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Climate change and malaria: analysis of the SRES climate and socio-economic scenarios

M. van Lieshout[a,*], R.S. Kovats[b], M.T.J. Livermore[c], P. Martens[a]

[a] *International Centre of Integrative Studies, University of Maastricht, Maastricht, The Netherlands*
[b] *London School of Hygiene and Tropical Medicine, UK*
[c] *Climatic Research Unit, UEA, UK*

Abstract

The distribution and seasonal transmission of malaria is affected by climate, as both vector and parasite are sensitive to temperature. A global model of malaria transmission has been developed to estimate the potential impact of climate change on seasonal transmission and populations at risk of the disease (MIASMA v.2.2). "Population at risk" is defined as the population living in areas where climate conditions are suitable for malaria transmission. This assessment describes model simulations driven by the latest scenarios from the IPCC. The climate scenarios were derived from the Hadley Centre model HadCM3 runs with four SRES emissions scenarios: A1FI, A2, B1 and B2. The additional population at risk was determined under each of the SRES population scenarios by downscaling national estimates to the $0.5 \times 0.5^{\circ}$ scale grid and re-aggregating by region. Additional population at risk due to climate change are projected in East Africa, central Asia, China and areas around the southern limit of the distribution in South America. Decreases in the transmission season are indicated in many areas where reductions in precipitation are projected by the Hadley Centre model, such as the Amazon and in Central America. The outcomes of the malaria model are sensitive to (1) spatial distribution of precipitation projections and (2) population growth in those areas where there is new risk due to climate change. This paper describes a new method for describing vulnerability to the potential impacts of climate change. Countries were classified according to their current vulnerability and malaria control status using expert judgement. This vulnerability incorporates both socio-economic status, as a measure for adaptive capacity, and climate as malaria at the fringes of its climate-determined distribution is easier to control than malaria in tropical endemic regions. Thus, current malaria control status is used as an indicator of adaptive capacity. For those countries that currently have a limited capacity to control the disease, the model estimates additional populations at risk by 2080s in the range of 90 m (A1FI) to 200 m (B2b). The greatest impact under B2 reflects population growth in risk areas in Eurasia and Africa. Climate-induced changes in the potential distribution of malaria is projected in the poor and vulnerable regions of the world. However, climate change is not likely to affect malaria transmission in the poorest countries where the climate is already highly favourable for transmission.

Keywords: Climate change; Malaria; Adaptive capacity; Vulnerability

1. Introduction

Global climate change remains one of the biggest environmental threats over the coming century. The impacts on human population health are uncertain but are an important focus of the policy debate regarding mitigation and adaptation. An increase in malaria, in particular, has been strongly identified as a potential impact of climate change. The most recent IPCC assessment concludes that (IPCC, 2001a):

> In areas with limited or deteriorating public health infrastructure, and where temperatures now or in the future are permissive of disease transmission, an increase in temperatures (along with adequate rainfall) will cause certain vector-borne diseases (including malaria, dengue and leishmaniasis) to extend to higher altitudes [medium/high confidence] and higher latitudes [medium/low confidence]. Higher temperatures, in combination with conducive patterns of rainfall and surface water, will prolong transmission seasons in some endemic locations [medium/high confidence]. In other locations, climate change will decrease transmission via reductions in rainfall or temperatures that are too high for transmission

*Corresponding author.

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[medium/low confidence]. In all such situations, the actual health impacts of changes in potential disease transmission will be strongly determined by the effectiveness of the public health system.

The distribution of malaria is in theory limited by the climatic tolerance of the mosquito vectors and by biological restrictions that limit the survival and incubation of the infective agent in the vector population. Climate may play a major role in determining the distribution and abundance of insects, either directly or indirectly through its effects on habitats and animals. Climate change may have an effect on the geographical range of many malaria vector species (Rogers, 1996; Sutherst, 1998). Climate change per se would be expected to have the following spatio-temporal effects on malaria (Kovats et al., 2001):

- Increase its distribution where it is currently limited by low temperature—epidemic malaria may become present in new areas.
- Decrease its distribution where it becomes too dry for mosquitoes to be sufficiently abundant for transmission.
- Increase or decrease the months of transmission in areas with "stable" malaria, some areas may change from unstable to stable malaria, and some may change from stable to unstable malaria.
- Increase the risk of localised outbreaks in areas where disease is eradicated but vectors are still present, such as in Europe or the United States.

Human activities prevent the spread of pathogens (by treating human cases) and reduce mosquito populations either directly (by insecticide) or indirectly (habitat modification) (Bradley, 1998; Casman et al., 2000; Cox et al., 2002). Hence, the distribution of malaria is restricted in many countries, and the global distribution of malaria is well within its climatic limits. The effect of changes in climate on actual human disease burdens will depend on many social, economic and environmental factors that will vary between populations. It is therefore an important task to identify those areas where adaptive capacity is low and where climate change may increase transmission.

The IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2001b) documents a new suite of global development scenarios, which the IPCC may use as foundation for the Fourth Assessment Report. These new scenarios couple future emissions pathways to explicitly defined future paradigms of the world which have their own unique trends in population growth and socio-economic development. These scenarios are non-interventionist scenarios and imply no explicit climate policies to reduce emissions. The aim of the scenarios was to provide a consistent input to climate models and impact models. All scenarios are considered equally possible and there is no "best guess". The scenarios are presented in four "storylines" which represent internally consistent characterisations of future states of the world during the 21st century, including demographic and economic development, energy use and greenhouse gas emissions, together with associated changes in climate and sea level. Regional differences and interactions, especially between developing and industrialised countries, are also assessed. This paper describes an assessment of the effect of climate change and socio-economic development on future populations at risk of malaria, using SRES socio-economic scenarios and climate projections made using the HadCM3 climate model driven by SRES emissions scenarios.

