malaria transmission can be expressed as:

$$\frac{N_2}{N_1} = k\left[\frac{-\log(p)}{a^2 p^n}\right],$$

where N_2/N_1 is the number of malaria mosquitoes (N_2) per human (N_1), p is the survival probability of the mosquito, a is the frequency of taking human blood, and n is the incubation period of the parasite in the vector. The constant k incorporates variables assumed to be temperature independent (including the efficiency with which a mosquito infects a susceptible human and a human infects a susceptible mosquito; the propensity of the mosquito population to feed on humans; and the recovery rate in humans). We defined the epidemic potential of malaria as the reciprocal of the vectors population's critical density. This epidemic potential is a key summary parameter and is used as a comparative index to estimate the

effect on malaria risk of a change in ambient temperature and precipitation patterns, as simulated with the climate model. A high epidemic potential indicates that a smaller number of vectors or a less potent vector population may maintain a state of endemicity or give rise to occasionally epidemics in a given area.

Climate Effects

The distribution and population dynamics of malaria are probably more governed by abiotic than biotic factors (*19*). Of the possible abiotic influences on the transmission cycle of malaria, temperature and rainfall are the most important. Rainfall influences transmission by its role in the mosquito life cycle, while temperature acts as a regulatory force. Table 1 presents temperatures that are critical to malarial transmission.

The incubation period of the parasite in the vector must have elapsed before the infected vector can transmit the parasite. The relation between ambient temperature and latent period for different parasite species was calculated by using a thermal temperature sum as described by Detinova (*20*). The number of blood meals a mosquito takes from humans is the product of the frequency with which the vector takes a blood meal and the proportion of these blood 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 can be calculated by means of a thermal temperature sum, increasing as temperature rises (see Table 1).

The female mosquito has to live long enough for the parasite to complete its development. Between certain limits, longevity of a mosquito decreases with rising temperature and increases with increasing relative humidity (*21*). Mosquitoes prefer humidities above 60%, and optimum temperature for mosquito survival is in the range of 20–25°C. Excessive temperatures will increase mortality, and there is a threshold temperature above which death ensues. Similarly, there is a minimum temperature for the mosquito to become active. Based on data reported by Boyd (*22*) and Horsfall (*23*), we assumed a daily survival probability of 0.82, 0.90, and 0.04 at a temperature of 9, 20, and 40°C, respectively.

Rainfall plays a crucial role in malaria epidemiology because it provides the medium for the aquatic stages of the mosquito life cycle. Rain may prove beneficial to mosquito breeding if moderate, but if excessive it may flush out the mosquito larvae. Rainfall may also increase the relative humidity and hence the longevity of the adult mosquito. The relationships among changing temperatures, precipitation, and relative humidity, however, are complicated and the processes affecting atmospheric humidity suggest only a small change in relative humidity as the atmosphere gets warmer (*24*). The introduction of large-scale irrigation schemes has also reduced the significance of local rainfall in the epidemiology of vector-borne diseases to some extent (*25*). However, because rainfall may be a limiting factor in vector breeding, we imposed a minimum amount of precipitation needed for mosquito development. Using a minimum value of 1.5 mm per day allows us to exclude dry areas from malaria transmission, roughly coinciding with the present distribution limits of endemic malaria areas.

Uncertainties

Our estimate of the epidemic malarial potential, using *A. macullipennis* data on blood-digestion and a universal relationship between temperature and daily survival probability, contains many uncertainties. Ideally it should be calculated separately for each mosquito species in a given location. The epidemic potential of malaria is most sensitive to changes in mean survival probability and development time of the parasite. The effects of different values of maximum mosquito longevity and minimum temperature requirements for parasite development on epidemic malaria potential are illustrated in Figure 2. As temperature increases, epidemic potential increases until a maximum is reached. At high temperatures, the accelerated development of the parasite and the increased biting rate can no longer compensate for the decreasing mean life expectancy among the mosquitoes. The distributions shown in Figure 2 indicate that, in temperate climates, small increases in temperature can result in large increases in epidemic malaria potential, irrespective of the values chosen for the maximum daily survival probability (p_{max}) or minimum temperature for parasite development (T_{min}). Although the maximum values for the epidemic potential are found in the range 29–33°C, the actual transmission intensity also depends on vector abundance. Optimal temperature for the rapid expansion of a population of malarial mosquitoes is found between 20 and 30°C, which may increase transmission potential. Therefore, within this temperature range and with rainfall and humidity being optimal for mosquito breeding, our results will underestimate the change in transmission potential of mosquito populations due to climate changes. On the other hand, if the amount of rainfall (above the threshold limit of 1.5 mm day) is not optimal for mosquito breeding and development, our results are likely to overrate the changes in malaria risks.

