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Climate change engenders a better Early Warning System development across Sub-Saharan Africa: The malaria case

Ayansina Ayanlade [a,c,*], Consolato M. Sergi [b,f], Patrick Sakdapolrak [a], Oluwatoyin S. Ayanlade [d], Paola Di Carlo [e], Oyekanmi I. Babatimehin [c], Lemlem F. Weldemariam [a], Margaret O. Jegede [d]

[a] Department of Geography and Regional Research, University of Vienna, Universitätsstraße 7/5, 1010 Vienna, Austria
[b] Department of Laboratory Medicine and Pathology, University of Alberta, Edmonton, AB, Canada
[c] Department of Geography, Obafemi Awolowo University, Ile-Ife, Nigeria
[d] African Institute for Science Policy and Innovation, Obafemi Awolowo University, Ile-Ife, Nigeria
[e] PROMISE Departments, University of Palermo, Italy
[f] Anatomic Pathology Division, Children's Hospital of Eastern Ontario, University of Ottawa, Ottawa, ON, Canada

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ABSTRACT

It is expected that diseases are likely to spread to newer areas, and high-income countries may experience some illnesses that may have been restricted to low or middle-income countries. In addition, following the Intergovernmental Panel on Climate Change, the present study noted that climate change is likely to have many effects on the spatial and temporal distribution of malaria in many Sub-Saharan African countries. This study examines climate change effects on the geographical distribution of malaria occurrence and how extreme climatic events may perhaps be determining factors in the range of vectors for human diseases in SSA in the nearest future. Here, the study appraisals the symbiotic connection of (1) malaria transmission and association with the changes in temperature, rainfall, and humidity as well as their extremes in SSA and (2) the relationship between climate and malaria with the role of climate change in determining upsurge in malaria and meningitis occurrences in the SSA. The study concludes that major drivers of malaria occurrence are climatic elements such as precipitation and temperature. Therefore, we call for a better early Warning System on a proposed roadmap solution for Sub-Saharan Africa.

1. Introduction

Malaria is among the top ten epidemics facing African countries, leading to the death of all age groups. There is overwhelming evidence from scientific studies that extreme climate events resulting from climate change are likely to promote the prevalence of some diseases globally, but much more incidences in Sub-Saharan Africa (SSA). Malaria is presently one of the most dangerous diseases in the SSA regions, due to the humid and warm climatic type. The effects of climate change have been projected to include significant increases in floods, extreme heat events, drought, aridity, and wildfires. The majority of climate extremes manifest in temperature and precipitation changes, leading to floods, droughts, fires, and floods, droughts, fires, and heatwaves in many parts of the world. These pose considerable risks to the health of human populations, particularly in SSA (Yeboah et al., 2021; Wright et al., 2021; Pasquini et al., 2020). Hence, some population groups are at considerably higher risk of contracting malaria and developing severe diseases: infants, children under 5 years of age, and pregnant women in many SSA countries (Trisos et al., 2022). The recent report of the Intergovernmental Panel on Climate Change (IPCC) Working Group II AR6 further detailed high confidence that increases in many of these climate extreme events will challenge human health in sub-Saharan Africa (IPCC, 2021). The report also detailed that human health is sensitive to shifts in weather patterns and extreme climate events. Trisos et al. (2022) further indicated with high confidence that the climate has contributed to malaria outbreaks in the highlands of East Africa and that the malaria-carrying Anopheles mosquito will travel quickly; with range changes of up to 4 metres per year in elevation and 18 kilometres per year in latitude have been recorded. Thus, tens of millions more people are exposed to malaria in East and southern Africa.

Suppose the impacts of climate change on the incidence and spatiotemporal distributions of diseases are left unaddressed, then an increase in temperature, rainfall, and humidity may lead to an increase in the number of malaria-carrying mosquitoes at higher altitudes, increasing the transmission of malaria in regions where it had not previously been reported (Trisos et al., 2022). In that situation, this might potentially make it more difficult for SSA nations to achieve several of the Sustainable Development Goals (SDGs). This is because many

* Corresponding author.
E-mail address: ayansina.ayanlade@univie.ac.at (A. Ayanlade).

