



Climate Change and Malaria Epidemiology

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ABSTRACT

Climate change is increasingly recognized as a critical driver influencing the global epidemiology of malaria. Rising temperatures, changing rainfall patterns, and altered humidity levels have reshaped the geographical distribution, intensity, and seasonality of malaria transmission. This review synthesizes current evidence on the complex interplay between climate variability and malaria dynamics, emphasizing how warmer climates expand vector habitats, modify parasite development rates, and extend transmission seasons. Particular attention is given to regions at high altitude and those previously unsuitable for malaria, where climate change is creating new ecological niches for vectors. The paper also examines methodological approaches to studying climate-malaria linkages, highlights the uncertainties and challenges in predicting future disease patterns, and underscores the role of adaptive strategies in mitigating the health burden. Ultimately, the integration of climate science, epidemiological data, and public health interventions is essential to address the evolving threats posed by malaria in a warming world.

Keywords: Climate change; Malaria epidemiology; Vector-borne diseases; Anopheles mosquitoes; Global health; Disease modeling; Public health adaptation

INTRODUCTION

The nexus of climate change and its multifaceted consequences ambitiously occupies the centre stage in today's discourse of key health climate drivers. The 2007 report from the Intergovernmental Panel on Climate Change (IPCC) asserts that "warming of the climate system is unequivocal", based on the behaviour and shape of nonlinear climate drivers [1]. Climate change is already affecting human health but the nature and magnitude of impacts on infectious diseases remain unclear. The widely held view is that the burden of many infectious diseases transmitted via the environment and insect vectors will increase in response to climate change. Malaria, with substantial disease burden and sensitivity of transmission to environmental conditions, is regarded as a bellwether for the broader effect of climate change on infectious diseases [2]. Global prevalence is therefore expected to be altered by changes in temperature, rainfall, and humidity that influence the rate of development and survival of both the parasites and the vectors. Technical approaches to extract the local signal and quantify the impacts of climate change on the malaria transmission cycle are the subject of ongoing research, warranting a review of progress on the strength of the observed climate signal in the malaria data [3].

Understanding Malaria

Malaria transmission is mediated through a vector mechanical mode of transmission [2]. The female Anopheles mosquito that transmits the Plasmodium parasite acquires the pathogen by biting infected individuals. The mature parasite then develops in the vector before an infected bite transmits the pathogen to susceptible humans. Malaria symptoms typically appear 10–15 days after the infective bite, manifesting as fever, bodily aches, and chills [3]. If untreated, the infection can lead to severe anaemia, cerebral malaria, and subsequent death. The life cycle of the parasite depends on temperature, with warmer conditions accelerating its propagation within the vector [2, 3].

History of Malaria

Malaria is a vector-borne disease transmitted by female Anopheles mosquitoes and caused by one of four species of the parasite Plasmodium, leading to significant morbidity and mortality globally [2, 1]. In 2015, there were

approximately 214 million cases and 438,000 deaths, predominantly affecting children under five [2]. The disease has exerted a substantial social and economic burden in many malaria-endemic countries, exacerbated by climate change [3]. In recent years, the impact of climate change on human health has attracted considerable attention; the effects on malaria have been of particular interest because of its disease burden and its transmission sensitivity to environmental conditions [1]. Climate change is expected to increase the risk of vector-borne diseases such as malaria, especially in tropical regions that face significant health and development challenges. Current climate and recent warming trends already promote epidemic malaria in East African highlands and alter the spatial distribution of vectors and transmission seasons in various locations [6]. Future climate projections, therefore, form an essential input to transmission models, particularly for estimating the geographical extent of transmission and epidemic risk in new areas, enabling appropriate development and targeting of interventions [4]

Transmission Cycle

Malaria is caused by infection with Plasmodium parasites of the genus Plasmodium. Transmission occurs through the bite of an infected female mosquito of the genus Anopheles. Only a subset of approximately 430 recognized Anopheles species can transmit malaria effectively [2]. The complexity and specificity of the Plasmodium life-cycle within the mosquito vector provide natural constraints on transmission, as does the specificity of the vector-human encounter [4]. The transmission cycle begins when an infected female Anopheles mosquito ingests Plasmodium gametocytes while taking a blood meal from an infected vertebrate host. In humans, the parasite undergoes an asymptomatic hepatic stage before infecting erythrocytes and causing clinical disease. Additional gametocytes develop within the blood, providing the infectious forms necessary to continue the cycle. Risk is closely tied to the behavior and survival of the vector between infected and susceptible hosts, and any increase in vector longevity would profoundly affect transmission intensity [2, 4].

Symptoms and Diagnosis

Malaria symptoms manifest between 10 and 14 days following the infectious mosquito bite and generally persist for three to seven days in untreated cases [3]. The illness commences with a prodromal phase characterized by headache, fatigue, aches, and nausea. Subsequent paroxysms consist of cold shivers followed by fever, sweating, and prostration; however, presentations of irregular fever patterns are also common [4]. Other clinical features frequently observed include myalgia, diarrhoea, cough, and abdominal pain. The varied, non-specific symptoms demand a high index of clinical suspicion, particularly in areas where the disease is uncommon [2, 5, 4].

