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# Future malaria spatial pattern based on the potential global warming impact in South and Southeast Asia

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## Abstract

We used the Model for Interdisciplinary Research on Climate-H climate model with the A2 Special Report on Emissions Scenarios for the years 2050 and 2100 and CLIMEX software for projections to illustrate the potential impact of climate change on the spatial distributions of malaria in China, India, Indochina, Indonesia, and The Philippines based on climate variables such as temperature, moisture, heat, cold and dryness. The model was calibrated using data from several knowledge domains, including geographical distribution records. The areas in which malaria has currently been detected are consistent with those showing high values of the ecoclimatic index in the CLIMEX model. The match between prediction and reality was found to be high. More than 90% of the observed malaria distribution points were associated with the currently known suitable climate conditions. Climate suitability for malaria is projected to decrease in India, southern Myanmar, southern Thailand, eastern Borneo, and the region bordering Cambodia, Malaysia and the Indonesian islands, while it is expected to increase in southern and south-eastern China and Taiwan. The climatic models for *Anopheles* mosquitoes presented here should be useful for malaria control, monitoring, and management, particularly considering these future climate scenarios.

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## Introduction

A change in the distribution of malaria is foreseeable due to the potential consequences of anthropogenic climate change (WHO, 2001; Martens *et al*., 1995). In many regions, including those in south and southeastern Asia, malaria remains a significant cause of morbidity and mortality. Its status here is highly dynamic, constantly evolving and likely to be further aggravated by climate change (Rogers and Randolph, 2000; Hay *et al*., 2004). An increase in the Earth's temperature and precipitation can create conditions more conducive for the breeding of the malarial vectors (IPCC, 2007; Martens, 1998). Both the frequency and intensity of the disease are expected to increase, a situation that will primarily affect the poor and marginalised sections of our society (WHO, 2011a, 2011b). Thus, malaria remains a significant health and development problem in these regions. According to the World Malaria Report (WHO, 2011a, 2011b), around one billion people are at risk in these regions. The disease is deeply rooted in poor communities affecting national development and occupying a large share of health budgets.

Some studies suggest that climate change can alter the distribution of vector-borne diseases, including malaria, causing regions that are currently free of such diseases to be affected (Patz and Lindsay, 1999; Khormi and Kumar, 2012). Thus, climate change could extend the distribution of the *Anopheles* vector, which is found worldwide except in very cold regions, such as Antarctica (Rogers and Randolph, 2000). With respect to the geographical distribution of malaria in southern and southeastern Asia, a few studies illustrate the spatial or spatiotemporal risk distribution of malaria or its vectors and link the distribution with the current climatic factor values or economic resources. For instance, in Lao People's Democratic Republic (Lao PDR), a detailed *P. falciparum* risk map was developed and used to identify populations at risk and to guide resource allocation for the ultimate purpose of malarial control (Jorgensen *et al*., 2010). The main findings from the use of this map showed that *Plasmodium falciparum* dominated spatially in the northern and central regions of the country, while large areas did not have any transmission; the areas in which transmission and risk were high were in the southern regions. Additionally, 60% of the population was found to be at risk of contracting malaria (Jorgensen *et al*., 2010). In China, the central-south counties of Hainan had the highest malaria incidences with 75% of cases recorded during May and October and a positive correlation between cases and climatic factors such as temperature (Xiao *et al*., 2010).

Temperature and precipitation affect both vector and host range (Craig *et al*., 1999; Tanser *et al*., 2003; Khormi and Kumar, 2011). Mosquito breeding is the fastest in warmer climates, extending the geographic distribution of the vectors as temperatures rise. The range of the vector, and/or the range of a vertebrate host reservoir, usually limits the distribution of malaria. Many studies illustrate the malaria situation in south and south-eastern Asia. Some of these studies have focused on the medical profile of malaria, while others have investigated the association between the disease vectors and climatic factors. For example, Chareonviriyaphap *et al*. (2000) recorded all four known human malarial parasites in Thailand, where *Plasmodium falciparum* and *P. vivax* were found to be dominant.

The emergence of multi-drug resistant *P. falciparum* has been the most serious recent development. The association between malarial mosquitoes and temperature has been demonstrated in India (Dhiman *et al*., 2008). The development period related to different mosquito lifecycle stages was found to be affected by temperature. The anopheline mosquitoes take 10 days to reach adult stage after the eggs have hatched at the optimum temperature of 28°C with the duration increasing at lower temperatures and decreasing at higher up to 40°C, at which level the adult mosquitoes find it difficult to survive (Dhiman *et al*., 2008).