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vector-borne diseases, communicable and non-communicable diseases affecting people both in urban and rural settlements in SSA are much climate-sensitive (Rother et al., 2020; Rocklöv and Dubrow, 2020). The overall consequence of extreme weather conditions in SSA is much more evidence of malaria prevalence. The epidemiology of malaria has recently changed, though, and this raises the possibility that the environmental factors influencing disease patterns are also shifting. Malaria will become more prevalent and severe as a result of the effects of climate change when combined with poverty, particularly in SSA nations. Many of studies on climate-health issues have focused on statistical descriptions of climate change/variability impacts on diseases. However, we make agenda-setting to develop a better Early Warning System to monitor and model both spatial and temporal variations in malaria prevalence as climate changes. This short communication at understanding the climatic conditions that drive mosquito abundance and the occurrence of malaria. Besides the main emphasis in this study is that the future patterns of disease transmission can be predicted with the aid of better a Early Warning System as contingency plans put in place prior to a major disease outbreak.

2. Methods and study area

In this study, a critical review of studies on the observed and projected impacts of climate change on the distribution of malaria in sub-Saharan Africa (SSA) was examined. Theoretical articles from decades of empirical research on evidence of extreme climate events and their impacts on the occurrence of malaria were reviewed, based d on the justification that climate change now presents the most severe environmental challenge in many countries in SSA. This review is based on a number of overwhelming pieces of evidence from scientific studies that extreme climate events resulting from climate change are likely to promote the prevalence of some diseases globally, but much more incidences in SSA. These helped to understand climate extremes' spatial and temporal pattern as they affect malaria spatiotemporal distributions in SSA. This study examines climate change effects on the geographical distribution of malaria occurrence and how extreme climatic events may perhaps be determining factors in the range of vectors for human diseases in SSA in the nearest future. Here, the study appraisals the symbiotic connection of (1) malaria transmission and association with the changes in temperature, rainfall, and humidity as well as their extremes in SSA and (2) the relationship between climate and malaria with the role of climate change in determining upsurge in malaria and meningitis occurrences in the SSA. Lastly, the study positions the need for a better early Warning System on a proposed roadmap solution for Sub-Saharan Africa.

Sub-Saharan Africa lies in different agro-climatic belts with specific features based on precipitation and temperature characteristics which determine vegetation distributions. There has been growing concern about climate change and the need arises to take a critical look into the changes in the trends of climatic parameters in SSA (Herrmann and Hutchinson, 2005; Clement, 2013; Ayuba, 2007). In recent years, it has been reported that the Sudano-Sahelian agro-ecological of SSA is most affected by droughts, as the region is experiencing higher temperatures and low precipitation. Although, global climate models predict increasing temperatures and decreasing precipitation in many parts of the SSA continental areas. Climate change has already led to some changes in ecosystems in SSA and future climate change will strongly influence biodiversity, ecosystem processes, and human health. This suggests that the linkages between climate change and human health encompass multiple systems and sectors (Lindley et al., 2019; Yokohata et al., 2019).

3. Climate–malaria relationship: case studies in SSA

Climate change is expected to have a largely negative influence on human health in SSA. Recent studies on the relationship between climate and malaria have placed a strong emphasis on the part that climate change plays in predicting an increase in malaria cases in SSA countries (Diouf et al., 2022; Makinde et al., 2021; Diouf et al., 2017a; Ayanlade et al., 2020a). Some of these studies claimed that temperature is the key study parameter rather than rainfall while the majority of the studies noted that the rise in the number of inpatient and outpatient patients with malaria is significantly influenced by the lowest temperature, quantity of rainfall, and relative humidity (Makinde et al., 2021; Ayanlade et al., 2020b; Abiodun et al., 2018b). What is noticeable from these studies is that climate change can influence malaria transmission by increasing temperature while high temperatures can likewise shorten the parasite's reproduction cycle within the mosquito. On the other hand, Diouf et al. (2022) findings demonstrated the unimodal distribution of malaria prevalence, and the seasonal contrast in malaria transmission is strongly related to the latitudinal variation in rainfall. According to projections, the mean annual prevalence of malaria will decline in both climatological eras under both RCPs, although under the RCP8.5, the decline would be more pronounced. The results from this study, like other studies show that in the majority of West African countries, such as Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo, malaria transmission has been related to climate variability and change (Ayanlade et al., 2020a; Diouf et al., 2017a; Makinde et al., 2021).

