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Key Points:
- Populations in Niger, Nigeria, and Mali face risks from diseases due to high mosquito bite rates and immunity levels
- High temperatures in Niger increase disease spread, while in Nigeria, they may boost mosquito breeding, affecting malaria transmission
- The complex link between temperature and disease, influenced by factors like rainfall and humidity, poses prediction challenges

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The Analysis and the Impact of Surface Temperature Anomalies on the Health of Residents in the River Niger Basin Development Authority Area, West Africa

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Abstract This study investigates the impact of surface temperature anomalies on the health of residents within the River Niger Basin Development Authority (RIBDA) enclave, which covers Nigeria, Niger, and Mali in West Africa, with a focus on the regional implications for public health. Historical climate data from 1985 to 2014, sourced from the Climatic Research Unit Time-Series, Version 3.22 (CRU TS 3.22), was analyzed to comprehend past climate patterns and establish a baseline for future comparisons. Predictions for future climate conditions (2015–2044) were derived by adjusting the CRU data using temperature projections from the Community Climate System Model 4 under the Representative Concentration Pathway 8.5 scenario. To assess the potential impacts of these climate changes, particularly during the boreal summer season of July-August-September (JAS), the study utilized the Hydrology, Entomology, and Malaria Transmission Simulator (HYDREMATS). Findings indicate that surface temperature can intricately influence disease transmission, with varied effects on parameters such as Ro, EIR, prevalence, and immunity index. Observations revealed fluctuations in temperature anomalies over the years, with negative anomalies in 1991–1995 and positive anomalies in subsequent years. Although precise predictions for 2016–2044 are challenging based solely on data trends from 1985 to 2015, continued temperature rises could potentially lead to increased disease prevalence and decreased immunity index. Moreover, the analysis identified a notable temporal increase in mean annual temperature and mean annual maximum temperature from 1999 to 2020, suggesting a faster warming trend in maximum temperatures compared to minimum temperatures. This increase in temperature variability may alter the onset and cessation dates of the rainy season, affecting water availability, accessibility, and consumption, consequently fostering conditions conducive to health-related diseases. By incorporating predicted long-term temperature changes due to greenhouse gas emissions while maintaining current inter-annual climate patterns, this approach allows researchers to anticipate potential future health implications in the studied regions.

Plain Language Summary In this study, we explored how malaria spreads in Niger, Nigeria, and Mali, focusing on the role of climate factors like temperature and rainfall. In Niger, the potential for malaria spread was found to be low to moderate. Although mosquito bite rates were low, the population had low immunity, making them more susceptible to diseases like malaria and dengue. High temperatures can increase the prevalence of mosquito-borne diseases, leading to higher illness and death rates, especially among vulnerable groups like children and pregnant women. Unusual temperature patterns in Niger affected disease-related factors like transmission rates and immunity, though this may not hold for all diseases. In Nigeria, no clear link between rising temperatures and malaria transmission was found, but rainfall played a bigger role. More rain creates favorable conditions for mosquitoes, which can increase malaria spread. Mali's situation was complex, with no clear trends over time. The relationship between temperature and disease transmission involved multiple factors, like rainfall and humidity. Increased mosquito activity during higher temperatures could lead to more malaria cases, posing a public health challenge.

1. Introduction

Climate change and global warming have emerged as pressing environmental issues that significantly impact human health. Among the factors contributing to climate change, an increase in surface temperature is a key concern. In West Africa, where the impacts of climate change are already being experienced, it is crucial to have good knowledge of the potential health effects of surface temperature anomalies on the residents of the River

Niger Basin Development Authority Area. This understanding can help develop appropriate adaptation and mitigation strategies, ultimately contributing to the achievement of Sustainable Development Goals (SDGs) 3 and 13, aimed at ensuring good health and well-being, and combating climate change, respectively (Agyepong et al., 2017; Amegah et al., 2016; Chersich et al., 2020; Diboulo et al., 2012).

The effects of surface temperature on health are the subject of growing global research. The Lancet Countdown on Health and Climate Change 2020 report looks at exposure, vulnerability, labor capacity, and mortality as well as other aspects of the effects of heat and heatwaves. The result is a robust evidence compendium for planning, resilience, and adaptation for health. The results demonstrate that global ambient temperatures are rising along with the frequency and intensity of heat waves, which is harming human health and labor productivity globally (Watts et al., 2020).

Certain populations are inherently more susceptible to the negative health consequences of heat than others. These include children, outdoor laborers, and people who are 65 years and above. Additionally, individuals with chronic respiratory, cardiovascular, and diabetes disorders, as well as those living in metropolitan areas, are also more vulnerable. The populations of these susceptible individuals in a place or region serve as indicators that determine their heat vulnerability index (Bomblies et al., 2009; Cai et al., 2020; Ng et al., 2014; Watts et al., 2019).

However, these indicators do not include those who are more susceptible to the heat because of factors like poor health, low socioeconomic position, restricted access to healthcare, the prevalence of cooling devices or green spaces in cities, or the presence of heat early-warning systems Watts et al. (2020). Heatwaves do not create new health risks for people; instead, they exacerbate those that are already present especially in a place like Africa, a continent with limited resources that is already struggling with the simultaneous HIV/Coronavirus pandemic, non-communicable diseases, and other infectious diseases (Agyepong et al., 2017; Scovronick & Armstrong, 2012a, 2012b; Scovronick et al., 2018). Despite these great challenges, heat and heatwaves receive less attention in the national adaptation strategies of African nations including Botswana, Chad, Ghana, and Zimbabwe, among others and only a few studies have particularly addressed the effects of heat on health in Africa (Watts et al., 2017a, 2017b, 2018; Woodruff & Regan, 2019; Yamana & Eltahir, 2013; Yamana et al., 2013). Additionally, several African cities have not employed adequate heat-focused risk assessments.

A growing body of research has identified a range of adverse health effects linked to an increase in surface temperature; Oudin et al. (2016) found a significant association between high temperatures and an increase in hospital admissions for cardiovascular and respiratory diseases in Sweden, while Armstrong et al. (2019) found that high temperatures were associated with an increase in hospital admissions for dehydration and heat stroke in the United States.

