IMPACTS OF CLIMATE CHANGE ON GLOBAL HEALTH:
A SCOPING REVIEW ON THE CASE OF MALARIA

NURIA GÜIL OUMRAIT
Final Bachelor Degree Project
Human Biology
Universitat Pompeu Fabra

Supervisor: Fernando García Benavides
Department of Experimental and Health Science (CEXS – UPF)
**Abstract**

Anthropogenic climate change is having a potential impact on human health, being one of the main environmental and health challenges of our time. Malaria, the major killer of children worldwide, is critically the most climate sensitive vector-borne disease in the world. However, the link between climate change and malaria is still a subject of discussion within the scientific community and a question that remains unresolved. This scoping review aims to elucidate this relation through evidence collected from time series analyses, geographical comparison and outbreak studies performed in different endemic countries of malaria. Our results reveal that climatic variables (temperature, rainfall and humidity) are the prime determinants of geographical distribution, seasonality and incidence trends of malaria. Historical records in temperature rise and precipitation trends on account of anthropogenic global warming are clearly propitiating the occurrence of local malaria outbreaks, and the anomalous geographical shift of the vector and parasite towards regions where populations are immunologically unprepared. Furthermore, this review introduces computational models as a tool to predict forthcoming malaria scenarios driven by climate change, and discusses the possible implications for Western and low-income countries in the near future.

**Keywords:** climate change, malaria, temperature, rainfall, relative humidity, ENSO, anthropogenic activity.
INTRODUCTION

Climate change in IPCC (Intergovernmental Panel on Climate Change) usage refers to a statistically significant variation in the mean state of the climate and/or the variability of its properties, persisting for an extended period, typically decades or longer. This change can be caused by natural processes and/or human activity (1). The UNFCCC (United Nations Framework Convention on Climate Change) attributes climate change, directly or indirectly, to anthropogenic changes in the composition of the atmosphere and that is in addition to natural climate variability observed over comparable time periods (2). Climate change has been assessed by a set of indicators, among which are noteworthy the annual greenhouse gas index, arctic sea ice extent, atmospheric carbon dioxide, global surface temperatures, heating and cooling degree days, ocean chlorophyll concentrations and sea surface temperatures (1).

Since 1861, the Earth average temperature has increased by 0.6 °C with an exponential rise over the last decades (3). According to the last Assessment Report of IPCC, it is expected to rise to about 3.7 - 4.8 °C because of anthropogenic greenhouse gases (GHG) emissions by the end of this century (1). This phenomenon was coined as global warming by Wallace Broecker in 1975, whose early predictions on global surface temperature change have foreseen accurately the current scenario (4). Rise in temperatures results in stratospheric ozone depletion, soil degradation, desertification and oceans acidification. Consequently, this lead to the reduction of fresh-water resources, biodiversity loss, ecosystems degradation and, therefore, the productivity of agricultural land is reduced (5). Meanwhile, climate change is exerting harmful impacts on human health not only directly - caused by air pollution, heatwaves and extreme weather events such as storms, floods, droughts or cyclones - but also indirectly and with long-term consequences due to a reduction of food production and access to safe drinking water, water-borne infectious diseases and vector-borne infectious diseases (6). The latter group includes malaria disease, being the subject of study in this scoping review.

Malaria is a vector-borne disease caused by the protozoan Plasmodium, which infects human red blood cells. The disease is characterised by recurrent acute fever attacks and systemic disorders and is transmitted to humans through the bites of infected female Anopheles mosquitoes. Around the 90 % of malaria cases occur in sub-Saharan Africa. However, several countries from Latin America, Middle East and South-East Asia are also exposed to the risk of malaria epidemics (7).

Although the oldest references of malaria existence date from 2700 BC in China (8), malaria was still endemic in Western Europe and in the United States until the mid-late twentieth century, when eventually was eradicated thanks to the socioeconomic development and the enhancement in health care system (9). Even though there has been a great involvement by malaria eradication campaigns and the incidence of the disease has significantly decreased by 41 %, around 212 million clinical cases occur annually in tropical low-income countries. Furthermore, by 2015 there
were more than 429,000 reported deaths attributable to malaria, 70 % of which occurred in children aged under 5 years, being malaria still the major cause of children mortality in the world (7).

In the global warming process, the most compelling argument for focusing on the case of malaria is its strong association with climatological features, being previously described as the “most climate sensitive vector-borne disease” (10). Changes in temperature, rainfall and wind patterns due to global warming are clearly noticeable (1). Therefore, in the context of climate change there is an increasing risk of geographical expansion of malaria, which might entail more clinical cases and the spread into new areas, where populations lack of immunity preparedness.

**HYPOTHESIS**

My hypothesis is that climate change, due to anthropogenic activity, is having an impact on the incidence rates of malaria and its geographical distribution.

**OBJECTIVES**

The main aims of this work, in order to corroborate or discard the previous hypothesis, are the following:

- To identify and outline existing evidences found in the scientific literature upon the association between climate change and malaria.
- To prove the existence of risk in malaria geographical expansion based on the coexistence of *Plasmodium* and favourable climatic factors for the development of *Anopheles* vector and the parasite within the mosquito.
- To obtain a better understanding upon this relation, so that it could be served as a guidance to improve epidemic preparedness tools in malaria endemic areas.
- To highlight the critical impact of climate change on global public health, especially on low-income countries populations, who are burdening with the worst consequences of anthropogenic global warming.
- To elucidate future research directions towards a future free from malaria.