Health Impact

We estimated the effect of anthropogenic climate change on malaria incidence and disease burden for highly endemic areas, mainly found in tropical Africa, and for areas of lower endemicity found in other parts of Africa, South America, and Southeast Asia. In tropical Africa attention has been restricted to *P. falciparum*, the predominant species responsible for most malaria mortality. In areas of lower endemicity, we have simulated changes in numbers of healthy years lost for both *P. vivax* and *P. falciparum*. Most developed countries will be in a position to take mitigating measures as malaria transmission potential increases; here the numbers of healthy life lost due to malaria infection will remain negligible compared with the endemic areas in the world.

The model framework used to describe the malaria transmission dynamics in the human population is based on a standard population model (*26*) combined with an epidemiological model for infectious diseases (*27*). The population model calculates future population figures on the basis of United Nations projections (*28*), including those for fertility. The human population at risk to malaria is defined for a younger age class from 0 to 4 years old, and an older age class of 5 years and older to account for age-specific differences in fatality rates (*29*). This population is divided into the three categories of the epidemiological model: susceptible, infected, and immune (see Fig. 1). The rate at which people become infected depends on the basic reproduction rate, which changes with climatic conditions. After entering the infected state a person

Table 1. Some important temperatures in malaria transmission[a]

	Extrinsic incubation cycle (*Plasmodium* species)		Digestion of blood meal (*Anopheles* species)
	P. vivax	*P. falciparum*	*A. maculipennis*
Degree-days (°C day)	105	111	36.5
Threshold temperature (°C)	14.5–15	16–19	9.9

[a]The time needed to complete the parasite's extrinsic development and for the digestion of a blood meal by the mosquito can be expressed in formula by $DD/(T-T_{min})$, where degree-days (DD) represent the accumulation of temperature units over time, and threshold temperatures (T_{min}) are those below which the process does not occur.

runs a standard risk of contracting malaria, since the general level of prophylaxis is, and probably will remain, low in the populations concerned.

Malarial morbidity and mortality, as modeled here, show the epidemiological features of an infectious disease leading to immunity. In areas with stable, highly endemic malaria, morbidity and mortality in the economically active age groups are expected to be relatively lower than in the younger persons because of the acquisition of long-term immunity by survivors. In areas of low to moderate endemicity the health impact is the same for practically all age groups. The social and economic consequences of malaria are directly related to its severity, mainly due to anemia and premature death.

Our simulation includes the concept of disability-adjusted life years (DALY) (*30*) to arrive at a single measure of the health impact of malaria. For each death, the number of years of life lost is defined as the difference between the actual age at death and the present upper life expectancy for humans as a reference. In the case of disability due to malaria, the incidence of the disease is multiplied with the expected duration of the condition and the severity of the disability. An average disability weight of 0.6 has been added to the periods spent with malaria (we assumed that a clinical attack lasts for 7 days, occurring twice a year), accounting for only a partial loss of functional independence. The death and disability losses are combined and allowance is made for an annual discount of 3% for future losses and for age weights.

Although actual prevalence and incidence figures are not very reliable in most endemic regions, a good estimate of the infection rate can be obtained from the rate of increase of prevalence with age in young children. In our calculations, the initial force of infection is 2.0 per annum for the year 1990 in highly endemic regions and 0.1 in areas of lower endemicity (*31,32*).

In the estimates of the excess disease burden in endemic areas, the malaria conditions are assumed to be in equilibrium in the year 1990 (equilibrium values for disease burden, calculated for the year 1990, are: highly endemic areas *P. falciparum*: 73.3; low endemic areas *P. falciparum*: 5.8 and *P. vivax*: 1.4 DALYs/1000 population). For the stable, highly endemic regions of tropical Africa, this assumption seems to be justified. However, for the unstable areas of lower endemicity, this assumption will often be inappropriate.