The Impact of Climate Change on Vector Dynamics

Anopheline mosquitoes constitute the vector for malaria transmission, undergoing aquatic pre-adult stages and an adult stage that consumes blood and reproductive cycles [2]. Vector dynamics are influenced by climate variables such as temperature, precipitation, and humidity, which are fundamental to mosquito abundances and are likely to be affected by climate change [6]. Anopheles mosquitoes thrive in temperatures between 20 °C and 30 °C, yet they suffer increased larval mortality when temperatures exceed 34 °C due to physiological stress. Precipitation impacts the availability of stagnant water pools necessary for larval development, with both excess rainfall and drought conditions limiting suitable habitats. Humidity affects adult mosquito survival and oviposition behavior, such that decreases in humidity thereby reduce host-seeking activity and reproduction [2]. Under the IPCC A1B emissions scenario, characterized by balanced fossil and non-fossil energy sources, projected increases in temperature, a reduction in spring precipitation, and an increase in summer precipitation are expected in Europe, which will directly affect Anopheles vector abundance [6].

Temperature Effects

Temperature plays a key role in the impact of climate change on vector dynamics. Research indicates that ambient temperature influences the entire life-cycle of mosquitoes, including the development of the malaria parasite within the vector [2]. The sporogonic cycle takes approximately 9–10 days at 28°C and does not proceed below 16°C. Daily survival rates remain around 90% between 16°C and 36°C but decline rapidly above this range [5]. The highest expected survival during incubation occurs between 28°C and 32°C [4]. Temperatures above 21°C shorten the adult mosquito's gonotrophic cycle, thereby increasing the frequency of vector–host contact and the potential for parasite transmission. Several studies document a positive association between temperature and malaria incidence: a 1°C increase below 25°C raises epidemic risk in the Hluhluwe–Umfolozi game reserve in South Africa; average maximum temperatures greater than 26°C increase clinical malaria in a highland area of Ethiopia; and overall temperature trends correlate with the risk of the 1998 malaria outbreak in Burundi [7]. Rainfall contributes by creating breeding sites and maintaining the humidity levels required for mosquito survival. Several epidemics trace directly to heavy rains, and outbreaks are often preceded by specific rainfall patterns. Although the available evidence is extensive, some correlative studies fail to detect clear relationships, possibly due to methodological issues such as reliance on large-scale climate anomalies that may not represent local variability accurately. Detailed analyses with localized meteorological data are necessary to establish robust links between

climate change and malaria transmission [5]. The main objective for the study was to estimate the effects of temperature, rainfall and humidity on clinical malaria incidence. Data were derived from March 2003 to December 2005 using logistic regression with fractional polynomial (FP) transformations to model non-linear relationships. Vector stages are sensitive to hydroclimatic conditions, underscoring the importance of local meteorological measurements [1].

Precipitation Patterns

Rainfall contributes to the breeding grounds for the Anopheles mosquitoes. It creates pools of stagnant water where the female mosquito lays its eggs during the breeding cycle [1, 3]. When there is too much rain, the pools can either dry up or the water flows, washing away the mosquito eggs and larvae. The optimal conditions are usually around 100–200 mm per month of precipitation during the breeding season. When precipitation is outside of the required amount for a prolonged period, the number of breeding sites decreases [12, 14]. This causes a reduction in both the mosquito populations and malaria transmission. In the transmission cycle of malaria, it has been observed that the reproduction and survival of Anopheles mosquitoes is influenced not only by precipitation but also by relative humidity. These factors affect the presence of the Anopheles population and consequently the spread of the disease [16].

Humidity and Mosquito Survival

Humidity affects mosquito survival and, in consequence, the abundance of mosquito populations [2]. Most population models include temperature and rainfall but often exclude the effect of humidity on mosquito survival [8]. In some cases, relative humidity drops below 20%, in which low humidity has a major impact on mosquito lifespan and significantly impacts the abundance of mosquito populations. A new model of Anopheles gambiae s.l. survival focused on the combined effect of temperature and humidity is proposed, to assess the importance of humidity for mosquito populations in the Sahel region [8].

Geographical Distribution of Malaria

Malaria continues to pose a significant global health challenge, accounting for more than 214 million cases and 438,000 deaths worldwide in 2015 [2]. The disease is endemic to many tropical and subtropical areas where climatic conditions support high rates of mosquito population growth and parasite reproduction. Three distinct regions have traditionally been identified that generally support the appropriate transmission conditions: South America, sub-Saharan Africa and parts of southern Asia. A fourth region encompassing the Sahelian belt of Africa approximately between 12° N and 20° N may also provide a suitable environment with increased rainfall and the presence of irrigated agricultural projects [9]. Because malaria transmission is highly dependent on climate, climate change could alter its global distribution in a number of ways [10]. Analyses using climate model projections, for example, indicate that an expansion into the East African highlands above 2000 m is possible, given a stable climate by the end of the twenty-first century. Simultaneously, a contraction is projected for most of the Sahel region between 10° N and 15° N, which is consistent with a loss of seasonal malaria during the dry season. Malaria could disappear altogether from the northern Sahel while expanding across the central and southern Sahel, where changes in the seasonality of transmission might also be expected [11]. The predicted scenario suggests an overall redistribution of malaria rather than a global expansion of the disease, accompanied by shifts in seasonal transmission patterns.