**METHODOLOGY**

**Study design**

To achieve our objectives, we developed a Scoping Review. A scoping review is a novel style of review which consists in an iterative, conceptual and interpretative narrative synthesis approach to a particular topic. This allows the researcher to 1) Clarify working definitions and conceptual boundaries of a topic area, 2) outline what is known and identify gaps in the existing research, and 3) map existing literature of evidence (11). Hence, this scoping review uses the Arksey and
O’Malley methodology, which includes the following stages: 1) Identifying the research question. 2) Identifying relevant studies concerning my hypothesis and objectives. 3) Study selection considering the inclusion criteria. 4) Charting the data. 5) Collating, summarizing, and reporting the results (12).

The initial question was “Is climate change exerting a relevant impact on malaria distribution and incidence?”. The databases used for searching the information are PubMed and Web of Science. Starting with a general search with the keywords of ‘climate change’ and ‘malaria’ I found 1,389 articles, then, filtering by the title I obtained 320 publications, and eventually focusing on the abstracts I ended up with 107 articles, among which I selected 20 that contain the most relevant information for my results. See Figure 1 for flow of study selection methodology.

![Flow chart of study selection.](image)

The inclusion criteria for the study selection are as follows:

- Studies published within a time interval between 1994 and 2017, since the first year mentioned raises the first scientific paper that relates climate change and malaria.
- Qualitative, quantitative and cross-sectional studies on: 1) Climate change and malaria, 2) ENSO (El Niño Southern Oscillation) and malaria and 3) Anthropogenic ecological alteration and malaria.
- Relevance and statistical significance of their main findings.
- The geographical location where the studies were performed. Considering that Africa is the continent most affected by malaria, half of the studies from the articles are set thereat paying special attention to African highlands, that used to be malaria free zones, but that currently are experiencing climate-related changes in malaria incidence. Nonetheless, I decided to highlight the situation in endemic Asian regions, whose populations deal with extreme weather events
frequently. For the same reasons, I outlined some studies from South America, mainly from Amazon countries, whose rainforests and natural habitats are alarmingly being disrupted and damaged by human activity. In addition, in order to obtain an approach of Oceania setting, a report from Papua New Guinea was also included.

The articles have been grouped in different tables according to their design and methodology: 1) Time series studies, 2) Outbreak studies and 3) Geographical comparison studies. The following information was extracted from each paper: Author, year of publication, study country, study aim and key findings.

**RESULTS**

There are three factors that determine the occurrence of malaria in one region: the presence of *Anopheles* vector, the presence of hosts infected by *Plasmodium* parasite, and the existence of conducive climate conditions (13).

Temperature, rainfall and humidity are the main meteorological variables that exert a major influence on changes in the dynamic population of malaria parasite and its vector (14–17). Specific weather conditions are essential for the parasite development within the mosquito (sporogonic cycle). This weather dependence is especially remarkable during the mosquito stages. Thus, when the female *Anopheles* mosquito sucks blood from an infected human, it ingests the gametocytes, which enter in the sporogonic cycle. After a couple of weeks, the sporozoites are found in the *Anopheles*’ salivary glands and will be injected in the next human during a blood meal (18). Ambient temperature plays an essential role in determining the progress and speed of this process. Hence, mosquitoes require temperatures above 16 ºC to complete their life cycles, and the incubation time of the parasite within the vector is shortened in temperatures higher than 20 ºC (17). In addition, rain seasons are highly associated with malaria epidemics since they provide breeding sites for *Anopheles* to lay their eggs, ensuring humid conditions that prolong the life of the mosquitoes (19–22).

**Tables 1-5** present the 20 articles that have been included in the Scoping Review. These studies are performed in endemic malaria countries, and show climate-related modifications in the disease distribution and incidence that have occurred over the last decades, within the context of global warming. Interestingly, some African highlands, that used to be malaria-free areas, have recently experienced episodes of malaria due to changes in climate patterns of temperature and rainfall (22–24). For instance, climate change in Rwanda can be illustrated in the progressive replacement of mountain and temperate climate zones by hot lowland zones (25). Loevinsohn reported a steep rise of malaria incidence driven by these climate modifications and evidenced the known sensitivity of *Plasmodium* and *Anopheles* to temperature and rain. Noteworthy, despite the huge distinction of malaria incidence among high and low altitude communities, in terms of height they differed by a
mean of only 111 metres, which translated into mean temperature represents a slight difference of 0.7 °C (24).

The fact that minor changes in temperature can lead to significant shifts in malaria incidence has also been observed in Iran (26) and in Ugandan highlands, where only a rise of 1 °C in minimum temperature resulted to an increase of 70 % of Anopheles IRD (Indoor Resting Density) in swamps (27). Higher vector density implies higher risk of malaria transmission, which indirectly prompts the emergence of more clinical cases. The significance of minimum temperature was also documented in Shuchen County (China) and it was suggested to play a relevant role in the emergence of malaria outbreaks (28). By contrast, a study in Ghana found higher correlations with maximum temperature indices as high peaks of maximum temperatures preceded malaria peaks (29).

Water from the rainfall provides the optimal medium for the aquatic stages of the mosquito’s life cycle and increases the moisture and then, the longevity of the vector. Thereby, is not surprising that, in Iran mosquitoes have migrated from arid high areas to lowlands where there is a predominance of rivers and water sources (30). The same situation occurred in Papua New Guinea, but in this case, the mosquitoes settled in highlands due to increased rainfalls and temperature (31).