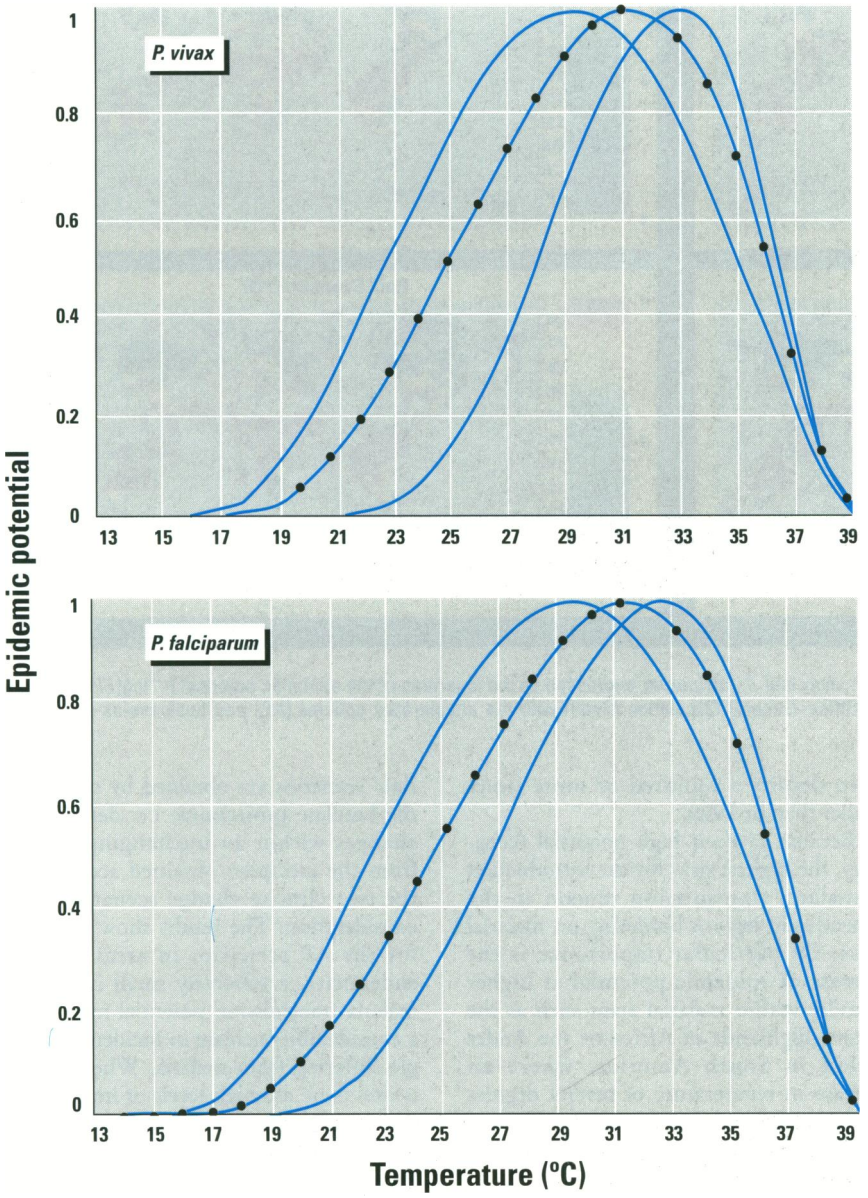

Figure 2. Epidemic potential (value 1 at maximum) as a function of temperature. The left-hand curve shows the epidemic potential for *P. vivax* with p_{max} = 0.8 and T_{min} = 14.5°C; for the central estimate the values are: p_{max} = 0.9 and T_{min} = 14.5°C; and for the right-hand curve: p_{max} = 0.95, T_{min} = 15°C. For *P. falciparum* the left-hand curve uses p_{max} = 0.8 and T_{min} = 16°C; central estimate: p_{max} = 0.9, T_{min} = 16°C; right-hand curve: p_{max} = 0.95, T_{min} = 19°C. For the central estimate the third-order polynomial coefficients used are: α = -4.40, β = 1.31 and γ = -0.03.

Results

We used the epidemic potential to estimate the effect potential of a change in average seasonal temperature and precipitation patterns on malaria transmission, as estimated using the UKMO-GCM. Figure 3 depicts the global distribution of the potential malaria risk areas and the estimates of absolute limits of the possible geographic extension of malaria transmission in the years 1990 and 2100 for the AP and BaU scenarios. The simulated 1990 malarial areas roughly agree with the global distribution of malaria transmission before the introduction of large-scale antimalaria campaigns (*21*). For *P. vivax* this includes large parts of the United States up to the Canadian border, southern and central Europe, Turkey, southern Russia, China, and Japan. *P. falciparum* malaria is restricted to more tropical areas because parasite development needs a minimum temperature of at least 16°C.