1.1. Malaria and socio-economic development

In Europe, malaria declined with socio-economic development, including modernisation of livestock production and farming. Epidemic malaria in the Netherlands was eradicated by the use of quinine in rural medical care and by the stabling of cattle away from human habitations, rather than a general reduction in the abundance of the *Anopheline* mosquito vectors (Najera, 1994). In England, the reduction in malaria transmission is thought to have been due to progressive improvements of a social, economic, agricultural, educational, and public health nature (Dobson, 1994; Reiter, 2000).

At the global level, the relationship between malaria and socio-economic development is not neatly defined. The extent to which a population is vulnerable to malaria depends on the degree of exposure and the measures that are available to limit transmission and treat infections. It has proved difficult to identify adequate indicators which could be used to model future adaptation to changes in disease risk associated with climate change and socio-economic development within an integrated assessment model (Martens and McMichael, 2001). First, malaria incidence is hugely influenced by geography and prevailing climate. The poorest countries tend to be in high-risk tropical and subtropical regions. Apportioning malaria causality between environment, income, and social practices is, therefore, problematic. Applying a quantitative relationship between socio-economic development and malaria incidence has not been seriously attempted, for a variety of reasons:

- No suitable indicator is available for socio-economic development to perform a global statistical analysis. Social capital, an indicator of equity in income distribution within countries is a more important indicator of health status than GDP per capita (e.g. Costa Rica and Cuba outperform Brazil in most health indicators).

- Political instability can undermine the influence of development (i.e. Russia, Azerbaijan).
- Economic development can increase transmission temporarily (this has been observed in relation to deforestation, population movement, water development projects).
- Many control programs depend on external co-operation and donor funding (e.g. Viet Nam).

The relationship between economic development and malaria is two-way. Poor economic development is an effect of malaria as well as a cause. The direct costs of treating and preventing malaria morbidity and lost productivity are considerable, in relation to available funds in a developing country. Further, malaria has been shown to slow economic growth in low income African countries creating an ever-widening gap in prosperity between malaria-endemic and malaria-free countries. The reduced growth in countries with endemic malaria was estimated to be over 1% of GDP per year. The cumulative effect of this "growth penalty" is severe and restrains the economic growth of the entire region (Sachs, 2001).

1.2. Malaria at the beginning of 21st century

Malaria is one of the world's most serious and complex public health problems. Each year, the disease causes an estimated 400–500 million cases and more than one million deaths, mostly in children (WHO, 2001). Malaria is undergoing a global resurgence because of a variety of factors. These include the complacency and policy changes that led to reduced funding for malaria control programs in the 1970s and 1980s, the emergence of insecticide and drug resistance, human population growth and movement, land-use change and deteriorating public health infrastructure.

The current distribution of malaria is illustrated in Fig. 1. Malaria is currently confined to tropical areas and poorer countries. The burden of mortality is unevenly distributed, with approximately 85% of all deaths and disease occurring in Africa. Fig. 1 also shows the distribution of malaria in the 1870s at the peak of its global spread. This is when global trade routes had allowed the infections to be spread to the New World, and before development and active control measures caused a reduction in the disease (McMichael et al., 2000).

There are two main species of malaria parasite: *Plasmodium vivax* and *P. falciparum*. There is an important difference between parasites in the minimum temperature for parasite development, as well as differences in current health impact and distribution. There are no accurate maps available for the current distribution of the different parasites. The historical distribution is likely to represent the distribution of *vivax* in temperate areas, as *falciparum* was until recently confined to tropical regions.

2. Methods and model

2.1. Malaria model

This assessment uses the malaria module of the MIASMA model (v2.2.) developed by Martens and colleagues (Martens et al., 1999; Martens, 1998). This model links GCM climate scenarios with an impact module that applies the formula for the basic reproduction rate (R_o) to calculate the transmission potential

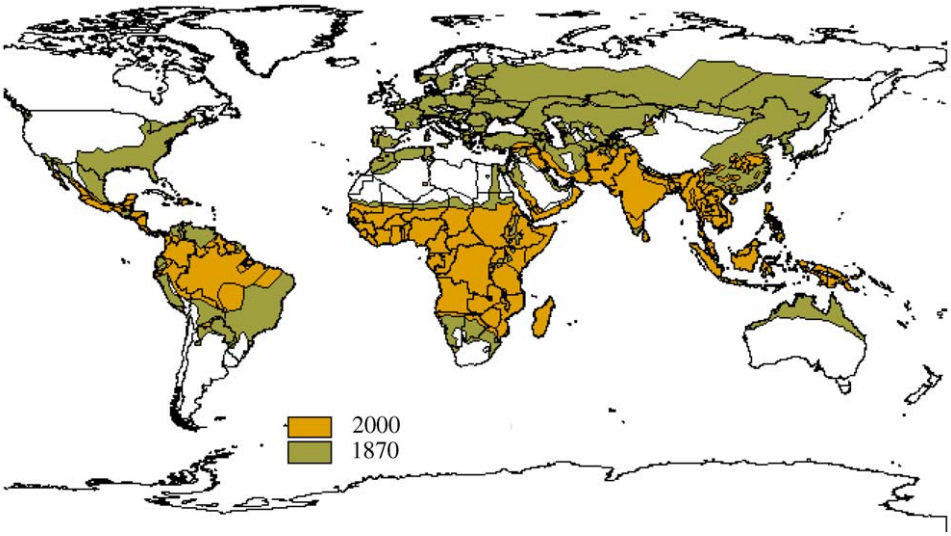


Fig. 1. Current distribution of malaria (Source: WHO, 2002) and the historical distribution (1870).

(TP) of the malaria mosquito population, and to estimate the population at risk.