Current Hotspots

The major endemic regions with high receptivity for malaria development include parts of Southeast Asia, India, Bangladesh, Pakistan, Sri Lanka, a narrow region in the Middle East, East America, the Pacific (mainly Solomon Islands), and most of Africa [8]. Transmission in Central and South America is generally silenced because of low temperatures or low humidity, less suitable for the development of Anopheles mosquitoes. The intensity of malaria transmission in Africa varies with the strength of rainfall, which affects the breeding sites of Anopheles mosquitoes. The current distribution map of malaria shows that the risk of the disease still remains high in many parts of the World [8]. The majority of the population exposed to malaria infection resides in the southern latitudes of sub-Saharan Africa, India, and Southeast Asia Ring, where the tropical climate is conducive to the development of the mosquito vector, as well as being poor and malnourished. Malaria is expected to remain endemic in these populations. It is also expected that malaria will reappear as a major health risk for people living above 1,800 m where it is currently not endemic [9]. This is because temperature in the highlands is projected to increase three times more than that in the lowlands. Further, the intensity of malaria transmission in East African countries is strongly correlated with temperature variation in addition to anomalies in rainfall [11].

Potential New Regions Due to Climate Change

The geographical distribution of malaria depends on the spatial presence of vectors capable of transmitting the disease [7, 9]. In areas where vectors cannot proliferate, local malaria transmission is unlikely [8]. Although vector species have varying abilities to transmit Plasmodium species, it is commonly assumed that each vector

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species can transmit all of them, provided prerequisites such as parasite development within the vector are met. Malaria-endemic zones are primarily confined to regions where the *Anopheles* vector is established, encompassing most tropical and sub-tropical areas globally [11]. Demonstrated malaria risk has been described in parts of South and Central America, Asia, India, Africa, and Oceania. Both temperature and precipitation regimes determine the spatial extent and stability of malaria transmission because they control vector abundance and the speed of parasite development in the vector [9, 11]. In some regions, increased temperature may bring these variables into a range more favorable to transmission. Conversely, in other regions, disturbances to ecosystems may disrupt vector breeding sites, particularly if an increase in temperature accompanies a change in precipitation regime. Climate change is therefore expected to modify the geographical distribution of malaria around the world [11]. In particular, a global temperature increase may cause some currently non-malarious areas to become suitable for malaria transmission when the temperature rises above a critical value. Wetter deserts at the southern edge of the Sahara and at the northern edge of Australia, where mean temperatures are already high, may become potential zones of emergence for malaria transmission in a warmer and wetter climate system [9]. Extensive lands in the USA, northern Mexico, and Brazil that are presently too cold to sustain malaria transmission may become endemic, unless malaria eradication is achieved worldwide by that time. Such examples illustrate how the climate may constrain the geographical distribution of malaria [10, 11].

Malaria Transmission Models

The mechanistic models developed to evaluate the effects of weather and climate variables on malaria transmission dynamics approximate the Parasite Development Rate and the Mosquito Development Rate as functions of temperature and rainfall [1, 5]. The resulting parameterization produces a climate-dependent malaria model that generates time series capable of closely reproducing observed malaria data [1]. These climate-driven mathematical models of malaria transmission dynamics may take the form of deterministic or stochastic transmission models embedded within static or fluctuating environments [5]. While the equations governing weather and climate models are themselves deterministic, their extreme sensitivity to initial conditions renders the development of comprehensive mathematical frameworks for their interaction inherently challenging [1, 4]. A hierarchical approach that employs generalized, coarse-grained models of each system facilitates the generation of pertinent insights into the impact of climate change on malaria transmission [4, 9]. Such models predominantly concentrate on characterizing the influence of global change on transmission dynamics, thereby providing general information on quantities like disease extinction, emergence, and invasion rates that prove useful for policy formulation and health planning [7]. Typically, a compartmental disease-structure framework is adopted, wherein mosquito populations are partitioned into susceptible, exposed, and infectious groups. Humans are assumed to exhibit an identical disease progression, ultimately acquiring permanent immunity [1, 6]. Although the effects of climatic variables on transmission are complex and warrant further quantification within modeling contexts, factors such as temperature, rainfall, land-use changes, and hydrologic processes are collectively influential. Consequently, models often employ simplifications of these effects to exemplify techniques and extract actionable insights, thereby balancing the detail afforded by comprehensive simulation models against the analytical tractability of simpler formulations [8]. When addressing the impact of weather and climate on malaria transmission, mathematical models serve as powerful instruments that aid in understanding potential implications for intervention strategies and eradication efforts. Achieving this understanding necessitates the incorporation of realistic representations of vector population dynamics and environmental responsiveness [6].

Mathematical Modeling of Transmission

Malaria transmission is modeled via adaptations of the Ross–Macdonald framework developed by Ross [12]. The human population is subdivided into susceptible, exposed, infectious, and recovered groups; and the mosquito population into susceptible, exposed, and infectious categories. Temperature acts upon the model through its influence on several key parameters. For instance, parasite development rates and mosquito development durations incorporate temperature dependence [1]. The model also integrates climate influences by allowing parameters such as daily temperature ranges and thermal thresholds to modulate transmission dynamics. Since temperature and rainfall affect mosquito breeding and survival, these environmental factors critically determine the timing, magnitude, and geographic extent of malaria epidemics [1].

Climate Variables in Models

Climate variables feature prominently in epidemiological malaria transmission models. They influence mosquito population dynamics, as well as details of the parasite life cycle within the vector. Models constraining mosquito population dynamics by temperature, precipitation, windspeed and relative humidity e.g., [6] allow simulated climatic fluctuations, including long-term trends, to inform the larval and adult populations. Once calculated, these figures update the numbers of susceptible, infected and infectious mosquitoes within a compartmental framework [6]. The parasite life cycle exhibits a much simpler dependence on climate: the extrinsic incubation period, the

time taken for ingested sporozoites to develop into the typically infectious salivary gland stage, decreases nearly exponentially with temperature over the range 16°C to 30°C. Care must be taken to model all other relevant processes on an equivalent timescale (e.g., recovery rates within the human population or the period between blood meals [7]. Within many models, the transmission rate directly depends on temperature through its effects on the length of the parasite genetic replication cycle within the *Anopheles* mosquito. Accordingly, rising temperature may substantially increase rates of transmission because it shortens the period before the mosquito becomes infectious and at risk of dying.