As you can see in Table 4, another interesting point to analyse is the striking association between malaria epidemics and El Niño Southern Oscillation (ENSO) events. This relationship has been found to be statistically significant in some parts of South America such as in Colombia (32) and Venezuela (33). Likewise, in Oriomia (Ethiopia) malaria outbreaks clearly occurred during El Niño events, which triggered anomalous high temperatures and heavy rains (34) . Although climate change and El Niño events are different phenomena with distinct causes, both have an impact on human health and are interconnected (35). Particularly, anthropogenic climate change is exacerbating the frequency and intensity of El Niño events (36).

Table 5 demonstrates that land use changes have promoted microclimate changes, especially in temperature rise, which may have driven to increased Anopheles density in African highlands (22). Lindblade et al. detected that the replacement of natural swamp vegetation by agricultural crops resulted to increased temperatures, which consequently, aroused the establishment of more mosquitoes in villages located close to cultivated swamps than in those based near to natural swamps. Thus, the risk of malaria transmission has been raised in cultivated areas (27).

In line with this, in Amazon countries the link between deforestation and malaria has been assessed. In Peruvian and Brazilian Amazon there was reflected the close relationship among the breeding behaviour of Anopheles and human-made disruptions of nature through deforestation activity (37,38). It is important to bear in mind that although the global mean temperature is forecasted to rise in a long time-span over this century, larger local increases on a shorter time period can derive from deforestation, with surface temperatures increasing by as much as 3-4 °C
This scenario promotes *Anopheles* larval presence in the Amazon rainforest heightening malaria risk among local populations (37-39).

**DISCUSSION**

The main findings in this study corroborate the stated hypothesis. Climate change, acting via meteorological mechanisms, is having a pernicious indirect effect on malaria. Since malaria is a highly climate sensitive disease, is easily influenced by temperature rise and modification of rainfall and moisture patterns. These changes, driven by global warming, are potential risk factors that are slightly leading to a shift in the spatial distribution of malaria and to an increase in the incidence rates in endemic countries. Furthermore, climate change also contributes indirectly to this scenario through its boosting effect on ENSO frequency and intensity in Tropic countries, where anthropogenic activity is sustaining a breeding ground for local malaria epidemics.

**Strengths and limitations of this study**

Since this study is a scoping review, the methodology is very preliminary in comparison with other styles of review (e.g. Meta-analysis). The theoretical association among climate change and malaria is fairly recent, there are few published data and, although the WHO and the IPCC underscore the existence of such link, it is still a subject of discussion within the scientific community (45).

Nonetheless, this scoping review provides updated data from 1994 until this present year and aids to outline, elucidate and refresh relevant findings upon the relationship of climate change and malaria. One may differ that the source of information, originating from developing countries, is less reliable due to their lack of high quality health infrastructures. Notwithstanding their difficulties, the selected studies show that the methodology of data collecting is accurate and rigorous.

There are some previous reviews in the literature regarding the impacts of climate change on human health (5,10,40,41), and some papers focused on climate change and vector-borne diseases (42). However, there are only two reviews on climate change and malaria. The first one was published 20 years ago (43), and therefore does not include updated information; and the other although it contains “climate change” and “malaria” as keywords, it is focused on from a socioeconomic perspective (44). Hence, a strength from this study is that is the first attempt to examine literature upon climate change and malaria in a scoping review.

**Changes in climatic variables lead to malaria outbreaks in endemic countries**

In most study outcomes, climatic changes in the three weather variables – temperature, precipitations and relative humidity – were significantly correlated with lagged malaria incidence and epidemics, in time series analyses and outbreaks studies, respectively (46). Typically, temperature was considered to be the most determining factor on malaria incidence since not only it exerts a critical influence on mosquito survival - as the rest of variables – but also on the parasite...
development (17). This was illustrated, for instance, in the cooler districts of Northwest Frontier Province in Pakistan, where despite having more precipitations; there were less reported cases of malaria suggesting that temperature was more influential than rainfalls (16). However, in some regions rainfall resulted to be the greatest factor linked to malaria (14,19, 20, 29, 31). Other studies reported a closest relationship among relative humidity with malaria incidence (21) and Anopheles density (22). The variety of the results shows the complexity and difficulty in assigning the most influential climate variable and suggests that this category differs from one region to another in accordance with other microclimate and environmental factors.

In terms of temperature, although Kipruto et al. detected that maximum temperature was the most associated factor to malaria, they concluded that such relation could be caused by micro-ecological differences in some regions (23). High temperatures accelerate the sporogonic cycle and the time taken for vector populations to breed. As a result of this, smaller adults are produced, and they require multiple blood meals in order to reproduce which translates into an increase of biting behaviour (47). On the other hand, minimum temperature sets the minimum threshold from which the mosquito can survive and conduct the process of Plasmodium development. That is why in most of the papers, minimum temperature was strongly more related to malaria than maximum temperature being one of the best predictors of malaria epidemics(27,28). Likewise, the studies performed in Iran (26) or in Rwanda and Uganda highlands (24,27) indicate that tiny variations in temperature may exert sharp impacts on the local transmission and incidence of malaria. Small perturbations in this variable are predisposing areas, that originally did not provide suitable conditions neither for Anopheles nor for Plasmodium, to become current risk areas prone to local outbreaks.