A unit of measurement, which encapsulates many of the important processes in the transmission of infectious diseases, is the basic reproduction rate (R_o). In the case of the malaria, R_o can be defined as the average number of secondary infections produced when a single infected individual is introduced into a potential host population in which each member is susceptible. If $R_o > 1$ the disease will proliferate indefinitely; if $R_o < 1$ the disease will die out. R_o is closely related to the vectorial capacity, a unit of measurement often used in malaria epidemiology.

TP is the reciprocal of the critical mosquito density (also called vector density threshold), a component of the vectorial capacity equation. The vectorial capacity itself is not modelled because it requires information that is inestimable on vector abundance on a global scale. The main components of the TP are listed in Table 1. The formula for the basic reproduction rate and vectorial capacity allows calculation of the critical density threshold of vector populations necessary to maintain malaria transmission. The relationships used to derive vectorial capacity, and hence its derivative TP, assume that vectors are evenly mixed and that they die at a constant rate, independent of age. TP is used here as a comparative index for estimating the impact of changes in environmental temperature and precipitation patterns on the risk of malaria (Martens et al., 1999). A high TP indicates that, despite a smaller vector population, or, alternatively, a less efficient vector population, a given degree of transmission may be maintained in a given area. TP is an estimate of the true vectorial capacity (VC) that changes from site to site, from vector to vector, and within and between transmission seasons.

The incubation period of the parasite in the malaria mosquito (the extrinsic incubation period) must have elapsed before the infected vector can transmit the parasite. The parasites develop in the vector only within a certain temperature range. The minimum average monthly temperature for the parasite development to be completed within 1 month was assumed to be 17°C. The proportion of parasites surviving decreases rapidly at temperatures over 32–34°C. The relation between ambient temperature and the extrinsic incubation period is very important for assessing the impact of climate change. It is calculated using a temperature sum first described by Macdonald (MacDonald, 1957).

Rainfall plays an important role in malaria epidemiology. Mosquitoes breed in standing water (usually freshwater pools or marshes) and, therefore, mosquito abundance is affected by rainfall and the availability of surface water. Rainfall also affects relative humidity and hence the longevity of the adult mosquito. The model assumes that a minimum level of monthly rainfall of 80 mm for at least four consecutive months (concurrently with the window of suitable temperature) is essential for seasonal malaria transmission. The value of 80 mm per month was derived by the MARA project (Mapping Malaria Risk in Africa) as a prerequisite for *endemic* malaria (Craig et al., 1999; MARA, 1998). However, there is evidence that transmission can occur in areas with less precipitation (Fig. 1). Certain vectors of malaria, such as *An. funestus*, are less dependent on rainfall, since they prefer to breed in more permanent habitats (Gillies and Coetzee, 1987).

As an indicator of relative changes in transmission risk, the use of TP may be conservative as it assumes that climate change does not affect the density of mosquito populations. Absolute values of TP should be interpreted with caution, as TP does not in itself describe where R_o is greater than 1, so that transmission can be sustained. It provides an indication of areas in which for given climate conditions the parasite development is fast enough to be completed before the vector dies. Therefore, we identified areas where the climate is suitable for malaria transmission for at least three months per year as a more robust indicator of climate-related risk.

The "population at risk" is defined as the total population living in an area where conditions are suitable for malaria transmission as defined by TP, and an average monthly precipitation of 80 mm. The reference scenario, from which additional population at risk estimates are calculated, is one that incorporates population growth but where the climate conditions are held at current levels as defined by the baseline climatology 1961–1990.

Table 1
Variables important in malaria transmission

Variable	Dependent on vector species	Dependent on temperature
Human-biting rate: daily biting rate of a female mosquito	Yes	Yes
Human susceptibility: Efficiency with which an infective mosquito infects a human	Yes	No
Mosquito susceptibility:		
Chance that an uninfected mosquito acquires infection from biting an infectious person	Yes	No
Daily survival probability of the mosquito.	Yes	Yes
Incubation period for the parasite inside the mosquito	No	Yes

2.2. Vector distributions

Malaria is transmitted by mosquitoes of the genus *Anopheles*. There are about 70 species that are vectors of malaria under natural conditions. The main vector species in Africa, the *Anopheles gambiae* complex, are the most efficient vectors in the world and are major factors in the high burden of disease in this region. In contrast, a large region in the Pacific Ocean (Polynesia and Micronesia) has always been free from *Anopheles*, and, therefore, malaria. Vectors are still present in Europe and North America. The model is constrained by the current distribution of malaria vectors. The vector distribution map is described in previous assessments (Martens et al., 1999). Additional populations at risk are estimated within the "current" vector distribution, assuming that the vector distribution does not change with changes in climate. Studies have modelled changes in the distribution of mosquito vector species under a range of climate scenarios (Bryan et al., 1996; Rogers, 1996; Sutherst et al., 1998). However, these assessments are for individual vector species or countries and no comprehensive global study is available that could be included in the model.

2.3. Climate scenarios

The climate scenarios are derived from experiments conducted with the third generation Global Climate Model (GCM) developed by the UK Hadley Centre (HadCM3) (Hulme et al., 1999). In total, seven experiments have been conducted using the new HadCM3 model:

- HadCM3A1FI (fossil fuel intensive)
- HadCM3A2 with three ensemble members [A2a, A2b, A2c]
- HadCM3B1
- HadCM3B2 with two ensemble members [B2a and B2b]

In each case the simulated climate is perturbed throughout the period 1990–2100 by changes in greenhouse gas concentrations as described in the SRES (IPCC, 2001b). Scenarios have subsequently been derived based on three 30-year averaged time slices centred on 2025, 2055, and 2085. The reference climate is a 30-year average computed from the period 1961–1990 (New et al., 1999).