In West Sumba District, situated in Lesser Sunda Archipelago, Indonesia, the geometric mean parasitaemia in infected individuals belonging to a study group of infected children and teenagers was found to decrease with age (Syafruddin *et al*., 2009). It was further established that malaria was associated with decreased haemoglobin concentrations in children under 10 years of age (Syafruddin *et al*., 2009), while asymptomatic *P. falciparum* and *P. vivax* parasitaemia were detected in 73 and 18 children, respectively (de Mast *et al*., 2010). In this study group, these authors also found that 84 and 83% of the children, respectively, had C-reactive protein concentrations below 5 mg/L. At the global scale, Caminade *et al*. (2014) compared the metrics of five statistical and dynamical malaria impact models for three future time periods (the 2030s, 2050s, and 2080s) using bias-corrected temperature and rainfall simulations from the Coupled Model Intercomparison Project Phase 5 (http://cmip-pcmdi.llnl.gov/cmip5/) climate models. They also investigated the modelling uncertainty associated with future projections of populations at risk for malaria owing to climate change arriving at an overall global net increase in climate suitability and a net increase in the population at risk, but with large uncertainties.

The aim of this study was to illustrate the potential impact of climate change on the spatial distribution of malaria in India, Indochina, Indonesia, China and The Philippines, with specific projections for 2050 and 2100, using climate variables such as temperature, moisture, heat, cold, and dryness. In general, a wealth of research has been conducted on malaria and climatic factors, but to our knowledge, no published study has considered the potential impact of climate change on malarial distribution at broad scales, especially not in south and south-eastern Asia, with specific projections for 2050 and 2100. Also in our study, we used the Model for Interdisciplinary Research on Climate-H (MIROC-H) model (Nozawa *et al*., 2007), the A2 Special Report on Emissions Scenarios (SRES) model (Nozawa *et al*., 2007), and climate variables, modelling the potential alterations in climate that may affect the distribution of malaria, which makes a difference between our study and other previously published studies.

## Materials and Methods

### Study area

This study was conducted in China, India, the countries of mainland Southeast Asia, Indonesia and The Philippines (Figure 1), one of the most densely populated regions in the world and with some of the highest population growth rates. The region is currently infested with *Anopheles* mosquitoes and also environmentally suitable for the malaria life cycle, so transmission persists around the year without a pause (Table 1).

### Data source of current status of malaria and Anopheles mosquitoes

The distribution data of mosquitoes and malaria cases in the study region (Figures 2 and 3) were collected from different sources, such as Health Ministries, International Health Organizations, the Centers for Disease Control and Prevention (CDC) in the United States (CDC, 2012), the Malaria Atlas Project (MAP) (http://www.map.ox.ac.uk/), malaria reports and published studies. In response to limitations, *i.e*. lack of software, hardware, training for mapping the various mosquito vectors on a fine scale, we used available resources, such as historical records, documents, and maps of a variety of known malaria areas from the MAP, for all major species found in the study areas. The known malaria areas are marked with dashed lines in Figures 2 and 3 to illustrate the approximate distribution of all *Anopheles* mosquitoes and malaria cases (where *Anopheles* data were missing).

### Software

We used the CLIMEX software package (Sutherst *et al*., 2007), which allows users to model the potential distribution of a species by incorporating various types of information, including direct experimental observations of a species' growth response to environmental variables, the phenology of the species and knowledge of its spatial distribution. The modelling is based on the premise that the distribution envelope of plants and poikilothermal animals is primarily determined by the climate (Andrewartha and Birch, 1954; Sutherst and Maywald, 1985; Poutsma *et al*., 2008; Tonnang *et al*., 2010; Khormi and Kumar, 2014, 2015).

The CLIMEX software develops an eco-physiological model based on the assumption that species will flourish during a favourable season,

**Figure 1. The study area.**

resulting in positive population growth, and that the population will decline during unfavourable seasons (Taylor *et al*., 2012). An annual growth index can be generated based on the current distributions and climatic conditions, and the growth index then gives the potential for mosquito population growth or decline during favourable and unfavourable conditions, respectively. Four stress indices (*i.e.* cold, wet, hot, and dry) and up to four interaction stresses (*i.e.* hot-dry, hot-wet, cold-dry, and cold-wet) are used to describe the probability that the population can survive unfavourable conditions. The weekly growth and stress indices are combined to form the ecoclimatic index (EI), which is an index of overall annual climatic suitability theoretically scaled from 0 to 100 (Sutherst *et al*., 2007; Taylor *et al*., 2012). The modelled species will only become established if EI>0. EI values near 100 (maximum) are rare, as this condition is usually confined to species within an equatorial range, given that this value would imply ideal growth conditions throughout the year (Sutherst *et al*., 2007; Taylor *et al*., 2012; Shabani *et al*., 2012; Khormi and Kumar, 2014). EI values near zero indicate a low probability of conditions conducive to population persistence in time and space.