**Malaria is rising upwards in terms of altitude: the case of African highlands**

In African highlands, while valleys have been the scenario of many malaria outbreaks, it was well known by the first European settlers in the continent that hills were one of the safest shelters to protect themselves during malaria seasons. In other words, altitude has been one of the natural ancient barriers against malaria (48). By contrast, over the end of twentieth century, those areas have turned out to be unstable regions susceptible to malaria transmission. Global warming along with agroforestry development, aggravated by limited health resources, are the main causative factors of this fact. Furthermore, unlike adult population from the lowlands, highlands inhabitants have little or no immunity against malaria; hence both adults and children can be affected by the parasite similarly. This fact explains why the fatality rate was dramatically higher for children aged under 2 years and inhabitants from high altitude areas in the outbreak occurred in Rwanda by 1987 (24). Thereby, highlands are particularly vulnerable regions because malaria epidemics may be triggered by subtle climatic changes, and these outbreaks can result to catastrophic consequences due to the lack of immunity against the disease in the local communities as also befell in Ethiopia by 1953 and 1958 (49).
Malaria distribution is moving up in altitude as warmer years are coming. Siraj et al. demonstrated empirically an increasing trend in malaria incidence from 1980 until the end of 1990 in highland regions of northwest Colombia and central Ethiopia. The case of Ethiopia is very illustrative since an increase of 1 °C in mean temperature over the decade resulted to an additional 2,166 reported cases during the main transmission season (50).

Conversely, Hay et al. published the first paper in which the attribution of climate change as a primary cause of the steep rise of malaria in the East African Highlands was rejected (45). By contrast, Patz et al. refuted their results since the global climate data set was used inappropriately given its coarse resolution and the large attitudinal variation within these regions (51). Furthermore, other nonparametric and parametric statistical analyses and dynamical models applied in the same highland sites with updated data contrast with the conclusions underlined by Hay et al. and strengthen the link among climate change and the increasing trend of malaria incidence in African Highlands(52).

The impact of El Niño and droughts on malaria incidence, and human activity as a disruptive element for Anopheles ecology

Global warming is also exacerbating the incidence and distribution of malaria through its current rise on ENSO events in terms of frequency and intensity (36,53–56). The link between these events and periodic outbreaks of malaria is tangible and was confirmed by Bouma et al. in Colombia, Venezuela and Ethiopia (32–34). The spread of malaria vectors from endemic areas in Paraguay to Argentina was also driven by El Niño events by 1991-92 (57). The understanding of such association could help Tropic countries to predict and prevent forthcoming epidemics. Furthermore, some authors have suggested that modifications in the ecosystem of southern South America caused by climate change would allow Anopheles darling to spread its habitat southwards (58,59).

Nevertheless, climate change and El Niño events not always lead to the emergence of malaria outbreaks. Excessive heavy rainfall can wash away breeding sites resulting in the elimination of the mosquito larvae (60). Besides that, many areas across the globe are experiencing dryness in their lands due to climate change. Drought has also been identified as a contributing factor in increased malaria mortality. Not only because drought-related malnutrition increases the susceptibility to infection among the individuals, but also it contributes to the reduction of lakes or rivers to small pools that serve as breeding sites for the mosquitoes (61). In contrast with this, increased temperatures and drought are having a negative effect on malaria vector populations in some regions since breeding sites lack of necessary humid conditions and the temperatures are too high for their survival. This has been seen in the Niayes area of Senegal, where A. funestus has almost disappeared and consequently, malaria incidence has remarkably dropped (62). This, in turn, has also promoted the vector migration towards other areas, which has caused further cases of malaria(30). Although soil dryness seems to be a protective element against malaria in some areas,
from a major global point of view, it is one of the main causes of malnutrition and dehydration, entailing other health and socioeconomic consequences. Because of this, dry spells are an issue that is being tackled in many African countries. However, studies in Ethiopia show that climate change adaptation strategies, such as the installation of irrigation systems in dry areas, have led to a significant increase in malaria incidence (63,64). This highlights the fact that such facilities, which provide water supplies and ease the productivity and life quality of local communities, need to be accompanied by precautionary measures in order to prevent the settlement of *Anopheles* populations.

In line with this, there are other anthropogenic factors that along with climate change are having a synergistic effect on malaria incidence and distribution. In our results, we highlighted land use change and deforestation as an example of human ecologic alteration. Between 1981 and 1990 there has been a clearance of 2.9 million hectares approximately, representing an 8% reduction in forest cover occurred in only one decade(65). Forest fragmentation and removal of vegetation (and thereby, transpiration of plants) disrupt the distribution of mosquitoes and alter local weather patterns significantly achieving temperature levels that are higher than those predicted by global climate change models under a doubling of carbon dioxide emissions (66,67). Thus, when swamps are cleared for crops cultivation, surface water provides suitable conditions for *Anopheles* breeding sites. Other authors have attributed recent malaria outbreaks to drug resistance problems (68) and new migratory flows due to war or environmental reasons(69). While indeed these factors contribute in the generation of suitable conditions for malaria epidemics, is undeniable that these processes are triggered by climatic variables acting as primary agents(70).