Studies in southern and central Africa have shown that understanding spatial variations in climatic parameters is critical to understanding the transmission rate and dynamics of malaria and aid control measures. Over southern Africa, changes in temperature and rainfall are increasing malaria transmission and that rainfall and temperature have much impact on malaria dynamics (Abiodun et al., 2020; Makinde and Abiodun, 2020; Lubinda et al., 2021; Lubinda, 2020; Abiodun et al., 2018a). It was discovered, from these studies that an increase in the average daily rainfall and temperature, over southern Africa, considerably increases the likelihood of contracting malaria. In contrast, the number of vulnerable and exposed people has an impact on the spread of the malaria-related illness. Studies have shown that the current climate is most suited for endemic malaria transmission in central Africa. Warmer temperatures are, however, predicted to have a mixed effect on malaria incidence in Central Africa, especially in warmer routes (Ryan et al., 2015, 2020; Olivier et al., 2022). In the Central African Republic, healthcare costs from malaria could drop by $3,307.84 per 1,000 people by the end of the century, with a decrease in cases of 47.88 per 1,000 (Egbendewe-Mondzozo et al., 2011).

The observed and projected impacts of climate change on malaria in West Africa are largely unclear, with some projections suggesting reductions in risk in warmer pathways (Ryan et al., 2015, 2020; M'Bra et al., 2018). However, a study recommend possibly the most extreme increases in the cost of malaria, with projected increases of $17,436 per 1,000 people in Cote d'Ivoire by the end of the century (Egbendewe-Mondzozo et al., 2011). In Nigeria for example, Jonathan et al. (2018) noted that changes in climatic variables, such as rainfall, temperature, and relative humidity, affect mosquito abundance and related malaria morbidity, but a significantly positive linear relationship where observed between malaria morbidity and temperature. Other studies have shown that malaria incidence was related to element, rather than temperature of local meteorological conditions in Nigeria, such as in Jos and Kano (Akinbobola and Hamisu, 2022), although with varied lag periods and orientations. In all, the findings from these studies demonstrated that local climatic conditions have a greater impact on malaria incidence and that the potential impact of climate change is limiting control and preventative activities. Malaria incidence and outbreaks in Southern and West Africa have been linked to an increase one to two months after periods of rainfall (Adeola et al., 2019; Ferrão et al., 2017; Diouf et al., 2017b; Trisos et al., 2022).

Malaria outbreaks in East African highlands may worsen, and the illness burden may rise (Niang et al., 2014), besides the extension of the Anopheles vector into higher elevations is associated with an increase in the incidence of P. falciparum infection as temperatures rise (Gone et al., 2014; Carlson et al., 2019; Trisos et al., 2022). Climate extreme is likely to worsen malaria occurrence as its outbreaks were linked with periods of substantial rainfall and extreme floods (Simple et al., 2018; Amadi et al., 2018). There likelihood that climate change may increase malaria epidemics and the disease burden in Ethiopia, Uganda, and Kenya. Nearly 100 million individuals in East Africa might be exposed to malaria for the first time under RCP 8.5 scenarios. Malaria treatment expenses might rise by much to $7,389.46 per 1,000 individuals by the end of the century (Egbendewe-Mondzozo et al., 2011). It was noticeable from the publications reviewed that climate change impacts on the geographical distribution and transmission of malaria. Though climate predicts, to a large degree, the natural distribution of malaria, there are many substantial research challenges associated with studying linkages among climate, ecosystems and infectious diseases. Climate-related impacts, for example, must be understood in the context of numerous other forces that drive infectious disease dynamics, such as the rapid evolution of drug- and pesticide-resistant pathogens, the rapid global spread of microbes and vectors via expanding transportation networks, and the deterioration of public health programs in some regions.