## Climate models, climate data, and climate change scenarios

Numerous climate models exist for characterising a future climate (IPCC, 2007). For this study, we used the MIROC-H model, which predicts that global temperatures will have increased by approximately 4.31°C by the year 2100 and that the mean annual rainfall will have decreased by 1% (Suppiah *et al*., 2007; Chiew *et al*., 2009). This climate model was selected since it has reasonably small horizontal grid spacing and because it performs well compared with models based on the observed climate at regional scales (Taylor *et al*., 2012). The temperature, precipitation, mean sea level pressure and specific humidity variables were also available in the CliMond dataset (https://www.climond.org/) for this model (Kriticos *et al*., 2011). The SRES model was not only selected to characterise one of the possible climate scenarios in the future, but also because its projections are neither too extreme nor too moderate. The SRES scenarios consider a world with high population growth, slow economic development and technological change (Kriticos *et al*., 2011). They assume neither maximal nor minimal greenhouse gas emissions.

**Table 1. Main epidemiological indices in the study area (data from Wijeyaratne *et al.*, 1988; Tang 1999, 2000; Bangali *et al.*, 2000; Lal *et al.*, 2000; Hatabu *et al.*, 2003; Wijesundera *et al.*, 2004; Kumar *et al.*, 2007; WHO, 2007; Nepal Ministry of Health and Population, 2007; Dash *et al.*, 2008; Budi *et al.*, 2009; Haque *et al.*, 2009; Lin *et al.*, 2009; Dhingra *et al.*, 2010; Lawpoolsri *et al.*, 2010; WHO, 2010a, 2010b, 2010c, 2010d, 2010e, 2011a, 2011b; WHO Regional office for SEA, 2011).**

| Countries | | Population at risk | | Parasites and vectors | |
|---|---|---|---|---|---|
| | | n | % | Major *Plasmodium* species | Major *Anopheles* species |
| India | High transmission (>1 case per 1000 population) | 272,000,000 | 22 | *P. falciparum* (50%),<br>*P. vivax* (50%) | *An. culicifacies,*<br>*An. fluviatilis,*<br>*An.stephensi,*<br>*An.minimus,*<br>*An.dirus, An.annularis* |
| | Low transmission (0-1 case per 1000 population) | 829,000,000 | 67 | | |
| Bangladesh | High transmission (>1 case per 1000 population) | 4,110,000 | - | *P. falciparum* (91%),<br>*P. vivax* (9%) | *An. dirus,*<br>*minimus, philippinensis,*<br>*sundaicus, albimanus,*<br>*annularis* |
| | Low transmission (0-1 case per 1000 population) | 11,900,000 | - | | |
| Indonesia | High transmission (>1 case per 1000 population) | 42,000,000 | 17 | *P. falciparum* (55%),<br>*P. vivax* (45%) | *An. sundaicus,*<br>*balabacensis,*<br>*maculatus, farauti,*<br>*subpictus* |
| | Low transmission (0-1 case per 1000 population) | 109,000,000 | 44 | | |
| Sri Lanka | High transmission (>1 case per 1000 population) | 501,000 | 2 | *P. falciparum* (17%),<br>*P. vivax* (83%) | *An. culicifacies,*<br>*subpictus,*<br>*annularis, varuna* |
| | Low transmission (0-1 case per 1000 population) | 20,600,000 | 98 | | |
| Myanmar | High transmission (>1 case per 1000 population) | 19,500,000 | 37 | *P. falciparum* (65%), | *An. minimus, dirus* |
| | Low transmission (0-1 case per 1000 population) | 12,100,000 | 23 | *P. vivax* (35%) | |
| China | High transmission (>1 case per 1000 population) | 196,000 | 0 | P. falciparum 58%;<br>P. vivax 42% | An. sinensis,<br>anthropophagus,<br>dirus, minimus |
| | Low transmission (0-1 case per 1000 population) | 576,000,000 | 42 | | |
| Bhutan | High transmission (>1 case per 1000 population) | 518,000 | 42 | *P. falciparum* (43%),<br>*P. vivax* (57%) | *An. maculatus,*<br>*culicifacies,*<br>*philippiensis, annularis* |
| | Low transmission (0-1 case per 1000 population) | 729,000 | 58 | | |
| Nepal | High transmission (>1 case per 1000 population) | 1,020,000 | 4 | *P. falciparum* (30%),<br>*P. vivax* (70%) | *An. fluviatilis, annularis,*<br>*maculatus* |
| | Low transmission (0-1 case per 1000 population) | 22,000,000 | 80 | | |
| Thailand | High transmission (>1 case per 1000 population) | 5,340,000 | 8 | *P. falciparum* (40%),<br>*P. vivax* (60%) | *An. dirus, minimus,*<br>*maculatus,*<br>*sundaicus* |
| | Low transmission (0-1 case per 1000 population) | 28,000,000 | 42 | | |
| Philippines | High transmission (>1 case per 1000 population) | 6,940,000 | 7 | *P. falciparum* (69%),<br>*P. vivax* (31%) | *An. flavirostris,*<br>*maculatus,*<br>*balabacensis, litoralis* |
| | Low transmission (0-1 case per 1000 population) | 70,200,000 | 73 | | |

The CliMond 10’ gridded climate data were used for modelling. The average minimum monthly temperature, average maximum monthly temperature, average monthly precipitation, and relative humidity at 09:00 h (RH$_{09}$) and 15:00 h (RH$_{15}$) represent the historical climate (averaging period 1950-2000). These five variables were used to characterise the potential climate of the future. We selected the two project dates (2050 and 2100) as providing a reasonable snapshot of the foreseeable future; one is in the near future; ≈37 years from now and one much later; ≈88 years from now.