Public Health Implications

Disease burdens caused by mosquitoes, in particular malaria, are expected to increase due to climate change. Consequently, populations in many areas around the world will be facing increased health risks. Endemic areas will experience an increased risk of malaria, and naïve populations in non-endemic areas will be exposed to new health risks [10]. Poor communities in emerging nations are often less able to cope with increased health risks caused by climate change because of inadequate health infrastructure [11]. The public health preparedness for the increase in health risks caused by climate change is currently insufficient, especially in countries with low per capita income. Governments of developing countries, therefore, need to strengthen their health systems to minimize the impact of expected health risks. Malaria is one of the major health problems, especially in tropical and subtropical regions [14]. The burden of the disease in Sub-Saharan Africa was estimated at 24–77 million episodes in 1995. While the main public health interventions adopted to minimize the disease burden are directed at minimizing morbidity and mortality through vector control, vaccination, and treatment, community education on the disease is essential in adapting to the disease risk and spread associated with climate change [9].

Increased Risk Populations

In the context of climate change and infectious diseases, certain populations already facing the greatest disease burden are holding the greatest risk of increased transmission [2, 13]. Of the estimated 229 million cases and 409,000 deaths in 2019, children account for a significant percentage of the burden [2]. Of malaria deaths in 2019, two-thirds were children under the age of five [13]. The populations of highest concern include children in poor communities in tropical and subtropical countries, where healthcare and disease prevention capacities are lower and the ability to implement vector control measures is poorer [2].

Healthcare System Preparedness

Malaria remains a substantial global health burden, with approximately half of the world's population at risk and around 438,000 deaths in 2015, primarily among children under the age of five [2]. Certain regions are particularly vulnerable, including sub-Saharan Africa, South Asia, and the Andean region of South America [5]. In Africa, malaria accounts for approximately one-fifth of childhood mortality. The epidemiology of malaria is highly sensitive to climatic conditions such as rainfall, humidity, and temperature, all of which directly impact the behavior of *Anopheles* mosquito vectors [2]. The capacity of healthcare systems, especially in developing countries, to manage existing malaria burdens poses a critical concern. Current low recovery rates from malaria contribute to a significant strain on health infrastructures [4]. Additionally, climatic factors critically influence the duration of the infective period in humans; higher temperatures reduce this duration, enabling humans to become infectious for longer periods on average and thereby amplifying transmission potential [1]. This extension of infectiousness increases the number of infectious bites per infected individual, exacerbating the risk of transmission. Consequently, healthcare systems in malaria-endemic regions face heightened challenges as climate change potentially intensifies transmission intensity and disease burden [6].

Mitigation Strategies

Vector control remains the most effective means of malaria mitigation, particularly for *Plasmodium falciparum*. Malaria mitigation has traditionally relied on insecticide-treated bed nets (ITNs), indoor residual spraying (IRS), and source reduction [3, 15]. However, physiological and behavioural changes in the mosquitoes, along with widespread pyrethroid resistance, highlight the need for additional vector-control tools [14]. Biologically based approaches include genetically modifying mosquitoes for lower malaria-transmission competence and using the bacterium *Wolbachia* to limit mosquito lifespan and vector competence. Early-stage development of spatial repellents and new classes of insecticides, such as pyrroles and neonicotinoids, may provide vigorous tools for malaria mitigation in the years ahead. Systemic insecticides, whereby mosquitoes ingest a lethal dose of insecticide with their blood meal, may also augment current vector-control strategies [15]. Vaccines and chemoprevention offer additional means for mitigation, with a growing pipeline of promising candidates. As of 2021, the RTS,S/AS01 vaccine, recommended for children ages 5–17 months, provides 39% protection against childhood malaria and lowers the risk of severe disease by 29%. Single low-dose injectable artesunate shows effectiveness in treating severe illness and reducing the risk of death by 22.5% compared with quinine. Chloroquine resistance, an example of the latter stratagem, has evolved multiple times [14]. As resistance emerges to new treatments,

treatment designs should continually consider the capacity for evolution. Combination therapies particularly triple-therapy combinations suppress waning efficacy, slowing the evolution of resistance to new treatments [13].

Vector Control Measures

Malaria vector control remains the most effective method to reduce transmission, comprising a variety of approaches that target mosquito populations directly or indirectly [3]. The long-established techniques of residual spraying and insecticide-treated nets (ITNs) continue to be prominent; the use of ITNs on a wide scale has resulted in a documented reduction in transmission in several situations [3]. Environmental management, such as larval habitat modification, is another active area of research. The potential of vaccination and treatments will be discussed separately. Despite the short history of insecticide spraying, resistance to these chemicals has already become widespread among *Anopheles* vectors in many areas. This is compounded by behavioural resistance (e.g., a population that prefers outdoor resting and outdoor feeding is less susceptible to an indoor residual spray). Although New World vectors still tend to be susceptible [4], insecticide resistance is a fundamental concern for control [5]. Spraying remains feasible, but precise knowledge of local vector behaviour (especially probable places of rest and bite time) is essential to determine the most effective approach. When vector susceptibility is confirmed and detailed behavioural knowledge is available, the choice of insecticide can be guided accordingly. A sprayed house offers socially complex issues, such as ingrained opposition in parts of South America and other areas [4].