Similarly, in West Africa, Adaji et al. (2019) found that high temperatures were linked to an increase in the incidence of meningitis. In this same region, Adelekan et al. (2017) found that high temperatures were associated with an increase in the incidence of malaria, a disease that is already prevalent in the region. Given that malaria is a major public health concern in West Africa, and climate change is likely to exacerbate its transmission, understanding the relationship between surface temperature anomalies and malaria transmission in the River Niger Basin Development Authority Area is particularly critical. This understanding can help develop policies aimed at protecting the health of residents in the area. Despite several studies on the influence of temperature on malaria transmission in West Africa, there remains a significant research gap in the understanding of surface temperature anomalies and their specific impact on the health of residents, particularly in the River Niger Basin Development Authority (RIBDA) area. Currently, there is limited knowledge of the spatial and temporal patterns of surface temperature anomalies and their influence on malaria transmission dynamics within this region. This crucial gap in research calls for a comprehensive investigation of the relationship between surface temperature anomalies and malaria transmission in the RIBDA area, as well as an evaluation of the potential health impacts on the local population.

Research studies have been conducted to investigate the impact of temperature on disease-related parameters in West Africa. These studies have found that high temperatures are associated with increased incidence of malaria and other vector-borne diseases. Boussari et al. (2019) conducted a 14-year time series analysis and found that high temperatures and low humidity were associated with increased malaria incidence in Mali. Samy et al. (2018) projected that climate change could lead to an increase in the transmission potential of vector-borne diseases in West Africa. This emphasizes the importance of understanding the complex relationships between environmental

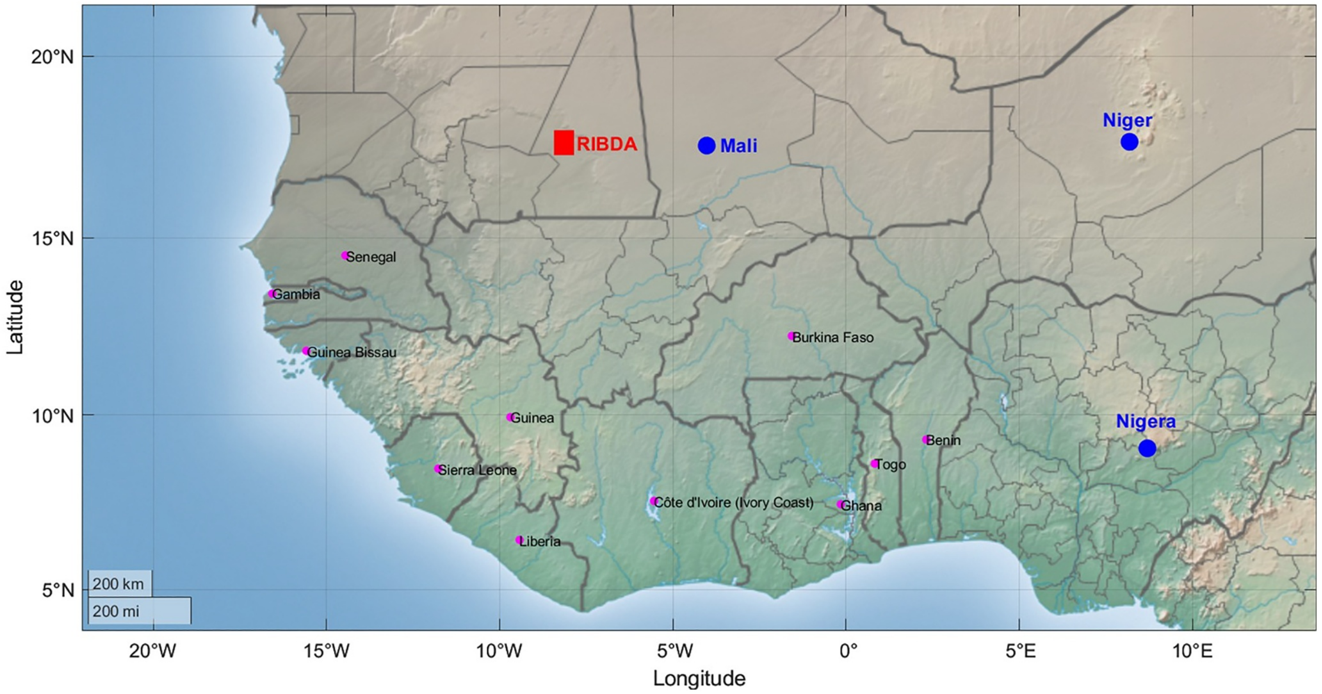

Figure 1. Map showing the locations of Nigeria, Niger and Mali in West Africa.

factors, disease transmission, and human behavior in developing effective disease control and prevention strategies. Thomson et al. (2019) also found that temperature had a significant impact on malaria transmission in West Africa. Additionally, Yakob et al. (2017) found that high temperatures could increase the transmission potential of the Zika virus, which is a significant concern in West Africa.

These research studies highlight the need to monitor and understand the impact of temperature on disease-related parameters in West Africa. This will enable public health officials to develop effective strategies to control and prevent the transmission of vector-borne diseases, reduce the burden of disease on the population, and prepare for the potential impacts of climate change on disease transmission. This study aims to fill the research gaps by conducting an in-depth investigation into the impact of surface temperature anomalies on the prevalence and transmission of malaria in the RIBDA region. Additionally, it seeks to identify the key factors contributing to the relationship between surface temperature anomalies and malaria transmission, while assessing the vulnerability of residents in the RIBDA area to malaria and other related diseases during the JAS period in three counties within the region (Nigeria, Niger and Mali). The outcomes of this study will provide valuable information for policymakers and public health practitioners, enabling them to develop effective strategies for malaria control and prevention in the region. Ultimately, this research will contribute to improving the health and well-being of the residents of the RIBDA area, reducing the burden of malaria, and enhancing the overall quality of life in the region.