## Prediction test and fitting the CLIMEX parameters

To test the model’s predictive capability, the initial intention was to use current *Anopheles* and malaria cases data, *i.e*. records that have a connection with the information applied, for estimation of model parameters. The test records covered the entire study geographic area. However, we observed a good match between the current distribution records of malaria and its vectors with the modelled EI from CLIMEX. We adjusted the used climatic parameters slightly to better fit the malaria vector distribution in the study area according to Tonnang *et al*. (2010). We used climatic parameters that are appropriate for the description of the potential geographical distribution of the whole group of *Anopheles* vector species in the study area. The *compare location function* was rerun until the estimated potential *Anopheles* species range best matched the observed or known distribution as limited by climate. Alternatively, CLIMEX parameters were optimised using the distribution data of *Anopheles* mosquitoes and malaria cases (where *Anopheles* data were missing), temperature, moisture indices and cold and dry stress. The parameters were fitted to the known and naturalised distribution of *Anopheles* mosquitoes and were adjusted iteratively until there was reasonable agreement with the current *Anopheles* or malaria case distribution. The fitted parameters were crosschecked with an independent set of current distributions to ensure that they were reasonable. All *Anopheles* mosquitoes were pooled and modelled together. As the study area contains several species of *Anopheles* mosquitoes, and also types of malaria, we collected information on appropriate climatic limits for breeding and reproduction of all *Anopheles,* then established a timely and comprehensive climate range for all

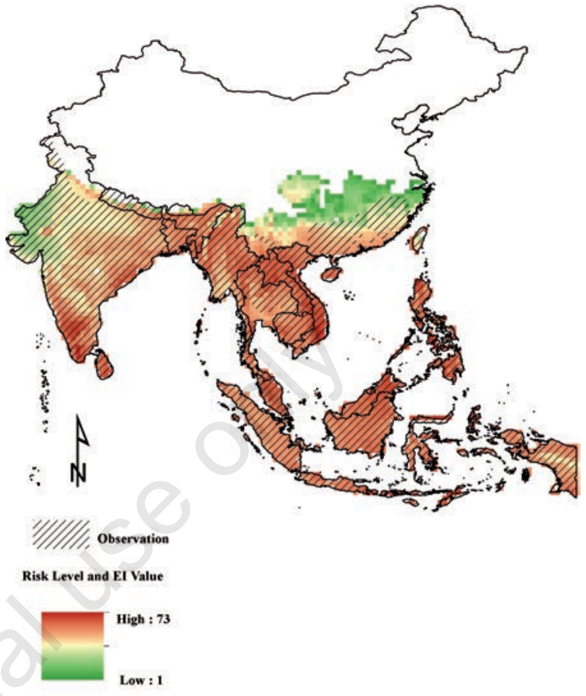

**Figure 2. Current regions conducive for Anopheles. The map is based on CLIMEX software for the reference climate (average period, 1950-2000). Suitability is based on the ecoclimatic index (EI) scale from 0 (unsuitable, white; *e.g.*, northern China) to 100 (highly suitable, red; *e.g.* Sri Lanka).**