**Seeking future effects: computational development of scenario-based models**

In light of the above, these evidences lead us first to reflect upon the disruptive impact that global warming is causing in malaria over populations from endemic countries. Scientific community opens to multiple possible future scenarios within the forecasted trends of temperatures and sea-level rise. In fact, systems biology scientists have designed and are working on predictive simulation models on the malaria distribution regarding the future climate projections. The introduction of MARA (Mapping Malaria Risk in Africa) project allowed defining climatic suitable areas for malaria transmission in Africa (71). However, its drawback is the assumption that malaria distribution limits are constrained only by climate without taking into account other factors. Alternatively, mathematical models (e.g. Liverpool Malaria Model) use equations that include climatic variables as well as biological parameters – i.e., parasite incubation rates, vector breeding, survival and biting rates (72). According to computer multiple modelling studies, it seems likely that global temperature increases of 2-3 °C will significantly raise the number of individuals who, in climatic terms, are at risk of malaria by around 3-5%, i.e. several hundred millions (73,74). It is also expected that malaria season would extend in many currently endemic regions (75). On the other hand, landscape-based modelling is
combined with climate-based models in order to assess the effects of anthropogenic alteration of natural habitats (76).

Around the 75 % of the non-African cases are concentrated in many countries from South and Southeast Asia, being areas high sensitive to weather conditions and very concerned about forthcoming malaria epidemics (7). Khormi et al. illustrated the potential impact of climate change on the spatial distribution of malaria in Southeast Asia by 2050 and 2100. This projection is based on meteorological variables including temperature, humidity, heat, cold and dryness. They 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. The current malaria geographical distribution had a 90 % of coincidence with the prediction done by the software providing further reliability on their results. According with this model, environmental suitability for malaria is forecasted to decrease in India, southern Myanmar, southern Thailand, eastern Borneo, Cambodia borders, Malaysia and Indonesia. This is due to potential changes in heat stress, being those countries excessively hot beyond the maximum threshold of survival values for the mosquito vector. By contrast, a decreased impact of cold stress is estimated to prone a rise of malaria in southern and south-eastern China and Taiwan (77). These results coincide with the predictions obtained by two general circulation models (GCMs) under stabilizing (RCP4.5) and very heavy (RCP8.5) emission scenarios; where an increase in China’s population exposure to malaria vector was forecasted by 2030 and 2050 (78).

Possible implications for Western countries

Anopheles genus mosquito is widely distributed among countries and regions worldwide (79). Although malaria is officially eradicated in Europe, Anopheles atroparvus, the major vector of malaria during the twentieth century, remains widespread from south-eastern Sweden to Portugal across the coasts of the Atlantic and around Mediterranean and Baltic Seas (80). In north Australia, there are still larvae of An. Farauti. Moreover, Anopheles quadrimaculatus, An. pseudopunctipennis and An. freeborni inhabit in some parts of United States and western Canada (79). One concern manifested by some authors is the possible resurgence of malaria in Western countries driven by several favorable factors, among which are: 1) The presence of autochthonous vector, 2) Prone weather conditions pushed by climate change and 3) Other globalization effects such as migratory influx, freight traffic and travelers arrival from endemic regions (81–85). For instance, during the 1990s occurred sporadic local outbreaks in New York and New Jersey in people without reported travel history. Notably, the common aspect among those cases was the exceptional hot and humid weather (86,87). In Europe, there are recent local reported cases in P. falciparum in France (88) and Germany (89). Moreover, in rural areas of Italy (90), Spain (91) and Greece have occurred autochthonous P. vivax infection; being very significant the last mentioned country since it hosted 20 cases by 2011 (92). None of these cases reported travel history. In Australia, although most of the
cases are contracted in Papua New Guinea, there is a current concern due to the proximity of both countries and hosting the same vector specie, *An. Funestus* (81).

Rogers et al. performed a prediction on *P. falciparum* future distribution in the world applying global circulation models (GCM) scenarios by 2050. According to this, as the climate warms, malaria parasites are likely to be introduced from tropical countries, expand their ranges within eastern Mediterranean coasts, south United States, north of Australia and westward in China (93). Interestingly, although Western Europe has hosted local cases and has climate patterns conducive for malaria transmission, this model does not forecast this area to become suitable for *P. falciparum* transmission in the coming future. This is consistent with previous experimental work that confirmed *Anopheles atroparvus* refractoriness to *P. falciparum*, the sub-Saharan African parasite. This explains why most of the autochthonous reported cases of malaria were caused by *P. vivax*, which arose from the Mediterranean area of South West Asia (94). Nonetheless, as occurred with Chikungunya Virus, the possibility of a mutation in *P. falciparum* resulting in a modification in *A. atroparvus* receptivity cannot be excluded (95).

Rather curiously, in Rogers’ et al. prediction, the northern coast of Australia and a tiny area in the southwest of US are false-positive areas with current suitable conditions for malaria transmission (93). This fact highlights the successful vector control campaigns in both countries and underlines our good surveillance systems and health infrastructures as potential safeguards to restrain large scale outbreaks. This may not be the case for developing countries where, unfortunately, health care services and medication are not attainable for all the citizens.

**Next steps towards a progress in malaria research and public health policies**

All the above-mentioned models are fairly accurate and rigorous. Nevertheless, whether these predictions are translated into reality depends on how fast the climate changes, how successfully humans adapt to new conditions and tackle the issue of malaria. Therefore, in this scoping review we highlight the following future research areas and measures to deal with climate related malaria:

- Persevering in epidemiological research upon climatic factors and malaria incidence and distribution as well as further development of comprehensive mathematical and land-use based models.
- Interdisciplinary research teams are needed to assess in depth links between climate change and malaria along with local socioeconomic factors in endemic and non-endemic regions. This is the key to predict the forthcoming risk of the disease and improve epidemic preparedness, especially in the most vulnerable and poor areas.
- In this scoping review, we included some examples that indicate that advances in infrastructure systems (e.g. irrigation, agriculture) in developing countries are not always followed by health improvements. Thus, we encourage doing more malaria research and investment in enhancing dwellings, environmental health and sanitation policies in low-income countries.
• Overall, it is essential to increase in global health surveillance and the active involvement by industrialized states in raising public health infrastructures in developing countries.