2. Material and Method

2.1. Study Area

The River Niger Basin Development Authority (RIBDA) is an organization responsible for the development and management of the River Niger Basin, which spans several countries in West Africa. For this study, we have selected three countries within the basin for analysis: Nigeria, Niger, and Mali (Figure 1). These countries were chosen due to their geographical location within the RIBDA catchment area, which provides a suitable ground for the study. The selection of Nigeria, Niger, and Mali is further justified by their shared geographical and climatic characteristics within the RIBDA basin. These countries are situated in the West African region, which is vulnerable to climate change impacts, particularly temperature anomalies. By focusing on these three countries, this study aims to capture regional climate variability, examine country-specific climate characteristics, investigate shared climate-related health risks, and inform regional climate change adaptation strategies. Nigeria is situated in the western region of Africa, between latitudes 4° and 14°N and longitudes 2° and 15°E, with a tropical climate characterized by high temperatures and humidity throughout the year. Niger, located in the central region of Africa, between latitudes 11° and 24°N and longitudes 0° and 16°E, also has a tropical climate with hot temperatures and low humidity. Mali, in the western region of Africa, between latitudes 10° and 25°N and longitudes 4° and 12°W, experiences a tropical climate with hot temperatures and low humidity. The selection of these countries is justified by their shared geographical and climatic characteristics within the RIBDA basin, allowing for a comprehensive analysis of the region (Oguntunde et al., 2011).

2.2. Data Collection

The Climatic Research Unit Time-Series Version 3.22 (CRU TS 3.22) is a widely used data set for studying global climate patterns. This data set provides monthly time series of observed climate data, including temperature and precipitation, at a spatial resolution of 0.5° latitude by 0.5° longitude. The data is available from 1901 to 2016 and is based on observations from meteorological stations around the world. For this study, the past climate data for the period 1985–2014 was obtained from CRU TS 3.22. This data was used to understand the historical climate patterns in the study region, which includes Nigeria, Niger, and Mali, and to establish a baseline for comparison with future climate projections.

To predict the future climate patterns, the Community Climate System Model 4 (CCSM4) under the Representative Concentration Pathway (RCP) 8.5 scenario. RCP 8.5 is a high greenhouse gas emissions scenario that assumes that no climate mitigation policies are implemented, resulting in a significant increase in greenhouse gas concentrations in the atmosphere. The CCSM4 is a global climate model developed by the National Center for Atmospheric Research. It simulates the Earth's climate system, including the atmosphere, oceans, land surface, and sea ice, and provides predictions of future climate patterns based on different greenhouse gas emission scenarios. To project future climate conditions for the period 2015–2044, the CRU climate data was adjusted using the 30-year average temperature increase predicted by the CCSM4 model under the RCP 8.5 scenario, which is employed to simulate future climate change. This approach enables the Community Climate to preserve current inter-annual climate variability while incorporating predicted long-term warming trends due to increasing greenhouse gas concentrations. The focus is on the July-August-September (JAS) temperature, a key indicator of regional climate conditions.

2.3. Model Description

For this study, the Hydrology, Entomology, and Malaria Transmission Simulator (HYDREMATS), was selected to simulate the complex interactions between hydrology, entomology, and malaria transmission. This choice was made due to HYDREMATS' ability to explicitly represent water pools available as breeding sites for anopheles' mosquitoes, simulate the flow of rainfall into topographical low points, and model the life cycle of the anopheles' mosquito. HYDREMATS simulates the flow of rainfall into topographical low points and water loss due to evaporation and infiltration to represent the hydrology component. The agent-based entomology model simulates the life cycle of the anopheles' mosquito, including the aquatic stages of mosquitoes, from egg to multiple larval stages, to pupa, and finally adult emergence. The parasite enters the mosquito's body at the first infected blood meal, which is used to develop and deposit its first clutch of eggs. Parasite development continues with degree-day dependence until the mosquito becomes infectious to humans. Transmission occurs when the infectious mosquito takes a second blood meal from a different human, and the parasite's intrinsic incubation period begins within the human body. A new mosquito takes a blood meal following the intrinsic incubation period and becomes infectious, repeating the transmission cycle.

The model also incorporates malaria transmission indices, including the entomological inoculation rate (EIR), which measures the number of bites per person per unit of time. The basic reproduction number (Ro) is a measure of disease transmission and is defined as the total number of secondary infections from a single case of malaria, assuming an entirely susceptible population. The malaria prevalence or parasite rate is defined as the proportion of a population (usually age 2–8) that is infected with malaria each year. The model also uses the immunity index, which is a quantity that indicates the level of acquired immunity in an individual, varying from 0 (immunologically naive) to 1 (fully developed immunity).

The model setup includes hydrology, entomology, and GIS components. The various inputs into the different components are summarized at the bottom of the schematic diagram of the model setup. The data used in the model are obtained from various sources. The past (1985–2014) rainfall and temperature data are obtained from the Climatic Research Unit Time-Series Version 3.22 (CRU TS 3.22), while the future (2015–2044) climate predictions are obtained by adjusting the CRU climate data using the 30-year average temperature increase predicted by CCSM4 under RCP 8.5 scenario (Bomblies et al., 2009). HYDREMATS is a comprehensive model that simulates the mechanistic links between environmental variables and malaria transmission with high temporal and spatial resolution. The model includes a hydrology component that represents water pools available as breeding sites to anopheline mosquitoes, an agent-based entomology model that simulates the life cycle of the anopheles mosquito, and various malaria transmission indices, such as EIR, Ro, prevalence, and immunity index. The model data are obtained from various sources, including the Climatic Research Unit Time-Series Version 3.22 (CRU TS 3.22) and CCSM4 under the RCP 8.5 scenario (Bomblies et al., 2008).

3. Result and Discussion

3.1. Nigeria

The results of the data analysis reveal yearly fluctuations in six key parameters in Nigeria between 1985 and 2015, including rainfall, surface temperature, Entomological Inoculation Rate (EIR), Prevalence rate, and Immunity level, which are presented in Figure 2. Figure 2 illustrates the yearly fluctuations of these six parameters, namely rainfall, surface temperature during July, August, and September (JAS), EIR, Prevalence rate, and Immunity level. Additionally, it shows the influence of rainfall and temperature on three malaria indices. The Rainfall column showed that the amount of rainfall received in Nigeria varied between 1,085 mm and 1300 mm over the past three decades, with the highest rainfall recorded between 2000 and 2005. The Temperature column indicated that the surface temperature during July, August, and September ranged from 25.46 to 25.96°C, with the highest temperature recorded in 2005–2010. Rainfall shows a general increase from 1985 to 2015, with the highest value of 1300 mm recorded between 2000 and 2005. However, there was a slight decrease in rainfall from 2010 to 2015, with the lowest value of 1090.5 mm recorded during that period. The surface temperature during JAS also shows an increase over the years, with the highest value of 25.96°C recorded in 2005–2010.