Vaccination and Treatment

Although global warming and mosquito proliferation remain difficult to avoid, it is nevertheless possible to reduce the severity of malaria outbreaks and the loss of human lives through the appropriate treatment of infected individuals [4]. Drugs such as Larium, Mefloquin, Chloroquine, Doxycycline, and the commonly used Quinines can all contribute toward reducing the burden of malaria, provided that infected persons seek treatment promptly [6]. In addition, a vaccine currently at an advanced stage of development offers promise for further mitigation. Purified protein vaccine candidates against the *P. falciparum* strains also hold potential for controlling the disease. Although it is only beginning to be acknowledged and recognized as a serious threat to human health, global warming is already, in all likelihood, facilitating the expansion of malaria vectors into new areas both around the Canadian-US border and across the northern continents [7]. As Svensmark and Friis-Christensen (1997) have demonstrated, epidemics of vector-borne diseases have generally been associated with, and followed, periods of global cooling and warming, caused by changes in the solar cycle and modulated by variations in the circulation of cosmic rays in the Earth's atmosphere [5]. When the appropriate treatment drugs are administered during such outbreaks, they can mitigate the severity of malaria epidemics and contain the disease within the newly affected areas [3, 5].

Adaptation Strategies

Effective adaptation strategies can reduce long-term impacts by increasing resilience and reducing exposure of human and natural systems to climate change impacts [5]. Even under best possible efforts to mitigate climate change, some level of its impact on the Earth's ecosystems, societies, and economy is inevitable [8]. The development and implementation of adaptation strategies is therefore essential to minimize the health risk. Numerous malaria-prone countries have taken up adaptation strategies including vector control, education, and health systems to ensure minimal cumulative societal effects from malaria transmission in a future climate, and many more are making plans to do so [17]. In most cases, adaptation measures focus on the reduction of vulnerability and the maximization of the use of available resources. In general, the impact of malaria on society and the structure of health-care systems differ greatly between developing, underdeveloped, and developed countries. Consequently, climate change presents different levels of risk for each [6]. The greatest groups at risk are villagers in tropical and subtropical areas of underdeveloped countries, where malaria is endemic and health-care systems as well as services are inadequate. In urban areas of developing countries, where the disease is under control and the population has a historically low level of immunity, a sudden epidemic of lower magnitude would nevertheless be highly significant. Even in countries where malaria is no longer endemic, its reappearance in new areas would put extra pressure on health services [5, 7].

Community Education and Awareness

Education and awareness programs are crucial components of community adaptation and resilience [15]. They inform individuals about the potential risks posed by climate change, including the increased likelihood of extended vector survival and the adaptation of vector species to new habitats. Such programs encourage communities to adopt more resilient practices, implement precautionary health measures, and participate actively in broader adaptive strategies [15, 16]. Educational initiatives also disseminate information about available mitigation and treatment options within healthcare systems, facilitating timely and effective responses. The implementation of educational campaigns is particularly important alongside vector control strategies, vaccination,

and treatment programs because mitigation measures may be insufficient on their own to limit the growing burden of malaria [16].

Policy Recommendations

In the context of a warming climate, countries face heightened exposure to malaria risk. Supported by the Regionalized Climate Projections (RCPs) RCP4.5 and RCP8.5 scenarios, model simulations indicate an increase in malaria transmission in the Kenya Highlands [3]. This necessitates the development of public health planning frameworks and policies geared towards adaptation and mitigation to alleviate the increased risk. Climate change will likely increase the geographic extent of malaria in Africa [4]. While these findings pertain to the specific context of the Lake Victoria Basin, reminiscent patterns are anticipated in other malaria-endemic regions. Networking and collaboration on mitigation of climate change are therefore imperative [5].

Case Studies

Malaria remains a significant global health burden despite considerable gains made through modern public health controls. The World Health Organization currently reports approximately 240 million malaria cases and nearly 627,000 deaths per year [1, 2, 5]. While progress has been observed over the last century, climate change has the potential to reverse these gains and allow malaria transmission in previously controlled or eradicated areas. Outbreaks of other vector-borne diseases are typically associated with longer-term weather patterns caused by ENSO events; however, malaria outbreaks often result from more complex and multiple drivers [11]. These include rapid declines in healthcare access, human migration, environmental manipulation, historical weather-dependent malaria cycles, disease cycling, or a combination of these factors [17]. Nevertheless, long-term meteorological conditions can raise total vulnerability, shaping the spatial distribution of malaria and creating transmission-prone zones. Current evidence indicates that climate change is modifying weather-related components of the malaria transmission cycle. Changes in temperature can influence hatching rate, developmental period, and mortality rates of female *Anopheles* mosquitoes; increased precipitation provides suitable breeding grounds. As a result, many parts of sub-Saharan Africa are projected to experience temperature and precipitation regimes conducive to increased vector survival, particularly under higher-emission climate scenarios [1, 18]. Other non-climatic risk factors such as land use, socio-political conditions, and urbanization also contribute to potential impacts. When coupled with climate-induced alterations in disease variability, certain locations may face a greater number of severe outbreaks. For instance, an outbreak affecting one million people in East Africa in 1997 was eventually contained. However, in Myanmar, a series of outbreaks from 2002 to 2006 resulted in more than 1.5 million malaria-related deaths, despite significantly lower disease intensity [19].