Climatic elements determine most of the time, the survival of mosquitoes as well as transmission of the parasites. The key message from the literature is that malaria transmission is very complex in that it is dependent on many factors (apart from the climatic element) which include deforestation, irrigation, agricultural practices, and urbanization among other factors. For example, malaria is one of the principal tropical illnesses connected with irrigation projects, and variations in malaria transmission patterns following irrigation development have long been a source of contention (Ijumba and Lindsay, 2001). Irrigation has also increased tremendously in many parts of SSA, this is a usual practice in order to increase agricultural productivity to feed the growing population. This irrigation was created by building a large number of dams and canals, which often caused seepage from canals and a rise in water table, thus creating a source of still water in which malaria vectors could breed. Irrigation has been observed to increase malaria transmission season in some parts of SSA, as the irrigation system changed areas from epidemic to endemic malaria regions. Although crop irrigation promises to alleviate hunger and promote economic progress, it has frequently been accused of the increase in malaria transmission around irrigation schemes in Ethiopia (Kibret et al., 2014, 2010; Haileselassie et al., 2022), Ghana (Kyei-Baafour et al., 2020), Tanzania (Ijumba et al., 2002) and Malawi (Mangani et al., 2022). Irrigation during rice cultivation, using ponds for fish aquaculture, and storing of water in tanks for livestock all provide excellent breeding environments for mosquitoes in Nigeria (Oladepo et al., 2010; Amaechi et al., 2018). Some other agricultural practices, such as aquaculture, can create large areas of stagnant waters that are suitable breeding grounds for malaria vectors (Johansen and Ferreira, 2021). Small-scale irrigation infrastructure, if not effectively maintained, can have severe environmental consequences and jeopardize the integrity of riparian ecosystems (SDG 15) (Loucks and Van Beek, 2017), as well as serve as breeding grounds for mosquitos (SDG 3) (Attu and Adjei, 2018).

4. Climate change is likely to intensify malaria occurrence

Several studies have reported that the distribution and incidence of malaria have changed as a result of climate change, increasing death and morbidity (Abiodun et al., 2018a; Agyekum et al., 2021; Akinbobola and Hamisu, 2022; Ayanlade et al., 2020a; Craig et al., 1999). Malaria is vulnerable to climate change in that both the parasite that causes the disease and the vector that distributes it are influenced by weather conditions (Fig. 1), particularly rainfall and temperature. Thus, climate change is a critical driver leading to malaria prevalence, as climatic factors are important drivers of malaria transmission and spatiotemporal distribution in SSA countries. Changes in temperature, rainfall, and humidity, for instance, are likely to cause a proliferation of malaria-carrying mosquitoes. Temperature, rainfall, and humidity have been associated with the malaria vector population dynamics, influencing the disease's spread (Table 1). What worsens the situation is that in many SSA countries, the health infrastructures are rarely climate-resilient, poor healthcare, and there is much resistance of malaria mosquitoes to insecticides which now threatens vector control effectiveness (Fig. 2). Some studies have further reported that climate change, particularly the effects of temperature, may have influenced this resistance (Soko et al., 2015; Pu et al., 2020) .

The influence of the climate on malaria varies as temperature thresholds of pathogens vectors differ (Table 1). The increase or decline in precipitation can influence malaria occurrences while temperature (both minimum and maximum temperature) plays a significant role in the life cycle of the malaria vector. Climate and health risk studies have compared temperature conditions to limiting thresholds for variation in incubation rates for mosquitos (Mordecai et al., 2019; Ware-Gilmore et al., 2021; Mordecai et al., 2020). It is observed that the impacts of temperature depend, though, on the species of the parasite the mosquito is carrying. Temperature affects many parts of the malaria life cycle: extrinsic incubation times, larval development, and mosquito maturation. As temperature increases from 21 °C to 27 °C, for instance, studies have described that the egg of the parasite in the mosquito decreases (Shapiro et al., 2017; Shukla, 2003). Other studies have reported that for most Anopheles vector malaria species, the optional temperature range for their development lies within 20 °C to 30 °C. However, the transmission of *Plasmodium vivax* requires a minimum average temperature of 15 °C and a maximum temperature of 39 °C (Table 1), whereas transmission by *Plasmodium falciparum* requires a minimum temperature of 19 °C. Other studies further revealed that the development of the parasite within the mosquito (saprogenic cycle) depends on temperature. Though the broad malaria transmission window in terms of temperature is between 15 °C and 40 °C, the number of days a particular temperature range persists provided the relative humidity remains conducive. It has been observed that the *P.vivax* vectors require 15 to 25 days to complete their cycle. Suppose the temperature remains within 15 °C to 20 °C. In that case, the life cycle may get completed within 6 to 10 days, for *P. falciparium*, assuming the humidity is conducive, the life cycle grit is completed within 20 to 30 days at the temperature range between 20 °C to 25 °C (Kim et al., 2019; Agyekum et al., 2021; Shocket et al., 2020). Rainfall provides favourable environmental conditions for mosquitoes to lay the eggs with optimum humidity conditions required for breeding mosquitoes. This ecological condition offers opportunities for the parasite to complete the necessary life cycle. This further revealed that climate change is likely to spread malaria in many parts of SSA. Therefore, climate is a significant factor for *Plasmodium* parasite development within the mosquito and mosquito survival.