Table 1 provides information on the effect of temperature on three key malaria indices: the entomological inoculation rate (EIR), reproduction number (Ro), and immunity index. The EIR column showed that the number of bites per person per unit time varied between 1.281 and 1.324. Although the values of EIR do not show any apparent trend with temperature, it has been well documented in literature that higher temperatures can increase the abundance of mosquitoes and their activity, leading to an increase in the transmission of malaria. The reproduction number (Ro) varied between 2.354 and 2.45. Higher temperatures can accelerate the development of the malaria parasite within the mosquito, leading to an increase in the number of infected mosquitoes and, consequently, an increase in the number of malaria cases. Finally, the immunity index varied between 0.875 and 0.894. The immunity index shows a general increase from 1985 to 2015, with the highest value of 0.894 recorded in 2010–2015. A low immunity index implies a higher susceptibility to malaria infection during the period, especially for vulnerable groups. This may increase the severity of the disease and the risk of complications. A low immunity index may also suggest inadequate access to healthcare, inadequate vaccination coverage, or poor nutritional status, all of which can weaken the immune system and make individuals more susceptible to infections.

The implications of these different parameter values depend on the parameter in question. For instance, higher rainfall and temperature can lead to more favorable breeding conditions for mosquitoes, increasing the transmission of malaria. Similarly, a higher EIR suggests a higher risk of being bitten by infected mosquitoes, which can also increase transmission. In contrast, a lower R0 and immunity index may indicate better protection against the disease, leading to lower transmission and prevalence. From the table, it is observed that Malaria Prevalence has the highest value of 73.16 during the semi-decadal period 2000–2005. On the other hand, the Immunity Index has the lowest value, with a minimum of 0.875 observed and relatively low Malaria Prevalence with value 72.65 during the semi-decadal period 2010–2015. This indicates that a high malaria prevalence rate may have negative public health implications.

Table 1 presents information on the effect of temperature on key malaria indices in Nigeria between 1985 and 2015. The data suggests that higher JAS temperatures are generally associated with higher entomological

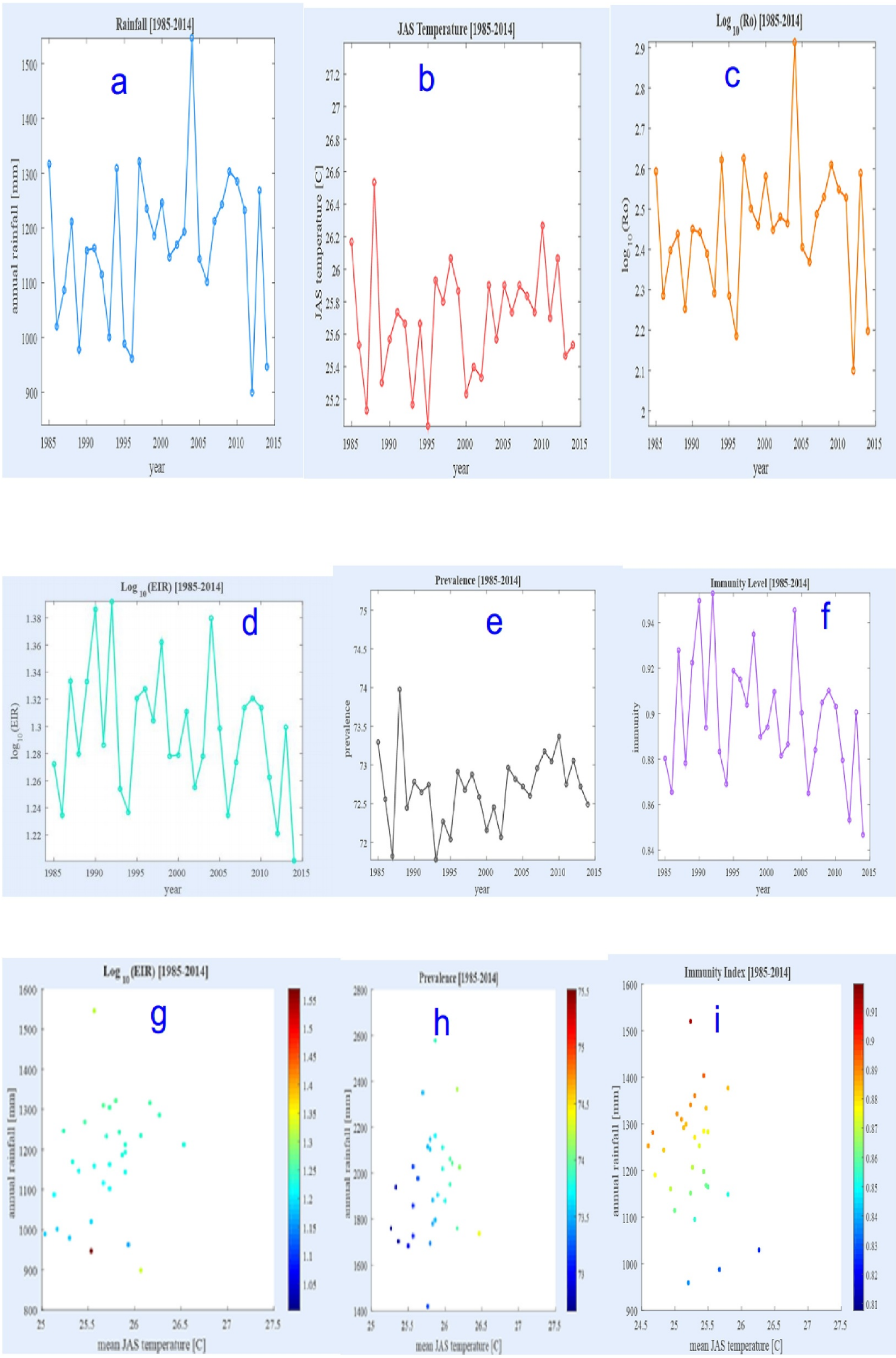

Figure 2. Illustrates the yearly fluctuations of six parameters in Nigeria between 1985 and 2015, namely rainfall, surface temperature during July, August, and September (JAS), the entomological inoculation rate (EIR), prevalence rate, and immunity level (a–f). Additionally, it shows the influence of rainfall and temperature on three malaria indices (g–i) (Source: http://eltahir.info/).