Comparing the potential geographic extent of malaria in 1990 to the actual malaria distribution indicates that the simulation of future risk areas must be interpreted to take account of local conditions and developments. In tropical and subtropical regions, climatic conditions are already favorable for mosquito breeding and reproduction, resulting in densities that exceed the critical value for a large portion of the year. However, in some regions "anophelism without malaria" exists, a phrase referring to the absence of malaria in the presence of both *Anopheles* and climate factors, in particular tempera-

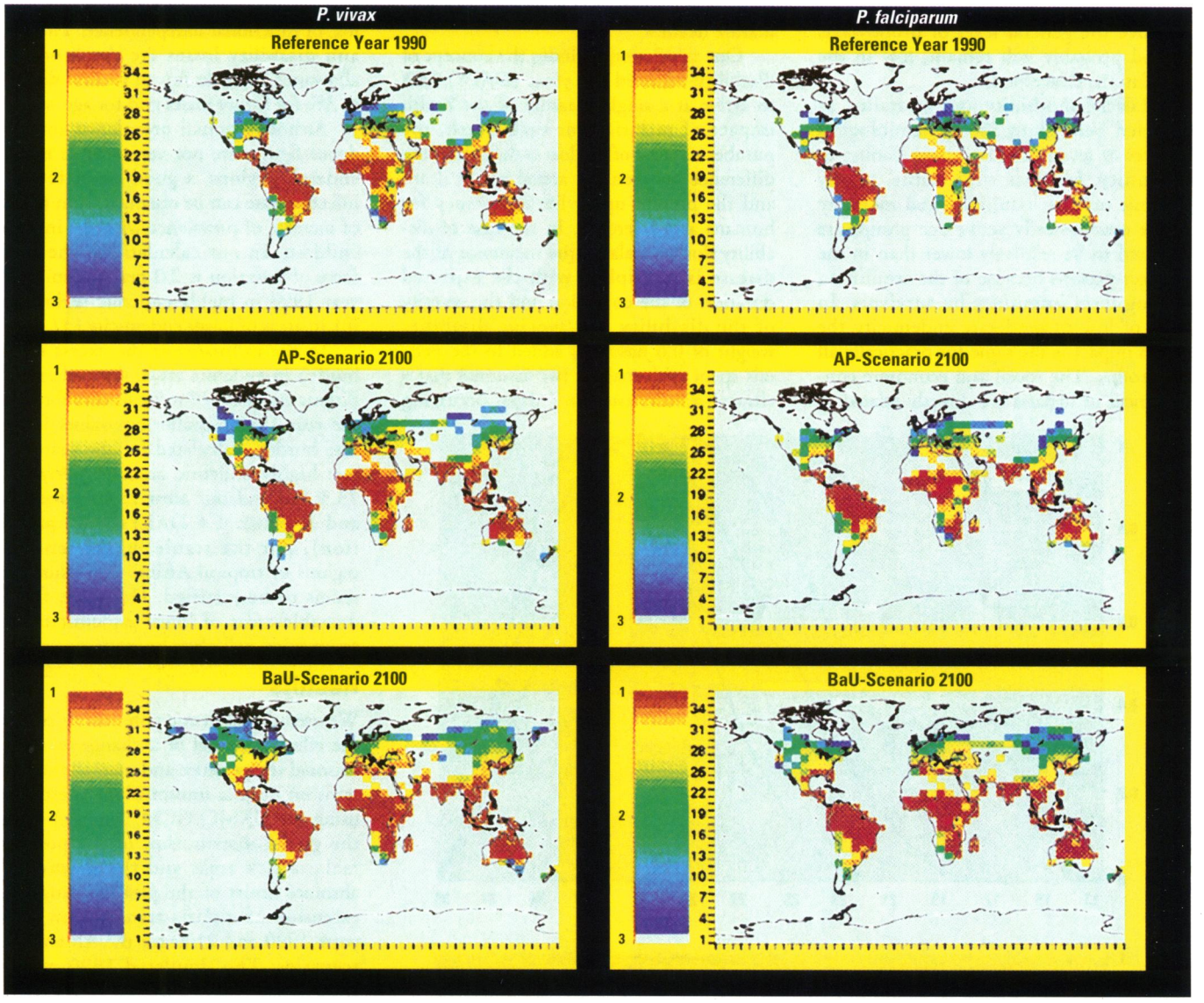

Figure 3. Potential malaria risk areas in 1990 and 2100 for *P. vivax* and *P. falciparum*, expressed as the logarithm of the epidemic potential [$-^{10}\log(EP)$], based on the climate patterns generated by the UK Meterological Office–General Circulation Model with the accelerated policies (AP) and business-as-usual (BaU) greenhouse gas emission scenarios.

ture, that are apparently conducive to transmission. Effective vector control measures, the treatment of infected individuals, and the specific characteristics of the human and/or mosquito population may explain this phenomenon. In the Central and South Pacific, no potential vectors are present, establishing a malaria-free zone in this area.

