CLIMATE SUITABILITY FOR STABLE MALARIA TRANSMISSION IN ZIMBABWE UNDER DIFFERENT CLIMATE CHANGE SCENARIOS

KRISTIE L. EBI[1], JESSICA HARTMAN[2], NATHAN CHAN[3], JOHN McCONNELL[4], MICHAEL SCHLESINGER[5] and JOHN WEYANT[6]

[1]*Exponent, Inc., 1800 Diagonal Road, Suite 300, Alexandria, VA 22314, U.S.A.*
E-mail: kebi@exponent.com
[2]*442 Amsterdam Avenue, Apartment 4-C, New York, NY 10024, U.S.A.*
[3]*Exponent, Inc., 149 Commonwealth Drive, Menlo Park, CA 94025, U.S.A.*
[4]*Department of Emergency Medicine, Oregon Health & Science University, 3181 SW Sam Jackson Park Road, Mail Code CR114, Portland, OR 97239, U.S.A.*
[5]*University of Illinois at Urbana-Champaign, 105 S. Gregory Street, Urbana, IL 61801, U.S.A.*
[6]*Stanford University, Stanford, CA 94305-4023, U.S.A.*

Abstract. Climate is one factor that determines the potential range of malaria. As such, climate change may work with or against efforts to bring malaria under control. We developed a model of future climate suitability for stable *Plasmodium falciparum* malaria transmission in Zimbabwe. Current climate suitability for stable malaria transmission was based on the MARA/ARMA model of climatic constraints on the survival and development of the *Anopheles* vector and the *Plasmodium falciparum* malaria parasite. We explored potential future geographic distributions of malaria using 16 projections of climate in 2100. The results suggest that, assuming no future human-imposed constraints on malaria transmission, changes in temperature and precipitation could alter the geographic distribution of malaria in Zimbabwe, with previously unsuitable areas of dense human population becoming suitable for transmission. Among all scenarios, the highlands become more suitable for transmission, while the lowveld and areas with low precipitation show varying degrees of change, depending on climate sensitivity and greenhouse gas emission stabilization scenarios, and depending on the general circulation model used. The methods employed can be used within or across other African countries.

1. Introduction

Malaria continues to significantly affect African health, society and economy. The World Health Organization estimated that in 2001, 963,000 of the 1,124,000 deaths due to malaria occurred in Africa (85.7%), and that of the 357,884,000 Disability Adjusted Life Years Lost in Africa in that year, about 10% were due to malaria (WHO, 2002). In sub-Saharan Africa, malaria remains the most common parasitic disease and is the main cause of morbidity and mortality among children less than five years of age and among pregnant women (Freeman, 1995; Blair Research Institute, 1996). Roughly 75% of the deaths from the direct effects of malaria occur in children (Snow et al., 1999). This estimate could double if the indirect effects of malaria (including malaria-related anemia, hypoglycemia, respiratory distress and low birth weight) are included when defining the burden of malaria (Breman, 2001).

Climatic Change (2005) 73: 375–393
DOI: 10.1007/s10584-005-6875-2

In 1998, it was estimated that approximately 8% of all deaths in Zimbabwe and 12% of all outpatient cases were attributed to malaria (Malaria Foundation International, 2004). Approximately 987,500 children under the age of five and approximately 219,000 pregnant women were at risk of malaria. Overall, about 45–50% of the population of Zimbabwe is at risk for malaria (Freeman, 1995; www.malaria.org/zw/countries/zimbabwe.htm).

There has been a global resurgence of malaria over the past two decades. Reasons suggested include failure of malaria control programs, population redistribution and growth, changes in land use, increasing prevalence of drug and pesticide resistance, degradation of public health infrastructure, and climate variability and change (Githeko and Ndegwa, 2001; Greenwood and Mutabingwa, 2002). Climate change may work against future efforts to bring malaria under control. For example, a recent model suggests that increasing temperatures could create environmental conditions that would allow a net increase in the geographic range of areas climatically hospitable for malaria vectors (Martens et al., 1999). With evidence suggesting that anthropogenic alteration of the climate system has already begun, understanding the range of possible impacts of projected climatic changes on future efforts to control malaria is imperative, particularly on national and sub-national scales (Albritton and Meira Filho, 2001).

While climate is an important driver of malaria, it is not the only one. The many determinants of malaria rarely act in isolation; these determinants form a web of interconnected influences, often with positive feedbacks between malaria transmission and other drivers (Janssen and Martens, 1997; Chan et al., 1999; Lindsay and Martens, 1998). Determinants of malaria can be divided into climatic and non-climatic drivers. The non-climatic socioeconomic and biological drivers that have a direct impact on malaria include drug and pesticide resistance, deterioration of health care, deterioration of public health infrastructure (including vector control efforts), demographic change, and changes in land use patterns. For example, unpublished data from western Kenya show that land use changes can alter the local microclimate in ways that affect vector development, such as deforestation (increased local temperatures by 1–2 °C) and cultivation of swamps in the highlands (increased water temperatures by as much as 3 °C, which decreased mosquito larval developmental time and thus increased the number of adults emerging in a given period) (Githeko, personal communication). We focused solely on climate in this model; future models will include qualitative or quantitative representations of non-climatic drivers of malaria and their interactions.

Climate and anomalous weather events have a direct influence on malaria transmission by either hindering or enhancing vector and parasite development and survival. Numerous laboratory and field studies have documented the influence of precipitation and temperature, which can be summarized as:

- Climate is a primary determinant of whether the conditions in a particular location are suitable for stable *Plasmodium falciparum* malaria transmission (Craig et al., 1999; MARA/ARMA, 1998).
- A change in temperature may lengthen or shorten the season during which mosquitoes or parasites can survive.
- Changes in precipitation or temperature may result in conditions during the season of transmission that are conducive to increased or decreased parasite and vector populations.
- Small changes in precipitation or temperature may cause previously inhospitable altitudes or ecosystems to become conducive to transmission by rendering hospitable higher altitudes that were formerly too cold or desert fringes that previously were too dry for mosquito populations to develop.

The impact of various climate change scenarios on the spatial distribution of climate suitable for stable *Plasmodium falciparum* malaria transmission was investigated for Zimbabwe because of its heterogeneity of climatic suitability (see Appendix for a discussion of the epidemiology of malaria in Zimbabwe). Specifically, there are areas in Zimbabwe where the climate is suitable for endemic malaria transmission, areas where transmission is absent, and areas where the climate is occasionally suitable, resulting in epidemics.

Zimbabwe lies at the southern distribution limit of malaria in Africa (Taylor and Mutambu, 1986). A central watershed lying above 1,200 m that runs from northeast to southwest divides Zimbabwe. Rivers arising from this watershed drain into the Zambezi system in the north and the Sabi-Limpopo systems in the south. Low-lying areas where malaria transmission normally occurs flank the central plateau. The central plateau rises to peaks as high as 2,592 m along the border with Mozambique. The middle and lowveld regions descend from the central plateau to an elevation of 162 m at the lowest point in the country (Figure 1). Annual mean temperatures correspond to the elevation gradient and range from 12 °C to greater than 25 °C (Figure 2).