The climate scenarios, consisting of 30-year averages of monthly temperature and precipitation data, are used in the model to represent a typical year. Therefore, the model is estimating climate suitability for an average year, and the suitability for stable or annual transmission. Weather extremes may trigger epidemics in particular areas but the impact of climate variability for malaria risk cannot be addressed with this model.

2.4. Population scenarios

The emissions scenarios are driven by assumptions about population growth and associated changes in energy consumption. The population scenarios vary greatly, as global population by 2100 is estimated to range from 7 billion (B1 and A1FI) to 15 billion (A2). The midrange estimate can be considered to be B2 (close to IS92a), which estimates a world population of 10 billion by 2100. The UN 2000 medium projection leads to a global population of 9.3 billion by 2050 (A1/B1 estimated 8.7 billion in 2050).

The regional population projections were downscaled to national totals at 5 yearly intervals by CIESIN. Populations grids ($0.5 \times 0.5^{\circ}$ grid) were generated (Arnell et al., 2003) using the Gridded Population of the World version 2 1995 data set and subsequently rescaled by *national* growth factors, to produce a global grid $0.5 \times 0.5^{\circ}$ for each scenario. The population grids do not take into account urbanisation or coastal migration.

Countries were grouped in 14 regions defined by the World Health Organization GBD (Global Burden of Disease) exercise according to geographical location and similar patterns of mortality (Fig. 2) (Ezzati et al., 2002). Population growth is greatest in A2 in all regions except in Africa where the projected population is greatest under the B2 scenario (Fig. 3).

2.5. Adaptive capacity and vulnerability

The MIASMA malaria model is essentially a global biophysical model. Linkage of the output to socio-economic systems and vulnerability is a difficult but essential task in addressing questions about global climate change. Few studies have previously attempted this with respect to malaria (Martens et al., 1997; Tol and Dowlatabadi, 2001).

The main outcome of this assessment is the additional population at risk due to climate change. This assessment will describe potential populations at risk based on the *current* level of adaptation to malaria. For the current situation all countries were classified as one of six groups (A–F) based on current vulnerability to malaria (Kovats et al., 2003) (Fig. 4). The countries in each control group were identified by expert judgement and current classifications used by the WHO Regional Offices (McMichael et al., 2004). We further simplified the groups as those with "poor" (groups D, E, and F) and "good" (groups A, B, and C) adaptive capacity with respect to malaria.

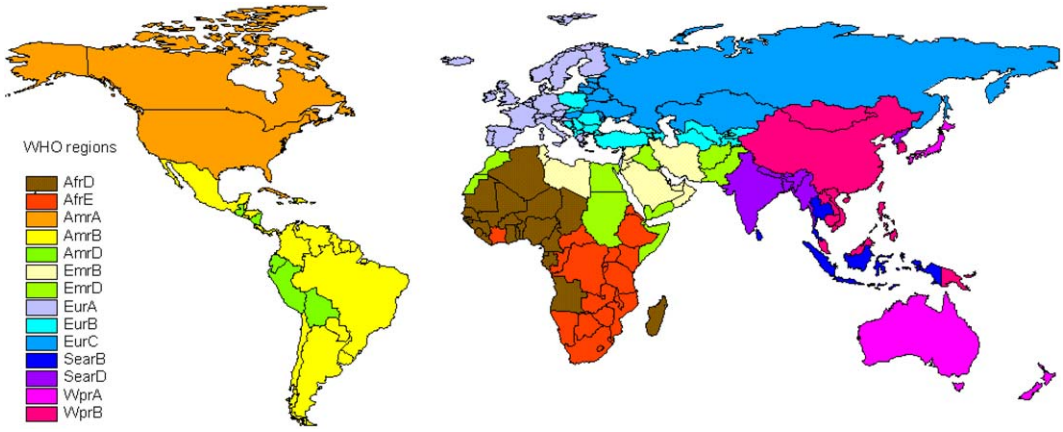


Fig. 2. WHO regions.

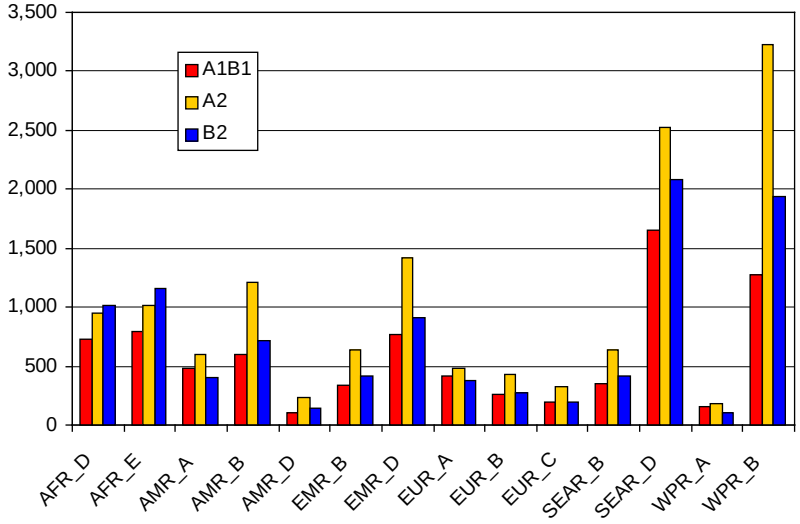


Fig. 3. Population (millions) by region in 2080s for each scenario.