Table 1
Climate Data and Malaria Transmission Indices for Nigeria (Source-http://eltahir.info/)

Semi-decadal year	Rainfall (mm)	Temperature °C	Ro	EIR	Malaria prevalence	Immunity index
1985–1990	1085.0	25.82	2.450	1.310	72.67	0.885
1990–1995	1130.0	25.52	2.384	1.324	72.42	0.894
1995–2000	1220.0	25.46	2.416	1.296	72.62	0.894
2000–2005	1300.0	25.64	2.408	1.305	73.16	0.894
2005–2010	1235.0	25.96	2.424	1.305	72.88	0.885
2010–2015	1090.5	25.84	2.354	1.281	72.65	0.875

inoculation rate (EIR) values, which is due to the influence of temperature on the life cycle of the Anopheles mosquito, the vector responsible for malaria transmission, and its ability to transmit the parasite. Additionally, the data shows a clear pattern of decline in the reproduction number (Ro) with lower Ro values observed during the years with the lowest temperature (2010–2015) and higher values during the years with the highest temperature (1985–1990). However, other factors, such as parasite prevalence and human behavior, may also influence Ro values. Regarding the effect of temperature on immunity, the data suggests that higher JAS temperatures are generally associated with higher immunity levels. This may be due to the increased exposure to the parasite resulting from higher malaria transmission rates, which can lead to increased resistance to malaria. However, prolonged exposure to high temperatures can impair the development of the immune system, leading to decreased resistance to malaria.

Figure 3 displays the anomalies that represent the deviation of each variable from its average value, which is useful in identifying patterns or trends in the data. The figure shows that between 2000 and 2010, there was a period of above-average temperatures and higher malaria prevalence, while Ro and EIR remained relatively stable. In contrast, the period from 1990 to 2000 had lower temperatures, lower Ro and EIR, and lower malaria prevalence. The Ro anomaly indicates positive and negative values, reflecting increased or decreased malaria transmission efficiency during semi-decadal periods. Similarly, the EIR anomaly column displays positive and negative values, indicating an increase or decrease in the number of infected mosquitoes during semi-decadal periods. The malaria prevalence anomaly shows positive and negative values, indicating an increase or decrease in the number of people infected with malaria. Finally, the immunity index anomaly column shows positive and negative values, indicating an increase or decrease in people's resistance to malaria. These anomalies have significant implications for the health of people in Nigeria. Positive Ro anomalies suggest that malaria transmission was more efficient during that period, leading to more cases and potentially higher mortality rates.

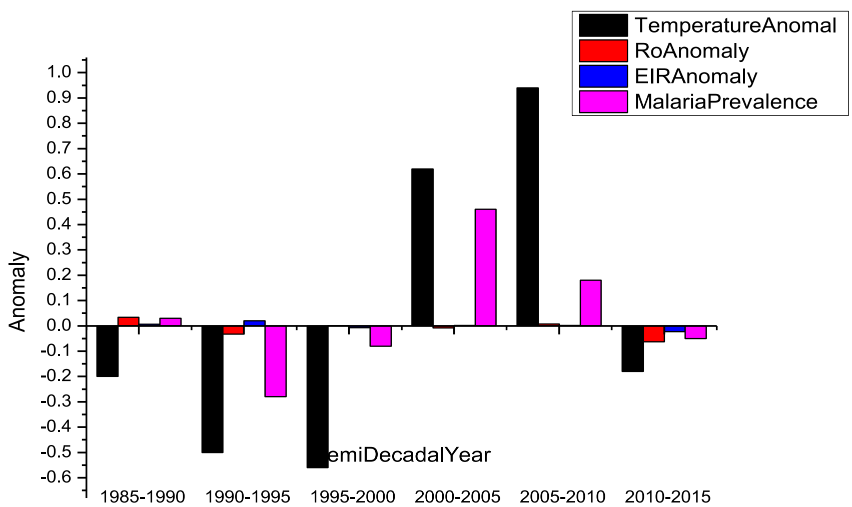

Figure 3. Graphical representation of temperature anomaly against related climatic parameters in semi-decadal year in Nigeria from 1985 to 2015.

Table 2
Temperature and Related Parameters Anomalies in Nigeria

Semi-decadal year	Temperature anomaly	Ro anomaly	EIR anomaly	Malaria prevalence anomaly	Immunity index anomaly
1985–1990	−0.20	0.0335	0.0065	0.03	−0.0162
1990–1995	−0.50	−0.0325	0.0205	−0.28	−0.0072
1995–2000	−0.56	0.0005	−0.0075	−0.08	−0.0072
2000–2005	0.62	−0.0085	0.0015	0.46	0.0228
2005–2010	0.94	0.0075	0.0015	0.18	0.0838
2010–2015	−0.18	−0.0625	−0.0225	−0.05	−0.0262

Conversely, positive immunity index anomalies suggest that people were more resistant to malaria, leading to fewer cases and lower mortality rates. There is no clear pattern between temperature anomaly and the other anomalies. For example, during the 1990–1995 semi-decadal period, the temperature anomaly was negative, but the Ro anomaly was positive, while during the 2000–2005 semi-decadal period, the temperature anomaly was positive, but the Ro anomaly was negative. Similarly, there is no clear pattern between the temperature anomaly and the EIR anomaly, malaria prevalence anomaly, and immunity index anomaly. Overall, these data indicate that environmental factors, such as temperature, play a significant role in malaria transmission and the health of people in Nigeria. It is crucial to continue monitoring these factors and implementing appropriate measures to prevent and control malaria in the country. An increase in temperature is associated with an increase in the infectiousness of malaria, leading to a higher Ro anomaly. This means that an increase in temperature can increase the risk of malaria transmission. This is because higher temperatures can increase the rate of reproduction of malaria parasites in mosquitoes and reduce the time it takes for the parasites to develop to infectious stages.

A positive correlation between temperature and EIR anomaly suggests that an increase in temperature can lead to an increase in the intensity of malaria transmission. This is because higher temperatures can accelerate the development of malaria parasites in mosquitoes and shorten the lifespan of mosquitoes, resulting in more bites per mosquito and a higher chance of transmitting the disease to humans. However, an increase in temperature can also reduce the number of people affected by malaria, resulting in a negative correlation between temperature and prevalence anomaly. This is because higher temperatures can limit the survival and reproduction of mosquitoes, which are the primary vectors of malaria.