The climate of Zimbabwe can be broadly divided into three seasons: the cool dry season (April–July); the hot dry season (August–October); and the hot wet season (November–March). Typically, precipitation ranges from less than 400 mm during the average rainy season in the southern lowveld region to upwards of 800 mm in the highveld regions near the capital, Harare, and in the eastern highlands (Figure 3).

Zimbabwe experienced a warming and drying trend over the past 100 years that overshadowed the normal strong decadal and interannual variability. The instrumental surface air temperature suggests an increase of up to 0.8 °C in some parts of Zimbabwe, with the winter months (June–November) showing a slightly larger warming than the summer months (December–May) (Hulme et al., 2001; Unganai, 1996). This warming trend was accompanied by a 10% reduction in rainy season precipitation.

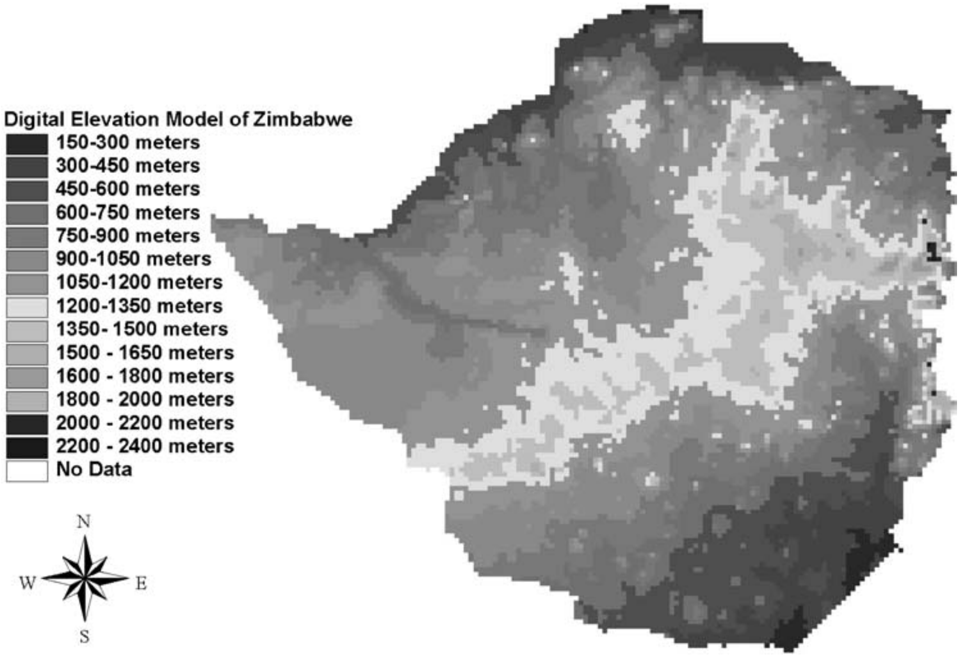

Figure 1. Elevation (Zimbabwe).

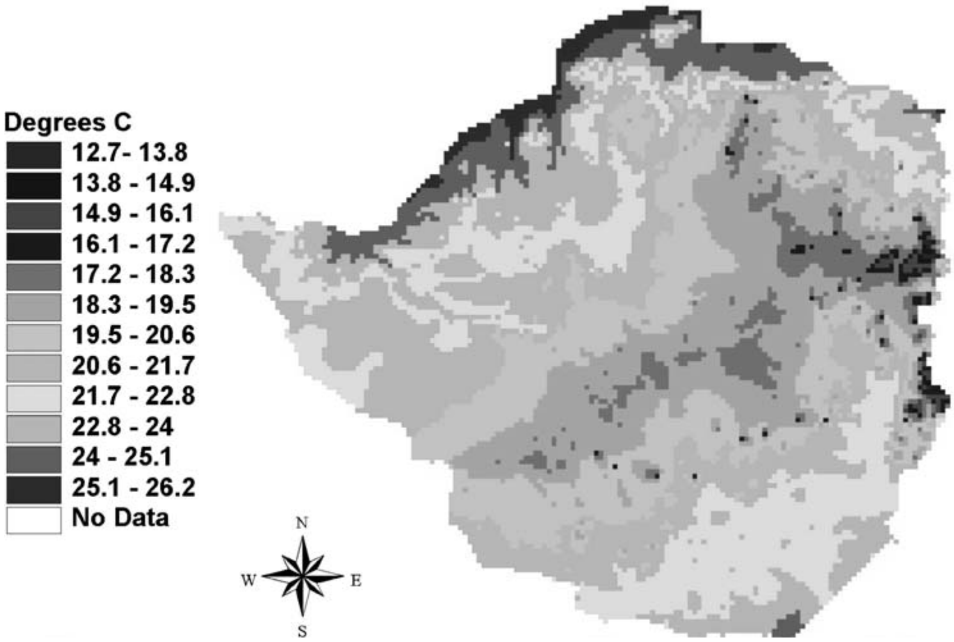

Figure 2. Annual mean temperature 1920–1980 (Zimbabwe).

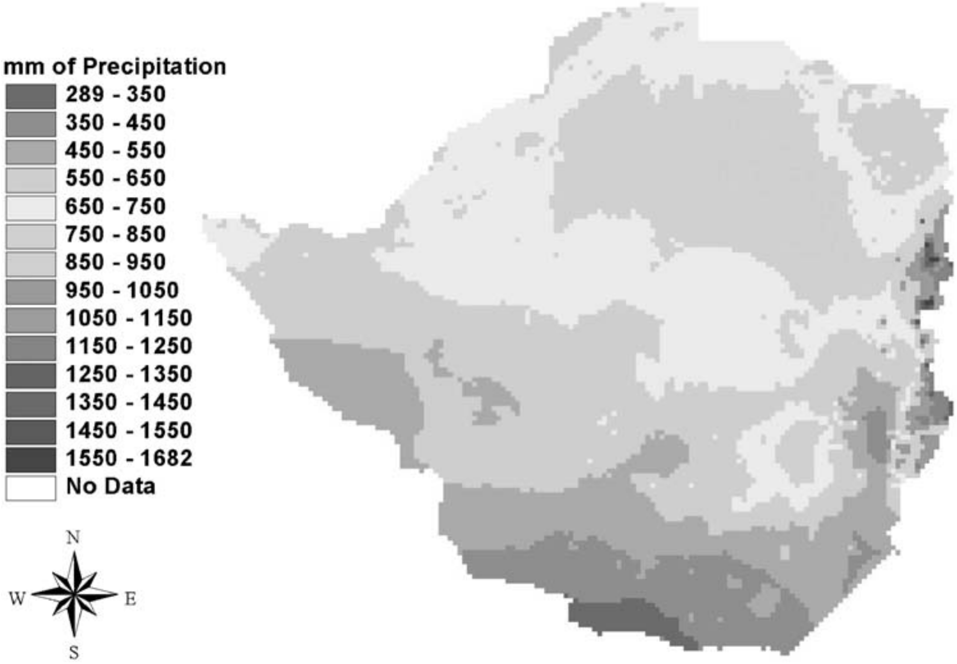

Figure 3. Annual total precipitation 1920–1980 (Zimbabwe).