3. Results

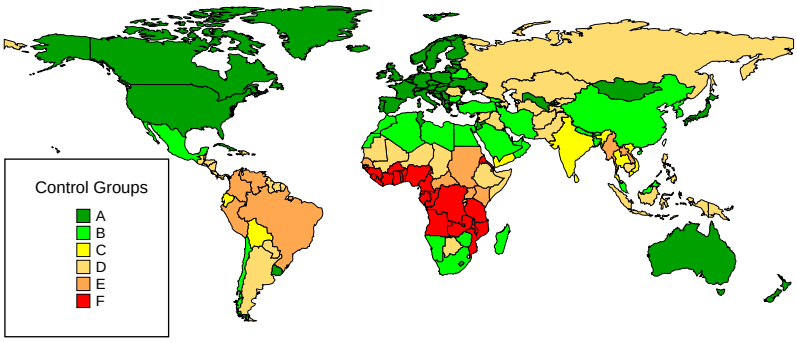
3.1. Global assessment

Estimates of the additional population at risk >1 month by 2080s range from more than 220 million (A1FI) to over 400 million (A2) when climate factors and population growth are included in the model. Fig. 5 shows the global additional population at risk in areas where the climate is suitable for at least three consecutive months. The vast majority of additional population at risk occurs where the potential transmission season has increased from 0 to 1 or 2 months per year (i.e. expansion of the yellow zones into currently "no-risk areas" in Fig. 6). These areas may potentially be at risk of unstable malaria, but even with climate change, the absolute risk as defined by TP remains low. The global estimates are severely reduced if transmission risk for more than 3 consecutive months per year is considered. A net reduction in the global population at risk is projected under the A2 and B1 scenarios. The greatest negative impact, i.e. in particular due to an increase of the number of consecutive months from less than 3 to more than 3, occurs under A1FI (100 million additional people at risk).

The MIASMA model estimates the population at risk of malaria under the current climate to be 3.1 billion (60% of total current population). The model estimates that the population at risk in the medium and high risk regions (groups C–F) to be in the region of 40% of the world's population. This approximates to the estimate of WHO of people living in countries with sustained malaria transmission (Fig. 1).

3.2. Regional assessment

Vulnerability to malaria varies between regions. The largest current population at risk is in Asia. The burden of disease, however, is concentrated in sub-Saharan Africa in areas of endemic transmission. Three out of



	Original endemicity	Malaria control status	Vulnerability
A	Low or malaria free	Malaria free	Countries where malaria transmission does not occur or sporadically occurs after importation. Included in this list are countries where malaria has never existed, has disappeared over time without human intervention and where there is active control to maintain eradication.
B	Low	Good	Countries with strong health systems and effective malaria control where there is low malaria endemicity. It is likely that these countries will cope with any increases in malaria that changes in climate may cause.
C	High	Good	Countries where malaria transmission is high and there are effective and well-funded control programmes in place. There is likely to be a relatively strong health care system where malaria control is a priority. In countries where the health care system is weaker large amounts of foreign aid will allow for effective malaria control.
D	Low	Poor	Countries where malaria remains at a low level despite poor control efforts. The health structure is likely to be poor or moderate and there is very little funding for malaria control programmes. Countries may previously have had effective control programmes, which have declined in recent years. These countries may be migrating towards high malaria status. It is unlikely that these countries will have the structural or economic capacity to cope with any increases in malaria that climate change will bring.
E	High	Poor	Countries where malaria transmission is high and control programmes are ineffective, under funded or are in the process of breaking down. The health system may be damaged through chronic underfunding of services, war or natural disaster. These countries are unable to deal with their current malaria situation and any climate-induced increases in malaria would further burden a weak healthcare system.
F	Very high	Poor	Highly efficient vectors, poor malaria control, and a weak and limited health structure create an environment where malaria is probably one of the leading causes of death in these countries. Climate change may have little impact upon the malaria situation in these countries due to its current intensity and year round transmission, except in highland areas that are current malaria free.

Fig. 4. Countries classified according to current malaria control status.

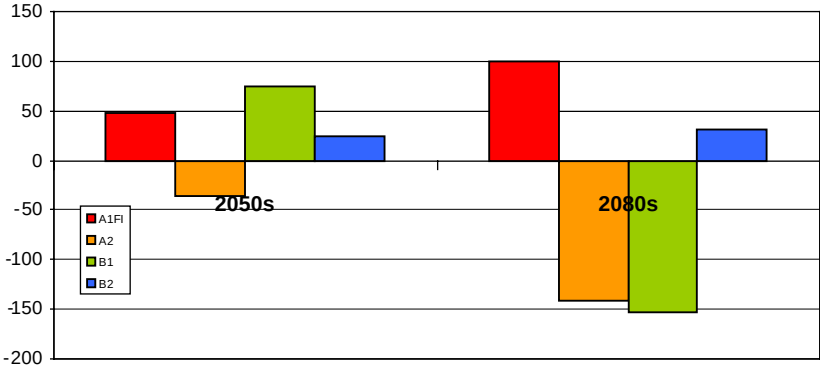


Fig. 5. Global additional population at risk (millions) > 3 consecutive months due to climate change, incorporating projections of population growth by the 2050s and 2080s, compared to current climate conditions.

the fifty countries in the WHO European Region are currently endemic for malaria: Azerbaijan, Tajikistan and Turkey. Table 2 shows additional populations at risk of the countries in each WHO Global Burden of Disease region (whereby countries are grouped according to geographical location and similar patterns of

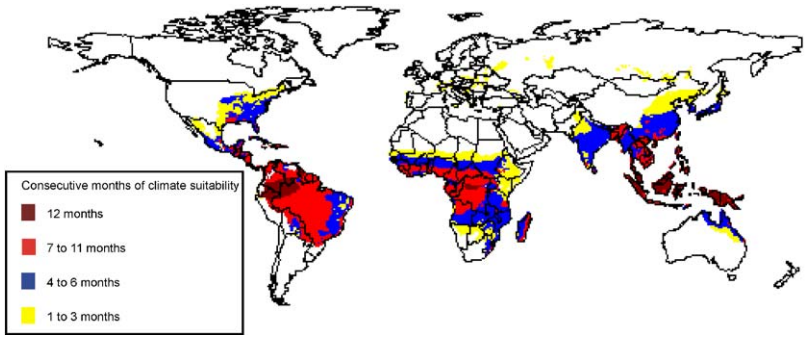


Fig. 6. Modelled seasonal transmission under baseline climate (observed 1961–1991).