5. Malaria increases economic burden as climate changes

Malaria is rated as the major causing factor of most mortality and morbidity occurring in Africa (Mbacham et al., 2019; Papaioannou et al., 2019). Nearly 90% of the world's malaria cases are in Africa, but this is significantly causing most deaths occurrence among young children and old age people in SSA countries (WHO, 2015a,b). Consequently, malaria places a staggering economic burden on the already strained African economy. The disease has been estimated to cost many SSA countries billions of dollars every year in gross domestic product (Malaria, 2005; Carrasco-Escobar et al., 2021; Rakuomi et al., 2017). Moreover, the incidence of malaria in the past decades has increased.

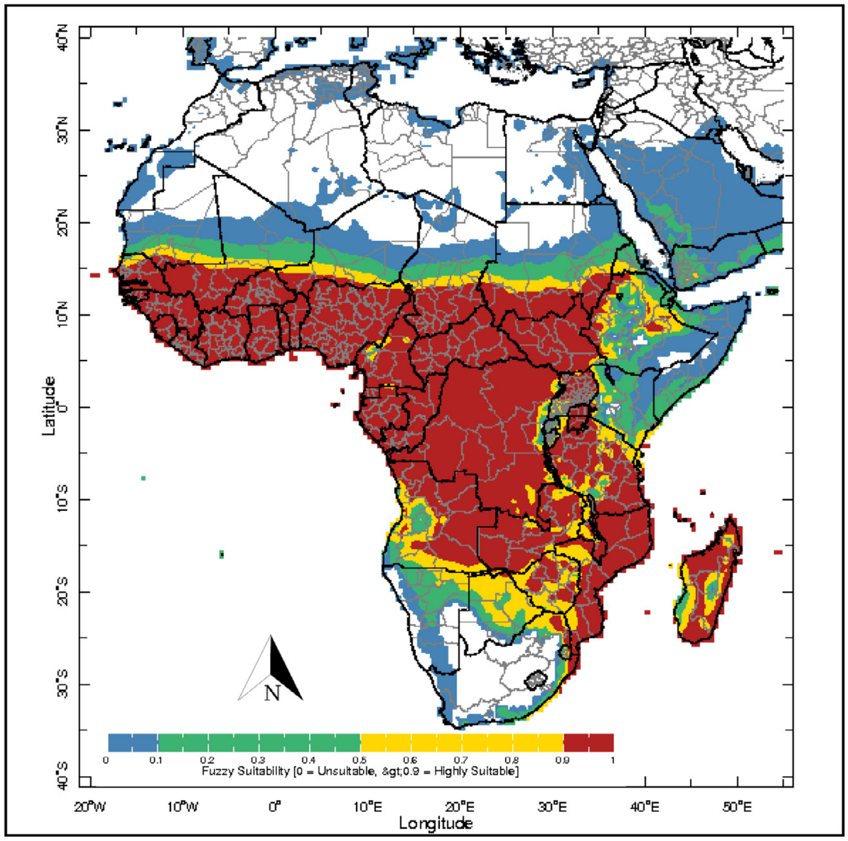

Fig. 1. Climatic suitability for malaria transmission. The map is based on the Malaria Risk in Africa (MARA). *Credit: IRI, 2021* (http://iridl.ldeo.columbia.edu/maproom/Health/Regional/Africa/Malaria/MARA_Distribution_Model.html).