The benefit of using a country with multiple levels of climatic suitability is that, for each scenario of climate change, we can observe the range of projected levels of suitability and identify key areas that appear most vulnerable.

2. Methods

We utilized the COSMIC program (Schlesinger and Williams, 1997) to generate Zimbabwe-specific scenarios of climate change that were then used as inputs for a model of climate suitability for stable *Plasmodium falciparum* malaria transmission to generate maps of future transmission potential. Our model was based on the MARA/ARMA (Mapping Malaria Risk in Africa/Atlas du Risque de la Malaria en Afrique) decision rules and developed using the ArcView 3.2 Geographic Information System (ESRI, Richlands, CA).

2.1. CLIMATE SUITABILITY FOR STABLE MALARIA TRANSMISSION

Achievements of the MARA/ARMA project include mapping and modeling the baseline distribution of malaria in sub-Saharan Africa. The MARA/ARMA climatic suitability model for malaria transmission is a biological model based on the minimum and mean temperature constraints on the development of the

Plasmodium falciparum parasite and the *Anopheles* vector, and on the precipitation constraints on the survival and breeding capacity of the mosquito. MARA/ARMA determined the decision rules by reviewing laboratory and field studies throughout Africa and by evaluating current malaria distribution maps (Craig et al., 1999; MARA/ARMA, 1998). The maps created using the MARA/ARMA model approximate the edge of malaria distribution across Zimbabwe and the African continent quite well (Craig et al., 1999). It is important to note that the MARA/ARMA decision rules do not project transmission intensity, nor do they project the number of resulting malaria cases.

MARA/ARMA uses three variables to determine climatic suitability for a particular geographic location: mean monthly temperature, winter minimum temperature, and total cumulative monthly precipitation. An important distinction between this model and others is that the MARA/ARMA decision rules were developed using fuzzy logic to resolve the uncertainty in defining distinct boundaries to divide malarious from non-malarious regions. Rather than using a Boolean designation of climatically suitable or not, an area can be assigned a fuzzy logic suitability value ranging from zero (not suitable) to one (suitable). A value of one means that malaria transmission is most likely stable. A value of zero means that transmission is very unstable, with malaria either absent or with rare epidemics. Values between zero and one (0.1–0.9) represent a gradient from unstable to increasingly stable transmission. For all variables, assignment of fuzzy logic values between zero and one were based on a sigmoid curve, as shown in Figure 4. Utilizing fuzzy logic over Boolean sets allows for a more fluid spatial and temporal definition of the geographic extent of malaria transmission.

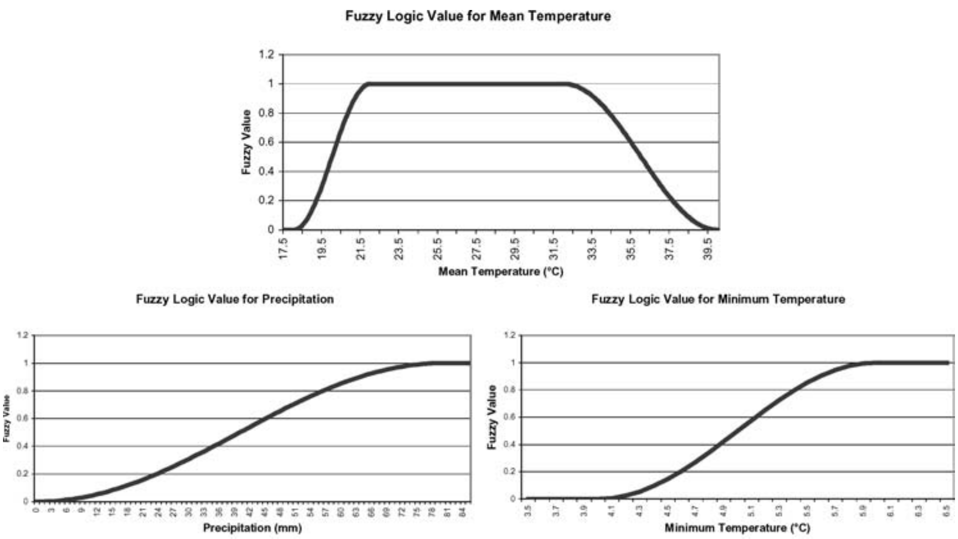

Figure 4. Assignment of fuzzy logic values to climate variables.

Temperature is a major factor determining the distribution and incidence of malaria. Temperature affects both the *Plasmodium* parasite and the *Anopheles* mosquito, with thresholds at both temperature extremes limiting the survival or development of the two organisms (Craig et al., 1999; MARA/ARMA, 1998). *Anopheles* must live long enough to bite an infected person, allow the parasite to develop and then bite a susceptible human. The lower temperature threshold of 18 °C is based on the time required for parasite development and length of mosquito survivorship at that temperature; below 18 °C few parasites can complete development within the lifetime of the mosquito. The mosquito survivorship rate peaks at 31 °C. At this point, less than 40% of the mosquitoes survive long enough for the parasite to complete its development cycle. As temperatures rise above 32 °C, the mosquito's probability of survival decreases. However, higher temperatures enable the mosquitoes to digest blood meals more rapidly, which in turn increases the rate at which they bite. This increased biting rate coupled with faster development of the parasite leads to increased infective mosquito bites for those mosquitoes that do survive (Craig et al., 1999; MARA/ARMA, 1998). The upper temperature threshold for both mosquitoes and larvae to survive is 40 °C.

Based on these biological constraints on the vector and parasite, MARA/ARMA designated the following rules for assigning fuzzy logic values to mean temperature:

- The fuzzy logic value increased from zero at ≤18 °C to one at 22 °C;
- 22–32 °C was considered 100% suitable for stable transmission (a value of one was assigned); and
- Fuzzy logic values decreased from one at >32 °C to zero at 40 °C.

The second climate variable was winter minimum temperature. Ground frost (ambient temperatures of 4–5 °C) kills mosquito populations and prevents the persistence of a stable year round mosquito population (Craig et al., 1999; MARA/ARMA, 1998). In the MARA/ARMA decision rules, if minimum temperatures dropped low enough for frost to form during a month, it was assumed that vector populations could not become established. The temperature at which frost occurs was designated as 5 °C, with the lower and upper limits set at 4 °C (fuzzy value of zero) and 6 °C (fuzzy value of one).

Total monthly precipitation was the third climate variable used. Mosquitoes require water for their eggs to develop into larvae and ultimately emerge as winged adults. The MARA/ARMA team examined current precipitation and temperature requirements in areas where the epidemiology of malaria was well understood to define the relationship between precipitation and mosquito survivorship and abundance (Craig et al., 1999; MARA/ARMA, 1998). Based on these examinations, monthly precipitation of at least 80 mm was designated as suitable for stable transmission (fuzzy logic value of one). Where there was no precipitation, a fuzzy value of zero was assigned. Fuzzy values from zero to one were assigned across the continuum of precipitation levels from 0 mm to ≥80 mm.