Table 2
Additional population at risk of malaria by WHO region by 2080s (millions)

	A1FI		A2		B1		B2	
	>3	>1	>3	>1	>3	>1	>3	>1
West Africa AFR_D	−46	−13	−35	−11	−25	−1	−8	−2
Sub-Saharan Africa AFR_E	49	44	53	56	21	38	51	67
North America AMR_A	−15	9	−46	33	−9	15	11	13
Latin America AMR_B	−92	−21	−169	−40	−29	16	−49	14
W. South America AMR_D	−19	−5	−42	−7	−12	2	−17	1
West Asia EMR_B	0	39	0	62	0	34	0	20
West Asia EMR_D	23	140	16	237	−2	100	62	139
Western Europe EUR_A	−1	7	−1	22	−1	4	0	33
Central Europe EUR_B	−1	19	−1	33	−1	25	−1	15
Eastern Europe and CIS EUR_C	1	−12	1	−13	1	−2	1	−14
South East Asia SEAR_B	0	0	−1	0	0	0	0	0
South Asia SEAR_D	102	7	−77	13	−104	6	−35	9
Australasia WPR_A	17	1	17	1	13	1	9	1
East Asia WPR_B	82	12	143	29	−6	11	7	12
World	100	227	−141	416	−153	250	31	307

mortality). The regions are illustrated in Fig. 2. The greatest increases in the population at risk for less than 3 months occurs under scenario A2. The greatest additional populations at risk are in the following regions:

- Afr E region which includes East Africa and Southern Africa.
- Emr D which includes Pakistan and Afghanistan.
- Wpr B which includes China.

Net reductions in the population at risk are primarily attributable to decreases in precipitation in the climate scenarios. These locations vary between climate scenarios although most scenarios indicate reduced transmission in tropical South America, Central America, Pakistan, north-west India, and around desert regions. Mosquito species vary in their dependency of precipitation in relation to the availability of breeding sites. To illuminate the sensitivity of the modelled additional population at risk for the used threshold, the model was also been run without the conditional statement for precipitation for South America. Comparison of Tables 2 and 3 illustrates to what degree the projected decrease of additional population at risk in South America is due to the chosen threshold for average monthly precipitation of 80 mm.

Table 3
Estimated increases in populations at risk due to temperature change alone (no threshold for precipitation) for three regions in America

Regions	A1F1 2050	A2 2050	A1FI 2080	A2 2080
>1 month				
AMR_A	6	7	7	9
AMR_B	34	51	39	78
AMR_D	2	3	2	4
>3 months				
AMR_A	86	91	106	129
AMR_B	54	73	53	112
AMR_D	2	3	2	4

An important finding in this assessment is that some additional population at risk due to climate change is now indicated in Africa. The higher resolution climate grid is able to describe regions that the model shows as unsuitable for malaria under the observed climate and that become suitable with climate change. A continental

model of malaria in Africa (the validated MARA model) also shows malaria transmission limited in East Africa under the current climate (MARA, 1998). A combination of the resolution of the data and methodology used precluded the accurate delimitation of the highland regions. Highland malaria is defined as malaria that occurs around the altitudinal limits of its distribution, and is, by definition, unstable (epidemic). Previous assessment have indicated that small changes in the distribution of malaria may expose large numbers of people to infection as the East African highlands are densely populated (Cox et al., 2002; Lindsay and Martens, 1998).

3.3. Vulnerability assessment

Additional populations at risk were grouped according to the vulnerability classes under the range of scenarios (Table 4). The vast majority of additional population at risk is projected in group D (see Fig. 4 for countries). It is reasonable to assume that malaria in group D countries is currently restricted by climate factors in specific arid and highland regions. The ability of Group D countries to manage any climate-induced increase in malaria will depend on their capacity to develop and sustain malaria control programmes.

A net decrease in populations at risk due to climate change is indicated in Group E countries, where climates, in general, are already favourable for transmission. Climate scenarios indicate on average less suitable climate conditions in these countries leading to net reductions in the potential transmission zone.

The poorest countries are within Group F. Net reductions in population at risk is also projected within this group if > 3 months transmission is considered. Climate change may have little impact upon the malaria situation in these countries due to its current intensity and year round transmission. The current climate is already extremely favourable for transmission. However, it is important to disaggregate the risk within this group, as an increase in risk is projected for some countries with extensive highland areas (e.g. Kenya and Ethiopia) (see Fig. 7).

For those countries that currently have a limited capacity to control the disease (groups D–F), the model estimates an additional population at risk (> 1 month) of between 90 (A1FI) to over 200 (B2b) million by the 2080s. The ensemble members provide a range of estimates for A2 and B2. Fig. 7 illustrates the regions where net additional population at risk increases and decreases for countries with good and poor adaptive capacity. The maps indicate a ''northward'' extension of the areas with suitable climate conditions for transmission. Regions in South East Asia (''green'' areas) are indicated to be vulnerable for changes in socio-economic conditions with respect to malaria.