Successful Interventions

Climate and other environmental changes significantly influence malaria transmission dynamics and impose additional challenges to control efforts. Malaria control interventions over the last decade have been effective in some African countries [3]. Nonetheless, challenges remain, and understanding the roles of climate and the environment on malaria risk is highly valuable. Mitigation strategies against malaria include vector control, vaccination, and treatment, as successful prevention of the disease continually relies on reduced exposure to vectors [12]. Mosquito nets, insecticides, larvicides, and indoor residual spraying are vector control methods frequently employed under the mitigation strategy to eradicate the breeding and biting of mosquitoes. Additionally, neem and eucalyptus plants serve as effective mosquito repellents [13]. Preventive vaccinations strengthen the immune system of those immunized against the disease, while the administration of drugs such as chloroquine and Artemisinin-based combination therapies (ACTs) effectively cures those affected [17].

Lessons Learned from Outbreaks

Lessons from the history of malaria outbreaks demonstrate that large epidemics often occur at the margins of endemic areas or involve 'exotic' parasites entering susceptible populations [3]. Epidemics are also common during prolonged dry seasons followed by heavy rains, when vector and parasite populations can increase dramatically. Re-emergence often occurs in areas where transmission was low or had been absent for a period sufficient for population immunity to decline. The epidemic in sub-Saharan highlands, for example, affected populations with little long-term immunity [4]. The recent invasion of *Anopheles arabiensis* (Vector of malaria in Africa) into Brazil's extra-Amazonian region after an absence of several decades similarly raises concerns about renewed susceptibility in local populations [3]. The potential for "out-of-Africa" expansion of vectors into presently unsuitable climates is a global threat. However, malaria epidemics cannot materialize without the reintroduction of parasites into vulnerable populations. Models that do not account for parity and history may, therefore, tend to overestimate transmission potential where these are unconsidered, particularly at the margins of current distribution [2].

Future Research Directions

Considering the multifaceted relationship between climate change and vector-borne diseases, ongoing research is exploring innovative strategies to further understand and address emerging challenges [11]. One avenue involves the development of new technologies, including sophisticated malaria-control systems that integrate multiple layers of data from diverse sources and sensors [3]. These systems are designed to provide real-time, detailed descriptions of potential outbreak zones, thereby informing timely public-health interventions. In addition, longitudinal studies that incorporate advanced climate projections aim to capture the evolving interactions between environmental variables and disease dynamics [9]. By generating complementary temporal and spatial data such as changes in vegetation patterns and the abundance of malaria vectors these studies seek to refine predictive models and enhance the scientific understanding of malaria transmission in a changing climate [16].

Innovative Technologies

Innovative technologies hold promise for fundamentally altering our understanding of the synergies between climate change and malaria epidemiology [14]. The capacity to introduce large quantities of sterilized male mosquitoes into natural populations offers an intriguing method of population control. Sterile insect techniques have previously eradicated the New World screwworm in the United States. On the vaccine front, Mosquirix (RTS, S) is the first vaccine to complete a pilot program; however, with a 70 % protection rate against the cerebral type of malaria, it does not offer a complete solution [15]. New technologies can also benefit the epidemiological forecasting of malaria in the context of climate change through the ability to generate new data sources. Integrating the environmental resilience of both mosquitoes and the parasites they carry into models is particularly important. A second major trend involves the utilization of data spanning multiple decadal scales obtained from satellite missions [17]. Unlike the coarse information presented by GCM models, satellite sensors enable much finer temporal and spatial investigations. While satellites cannot monitor the very small-scale environmental properties that influence mosquito populations, their extensive and long-term capabilities offer valuable insights [19].

Longitudinal Studies

Longitudinal studies elucidate the components of climate variability that confound public health interventions both to prevent and mitigate malaria [18]. Improvements in the forecasting of meteorological hazards, including evolving seasonal and intra-seasonal signals, offer the potential for increased lead-time in outbreak alert [9]. Time-series analyses of severe malaria provide insight into spatially heterogeneous declines of the disease in conjunction with targeted control [18]. A better understanding of how climate interacts with fundamental drivers of vector dynamics and the transmission cycle in a given hydro-climate regime would support the development of spatially explicit, predictive malaria models that can also be evaluated in a longitudinal context [9].

Global Collaboration Efforts

International health organizations play a key role in facilitating collaborative efforts across countries and assessing malaria risk associated with climate change [19]. Long-distance travel can introduce these climate-sensitive diseases to non-endemic areas. Transboundary approaches are needed to address the spread of these diseases, especially since numerous climate-sensitive infectious diseases have the potential to re-emerge in regions where they have not been reported for decades and expand to new geographic locations [20].

International Health Organizations

International health organizations have at their disposal a variety of resources and techniques to mitigate the effects of malaria [4]. Prevention of malaria infection remains the key to malaria control, and several new approaches are being developed, including the use of vaccine therapy. Vector surveillance is important for the effective management of insecticide application [4]. Water management is helpful and includes flushing stagnant water sources, draining marshes, elimination of tall grasses and vegetation, and management of irrigation and water flows [5]. The Malaria Club of the Indian Medical Association and Alert Malaria are engaged in malaria control through community participation [10]. Despite such widespread efforts, there is a continuing need to develop new strategies that will enable the reduction of the heightened risk, especially in less developed parts of the world [3, 7].