The MARA/ARMA decision rules further stipulated that both temperature and precipitation have to be favorable at the same time of the year to allow transmission, and suitable conditions have to continue long enough for the transmission cycle to be completed. A five-month period was considered a sufficient length of time for conditions to be suitable for stable transmission. For each grid cell, the most constraining fuzzy logic value was determined using a multi-step process. The fuzzy logic values for mean monthly temperature and precipitation were ascertained for each grid cell for every month in the time series. The lowest precipitation or mean temperature fuzzy value over a moving five-month period was assigned (i.e., January through May, then February through June, etc.). Then the minimum winter temperature value for each five-month period was determined and compared with the fuzzy value assigned for mean temperature and precipitation and the lowest value of the most constraining variable was assigned. This approach produced a conservative climatic suitability value.

2.2. BASELINE CLIMATOLOGY

Baseline climate was derived from a mean monthly climatology in a 0.05° latitude by 0.05° longitude raster format, compiled from data spanning 1920–1980 for all of Africa (Hutchinson et al., 1995). Monthly total precipitation, mean temperature, and the range between minimum and maximum temperatures were extracted. As an average climate representing over 60 years of data, this baseline climatology is not necessarily representative of any given year or even the most recent decade.

2.3. CLIMATE PROJECTIONS

Future climate projections were created in COSMIC, the output of which was the change in mean temperature (°C) and monthly precipitation from 1990 to 2100. These changes in mean temperature and precipitation were added to the baseline climatology for each of the roughly 14,000 grid cells in Zimbabwe to present different scenarios of climate in the year 2100.

To represent a range of possible future climates, we chose 16 climate projections generated from the COSMIC program (Hutchinson et al., 1995; Williams et al., 1998; Mendelsohn et al., 2000) to create Zimbabwe-specific projections of monthly precipitation and mean temperature starting in 1990 and carried out to 2100. COSMIC uses an energy-balance-climate/upwelling-diffusion-ocean model to calculate the change in global mean temperature and precipitation under different radiative forcing scenarios. COSMIC then scales the projected geographic and seasonal climate patterns produced by the general circulation models (GCMs) to individual countries using an intertemporal scaling procedure. The four GCMs chosen were: the Canadian Centre for Climate Research (CCC) (McFarlane et al., 1992), United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell, 1987),

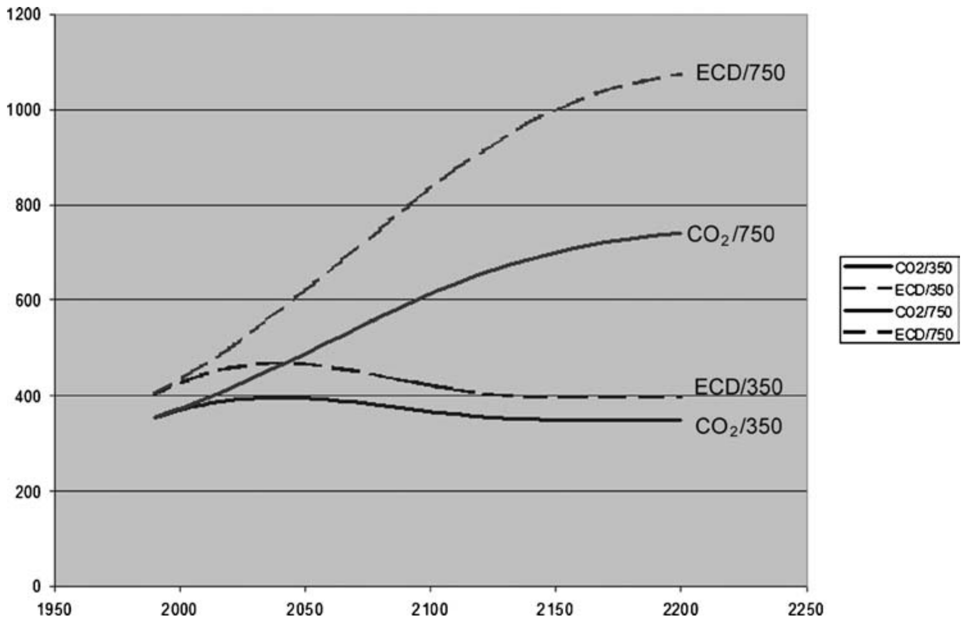

Figure 5. Equivalent carbon dioxide (ECD) and CO_2 emissions under the IPCC 350 and 750 ppmv stabilization scenarios.

Goddard Institute for Space Studies (GISS) (Hansen et al., 1988), and the Henderson-Sellers model using the CCM1 at NCAR (HEND) (Henderson-Sellers et al., 1993). Climate sensitivities of 4.5 °C (high) and 1.4 °C (low) were used, where climate sensitivity is the estimated increase in the global mean surface air temperature after a doubling of atmospheric CO_2 concentrations relative to the atmospheric concentrations before the industrial revolution. Finally, the equivalent CO_2 (ECD) analogues to the 350 and 750 ppmv greenhouse gas emission stabilization scenarios of the IPCC Second Assessment Report were used (ECD concentration is the amount of CO_2 that gives the same radiative forcing as the radiative forcing by all greenhouse gases combined (i.e., CO_2, N_2O, CH_4, and CFCs)). Figure 5 shows the greenhouse gas emission trajectories for the ECD equivalent and the IPCC 350 and 750 ppmv stabilization scenarios in which CO_2 is the sole greenhouse gas. Aerosols were excluded because of the many uncertainties related to modeling their radiative forcing on the climate system.

2.4. CREATING MAPS OF FUTURE CLIMATE SUITABILITY FOR STABLE MALARIA TRANSMISSION IN ZIMBABWE

COSMIC projected the change in monthly mean and minimum temperature and monthly total precipitation for each month from the 1990 baseline year to 2100. These changes on a national level were added to the baseline 0.05° latitude by 0.05°

longitude gridded climatology of Zimbabwe. The MARA/ARMA decision rules were then applied to the future climate scenarios and were used to determine a fuzzy logic climate suitability value for each grid cell.

Three assumptions were made in order to incorporate the climate projection from the GCMs into the climatic suitability model. The first was that the range between minimum and maximum temperatures would not decrease over the next 100 years. While the global trend has suggested a decrease in the diurnal temperature range, with nighttime minimum temperatures rising at double the rate of daytime maximum temperatures, the trend in Zimbabwe has been an increase in the diurnal range due to increases during the rainy season (Unganai, 1996; Hulme et al., 2001). Because of this uncertainty, the range between minimum and maximum temperatures during the baseline period (1920–1980) was kept constant for the climate projections. A second assumption was that permanent water bodies did not change the MARA/ARMA precipitation requirements for a given geographic location. Finally, it was assumed that climate did not change between the baseline and 1990.