CONCLUSION

Low-income countries are burdening the worst consequences of climate change in all its aspects (environmental, sanitary and socioeconomic) without being the primarily responsible for this situation.

Climate change effects on health are a particular threat for the poorest populations. By 2000, while in developed countries the number of total DALYs (Disability-Adjusted Life Year)/million population related to climate change accounted for 8.9, in the remaining regions the number was up to 340 times over (e.g. in Africa was around 3,071.5) (73). Among the indirect impacts, which cause by far the greater damages to human health in terms of morbidity and mortality, there is the increasing susceptibility in the emergence of more epidemics in malaria, and the spread of the disease towards higher altitudes and latitudes where populations are less resilient. Being malaria one of the most extended and climate sensitive diseases in the world, with its vector highly widespread, more than the 40 % of the world’s population are exposed to the risk of acquiring the disease (7).

Malaria, at the same time, is a paradigm of health, socioeconomic and environmental inequity issue in the world. The eradication of malaria from industrialized countries, after the Second World War, demonstrated that this goal could only be achieved if technology and economic resources were available. Hence, despite climate change hazard, if malaria is attached as a matter of the utmost importance by Western states through accelerated vaccine development along with technical and financial support to strengthen and speed the growth of developing countries, the situation would change drastically. Likewise, major political involvement and awareness in the fight against climate change is a top priority within the current context. Reaching the Global 2030 malaria goals along with more effective environmental management will not only save millions of lives, but also will encouragingly reduce poverty and promote the progress towards healthier and more equitable societies.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Fernando G. Benavides for his willingness to tutoring the review, for being patient and providing very valuable and helpful advice during the development of the project.
REFERENCES:


44. Suk JE. Climate change, malaria, and public health: accounting for socioeconomic contexts in past


countries. Rome; 1993.


73. Woodward A et al. Climate change and human health Editors. WHO. 2003;


### Table 1. Description of outbreaks studies on climate change and malaria.

<table>
<thead>
<tr>
<th>Author and year of publication</th>
<th>Study country</th>
<th>Study Aim</th>
<th>Key findings</th>
</tr>
</thead>
</table>
| **Loevinsohn, 1994 (24)**    | Rwanda        | To investigate the contribution of climate to a malaria outbreak occurred in 1987 in Rwanda, where malaria incidence was increased by 337 % over the 3 previous years. | ▪ 1987 set a record in high temperatures and precipitations.  
▪ Case-fatality increased significantly (Relative Risk = 4.85, p < 0.001).  
▪ The rise was greatest in children under 2 years old (564 %) and people living in high-altitude areas (501 %).  
▪ The increase in higher altitudes was predicted by the environmental temperature.  
▪ An autoregressive equation that included lagged impacts of temperature and rainfall explained the 80 % of the shift in monthly malaria incidence. |
| **Bouma et al., 1996 (16)** | Pakistan      | In the Northwest Frontier Province of Pakistan malaria incidence increased from a few hundred reported cases in 1983 to more than 25,000 by 1990. Thus, they analysed the influence of temperature, rainfall and humidity on the autumnal outbreaks of *P. Falciparum* in this area. | ▪ Since 1876 there has been an increase in October rainfall (more than 100 %) and in mean November and December temperatures by 2 ºC and 1.5 ºC, respectively. Humidity in December has also been increasing significantly since 1950.  
▪ Rainfall, temperature and humidity peaks in autumn were all correlated ($r^2 = 0.82$) with the *P. falciparum* rate since 1981 and the annual *P. falciparum* proportion since 1978.  
▪ In cooler districts, although there was more rainfall amount, malaria incidence was lower than in the rest of the Province. |