Table 2 presents the anomalies of temperature and related parameters in Nigeria for semi-decadal periods from 1985 to 2015. The temperature anomaly column shows a fluctuation in temperatures, with a warming trend from 2000 to 2010 and a cooling trend from 2010 to 2015. This fluctuation has implications for malaria transmission, as warmer temperatures can increase the contagiousness and transmission of the disease. The Ro anomaly column represents the reproduction number, which measures the contagiousness of malaria. The column indicates a decrease in malaria contagiousness from 1990 to 2000, followed by an increase from 2000 to 2010, and a subsequent decrease from 2010 to 2015. This trend suggests that malaria transmission is influenced by temperature anomalies, with warmer temperatures potentially increasing contagiousness. The EIR anomaly column represents the entomological inoculation rate, which measures the number of infective mosquito bites per person per year. The column shows a decrease in malaria transmission from 1995 to 2000, followed by an increase from 2000 to 2010, and a subsequent decrease from 2010 to 2015. This trend is consistent with the Ro anomaly column, suggesting that malaria transmission is influenced by temperature anomalies. The malaria prevalence anomaly column indicates a decrease in malaria prevalence from 1990 to 2000, followed by an increase from 2000 to 2010, and a subsequent decrease from 2010 to 2015. This trend suggests that malaria prevalence is influenced by temperature anomalies, with warmer temperatures potentially increasing prevalence. Finally, the immunity index anomaly column shows a decrease in immunity from 1990 to 2000, followed by an increase from 2000 to 2010, and a subsequent decrease from 2010 to 2015. This trend suggests that immunity to malaria is influenced by temperature anomalies, with warmer temperatures potentially decreasing immunity. Overall, the table suggests a potential link between temperature anomalies and malaria transmission, with warmer temperatures potentially increasing contagiousness, transmission, and prevalence, while decreasing immunity.

In Figure 4, the forecast for the period of 2015–2044 highlights a significant trend of rising temperature anomaly and Ro anomaly, coupled with a slight increase in EIR anomaly, and a decrease in malaria prevalence and

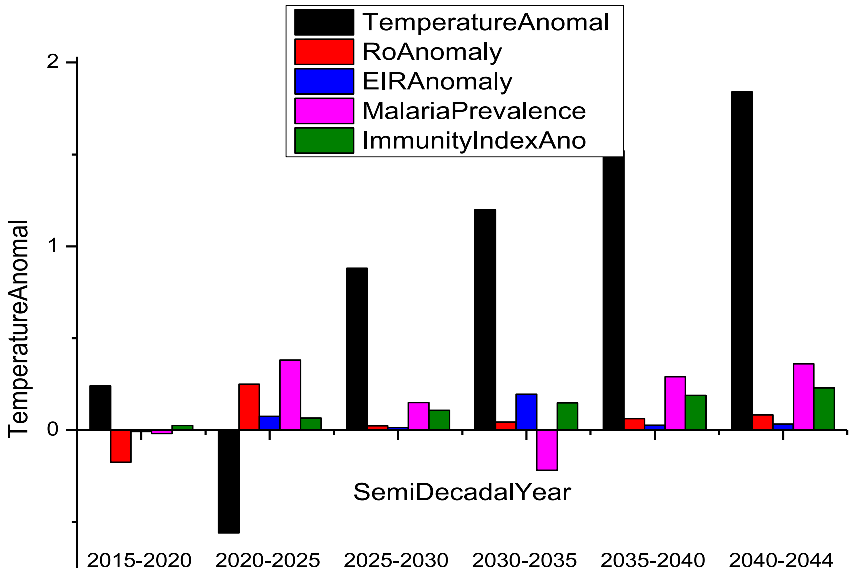

Figure 4. Graphical representation of forecast temperature anomaly against related malaria indicator parameters in semi-decadal year in Nigeria (2016–2044).

immunity index anomalies. These trends may have far-reaching implications for global health, particularly for malaria transmission. The increasing temperature anomaly indicates potential changes in weather patterns, sea levels, and ecosystem functioning, which can significantly impact agriculture, water availability, and human health. The rising Ro anomaly suggests a higher risk of malaria transmission, especially in endemic regions, which can have severe consequences for vulnerable populations, such as children and pregnant women. While the increase in EIR anomaly is relatively small, it could still contribute to a higher risk of malaria transmission. The reduction in malaria prevalence and immunity index anomalies could be a result of improved public health interventions and healthcare access, but this may also leave populations susceptible to future outbreaks due to decreased natural immunity. Overall, these trends represent both challenges and opportunities for global health, underlining the significance of continued research and monitoring to inform effective public health interventions and mitigate potential negative impacts on human well-being.

3.2. Mali

Figure 5 illustrates the yearly fluctuations of six parameters in Mali between 1985 and 2015, namely rainfall, surface temperature during July, August, and September (JAS), the entomological inoculation rate (EIR), prevalence rate, and immunity level. Additionally, it shows the influence of rainfall and temperature on three malaria indices. The rainfall pattern in the region is characterized by notable fluctuations over the studied period. A significant increase in rainfall is observed from 1985 to 1990 to 1996–2000, followed by a decline in subsequent years. The fluctuations in rainfall may lead to changes in the distribution and prevalence of disease vectors, such as mosquitoes, which are sensitive to environmental factors like rainfall. In contrast, the temperature in the region remains relatively stable over time, with no discernible trend. This stability may not have a profound impact on disease transmission or immunity, as temperature is often a key factor in shaping disease dynamics. However, it is essential to note that even small changes in temperature can have significant effects on disease transmission, particularly in regions with limited resources and infrastructure. The reproduction number (Ro) and entomological inoculation rate (EIR) fluctuate over time, with slight increases and decreases during periods of higher rainfall. The Ro value, which measures disease contagiousness, appears to increase during periods of higher rainfall, suggesting that increased rainfall may contribute to enhanced disease transmission. Conversely, the EIR value, which indicates disease transmission risk, decreases during periods of higher rainfall, highlighting the complex relationships between climate, disease transmission, and immunity.