3. Results

Figure 6 shows the baseline fuzzy logic climate suitability for stable *Plasmodium falciparum* transmission in Zimbabwe. Areas where malaria is endemic in the average year are denoted with dark coloring (fuzzy value of >0.9). White

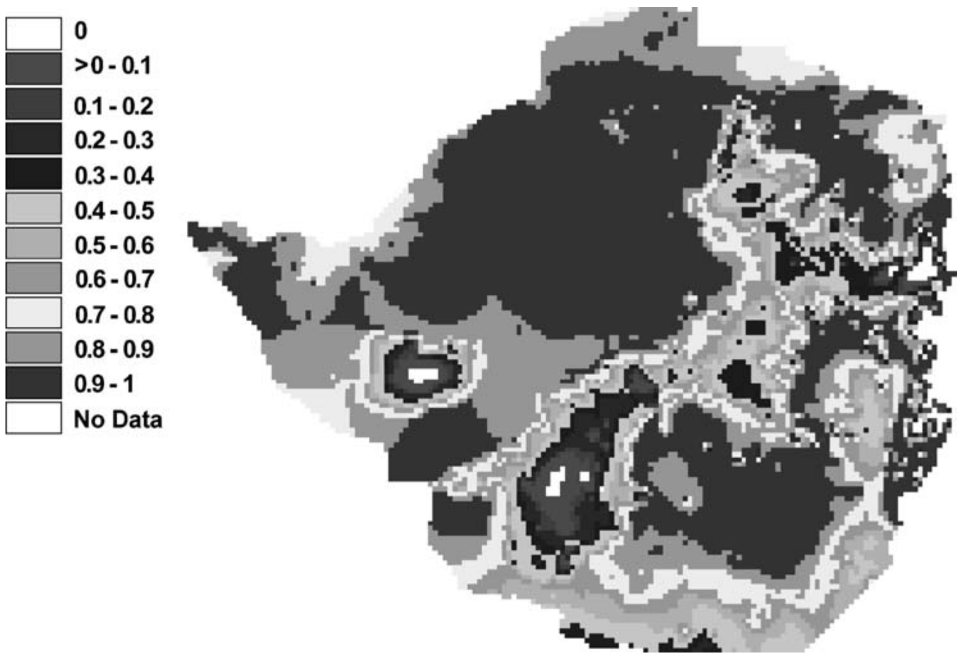

Figure 6. Baseline fuzzy logic climate suitability for stable malaria transmission in Zimbabwe.

indicates locations where climatic conditions inhibit malaria transmission (fuzzy value of zero). For fuzzy logic values between 0.9 and zero, malaria transmission is expected to vary between years, with epidemics or strongly seasonal malaria present. The highland areas are clearly identified by their low fuzzy logic values. This map reasonably reflects current maps of endemic malaria in Zimbabwe (www.malaria.org/zw/countries/zimbabwe.htm).

Figure 7 shows a range of possible future temperatures in the year 2100, from marginal increases in temperature to an increase of 4–5 °C in the HEND 750 ppmv stabilization scenario with a climate sensitivity of 4.5 °C.

Figure 8 shows that projected changes in precipitation differ both in magnitude and direction of change in the year 2100. While all scenarios project an increase in temperature, the GISS and UKMO scenarios project a net increase in precipitation while the HEND and CCC scenarios suggest a net decrease. The HEND 750 ppmv stabilization scenario with a climate sensitivity of 4.5 °C projected the most dramatic variation in precipitation, with an increase of over 30 mm in the spring months (November–January) and a decrease of over 60 mm in the summer (February–April).

Model results are shown in Figure 9 and Table I. In the baseline climate suitability scenario, 40% of Zimbabwe was suitable for stable transmission (fuzzy value >0.9). The magnitude and direction of change varied for the four GCMs, following the direction and amplitude of projected changes in temperature and precipitation. Under the smallest scenario of climate change, with a climate sensitivity of 1.4 °C and a stabilization of greenhouse gases at 350 ppmv, the projected net change was small with a maximum increase of 5% in the area of stable malaria transmission

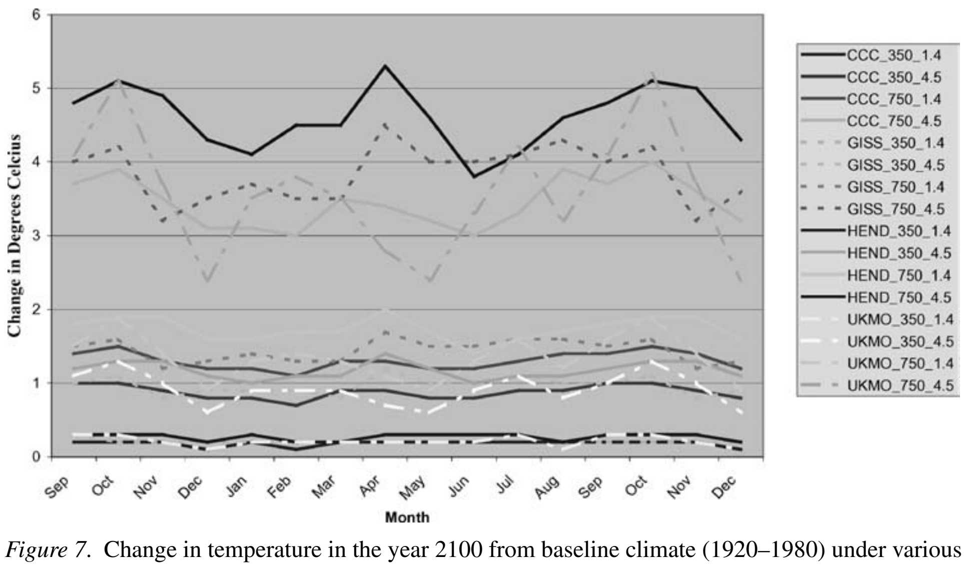

Figure 7. Change in temperature in the year 2100 from baseline climate (1920–1980) under various climate change scenarios in Zimbabwe.

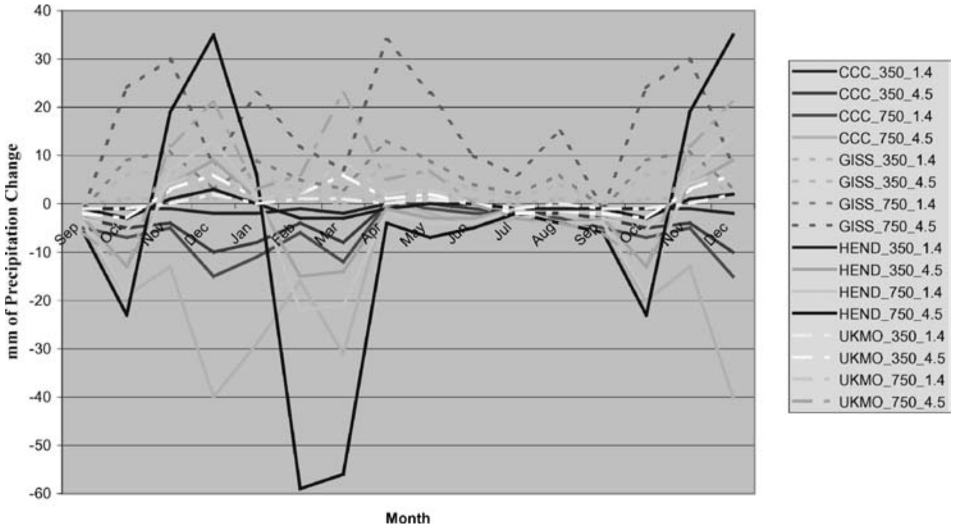

Figure 8. Change in precipitation in the year 2100 from baseline climate (1920–1980) under various climate change scenarios in Zimbabwe.