### Table 2. Description of time series studies on climate change and malaria.

<table>
<thead>
<tr>
<th>Author and year of publication</th>
<th>Study country</th>
<th>Study Aim</th>
<th>Key findings</th>
</tr>
</thead>
</table>
| **Ndiaye et al., 2001 (19)** | Senegal       | To find out the correlation between climate variability and the 661 deaths from malaria in Niakhar (Senegal) from 1984 to 1996. | ▪ Mortality peaks occurred two months after the rainfall peaks.  
▪ There was a positive and significant correlation between malaria mortality within the rainfall season (between August and December) and rainfall variability in August ($r = +0.61$, $p = 0.02$).  
▪ Monthly rainfall series and mortality series at one and two-month lag were slightly significantly correlated ($r = + 0.43$, $p = 0.0004$ and $r = + 0.26$, $p = 0.03$, respectively). |
| **Bi, 2003 (28)**             | China         | To evaluate the impact of climate variability on the transmission of malaria in Shuchen County (China) during the period 1980-1991. | ▪ Temperature, relative humidity and rainfall were positively correlated with monthly incidence of malaria in Shuchen County, with one-month lagged effect. ($r > 0.6$, $p < 0.0001$)  
▪ Minimum temperature was more related to malaria incidence than maximum temperature. |
<table>
<thead>
<tr>
<th>Authors</th>
<th>Location</th>
<th>Study Objective</th>
<th>Key Findings</th>
</tr>
</thead>
</table>
| Devi et al., 2006 (20) | India    | To investigate the effects of climatic factors on malaria incidence and to determine the essential events owing to climatic variability during 1999-2002. | - Monthly malaria incidence and meteorological variables (temperature, humidity, and rainfall) were positively correlated.  
  - The greatest association was found among malaria incidence and rainfall ($r=0.718$, $p<0.0001$) with a lag of one month. |
| Huang et al., 2011 (21) | Tibet    | To analyse the association between malaria incidence and monthly meteorological data (rainfall, relative humidity and temperature) between 1986 and 2009 in Motuo County (Tibet). | - The three meteorological variables were correlated with malaria reported cases. Relative humidity was the most closely variable correlated to malaria incidence. ($r=0.543$, $p<0.01$).  
  - Malaria epidemics were correlated with rainfall with a lag from one to three months ($r>0.4$) and with temperature and relative humidity with a lag from zero to two months ($r>0.5$). |
| Henninger et al., 2013 (25) | Rwanda   | To perform a regional climatic analysis in the entire territory of Rwanda and investigate the possible spread of Anopheles mosquito linked to local climatic changes from 1931 until 2011. | - There has been a significant shift in the climate zones of Rwanda. Overall, the most remarkable modifications have occurred in the “mountain climate” regions, that have been reduced due to the highest rainfall decrease and temperatures records that are unusual for these altitudes. For the same reasons, the east-Rwandan, dry and hot lowland zone has extended encroaching the temperate zone of the central highlands.  
  - The rise of malaria incidence took place in the original and expanded dry and temperate zones. |
| Weli et al., 2015 (14) | Nigeria  | To explore the climate impact on malaria incidence in Port Harcourt for a time span of 65 years (1950-2014). | - Since 1950, there has been an increase of 1581 mm of rainfall and a temperature warming of 3 °C in Port Harcourt. This led to an increase of 8934 cases until 2014 ($t=5.69$, $p<0.05$).  
  - July and September are the months with most incidences of precipitations, and coincide with the double maxima of malaria caseloads with 1006 and 1540 reported cases, respectively. ($r=0.805$, $p<0.05$). |
| Mohammad khani et al., 2016 (26) | Iran     | To evaluate the effect of temperature, humidity and rainfall on malaria incidence in the southern cities of Kerman province from 2000 to 2012. | - Temperature was the climate variable that had the greatest influence on malaria incidence.  
  - A 1 °C increase in maximum temperature in a specific month was related to a 15 % and 19 % increase on malaria incidence on the same and following month, respectively ($p=0.001$). |
| Kipruto et al., 2017 (23) | Kenya    | To describe the effects of variability of maximum temperature, precipitation and vegetation indices on seasonal epidemics of malaria in Baringo County (Kenya) through a time series analysis between 2004 and 2014. | - There has been a significant increase in malaria incidence in the highland and midland regions linked to fluctuations in precipitations and maximum temperature.  
  - Rainfall at a time lag of 2 months resulted in a rise in malaria transmission across four ecological zones studied (riverine, lowland, mid-altitude and highland), whereas an increase in temperature at time lags of 0 and 1 month resulted in a rise in malaria incidence in the riverine and highland zones, respectively. |
Salahi-Moghaddam et al., 2017 (30) Iran To investigate the distribution of Anopheles in relation to environmental variables in Iran.

To study whether there has been a shift in the distribution during the last 50 years under the context of climate change.

- Iran is facing with significant changes in the climate marked by the lack of precipitation, sudden and heavy episodes of rainfall and extreme temperatures. One of the consequences is the shift in geographical distribution of Anopheles in the country.
- The main mosquito species that have moved towards other parts of the territory are An. culicifacies and An. Fluviatilis.
- An. culicifacies, the major malaria vector in Iran, has been migrating towards the southern and eastern parts, from high to low lands, where there are more episodes of rainfall.
- During the past decades An. fluviatilis has shifted from highlands (1050 m) towards southern areas (141 m) \( (p < 0.001) \) since those were regions with more humidity and water availability.

### Table 3. Description of geographical comparison studies on climate change and malaria.

<table>
<thead>
<tr>
<th>Study</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minakawa et al., 2002 (22)</td>
<td>Kenya</td>
<td>To determine whether climatic factors have influenced on the distribution and abundance of three malaria vector species, An. gambiae, An. arabiensis and An. funestus in western Kenya and in the Great Rift Valley.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regarding Anopheline distribution, the three species were abundant in the lower part of western Kenya, while An. gambiae was not found in the Great Rift Valley. Although An. gambiae and An. funestus were recorded in sites above 1,700 m in western Kenya, their densities were below 1 per house. The most distributed vector was An. funestus.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The density of An. funestus increased to 40.5 % during the dry seasons, while the proportion of An. gambiae was reduced to 51.8 % from the 70 % pertaining to rainy seasons in western Kenya.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moisture variable was highly positively correlated with An. gambiae relative abundance ( (r^2 = 0.82) ).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature had a significant influence on vector proportion for all three species.</td>
</tr>
<tr>
<td>Klutse, 2014 (29)</td>
<td>Ghana</td>
<td>To examine the association among malaria occurrence, temperature and rainfall patterns and the potential effects of climate change on malaria epidemiological trends. Therefore, they analysed weather data and malaria caseloads in two ecological zones in Ghana (Ejura and Winneba in the transition and coastal savannah zones, respectively) over 8 years (from 2001 to 2008).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>There was a lag negative correlation of up to four months after rainfall peaks and monthly peaks of malaria ( (r= -0.72; p &lt; 0.05) ).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean monthly maximum temperature and monthly malaria reported cases were positively correlated at four-month lag in Enjura, ( (r= 0.68, p &lt; 0.05) ); whereas in Winneba the strong correlation was observed at two-month lag ( (r= 0.70; p \text{ value} &lt; 0.05) ).</td>
</tr>
<tr>
<td>Park et al., Papua</td>
<td>Papua</td>
<td>To assess the malaria incidence rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In the highland area of Papua New Guinea - especially in the Eastern Highland Province - there has</td>
</tr>
</tbody>
</table>
New Guinea concerning the geographic and climatic conditions.