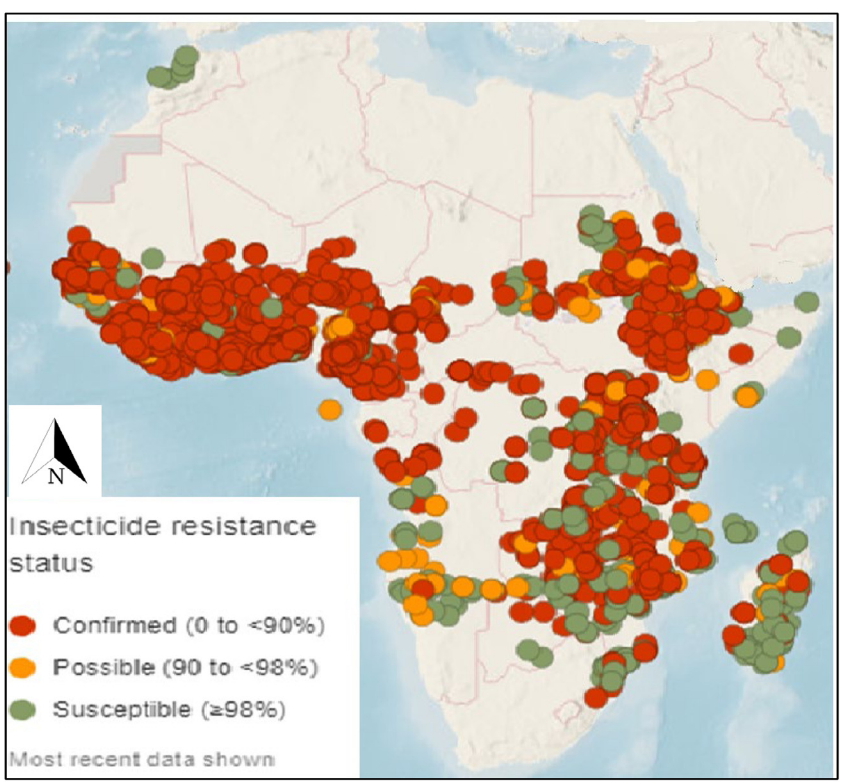

Fig. 2. Malaria-transmitting mosquitoes and insecticide resistance across Africa. *Credit: WHO, 2021.* Map production: Global Malaria Programme. World Health Organization. WHO 2019.

Table 1
Temperature, rainfall and humidity influence survival of mosquito.

Disease	Malaria	Malaria		Reference
Pathogen T_{min} (°C) T_{max} (°C)	*Plasmodium vivax* 5–15 33–39	*Plasmodium falciparum* 16–19 33–39	Ambient temperature plays a significant role in the life cycle of the malaria vector	(Henrici et al., 2019), Henrici et al. (2019), Ryan et al. (2020), Snow et al. (2017) Tanser et al. (2003)
Rainfall	Rainfall with humidity (50 to 60%) provides a suitable breeding environment for mosquitoes to lay the eggs and long term survival of mosquito		Ayanlade et al. (2020a), Chowdhury et al. (2018), Lingala (2017)	

This has correspondingly increased research interest in the mapping and predictive modelling of the distribution, intensity, and seasonality of malaria transmission.

For example, in 2019, WHO mapped and described that the top six countries that accounted for approximately half of all malaria deaths worldwide are SSA countries. Such countries according include Burkina Faso (4%), the Democratic Republic of the Congo (11%), Mozambique (4%), Niger (4%), Nigeria (23%), and Tanzania (5%) (WHO, 2020). On the order hand, climate change is likely to intensify the malaria occurrence in the region. The extent of these effects continues to generate intense debate, especially in the projected impact of climate change on the global distribution of malaria. Different approaches have resulted in widely varying estimates. For example, the recent IPCC report noted that climate change is likely to have many effects on human health, including; changes in the distribution of the disease and seasonal transmission of some diseases such as malaria (IPCC, 2021). However, the effect of climate on malaria might be sometimes unstable or difficult to infer due to other prominent factors; for example, socioeconomic, environmental, and behavioural factors can either aid or negate the climatic influences on malaria. The changes in the characteristics and distribution of malaria are primarily determined by climatic factors, majorly temperature, humidity, rainfall, and aerosols. Therefore, the geographical distribution of climate is a driving factor in spreading vector diseases such as malaria. The monsoon precipitation has been projected to increase, with a delayed onset and a delayed retreat and increased mean temperature in many SSA countries (IPCC, 2021). Thus, the seasonality in wet trends and extreme climatic events can alter the suitable environment for many vector-borne diseases, especially malaria occurrence in SSA (Sherrard-Smith et al., 2020; Ayanlade et al., 2020a). The implications of these are that the daily mean temperature exceeding a typical 21.5 °C threshold may effectively increase the incubation of many mosquito vectors, thus increasing the incidence of malaria in many SSA countries (Mordecai et al., 2020; Semakula et al., 2017; Snow et al., 2017).