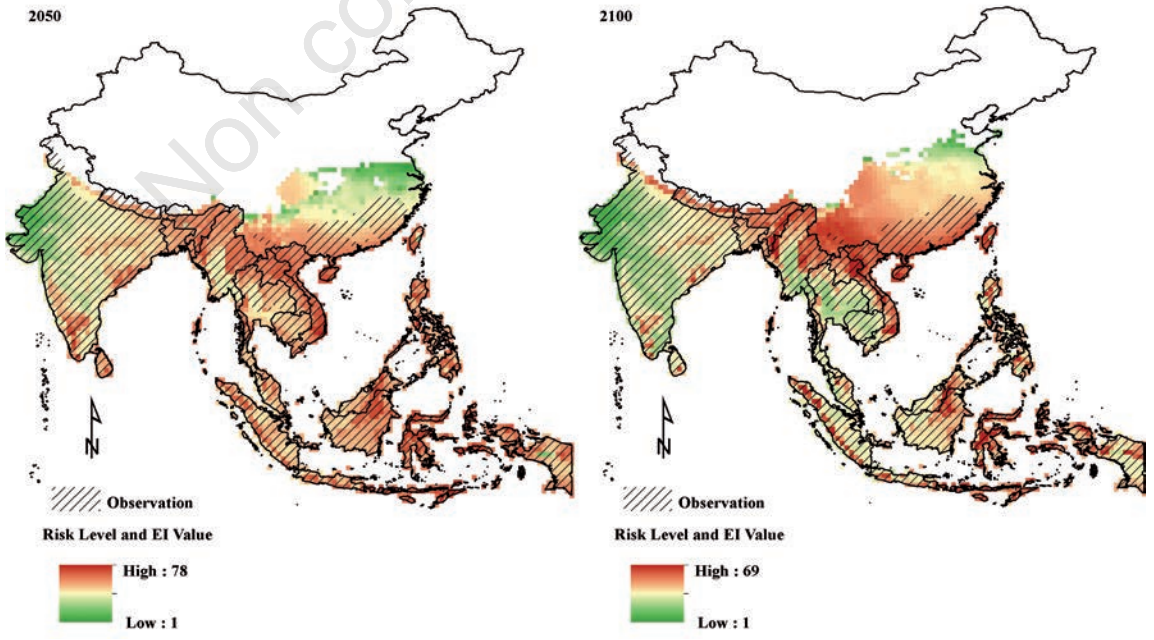

**Figure 3. The projected ecoclimatic index (EI) conducive for Anopheles in 2050 and 2100. Suitability is based on the EI scale from 0 (unsuitable, white; *e.g.,* northern China) to 100 (highly suitable, red; *e.g.* Vietnam).**

species, including lower and upper optimal temperatures, which may help all *Anopheles* types to breed, survive, or spread the disease. We were fully aware that each type of mosquito can have a specific type of environment that is suitable for breeding and malaria transmission, involving vegetation cover, human practices and other characteristics and may support the reproduction of mosquitoes better in one area more than in another location. However, from the reviewed literature, we found that differences in the impact of climatic factors on the reproduction of different mosquito species may not be very large.

Research has shown that the ranges of minimum and maximum temperature for malaria parasite and vector development determine the impact of temperature on malaria transmission (Pampana, 1969; Bouma *et al*., 1995; Patz *et al.*, 1999). *Anopheles* mosquitoes can develop at minimum temperatures between 8-10°C, while the minimum temperatures for parasite development are between 14-19°C, with *P. vivax* depending on lower temperatures than *P. falciparum* (Pampana, 1969; Bouma *et al*., 1995; Patz and Lindsay, 1999). The optimum temperature for *Anopheles* mosquitoes is 25-27°C, and 40°C is the maximum temperature for both vectors and parasites (Russell *et al*., 1963; McMichael *et al*., 1996, 1998). We set the limiting low temperature ($DV_0$) at 10°C, the lower optimal temperature ($DV_1$) at 25°C, the upper optimal temperature ($DV_2$) at 27°C, and the limiting high temperature ($DV_3$) at 40°C. These values provided the best fit for the observed distribution of *Anopheles* and malaria cases.

The lowest limiting moisture ($SM_0$) was set at 0.007 because it represents the permanent wilting point, and this number provided a good fit with the observed distribution of *Anopheles* and malaria cases in drought areas, particularly in some areas of Iraq and Saudi Arabia. The lower ($SM_1$) and upper ($SM_2$) optimum moisture and the highest limiting moisture ($SM_3$) were set at 0.013, 0.5, and 5, respectively, since these values provided an appropriate fit to the observed distributions.

The heat stress parameter (TTHS) was set at 40°C, since it is reported that in some countries (*e.g*., Saudi Arabia), *Anopheles* survives up to this temperature (McMichael *et al*., 1996). The heat stress accumulation rate was set at 0.9 week$^{-1}$, which allows *Anopheles* to survive in most areas in southern Oman and western and southeastern Iran. The dry stress parameter was set at 0.001 for the dry stress threshold and -0.001 week$^{-1}$ for the dry stress rate. Cold stress parameters were set at 4°C for the cold stress temperature threshold (TTCS), -0.001°C for the cold stress temperature rate, 8°C for the minimum degree-day cold stress threshold, and -0.001°C for the degree-day cold stress rate, since these adjusted values provided an appropriate fit with the observed distribution. Details about all of these parameters and how they are used in CLIMEX can be found in Sutherst (2003).