Table 4
Additional population at risk by control group, by 2080s, compared to reference scenario (millions)

	Adaptive capacity	A1FI	A2	*A2a*	*A2b*	*A2c*	B1	B2	*B2a*	*B2a*
Grids with > 3 month transmission										
		A1FI	A2	A2a	A2b	A2c	B1	B2	B2a	B2b
A	Good	0	−34	−24	−12	−66	3	19	14	24
B	Good	86	148	39	165	240	−13	−10	−32	11
C	Good	97	−87	−363	−31	132	−106	−39	−232	153
D	Poor	28	24	25	15	32	30	138	113	162
E	Poor	−82	−162	−162	−159	−166	−58	−73	−88	−58
F	Poor	−27	−30	−44	−30	−16	−8	−3	−10	4
World		*100*	*−141*	*−528*	*−52*	*156*	*−153*	*31*	*−236*	*297*
Grids with > 1 month transmission										
A	Good	24	82	*74*	*84*	*88*	43	59	*56*	*62*
B	Good	63	105	*95*	*112*	*109*	52	35	*35*	*35*
C	Good	46	100	*121*	*64*	*114*	23	35	*36*	*35*
D	Poor	114	175	*160*	*192*	*174*	124	167	*143*	*190*
E	Poor	−37	−67	*−56*	*−56*	*−88*	−6	−10	*−24*	*3*
F	Poor	16	21	20	21	21	14	21	*20*	*22*
World		227	416	*414*	*416*	*418*	250	307	266	347

4. Discussion

Climate-induced changes in the potential distribution of malaria are projected in developing countries that currently lack strong or sustained malaria control programmes. As with other assessments in this volume, population growth is a more important driver in the projection of absolute numbers of future populations at risk than changes in climate.

This assessment has important similarities with the assessment of populations at risk of coastal flooding (Nicholls, 2003). Health impacts are confined to specific locations and, therefore, the model is sensitive to the spatial distribution of population growth and changes in temperature and precipitation changes. The range of estimates for the ensemble members for A2 and B2 is significant. The range of the population at risk > 3 months varies from −500 million to plus 150 million for A2 scenarios and −200 million to plus 300 million for B2 scenarios. The results of the MIASMA model should be interpreted in the light of uncertainties related to climate change and the model parameters. An important advantage of the current assessment is that it separates out the climate and socio-economic effects in a relatively transparent approach.

4.1. Caveats

There is a lack of information on role of precipitation in the transmission of malaria. The threshold estimate used in the model is derived from studies of endemic transmission in Africa. This threshold may

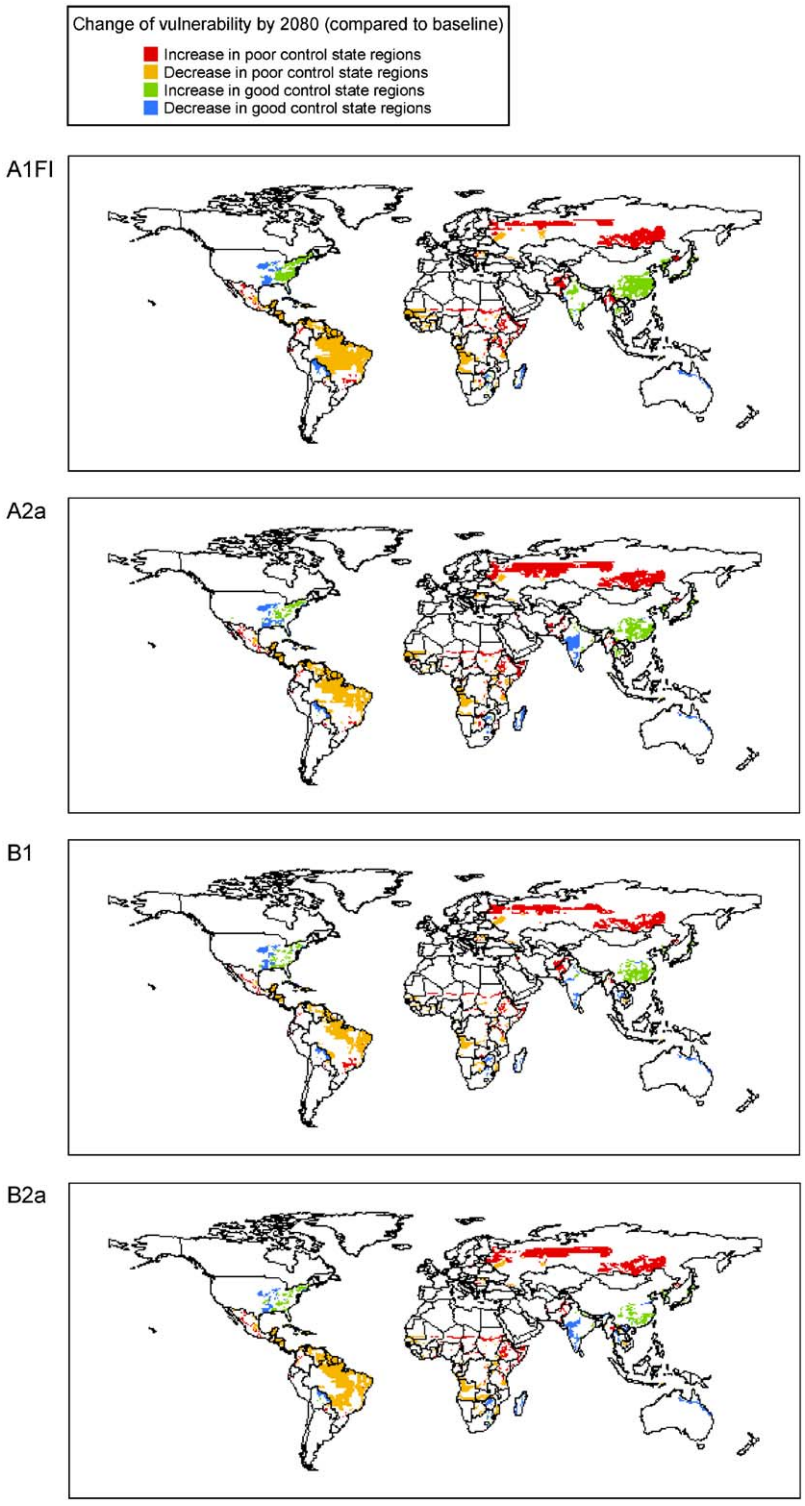


Fig. 7. Additional population at risk by 2080s under the four SRES climate scenarios.

not be optimal to transmission in areas outside of Africa. Further, climate model projections for precipitation are more variable and less robust adding further uncertainty.