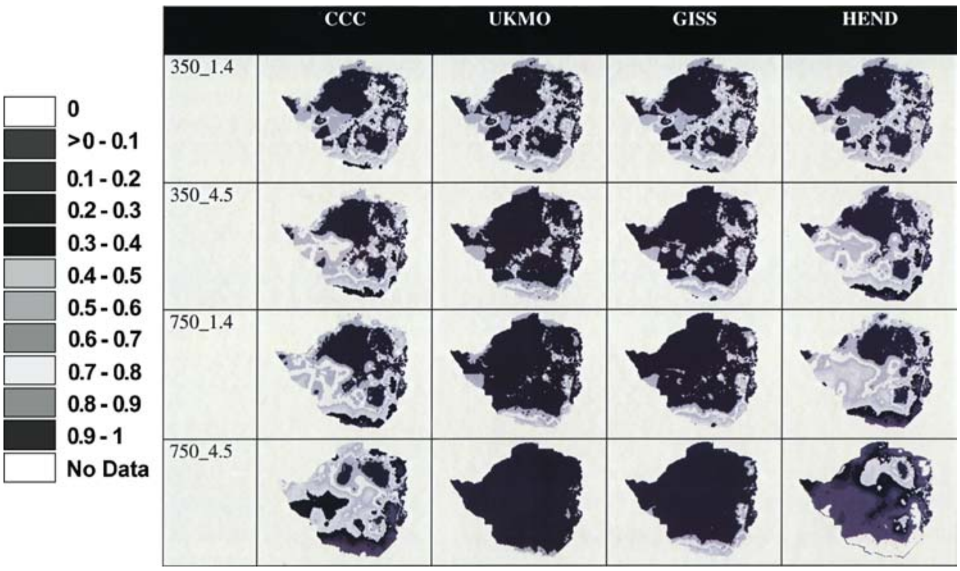

Figure 9. Climate suitability for stable malaria transmission in 2100 under various climate change scenarios in Zimbabwe.

in the UKMO and GISS models and a decrease of 1% in the CCC GCM. Under the highest scenario of climate change, where the climate sensitivity was set at 4.5 °C and the stabilization scenario was equivalent to 750 ppmv, the projected net change varied from the HEND model projecting that only 3% of Zimbabwe

TABLE I
Percent of Zimbabwe with climate suitable for stable malaria transmission

	General circulation model			
Scenario (ppmv/°C)	CCC (%)	UKMO (%)	GISS (%)	HEND (%)
350/1.4	39	45	45	41
350/4.5	37	68	66	34
750/1.4	34	77	76	25
750/4.5	10	96	86	3

Baseline 40%; Fuzzy logic value ≥0.9.

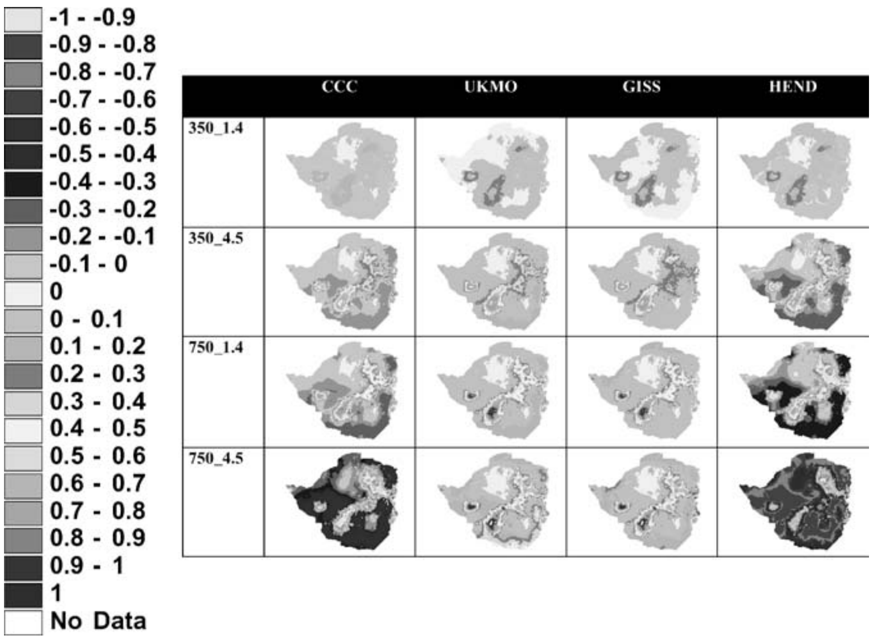

Figure 10. Change in climate suitability for stable malaria transmission in 2100 from baseline climate (1920–1980) in Zimbabwe.

may be suitable for malaria transmission to the UKMO model suggesting that 96% of Zimbabwe may have climate suitable for stable transmission.

As seen in Figure 10, even with little net change in climate suitability, as in the CCC 350_1.4 °C scenario, there is the potential for redistribution of areas that are suitable, with the central plateau becoming more suitable for transmission and the lowveld areas becoming slightly less suitable. The central plateau, where the human population is currently concentrated, potentially becomes more suitable for malaria transmission in all but the HEND 750_4.5 °C scenario. The anomalous change for this scenario can be accounted for by the dramatic decrease in precipitation, particularly in the crucial month of March, rendering all but the highest elevations in Zimbabwe unsuitable for malaria transmission.

4. Discussion

The climate scenarios chosen produce a range of possible climate suitability futures where stable malaria transmission in Zimbabwe might either increase or decrease, depending on climate sensitivity, the greenhouse gas emission stabilization scenario, and the general circulation model used. The results illustrate the importance of not relying on one climate scenario; the potential future geographical distribution of malaria varies depending on which scenario is used, with up to a 56% increase with the UKMO_750_4.5°C scenario. Using a high-resolution climate baseline capable of showing the climatic heterogeneity that exists in Zimbabwe allows the examination of fluctuations in suitability under different scenarios and enables decision makers to identify localized areas vulnerable to climate change.

Despite the wide range in the resulting percent of the area that may become suitable, the predominant pattern across the scenarios suggests that climate suitability for malaria transmission in Zimbabwe is more likely to increase than decrease in the central plateau where the population is currently concentrated. Evaluation of the results by decade (not shown) suggests that most of Zimbabwe could have near-complete climate suitability for stable malaria transmission by 2050 under the scenario showing the greatest change (UKMO_750_4.5 °C). Within this scenario, precipitation and temperature increase linearly and there is no interannual or decadal variability.

Considerable progress has been made in climate modeling since the models included in COSMIC were developed. However, the advantage of COSMIC is that using several models allows exploration of uncertainty around climate projections. The HEND and CCC models produced results different from the UKMO and GISS models. Understanding and narrowing the sources of differences in model results will be valuable to decision makers.

Decision makers also need to understand how quickly climate suitability might change, because rapid climate change might require different mitigation and adaptation options than a gradual change in climate. The uncertainty in the rate and geographic range of change emphasizes the importance of establishing the capacity to monitor changing temperature and precipitation patterns to determine when and where climate suitability for malaria transmission might change, and to establish surveillance programs to determine changes in malaria incidence or intensity along the edges of its established range.