Many of those statistical measures, such as analysis using area under the curve, could be easily done through all correlative models, but not the mechanistic measure used in our study. Therefore, to attempt to validate the climatic condition models suitable for malaria, we used the climatic variables available in CLIMEX for the average period of 1950-2000 to predict the current climate situation. These parameters can also act as reference for assessing the accuracy of future predictions and climatic factors, and the model can be used to find the future potential distribution of malaria and its vector mosquitoes. In other words, we used an EI model that is conducive for *Anopheles* and also available in CLIMEX as a reference climate (averaging period=1950-2000). Then we compared the output of the malaria models for the observed climate baseline datasets and general circulation modelled baselines and compared those outputs with other published malaria endemicity maps. Pre-intervention malaria endemicity estimates were based on a synthesis of historical records, documents, and maps of a variety of malariometric indices for all major species found in the study area. We derived recent malaria endemicity estimates from sources such as the MAP, and the sources illustrated above for comparison purposes. The MAP dataset integrates survey data with socioeconomic and environmental predictors in a Bayesian model producing approximately mapped malaria endemicity on the South and Southeast Asia regional scale, which helped the comparison between the malaria model outputs for which the epidemic and suitable climate conditions regions were defined (Figure 2). The present-day malaria distribution used to establish the climatic constraints currently operating with respect to malaria were applied to future climatic scenarios to predict future distributions.

## Results

### Model fit and validation

The current observed areas of malaria prevalence were consistent with those showing high EI values in the CLIMEX model. The match between prediction and reality was high; more than 90% of the observed malaria distribution areas (collected from MAP and other sources as mentioned above) were filled within the currently known suitable climate conditions, which confirmed that the selected parameters (*e.g*., heat, moisture, dryness, and temperature indices) were at optimum or near optimum levels with a strong match between the observed distribution and the modelled EI (Figure 2).

For model validation, we observed a good match between the current distribution records of malaria and its vectors with modelled EI from CLIMEX. The model shows India, some areas of southern China, all countries in Indochina, The Philippines, and Indonesia currently having suitable to highly suitable conditions for the mosquitoes to survive and for malaria transmission. The distribution of the mosquitoes is limited in central and northern China and the very far north of India, primarily due to cold and dry stress.

### Future potential distribution

The projected suitable climate for malaria for 2050 and 2100 is shown in Figure 3. For 2050, a decrease in the climate suitability is projected in India (predominantly in the northern and eastern of the country), southern Myanmar, southern Thailand, the region bordering Malaysia, Cambodia, eastern Borneo and the Indonesian islands. Nonetheless, even if the suitability measures (the EI values) decrease, most of the areas should remain conducive for the spread of malaria and its vectors. The regions where the climate suitability for malaria would increase are southern and south-eastern mainland China and Taiwan.

We found the trend for 2100 similar to that for 2050. Suitability and the extent of suitable areas would decrease in some regions, while they would increase in others. The regions in which climate suitability would decrease (according to lower EI values) include most of India except the Assam region, southern Vietnam, central to southern Myanmar, Malaysia, Thailand, eastern Borneo, the Indonesian islands and The Philippines. The regions in which climate suitability would increase (higher EI values) include the Assam region in India, northern Myanmar, Lao PDR, northern Vietnam, the southern regions of mainland China and Taiwan. If our predictions hold, large areas in China should become conducive to the survival of the malaria parasites and their vectors, especially Hainan Island, areas near the southern border near Hong Kong, Macau, Southern Yunnan and the regions west of Guangzhou close to the Vietnamese border. The largest decreases should be observed in India, Sri Lanka, Myanmar, Malaysia, Thailand, Cambodia, southern Vietnam, western Borneo, Java and Sumatra.

Future projections show an overall reduction in the climate suitability for *Anopheles* in India, all countries in Indochina, the Philippines, and Indonesia (Figure 3). This was due to changes in heat stress, causing large areas to have heat stress (TTHS) beyond the maximum survival values for the malaria vector (>40ºC). Large areas in India, all countries in Indochina, The Philippines, and Indonesia are currently below the heat stress limits. However, in 2050 and 2100, these areas will become excessively hot for *Anopheles* survival, with the heat stress increasing beyond the maximum value (Figure 4). These results highlight areas where climate suitability is expected to decrease in the future, which is useful information when making informed decisions about the allocation of resources for mosquito control.

The southern regions of China constitute new areas of South and Southeast Asia that might become at risk for malaria mosquito infestation in the future or in which suitability is presumed to increase. Large areas of southern China that are currently unsuitable or marginal (Figure 2) would become suitable for the survival of *Anopheles* (Figure 3). This increase in suitability would be due to the decreased impact of cold stress (TTCS). Currently, most of China has moderate-to-high cold stress levels (Figure 5), creating unfavourable conditions for *Anopheles* mosquitoes. By 2100, it is projected that large areas of southern China will pass from being below the critical cold stress value to within the suitable range for *Anopheles* survival. These highly suitable areas have very high population densities, greatly increasing the number of people who could be exposed to the *Anopheles* mosquito presence and thus also to malaria.