This Table 3 presents a time series of several parameters related to climate, disease transmission, and immunity from 1985 to 2015. The rainfall in the region varies from 106.9 to 192.6 mm over the studied period. There is a clear trend of increased rainfall in the region from 1985–1990 to 1996–2000, with a peak in 1996–2000, followed

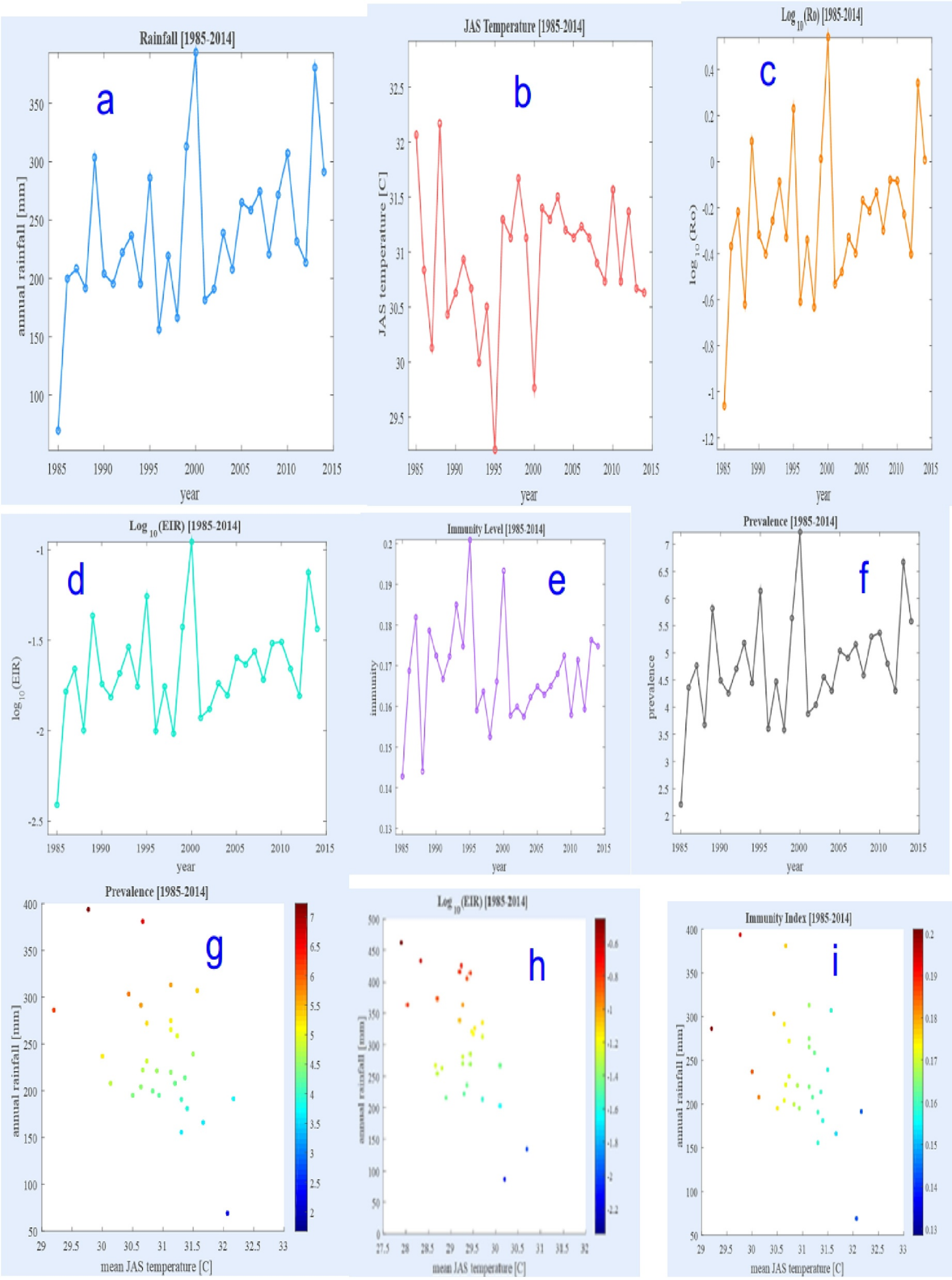

Figure 5. Illustrates the yearly fluctuations of six parameters in Mali between 1985 and 2015, namely rainfall, surface temperature during July, August, and September (JAS), the entomological inoculation rate (EIR), prevalence rate, and immunity level (a–f). Additionally, it shows the influence of rainfall and temperature on three malaria indices (g–i) (Source http://eltahir.info/).

Table 3
Climate Data and Malaria Transmission Indices for Mali (1985–2015) (Source-http://eltahir.info/)

Semi-decadal year	Rainfall (mm)	Temperature (°C)	Reproduction number (Ro)	EIR	Prevalence	Immunity index
1985–1990	133.3	33.76	−0.30	−1.53	3.67	0.16
1991–1995	106.9	34.72	0.268	−1.35	18.4	0.31
1996–2000	192.6	33.12	0.454	−1.29	11.6	0.19
2001–2005	113.6	32.76	0.506	−1.38	22.8	0.23
2006–2010	150.8	31.88	−0.052	−1.36	15.6	0.21
2011–2015	188.4	33.72	0.36	−1.06	11.6	0.26

by a decline in the subsequent years. The temperature in the region ranges from 31.88°C to 34.72°C. There is no clear trend in temperature over the studied period, but it generally remains within a narrow range. The reproduction number (Ro) is a measure of the contagiousness of a disease. A value of Ro < 1 indicates that the disease is declining while a value of Ro > 1 indicates that it is spreading. The Ro value in the region fluctuates over the studied period, ranging from −0.30 to 0.506. There is no clear trend in Ro over time, but it appears to be slightly higher during the period of higher rainfall (1996–2000). The entomological inoculation rate (EIR) is a measure of the intensity of transmission of a vector-borne disease. A higher EIR indicates a higher risk of infection. The EIR value in the region ranges from −1.53 to −1.06 over the studied period. There is no clear trend in EIR over time, but it appears to be slightly lower during the period of higher rainfall (1996–2000).