It is important to emphasize that the potential geographic distribution modeled in this study does not directly translate into actual cases of malaria. Areas of the United States and Europe have climates suitable for malaria transmission, yet only a limited number of cases occur (and those are generally imported) because of the strength of the public health infrastructure and other factors (Reiter, 2001). In addition to climatic variables, a number of other factors will influence whether the future geographic distribution of malaria is different from today, including parasite drug resistance, demographic change, changes in land-use patterns, and the success of intervention programs such as Roll Back Malaria (RBM) and the Multilateral Initiative on Malaria (MIM).

A factor of concern over the short-term is increasing parasite drug resistance. Although the current malaria control and prevention measures used in Africa include personal protection, drug use, and vector control strategies, most control is based almost exclusively on chemotherapy (Breman, 2001). Increasing drug resistance has resulted in a two- to three-fold increase in malaria admissions and deaths for severe malaria. This trend is expected to continue over at least the short-term (Trape, 2001).

Demographic changes (e.g., increased human mobility, population growth, and redistribution) affect malaria risk (Greenwood and Mutabingwa, 2002). Population redistribution results from urbanization, labor migration, conflict, and other factors. It allows the transport of both the vector and parasite, often exposing immunologically naïve populations to malaria (Trape et al., 1987). Dramatic climatic changes could create environmental refugees as populations are forced to migrate from areas where resources are few to urban areas or regions where they may have a means of support. Environmental refugees present an enormous opportunity for parasite and vector migration.

Pressures placed on environmental resources, which are often linked to population pressures, can also alter the landscape of malaria transmission. Altered vegetation coverage, surface water flows, and water storage methods as a result of agricultural intensification or population needs may alter the quantity and quality of breeding habitats for mosquitoes and the species composition of the community (Lindblade et al., 2000). In addition, climate change is likely to alter land-use patterns (agricultural use, urban areas, de- or afforestation) and so could potentially influence the mosquito population composition and size, resulting in changes in malaria transmission.

The objective of the Roll Back Malaria partnership is to halve the malaria burden in participating countries by the year 2010 through interventions that are adapted to local needs and by reinforcement of the health sector (Remme et al., 2001). Intensified national action will take place within a framework of country-level partnerships supported by a global partnership, with technical support networks available for assistance. Success of these and other intervention programs, including the development of an effective and inexpensive malaria vaccine, would reduce the burden of malaria both today and in the future.

Other factors that could influence malaria mortality in Africa include civil unrest, deterioration of public health systems, and HIV proliferation (Greenwood and Mutabingwa, 2002).

National expenditures on such public goods as vector control, health care delivery and infrastructure, disease surveillance, public education, and basic malaria research might dominate the future determinants of malaria risk and are typically limited by a country's GDP. Just as a country's GDP influences malaria risk, malaria has been shown to decrease economic growth in severely malarious countries by 1.3% per year (Gallup and Sachs, 2001). The result is that a disease such as malaria creates something of a vicious cycle for poorer countries. Malaria is likely to persist without the creation and maintenance of an appropriate public health infrastructure. However, the economic development necessary for these improvements is directly hindered by the presence of malaria itself. Changes in climate have the potential to make it even more difficult for poor countries to reduce the burden of malaria. A key research goal is to identify which of these many factors are most likely to drive the future distribution of malaria and to include modules for these factors into models such as ours.

A number of research groups have modeled the potential for malaria to spread as a consequence of global climate change (Martens et al., 1999; Rogers and Randolph, 2000; Tanser et al., 2003; van Lieshout et al., 2004). These models include both climate suitability and data on populations at risk, and statistical and biological approaches to modeling. The model results are consistent in that most of the future spread of malaria is projected to occur at the edges of the current geographical distribution where climate constrains transmission, generally because it is too cold for transmission to occur. The model developed by Tanser et al. (2003) used different climate scenarios based on simulations from the Hadley Centre (HadCM2 or HadCM3) and projected increases of more than 100% in person-months of exposure for Zimbabwe towards the end of the 21st century, primarily because of increases in highland malaria. The UKMO scenario used in our model is an older version of these scenarios. Because of the large number of differences among the simulations, it is not possible to directly compare our results, other than to note that we reached similar conclusions.

Our results are also consistent with a model for Zimbabwe developed by Lindsay and Martens that included three scenarios: an increase of 2 °C in monthly temperature; an increase of 2 °C with a 20% increase in precipitation; and an increase of 2 °C with a 20% decrease in precipitation (Lindsay and Martens, 1998). The results showed that the effect of temperature increase would be greatest on malaria transmission potential at higher altitudes. In the relatively drier lower altitudes, a monthly temperature increase of 2 °C combined with a 20% decrease in precipitation resulted in areas becoming too dry for malaria transmission, while a 20% increase in precipitation increased transmission potential. We found a similar variation with changes in temperature and precipitation across the climate scenarios used.

Given spatial information on areas where climate suitability for malaria transmission may change, decision makers can take these possible changes into account when prioritizing actions to enhance the capacity of future generations to effectively handle malaria risk.

Appendix: The Epidemiology of Malaria in Zimbabwe

Despite more than 50 years of vector control, malaria is still a substantial public health threat (Makono and Sibanda, 1999). More than 4 million of Zimbabwe's 12 million inhabitants live in malarious areas. Even with widespread under-reporting and self-treatment, 9,696 deaths and 6.4 million cases of malaria were reported between 1989 and 1996 (Makono and Sibanda, 1999). Three parasites have been identified as causing malaria in Zimbabwe, with *Plasmodium falciparum* responsible for about 97.8% of all cases (Taylor and Mutambu, 1986). *Anopheles arabiensis* is the vector of concern amongst the 38 species of *Anopheline* mosquitoes in Zimbabwe. *Anopheles funestus s.s.* (endophilic), *A. merus* (breeds in salt water), and *A. quadriannulatus* (zoophilic) are also present, yet are not believed to be substantial threats either due to past control efforts or their ecological constraints (Freeman, 1995).

Transmission is highly seasonal with the bulk of cases recorded at the onset of summer and the single rainy season (February and May), with peak transmission typically occurring in March (Taylor and Mutambu, 1986). Some areas of Zimbabwe, particularly the northern and southern lowveld regions, have year round malaria transmission with peaks in the austral summer months. Stable transmission is partially defined by temperature and precipitation, with altitude a proxy indicator of temperature. Zimbabwe has dramatic elevation ranges that correlate with maximum and minimum temperatures. This heterogeneity coupled with interannual climatic variability results in constantly shifting fringe areas that are prone to malaria outbreaks, similar to many countries in southern and eastern Africa (Freeman, 1995). High altitude regions, which are also the areas of densest human population, are currently malaria-free due to climatic constraints and to a long policy of "barrier spraying" in the transitional elevation zone (Freeman and Bradley, 1996).

Acknowledgments

The Electric Power Research Institute (EPRI) supported this work under contracts WO009242 and WO043518. Color versions of the figures are available from the author upon request.

References

Albritton, D. L. and Meira Filho, L. G., Coordinating lead authors: 2001, *Technical Summary. Working Group 1, Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Blair Research Institute: 1996, *1996 Annual Report: Epidemiology of Plasmodium falciparum drug resistance in Zimbabwe*, Blair Research Institute, Harare, Zimbabwe.