Figures 3 and 4 show that an expansion of the geographical areas susceptible to malaria transmission and a widespread increase of potential malaria risk are to be expected as the climate changes. The main changes would occur in areas with temperate climates where mosquitoes already occur but where development of the parasite is limited by temperature. By the year 2100 in large parts of North America, Europe, and Asia, the potential for malaria transmission would exist even with a mosquito density a hundred or more times smaller than in 1990.

Because of their high potential receptivity, the highest risks for the introduction of malaria transmission remain in the nonendemic regions bordering on malarial areas. Of particular importance is the increase of epidemic potential at higher altitudes within malarial areas such as the eastern highlands of Africa or the Andes region in South America, where an increase in temperature of several degrees may raise the epidemic potential sufficiently to change normally nonmalarial areas to areas with seasonal epidemics.

Figure 5 presents the excess disease burden as climate changes according to the AP and BaU scenarios. Because disease burden is influenced by the population's demographic evolution, values for the disease burden attributable to the AP and BaU scenarios are obtained by subtracting the baseline projections; i.e. demographic changes within an unchanging climate, from the estimates obtained according to the two climate change scenarios under consideration. The results show that, even for the AP scenario, in areas of lower endemicity, a relatively small increase in malaria transmission potential may lead to a considerable increase in incidence of people suffering from malaria. Where malaria is rife, there are high levels of immunity in the population, and the change is far less pronounced. However, the major part of the disease burden due to high-fatality malaria will remain in the highly endemic countries of tropical Africa.

Discussion

Recent research assessing malaria risk in relation to climate changes has either been

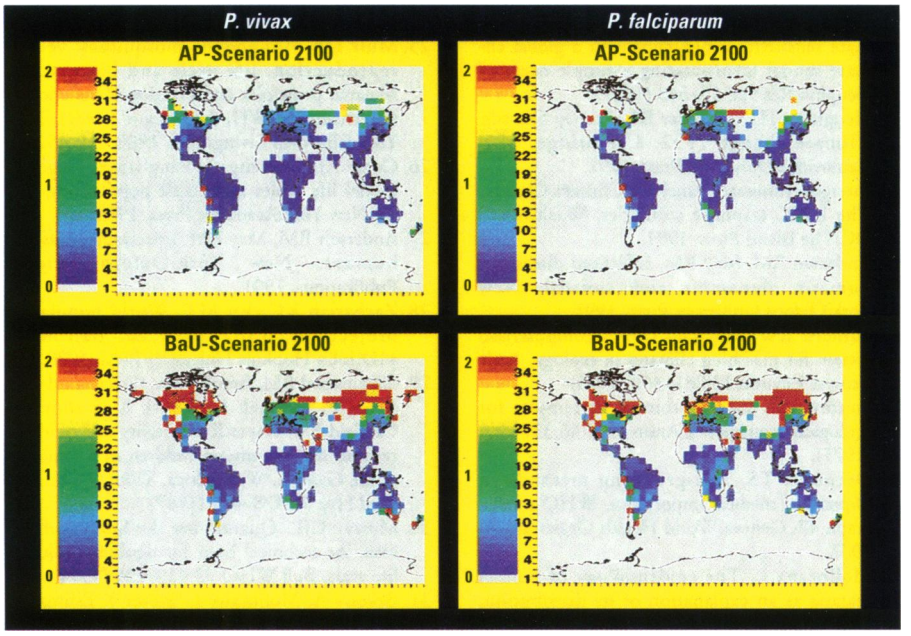

Figure 4. Estimated change of yearly mean epidemic potential (logarithmic scale) for *P. vivax* and *P. falciparum* in 2100 as compared with the year 1990 for the UK Meterological Office–General Circulation Model output with accelerated policies (AP) and business-as-usual (BaU) greenhouse gas emission scenarios.