Cross-Border Initiatives

Climate change threatens to spread vector-borne diseases across international borders, as manifested by concerns over the northward shift in malaria transmission in the United States [10]. Cross-border initiatives can address diseases that continue to cross state and international borders. Example initiatives include a malaria synchronization project between Mexico and Texas and a larger malaria eradication programme in the Amazon Basin, South America. International coordination of surveillance, vector control, and treatment can improve overall preparedness and response [18]. As climate change progresses, these programs will need careful planning and support. Changes in temperature, precipitation, or humidity can result in the relocation of many places into

climates more suitable or less suitable for mosquitoes. New mosquito locations can lead to cross-border vector transmission in two main ways: a resurgence of autochthonous cases and an increase in imported cases. Both require local preparedness. Understanding local transmission conditions helps ensure that the healthcare response is appropriate for the risk level [19].

Ethical Considerations

The epidemiology of malaria is intrinsically related to the prevalence of social determinants and speaks to issues of global justice [21]. The most vulnerable populations are those burdened by social determinants such as poverty, malnutrition, illiteracy, and limited access to health services. By privileging particular values, ethical questions also encompass broad areas of inquiry: the moral responsibilities of health-care workers, the ethical justification of particular public-health policies, and the appropriate role of economic and social utility as rationale or motivation for interventions [21]. Malaria eradication both requires and engenders a positive synergy between distributive justice and global public-health ethics. Vector-borne diseases require special consideration with regard to individual autonomy and informed consent, which by definition cannot be applied to uninfected vectors. Before individuals in an at-risk community can give their own consent to an activity, a substantial proportion of other similarly affected individuals must have already given their consent. Disease risk, therefore, inevitably limits the utility of individual informed consent and justifies community-level decision-making. Such a shift applies to vector control, mass drug administration, and vaccination [22]. The limited scope of individual choice in affected regions reinforces a central obligation to formulate effective treatment, prevention, and control programs. People living under the burden of malaria have a right to expect governments to provide access to effective diagnosis and treatment as well as protection against the associated risks. Disability or incapacity caused by malaria confers a related obligation to adjust responsibilities such as employment or school attendance to an individual's present capacity, status, and prognosis [20, 22].

Equity in Health

Strategies for climate change mitigation and adaptation in the public health sector already focus on protecting the most vulnerable [22]. Malaria increases globally can be gauged only by considering socioeconomics and health equity [23]. Peaceful coexistence with nature could mitigate climate change, reducing health risks, including parasitic exposure. Upcoming research needs to secure equitable access to climate information to prevent disproportionate effects on developing countries lacking mitigation means. Informed consent is central to data collection for both mitigation and adaptation strategies [22, 23].

Informed Consent in Research

The obligation to respect the autonomy of persons who participate in clinical studies has become a fundamental principle of research ethics. Much has been written about individual or participant informed consent as a central requirement of ethical research and about the challenges of ensuring that consent processes meet a minimum set of requirements [24]. There are a number of recognised difficulties associated with the practice of informed consent that remain relevant in any research context, for example, the challenge of enabling individuals to understand what they are being asked to consider, the imperative to overcome patients' fears, uncertainties about medical procedures, and the challenges involved in consenting on behalf of others or when capacity to give consent is compromised [23]. Many of these difficulties are compounded when research is conducted in an international environment where participants come from different cultural backgrounds and where awareness or understanding of biomedical procedures and concepts may be limited and valued differently, for example, differences between researchers' and participants' perceptions of risk or the authority of doctors and scientists compared with community members [25]. The need to obtain voluntary, informed consent from individuals who take part in research is enshrined in guidance documents and research regulations across the globe and the practice of informed consent in its contemporary form occupies a privileged place in the governance of biomedical research [23]. While consent processes serve two important ethical purposes to protect individuals by providing them with information about a project and enabling them to decline participation where they choose, and to ensure that researchers respect autonomy and decision making they also have a key role in legitimating research activities. Empirical work has begun to explore the ways in which these different functions come into play [25]. In particular, the scope of the consent obligation is being interrogated by bioethicists and social scientists drawn to the 'limits' of informed consent or concerned with assessing the ethical implications of research technologies which present specific challenges for the practice of informed consent [24, 25].

CONCLUSION

The evidence reviewed demonstrates that climate change is a pivotal factor reshaping the epidemiology of malaria by altering the ecology of vectors, parasites, and transmission environments. While climate alone does not fully determine malaria distribution, its interaction with socio-economic, ecological, and health system factors amplifies

risks, particularly in vulnerable regions. Projections indicate that previously malaria-free zones may become endemic, and areas with seasonal transmission may experience prolonged or intensified outbreaks. However, uncertainties in climate modeling, vector adaptation, and human resilience highlight the need for more integrated, interdisciplinary research. To mitigate these risks, adaptive strategies such as climate-informed surveillance, vector control innovations, sustainable land use, and strengthened healthcare systems must be prioritized. Addressing climate change as both a health and development challenge will be crucial in achieving long-term malaria control and elimination goals.