Population growth is an important factor for malaria and this model is very sensitive to projections of population growth. Further, confidence in population projections beyond 2025 and when downscaled to national levels is low. Without significant improvements in health care provision, malaria will become harder to treat and control simply because the susceptible reservoir of humans has expanded. Other trends such

as economic growth and urbanisation will tend to decrease population vulnerability to malaria. The estimates of additional population at risk are primarily forced by the estimates of population projections in "new" risk areas. The reduction in malaria risk with urban areas is well known (Lines et al., 1994). Increases in population may be largely confined to urban areas, for Africa and other regions. Therefore, this assessment may overestimate the additional population at risk.

4.2. Global assessments of climate change and malaria

Most modelling of the effects of climate change has focused on malaria (Martin and Lefebvre, 1995; Matsuoka and Kai, 1994; Rogers and Randolph, 2000). A recent paper has estimated the potential impact on the global distribution of dengue (Hales et al., 2002), but the potential impact of climate change on other vector-borne diseases have been neglected due the lack of appropriate models and reliable high resolution surveillance data with which to refine and validate them. Several assessments have been published using previous versions of the MIASMA model (Jetten et al., 1996; Martens et al., 1999), however, these are not directly comparable because:

- The threshold temperature for transmission has been changed. An increase in the threshold will reduce the estimates of the population at risk. The minimum mean temperature was increased to 17°C to ensure that the development cycle of the parasite could be finished within a month, the smallest time scale of the assessment.
- Previous assessments had relied in a single assumption of population growth. The SRES have significantly different assumptions regarding population growth to those underlying the IS92a scenario (one of the previous set of emission scenarios from the IPCC).
- The HadCM3 model used in this assessment incorporates the effect of sulphate aerosols and therefore climate forcings are different to those generated with HadCM3 when it was configured for earlier experiments with IS92a emission scenario.

The calibration and validation of global dynamic models is difficult because the underlying systems are never closed (Oreskes et al., 1994). The requisite historical data are not often available with sufficient spatial coverage (Martens, 1998). The use of assumptions and simplifications potentially decrease the quantitative accuracy of the assessment. However, modelling, allows for adequate prioritisation and estimation of risk (Patz and Balbus, 1996). A comparison of the historical map (Fig. 1) of malaria (representative for climate driven malaria) and the modelled seasonal transmission under baseline climatic conditions (Fig. 6) show similar distributions. This was not formally quantified due to the uncertainties around the dynamic natures of the edges of the distribution. Discrepancies between observed and projected malaria transmission potential in Europe are attributed to the assumption of the precipitation threshold.

A global modelling study used a statistical-empirical approach based on the current distribution of malaria (see Fig. 1) (Rogers and Randolph, 2000). Using an IS92a climate scenario, this study estimated no significant net change by 2050 in the portion of world population living in actual malaria-transmission zones, in particular suitable for *P. falciparum*. This statistical model does not explicitly take into account socio-economic effects, so that it implicitly assumes that climate is the only determinant of the distribution of malaria. The baseline map of current (1997) malaria distribution does not represent the distribution of the disease due to climate factors, but a complex of confounding factors (see above). Therefore, unlike the current assessment, it does not separate out the separate effects of climate and socio-economic factors.

In the previous assessment, the HadCM2 scenarios, the model estimated the number of additional people at risk in 2080 to range from 270 to 330 million for *P. falciparum*, based on a single population projection (similar to B2) (Martens et al., 1999). This additional population at risk includes populations in countries with high, medium and low capacity to control malaria.

4.3. Describing vulnerability

There is very little explicit discussion of health in the SRES documentation and there have been few attempts to interpret the SRES storylines specifically for health impacts. Scenarios for health, or the main determinants of health, have been developed for other projects (Martens, 2002; Martens and Hilderink, 2001). A further step is to consider the SRES storylines with respect to each of the groups (A–F), and in what way, and to what extent socio-economic changes affect membership of a group for a specific country. This can be done qualitatively using the available SRES documentation. A major concern for health is equity in access to health services, and equity in income distributions both within and between countries. Income distribution within countries can be assumed to stay on same as current trajectory within each SRES scenario. None of the four SRES storylines assume an extrapolation of current trends, and all show optimistic economic growth scenarios, however, it is likely that significant inequities both within and between countries will remain in future.

This study estimates future populations at risk for four sets of scenarios of climate change and population growth. The SRES scenarios only represent a limited

range of in particular socio-economic future worlds, which in turn affect future adaptive capacity. The economic scenarios do not take into account the fact that GDP growth is restricted in those low-income countries with a high burden of disease. Failure to do so is likely to bias upward the projections of economic growth.

5. Conclusions

Climate change will cause both increases and decreases in the areas suitable for transmission. The most important region for climate-related impacts on malaria is likely to be Africa and Asia. This assessment shows that climate change will expand the "potential" transmission zone in developing countries. However, climate change is not likely to affect malaria transmission in the Least Developed countries where the climate is already highly favourable for transmission. Many factors will determine the time at which individual countries achieve the capacity to control the disease. These will need to be addressed in future assessments of the potential impact of climate change on global malaria.

In addition, further research is needed to:

- Develop quantitative indicators of vulnerability to malaria and other infectious disease outcomes.
- To improve the parameterisation of rainfall in malaria models.
- Further research on modelling malaria should primarily be undertaken at regional or national scales with validated models, to identify more accurately those populations most at risk, based on regional environmental and socio-economic changes.

Elaborating these questions should enable the research community to more accurately address future vulnerability of populations living in high-risk areas, both from environmental and from a socio-economic point of view.

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