6. Call for the better development of the Early Warning System

Therefore, there is a need to develop an Early Warning System (EWS) for climate-induced malaria occurrence. Here, we emphasize and explain many uncertainties, about climate change impacts on human health. Therefore, we are calling for action on the need for better development of climate Early Warning System (EWS) for predicting the prevalence of malaria as climate changes. This ought to be a research priority in the SSA region.

Even though the infectivity and transmission processes unique to many diseases are likely complex, several factors have been identified as direct drivers of disease risk. For instance, several studies reported that; climate-related impacts have been understood in combination with other forces that drive infectious microorganisms and diseases dynamics (Chowdhury et al., 2018; Henrici et al., 2019; Ayanlade et al., 2020b,a; Mordecai et al., 2020; Ryan et al., 2020). Thus, to combat the burden of microorganisms that will disproportionately attack humans, climate change will necessitate a more diverse use of technology. Cuesta et al. (2021) used a unique method to preferentially deplete host 18S ribosomal RNA gene amplicons in order to disclose the composition of the eukaryotic microbial communities of Anopheles larvae collected in Kenya, Burkina Faso, and the Republic of Guinea (Cuesta et al., 2021). This study discovered 453 eukaryotic operational taxonomic units (OTUs) in nature that are linked to Anopheles larvae. In the Silva database, an average of 45 percent of the 18S rRNA sequences were grouped into OTUs with no taxonomic assignment. Therefore, it is obvious that the eukaryotic microbiome of insects is shifting due to climate change. Mosquitoes, for instance, are exposed to a variety of prokaryotic and eukaryotic bacteria in their microbiomes, which aids in the evolution of the innate immune system. The microbiome of Anopheles comprises a surprising number of new eukaryotic species. There is a difficulty since studying the eukaryotic microbiome of mosquitos is difficult. Separating eukaryotic microbial 18S rRNA sequences from the mosquito host or vertebrate blood meal is a higher technical difficulty (Belda et al., 2017). Cuesta et al. compare the composition of eukaryotic microbiome taxa to accessible 18S rRNA sequence databases, which are less developed than prokaryotic sequence databases. Based on sequence similarity and evolutionary placement, the study yielded taxonomy designations. More information on the eukaryotic microbiome and mosquito virome will shed light on the three-part interactions between viruses, prokaryotes, and eukaryotes that shape the ecological community of commensal symbiotic and pathogenic bacteria, affecting vectorial ability and mosquito physiology. Moreover, vertebrate host phylogeny influences gut archaeal diversity. Youngblut et al. (2021), collected adequate sequence data from 185 gastrointestinal samples using 16S rRNA gene amplicon sequencing with Archaea-specific primers. They came from 110 vertebrate species from five different taxonomic groups (Mammalia, Actinopterygii, Amphibia, Aves, and Reptilia), most of which were wild. Bathyarchaeia and Methanothermobacter, for example, were previously unknown Archaea–host interactions, according to Youngblut et al. Though, this was particularly common among Aves. In species with higher body temperatures, it was abundant. Although climate change with frequent droughts and flooding may influence our food more than that of our ancestors, host phylogeny explained archaeal diversity more strongly than nutrition. Mammalian herbivores appear to have the most robust cophylogeny. Methanobacteria, on the other hand, are the only class anticipated to have existed in the last common ancestor of mammals and all host species. Our understanding of Archaea–vertebrate connections will be crucial in the future to distinguish between natural climatic changes that occur without human intervention and man-made climate changes associated with the post-industrial revolution.

Accordingly, decisions concerning malaria prevention will be more effective using EWS. Early warning systems should be based on records of malaria on a monthly and weekly basis, with proper management control measures to fight these epidemics. The EWS for malaria can support the prediction of epidemics outbreaks. The system should comprise of components such as vulnerability, seasonality forecasts, monitoring of the environment and observed malaria morbidity. Monitoring climate extremes through the EWS is likely to help detect changes in environmental conditions suitable for the malaria epidemic over time and place. The research priority in SSA should be on the development of climate EWS which takes the exposure side into account and envisages the adaptation options. EWS development at countries and local levels is very important in SSA as available models are General Circulation Models (GCMs), which are not good enough for accurate local estimation. There is a need for scientific studies to be undertaken, on EWS development at country and local levels, to provide society with precise information on the real and potential climate–malaria variability, as well as, the mitigation and adaptation options available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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