REFERENCES

1. Beloconi A, Nyawanda BO, Bigogo G, Khagayi S, Obor D, Danquah I, Kariuki S, Munga S, Vounatsou P. Malaria, climate variability, and interventions: modelling transmission dynamics. *Scientific Reports*. 2023 May 5;13(1):7367.
2. Parham PE, Michael E. Modeling the effects of weather and climate change on malaria transmission. *Environmental health perspectives*. 2010 May;118(5):620-6.
3. Tonnang HE, Kangalawe RY, Yanda PZ. Predicting and mapping malaria under climate change scenarios: the potential redistribution of malaria vectors in Africa. *Malaria journal*. 2010 Apr 23;9(1):111.
4. Reiter P. Global warming and malaria: knowing the horse before hitching the cart. *Malaria journal*. 2008 Dec 11;7(Suppl 1):S3.
5. Ototo EN, Ogutu JO, Githeko A, Said MY, Kamau L, Namanya D, Simiyu S, Mutimba S. Forecasting the potential effects of climate change on malaria in the Lake Victoria basin using regionalized climate projections. *Acta Parasitologica*. 2022 Dec;67(4):1535-63.
6. Parham PE, Pople D, Christiansen-Jucht C, Lindsay S, Hinsley W, Michael E. Modeling the role of environmental variables on the population dynamics of the malaria vector *Anopheles gambiae* sensu stricto. *Malaria Journal*. 2012 Aug 9;11(1):271.
7. Yé Y, Louis VR, Simboro S, Sauerborn R. Effect of meteorological factors on clinical malaria risk among children: an assessment using village-based meteorological stations and community-based parasitological survey. *BMC public health*. 2007 Jun 8;7(1):101.
8. Yamana TK, Eltahir EA. Incorporating the effects of humidity in a mechanistic model of *Anopheles gambiae* mosquito population dynamics in the Sahel region of Africa. *Parasites & vectors*. 2013 Aug 9;6(1):235.
9. Ermert V, Fink AH, Morse AP, Paeth H. The impact of regional climate change on malaria risk due to greenhouse forcing and land-use changes in tropical Africa. *Environmental health perspectives*. 2012 Jan;120(1):77-84.
10. Tonnang HE, Kangalawe RY, Yanda PZ. Predicting and mapping malaria under climate change scenarios: the potential redistribution of malaria vectors in Africa. *Malaria journal*. 2010 Apr 23;9(1):111.
11. Jambou R, Njedanoun M, Panthou G, Descroix L. Malaria transmission in Sahelian African regions, a witness of climate changes. *International journal of environmental research and public health*. 2022 Aug 16;19(16):10105.
12. Moukam Kakmeni FM, Guimapi RY, Ndjomatchoua FT, Pedro SA, Mutunga J, Tonnang HE. Spatial panorama of malaria prevalence in Africa under climate change and interventions scenarios. *International journal of health geographics*. 2018 Jan 16;17(1):2.
13. Sargent K, Mollard J, Henley SF, Bollasina MA. Predicting transmission suitability of mosquito-borne diseases under climate change to underpin decision making. *International journal of environmental research and public health*. 2022 Oct 21;19(20):13656.
14. Nissan H, Ukawuba I, Thomson M. Climate-proofing a malaria eradication strategy. *Malaria journal*. 2021 Apr 17;20(1):190.
15. KEDIR A, SULTAN M, AMANO T, GURRE A. Communities' Perceptions on the Relationship between Climate Variability and the Incidence of Malaria and Coping Strategies to Prevent Malaria Infection in Arsi Nagelle District, Oromia Regional State, Ethiopia. *Communities*. 2017;57.
16. Manyangadze T, Tarume B, Mavhura E. Local communities' perceptions on malaria prevalence in the face of climate change in Chimanimani District, Zimbabwe. *Climate and Development*. 2024 Dec 20:1-8.
17. Ssempiira J, Kissa J, Nambuusi B, Mukooyo E, Opigo J, Makumbi F, Kasasa S, Vounatsou P. Interactions between climatic changes and intervention effects on malaria spatio-temporal dynamics in Uganda. *Parasite epidemiology and control*. 2018 Aug 1;3(3):e00070.
18. Chaves LF, Hashizume M, Satake A, Minakawa N. Regime shifts and heterogeneous trends in malaria time series from Western Kenya Highlands. *Parasitology*. 2012 Jan;139(1):14-25.

19. Megersa DM, Abera M, Geremew T, Zainab R, Luo XS. Effects of climate change on the transmission of malaria in Africa. *Theoretical and Applied Climatology*. 2025 Aug;156(8):1-9.
20. Piovezan-Borges AC, Valente-Neto F, Urbietta GL, Laurence SG, de Oliveira Roque F. Global trends in research on the effects of climate change on *Aedes aegypti*: international collaboration has increased, but some critical countries lag behind. *Parasites & vectors*. 2022 Sep 29;15(1):346.
21. Jamrozik E, de la Fuente-Nunez V, Reis A, Ringwald P, Selgelid MJ. Ethical aspects of malaria control and research. *Malaria journal*. 2015 Dec 22;14(1):518.
22. Dinku T, Kanemba A, Platzner B, Thomson MC. Leveraging the climate for improved malaria control in Tanzania. *Earthzine Special Issue on "Earth Observations for Health"*. [<http://www.earthzine.org/2014/02/15/leveraging-the-climate-for-improved-malaria-control-in-tanzania/>]. 2014 Feb 15.
23. Carrasco-Escobar G, Fornace K, Benmarhnia T. Mapping socioeconomic inequalities in malaria in Sub-Saharan African countries. *Scientific reports*. 2021 Jul 23;11(1):15121.
24. Gikonyo C, Bejon P, Marsh V, Molyneux S. Taking social relationships seriously: lessons learned from the informed consent practices of a vaccine trial on the Kenyan Coast. *Social science & medicine*. 2008 Sep 1;67(5):708-20.
25. Tindana P, Bull S, Amenga-Etego L, de Vries J, Aborigo R, Koram K, Kwiatkowski D, Parker M. Seeking consent to genetic and genomic research in a rural Ghanaian setting: a qualitative study of the MalariaGEN experience. *BMC medical ethics*. 2012 Jul 2;13(1):15.

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