Breman, J. G.: 2001, 'The ears of the hippopotamus: Manifestations, determinants and estimates of the malaria burden', *Am. J. Trop. Med. Hygiene* **64**(Suppl 1), 1–11.

Chan, N. Y., Smith, F., Wilson, T. F., Ebi, K. L., and Smith, A. E.: 1999, 'An integrated assessment framework for climate change and infectious diseases', *Environ. Health Perspect.* **107**, 329–337.

Craig, M. H., Snow, R. W., and le Sueur, D: 1999, 'A climate-based distribution model of malaria transmission in sub-Saharan Africa', *Parasitol. Today* **15**, 105–111.

Freeman, T.: 1995, *Malaria: Zimbabwe 1995. A Review of the Epidemiology of Malaria Transmission and Distribution in Zimbabwe and the Relationship of Malaria Outbreaks to Preceding Meteorological Conditions*, Unpublished document, March 1995.

Freeman, T. and Bradley, M.: 1996, 'Temperature is predictive of severe malaria years in Zimbabwe', *Trans. Royal Soc. Trop. Med. Hyg.* **90**, 232.

Gallup, J. and Sachs, J.: 2001, 'The economic burden of malaria', *Am. J. Trop. Med. Hygiene* **64**(Suppl 1), 85–96.

Githeko, A. K. and Ndegwa, W.:2001, 'Predicting malaria epidemics in the Kenyan highlands using climate data: A tool for decision makers', *Global Change Human Health* **2**, 54–63.

Greenwood, B. and Mutabingwa, T.: 2002, 'Malaria in 2002', *Nature* **415**, 670–672.

Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedell, S., Ruedy, R., Russel, G., and Stone, P.: 1988, 'Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model', *J. Geophys. Res.* **93**, 9341–9364.

Henderson-Sellers, A., Dickinson, R. E., Durbridge, T. B., Kennedy, P. J., McGuffie, K., and Pitman, A. J.: 1993, 'Tropical deforestation: Modeling local to regional-scale climate change', *J. Geophys. Res.* **98**, 7289–7315.

Hutchinson, M. F., Hix, H. A., McMahon, J. P., and Ord, K. D.: 1995, *Africa: A Topographic and Climatic Database*, Centre for Resource and Environmental Studies, Australian National University.

Hulme, M., Doherty, R. M., Ngara, T., New, M. G., and Lister, D.: 2001, 'African climate change: 1900–2100', *Clim. Res.* **17**, 145–168.

Janssen, M. and Martens, P.: 1997, 'Modelling malaria as a complex adaptive system', *Artificial Life* **3**, 213–236.

Lindblade, K. A., Walker, E. D., Onapa, A. W., Katungu, J., and Wilson, M. L.: 2000, 'Land use change alters malaria transmission parameters by modifying temperature in a highland area of Uganda', *Trop. Med. Int. Health* **5**, 263–274.

Lindsay, S. W. and Martens, P.: 1998, 'Malaria in the African highlands: Past, present and future', *Bull. WHO* **76**, 33–45.

Makono, R. and Sibanda, S.: 1999, 'Review of the prevalence of malaria in Zimbabwe with specific reference to parasite drug resistance (1984–96)', *Trans. Royal Soc.Trop. Med. Hygiene* **93**, 449–452.

Malaria Foundation International, www.malaria.org/zw/countries/zimbabwe.htm. Accessed April 2004.

MARA/ARMA: 1998, *Towards an Atlas of Malaria Risk in Africa*, Durban, South Africa.

Martens, P., Kovats, R. S., Nijhof, S., deVries, P., Livermore, M. T. J., Bradley, D. J., Cox, J., and McMichael, A. J.: 1999, 'Climate change and future populations at risk of malaria', *Global Environ. Change* **9**, S89–S107.

McFarlane, N. A., Boer, N. A., Blanchet, J. P., and Lazare, M.: 1992, 'The Canadian Climate Centre second generation general circulation model and its equilibrium climate', *J. Clim.* **5**, 1013–1077.

Mendelsohn, R., Schlesinger, M., and Williams, L.: 2000, 'Comparing impacts across climate models', *Integrated Assess.* **1**, 37–48.

Reiter, P.: 2001, 'Climate change and mosquito-borne disease', *Environ. Health Perspect.* **109**, 41–161.

Remme, J., Binka, F., and Nabarro, D.: 2001, 'Toward a framework and indicators for monitoring Roll Back Malaria', *Am. J. Trop. Med. Hygiene* **64**(Suppl 1), 1–11.

Rogers, D. J. and Randolph, S. E.: 2000, 'The global spread of malaria in a future, warmer world', *Science* **289**, 1763–1769.

Ropelewski, C. F. and Halpert, M. S.: 1987, 'Global and regional scale precipitation patterns associated with the El Niño-Southern Oscillation', *Mon. Weather Rev.* **115**, 1606–1626.

Schlesinger, M. E. and Williams, L. J.: 1997, *COSMIC—Country Specific Model for Intertemporal Climate*, EPRI, Palo Alto, CA.

Snow, R. W., Craig, M., Deichmann, U., and Marsh, K.: 1999, 'Estimating mortality, morbidity, and disability due to malaria among Africa's non-pregnant population, *Bull. WHO* **77**, 624–640.

Tanser, F. C., Sharp, B., and le Sueur, D.: 2003, 'Potential effect of climate change on malaria transmission in Africa', *Lancet* **362**, 1792–1798.

Taylor, P. and Mutambu, S. L.: 1986, 'A review of the malaria situation in Zimbabwe with special reference to the period 1972–1981', *Trans. Royal Soc. Trop. Med. Hygiene* **80**, 12–19.

Trape, J.: 2001, 'The public health impact of chloroquine resistance in Africa', *Am. J. Trop. Med. Hygiene* **64**(Suppl 1), 12–17.

Trape, J. F., Quinet, M. C., Nzingoula, S., Senga, P., Tchichelle, F., Carme, B., Candito, D., Mayanda, H., and Zoulani, A.: 1987, 'Malaria and urbanization in Central Africa: The example of Brazzaville. Part B: Pernicious attacks and mortality', *Trans. Royal Soc. Trop. Med. Hygiene* **81**(Suppl 2), 34–42.

Unganai, L. S.: 1996, 'Historic and future climatic change in Zimbabwe', *Clim. Res.* **6**, 137–145.

Van Lieshout, M., Kovats, R. S., Livermore, M. T. J., and Martens, P.: 2004, 'Climate change and malaria: Analysis of the SRES climate and socio-economic scenarios', *Global Environ. Change* **14**, 87–99.

Williams, L., Shaw, D., and Mendelsohn, R.: 1998, 'Evaluating GCM output with impact models', *Clim. Change* **39**, 111–133.

Wilson, C. A. and Mitchell, J. F. B.: 1987,' A doubled CO2 climate sensitivity experiment with a global climate model including a simple ocean', *J. Geophys. Res.* **92**, 13315–13343.

World Health Organization: 2002, *The World Health Report 2002: Reducing Risks, Promoting Healthy Life*, WHO, Geneva.

(Received 13 May 2003; in revised form 10 November 2004)