To determine the effect of altitude on the expansion trend of malaria over the last decade in Papua New Guinea.

been a significant increase of malaria incidence (292 cases/100000/yr, p = 0.021), whereas in the southern coastal region there has been a significant decrease (-921.3 cases/100000/yr, p = 0.0024).

- Malaria incidence fluctuation corresponded to a seasonal trend pattern associated with rainfall. In the Eastern Highland Province, malaria incidence rate peaked during the late wet season after rainfall season accompanied by increases in monthly maximum and minimum temperatures. Conversely, in the southern coastal region, the reduction in malaria incidence was related to declining rainfall.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 (31)</td>
<td>New Guinea</td>
<td>concerning the geographic and climatic conditions. To determine the effect of altitude on the expansion trend of malaria over the last decade in Papua New Guinea.</td>
</tr>
</tbody>
</table>

Table 4. Description of time series studies on ENSO (El Niño-Southern Oscillation) and malaria.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bouma et al., 2016</td>
<td>(34)</td>
<td>Ethiopia</td>
<td>To determine whether there is a linking between warmer temperatures associated with ENSO and a higher malaria risk for Oromia (Ethiopia) within the time period between 1982 and 2005.</td>
</tr>
</tbody>
</table>

- In El Niño years and in the year following an El Niño, the number of malaria reported cases increased by 17.3 % and 35.1 %, respectively, being usually higher than the 5-year moving average (p < 0.01).
- There is a significant correlation between high Sea Surface Temperature (SST) anomalies and incidence rates of malaria (r = 0.62, p < 0.001).

- In years following ENSO events, malaria mortality and morbidity have resulted in a significant increase by 36.5 % (p= 0.004).
- SST occurred during El Niño were moderately correlated with malaria incidence in the year following an ENSO (r= 0.50, p<0.001).

- There was a high association among malaria incidence and elevated temperatures (+1.6 °C) in the Pacific (r²= 0.6, p < 0.001).
- A 70 % increase in malaria risk was expected for the period from August 2016 to July 2017.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindblade et al., 2000</td>
<td>(27)</td>
<td>Uganda</td>
<td>To investigate the effect of land use change on malaria transmission in the south-western highlands of Uganda between December 1997 and July</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The higher proportion (64.7 %) of An. gambiae was collected from villages located alongside cultivated swamps.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High levels of IRD (Indoor Resting Density) of Anopheles were reported during and following the rainfall months. Moreover, the difference in IRD of the vector among natural and cultivated swamps</td>
</tr>
</tbody>
</table>
To assess differences in temperature, humidity and saturation deficit between natural and cultivated swamps. was highly notorious during the same time span.

- Both mean maximum and minimum temperatures were approximately 0.9 °C higher in villages located near cultivated swamps than in those located near natural swamps ($p < 0.0001$). These temperature differences were consistent over time.
- Dwellings located near cultivated swamps had 2.14 times the IRD of houses located along natural swamps.
- As the average minimum temperature increased 1 °C, the IRD increased by 73 %.
- The wet season was correlated with 13 times increase in IRD over the dry season.

**Vittor et al., 2009 (37)**

Peru

To examine the larval breeding habitat of *Anopheles darlingi* in transects with different degrees of ecologic alteration in the Peruvian Amazon in order to find out the most significant determinants of *An. darlingui*. In particular, focusing on deforestation activity.

- Seasonality, algae, water body size, presence of human populations, and the amount of forest and secondary growth are significant determinants that conditioned the presence of *An. darlingi* in the Peruvian Amazon.
- *An. darlingi* was found most frequently - around 17.1 % of larvae were positive - in sites with little forest remaining. In sites with moderate forest about 10 % of the larvae were positive for *An. darlingi*. On the contrary, in the primarily forested sites there was only a frequency of 2.3 % *An. darlingui* larvae.
- Sites with *An. darlingi* larvae had an average of 24.1 % forest cover, in contrast with the 41.0 % for sites without *An. darlingi*. ($p < 0.0001$).

**Terrazas et al., 2015 (38)**

Brazil

To investigate the distribution of malaria in the Brazilian State of Amazonas, and assess the correlation between the incidence rates and environmental factors (deforestation and local drainage network) as well as population socio-economic indicators (municipal human development index - MHDI- and poverty rate).

- Between 2003 and 2012, 12,976.02 of indigenous suffered malaria, compared with 3,749.82 of non-indigenous population.
- There was a negative correlation between the two socio-economic indicators and the incidence of malaria.
- Regarding environmental factors (average annual deforestation rate and % of areas under the influence of watercourses), the correlation with malaria incidence turned out to be positive.