## Discussion

Studies with a spatial perspective face problems because of the detailed spatial data required relating to the disease and transmitters, especially in developing nations. Many difficulties are involved in collecting new, high-quality, detailed spatial malaria data, as well as mapping the mosquito vectors and their types on a fine scale due to the lack of software, hardware, training, and the fact that some decision makers do not understand spatial data and their application. We relied therefore on available resources as mentioned for all major mosquito species found in the study areas. The known malaria areas are marked with hashed lines in Figures 2 and 3 to illustrate the approximate distribution of all *Anopheles* mosquitoes and malaria cases (where *Anopheles* data were missing). We explored the sensitivity of malaria transmission dynamics in South and Southeast Asia, as currently understood, in terms of the projected levels of climate change by combining and integrating the current locations of malaria and its vectors with the current suitable climatic parameters to obtain a better picture of changes in the malaria risk areas associated with future climate scenarios.

The changes in the suitability for *Anopheles* expected warrant strategic control measures to prevent its spread. Those areas may need more detailed risk evaluations regarding the spread of mosquitoes, and the assessment and management of mosquito risk depend to a large extent on projections of habitat suitability. A fundamental aspect of such assessments can be formed from the response of *Anopheles* to changes in climate, especially in areas that are at risk and will continue to be at risk from the mosquito in the future. Monitoring these areas could be

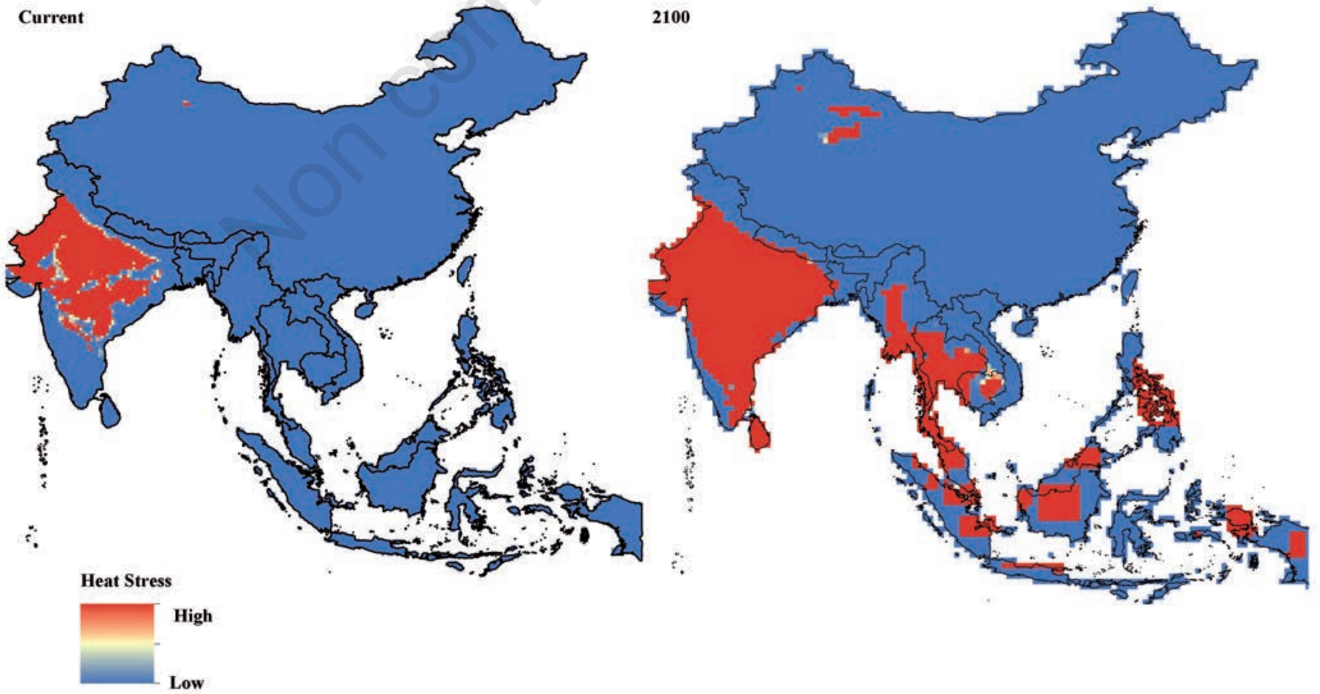

**Figure 4. Changes in heat stress for *Anopheles* by 2100.**

important, and health professionals could use these projections in decision-making and prioritising areas for eradication and control. The projections about the effects of climate change on *Anopheles* could also be used to determine areas in which mosquito containment would be cost-effective.