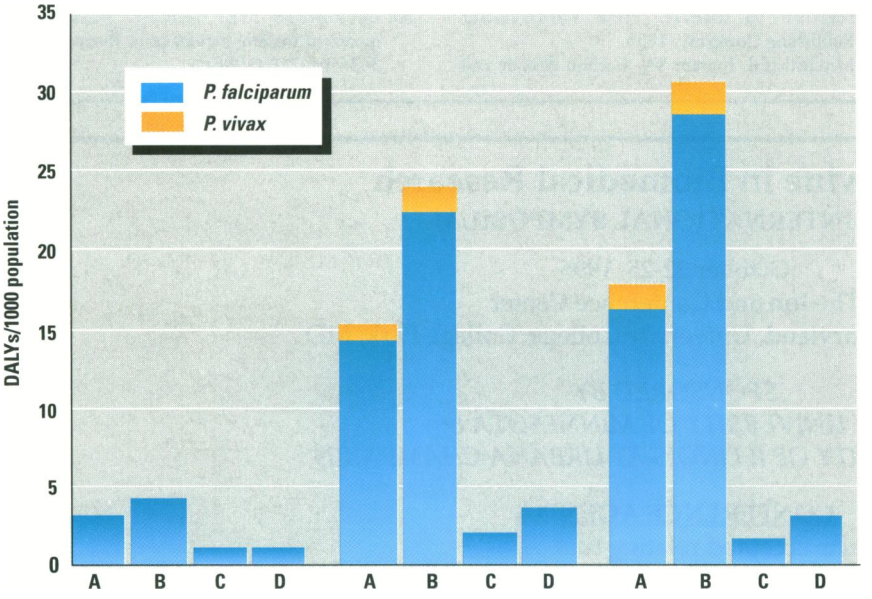

Figure 5. Projection of additional numbers of healthy years lost (*P. vivax* and *P. falciparum*) for highly endemic areas (HE) mainly found in tropical Africa, and areas of lower endemicity (LE) found in other parts of Africa, South America, and Southeast Asia. A, LE areas with accelerated policies (AP) scenario; B, LE areas with business-as-usual (BaU) scenario; C, HE areas with AP scenario; D, HE areas with BaU scenario]. DALY, disability-adjusted life years.

qualitative (*2,3,5*) or does not comprehensively model the cause–effect chain (*1,4,6*). In this study we combined and integrated the present state-of-the-art knowledge and expertise from various disciplines to obtain a global picture of changes in malaria risk areas and health impact, associated with the different climate scenarios. Studies such as this explore the sensitivity of malaria transmission dynamics on a global scale, as currently understood, to projected levels of climate change.

As climate changes in the direction predicted by the IPCC, simulation experiments show a widespread increase in transmission potential of the malaria mosquito population and an extension of the areas conducive to malaria transmission. A global mean temperature increase of several degrees in the year 2100 increases the epidemic potential of the mosquito population in tropical regions twofold and more than 100-fold in temperate climates. There is a real risk of reintroducing malaria into nonmalarial areas, including parts of Australia, the United States, and Southern Europe, associated with imported cases of malaria, since the former breeding sites of several *Anopheles* species still exist. However, because effective control measures are economically feasible in most developed countries, it is unlikely that anthropogenic climate changes would recreate a state of endemicity in these areas. Increased surveillance in previously malarial but not in *Anopheles*-free areas will be necessary, however.

A different situation can be expected in currently endemic areas and areas bordering on them in the subtropics, a result supported by other studies (*7,33*). In the highly endemic malarial areas of tropical Africa, the incidence of malaria and consequently the number of years of healthy life lost due to malaria may increase. In the malarial areas of lower endemicity, the incidence of infection is far more sensitive to climate changes. Therefore, anthropogenic climate change may have substantial effects on years of life lost in such areas.

The change in malaria risk as simulated must be interpreted within the framework of local conditions and developments, such as the health services, the parasite reservoir, and mosquito densities. The large-scale migration of populations from areas in which malaria is endemic into receptive areas, a movement induced by rural impoverishment and inevitably influenced by climatic changes, will play an important role in the dynamics of the disease. Therefore, the extent of an increase in malaria risk will be superimposed upon the change in malaria transmission associated with socioeconomic development, population growth, and the effectiveness of control measures. Given that resources are insufficient to deal adequately with malaria in the most affected regions, increased risk of malaria due to climate change may seriously affect human health in the next century.

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