This study was limited to the use of climatic factors, which are not the only main determinant factors for *Anopheles* species existence, but they are the only factors with available data that provide an initial estimate of the potential range of *Anopheles* species in South and Southeast Asia. The study findings illustrate the substantial influence that the direct effects of climate change may constitute in terms of malaria vector redistribution in these regions and should be interpreted as an indication of the sensitivity of malaria vectors to climatic changes, temperature rise in particular. For elaborating future risk evaluations of climate change and malaria and to enhance malaria management and control, health officers should monitor climate-based analyses and environmental, social and economic factors to provide better guidance in taking sustainable and efficient measures (Tonnang *et al*., 2010; Khormi and Kumar, 2014). Flooding is a climate-related type of disaster that should be taken into account. Such events may change the dynamics of *Anopheles* mosquitoes due to the conditions that will be created, resulting in proliferation and enhancing mosquito-human contact (Tonnang *et al*., 2010).

We noted that a whole group of *Anopheles* vector species are relevant and that their distribution areas and ecologies vary to a large degree. This paper does not account for the differences in climate requirements of the various species of the *Anopheles* mosquitoes present in the region, as the aim was to look at the whole group of *Anopheles* mosquitoes and model the risk at the broad regional scale. The modelling approach presented here can be used to develop species-specific models where necessary. Sinka *et al*. (2011) describe the projected ranges of the 41 dominant vector species of malaria. We also noted that, in the Asian region, the occurrence distributions and ecologies of the various species overlap considerably, a fact that validates the broad-scale approach taken.

This study illustrates the substantial influence that the direct effects of climate change may constitute in terms of malaria vector redistribution in South and Southeast Asia. This study may provide opportunities to specify the health burden of malaria and its vectors within potential hotspots and provide a platform that can promote further investigations into the factors responsible for increased or decreased disease risk, including economic, social, environmental, and etiological factors.

## Conclusions

The increase in the Earth's temperature and precipitation can create conditions more conducive to the breeding of malaria vectors. The models developed in the present study could be highly effective for malaria prevention. They can be used for malaria control management and improved surveillance, as they show that climate change may play a critical role in determining the potential distribution of the malaria parasites and their vectors. Climate is not only the main determinant factor for the spatial distribution of *Anopheles* species, but also the only factor with available data that can help to estimate the potential range of their distributions. The study results should be taken as an indication of the sensitivity of malaria vectors to global climatic changes, particularly to temperature rise. The models presented provide valuable information for understanding climates that are conducive for the survival of mosquitoes and on how changes in suitability levels can affect species survival.

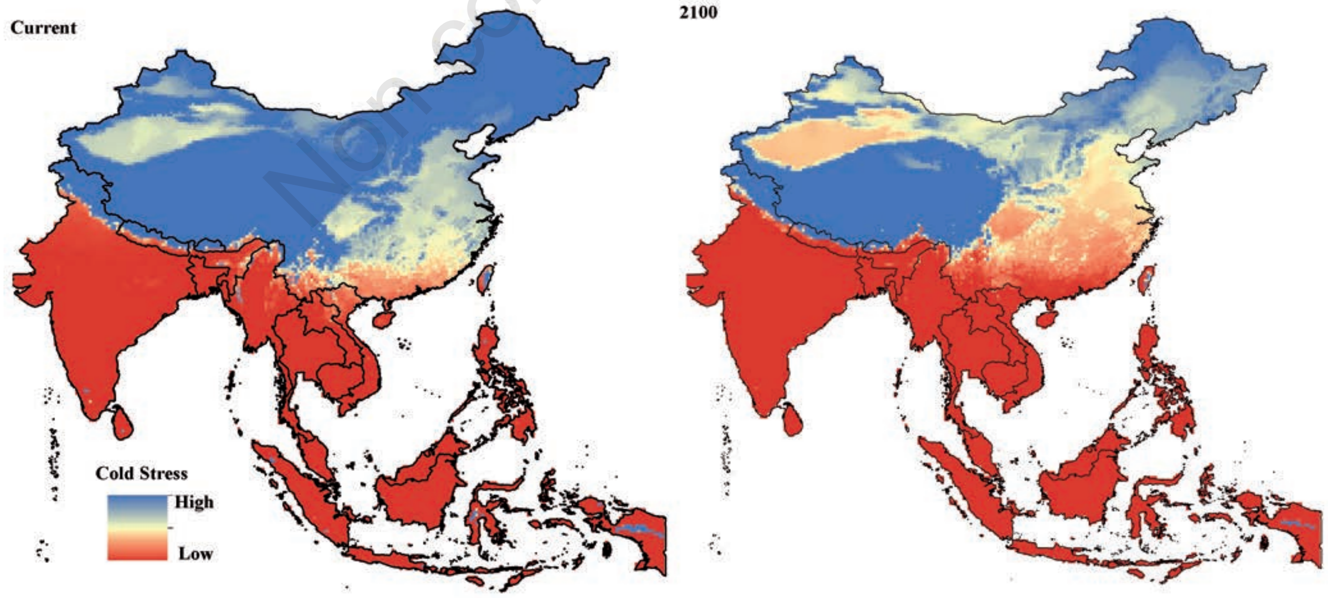

**Figure 5. Changes in cold stress for *Anopheles* by 2100.**

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