The prevalence of a disease refers to the proportion of individuals in a population who are infected. The prevalence in the region ranges from 3.67% to 22.8% over the studied period. There is no clear trend in prevalence over time. The immunity index measures the level of immunity in a population. A higher immunity index indicates a higher proportion of immune individuals in the population. The immunity index in the region ranges from 0.16 to 0.31 over the studied period. There is no clear trend in the immunity index over time. The effect of temperature on Ro, EIR, prevalence, and immunity index is complex and depends on several factors. For example, higher temperatures can increase the survival and reproduction of vectors, leading to higher EIR and prevalence. However, higher temperatures can also reduce the lifespan of vectors, leading to lower EIR and prevalence. Similarly, higher temperatures can increase the transmission efficiency of a pathogen, leading to higher Ro, but it can also increase the host immune response, leading to a lower Ro. In summary, this table provides a snapshot of several important parameters related to climate, disease transmission, and immunity over 30 years. While there is no clear trend in most of the parameters over time, the effect of temperature on disease transmission and immunity is complex and depends on several factors.

The effect of temperature anomalies on various health indicators in Mali can be complex and dependent on several factors (Table 4). However, a comprehensive analysis of the anomaly table reveals some general observations. The temperature anomalies ranged from −2.39°C to 0.45°C, indicating significant fluctuations in temperature over the semi-decadal periods in Mali. Looking at the Reproduction Number (Ro), we can see that the temperature anomaly had a mixed effect on Ro, with some years showing a positive correlation between temperature and Ro and others showing a negative correlation. This suggests that the effect of temperature on disease transmission is not straightforward and may depend on other factors such as rainfall and humidity. On the other hand,

Table 4
Temperature and Related Parameters Anomalies in Mali

Semi-decadal year	Rainfall anomaly (mm)	Temperature anomaly	Ro anomaly	EIR anomaly	Prevalence anomaly	Immunity index anomaly
1985–1990	−32.56	−0.51	−0.23	−0.19	−0.02	−0.07
1991–1995	−59.99	0.45	0.34	0.09	0.68	0.15
1996–2000	26.71	−1.15	0.53	0.15	−0.62	−0.07
2001–2005	−52.29	−1.51	0.59	0.04	0.56	0.01
2006–2010	−15.09	−2.39	−0.50	0.02	−0.42	−0.01
2011–2015	22.77	−0.56	0.18	0.78	−0.62	0.04

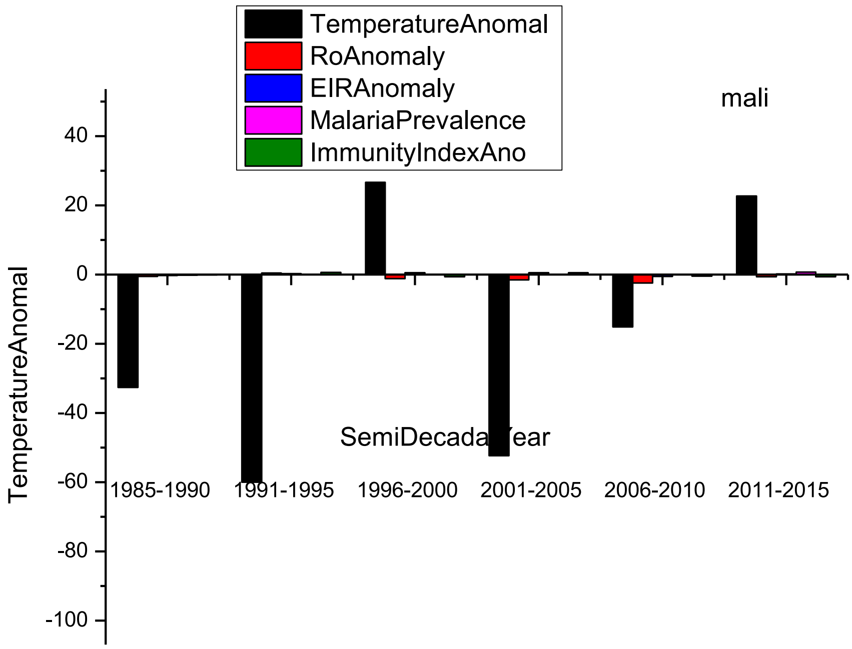

Figure 6. Graphical representation of temperature anomaly against related climatic parameters in semi-decadal year in Mali from 1985 to 2015.

Entomological Inoculation Rate (EIR) had a positive correlation with temperature anomalies in most years, except for 2006–2010. This is consistent with the known biology of mosquitoes, which are cold-blooded and require warm temperatures for optimal growth and reproduction. Therefore, higher temperatures can increase mosquito populations and hence EIR (Figure 6).

The effect of temperature anomalies on disease prevalence was mixed. Some years showed a positive correlation, while others showed a negative correlation. This suggests that the effect of temperature on disease prevalence is complex and may depend on other factors such as rainfall, humidity, and the availability of effective treatments. Similarly, the effect of temperature anomalies on immunity index was mixed. Some years showed a positive correlation, while others showed a negative correlation. This suggests that the effect of temperature on immunity development is complex and may depend on other factors such as the prevalence of the disease, vaccination coverage, and the quality of healthcare.

In Figure 7, the predicted Ro values are also consistently lower than the historical mean, with a maximum anomaly of −0.22 in the period of 2041–2044. This suggests that the transmission potential of malaria is decreasing over time. This may be due to factors such as improved healthcare, mosquito control measures, or changes in the environment. The negative temperature anomaly may also be contributing to the decrease in Ro, as mosquitoes that transmit malaria are sensitive to temperature changes. The table of anomalies above shows that the predicted temperatures for the period of 2016–2044 are consistently lower than the historical mean. This means that the temperature anomaly is negative throughout the predicted period, with a maximum anomaly of −0.62°C in the period of 2041–2044. The predicted EIR values are consistently higher than the historical mean, with a maximum anomaly of +0.77 in the period of 2041–2044. This suggests that the risk of malaria infection is increasing over time. This may be due to factors such as changes in mosquito behaviour, land use, or human population dynamics. The negative temperature anomaly may also be contributing to the increase in EIR, as mosquitoes that transmit malaria may be more active in cooler temperatures. The predicted prevalence values are consistently lower than the historical mean, with a maximum anomaly of −1.80 in the period of 2016–2020. This suggests that the overall burden of malaria in the population is decreasing over time. This may be due to factors such as improved healthcare, better access to antimalarial drugs, or changes in mosquito control measures. The negative temperature anomaly may also be contributing to the decrease in prevalence, as mosquitoes that transmit malaria are less active in cooler temperatures. The predicted Immunity Index values are consistently higher than the historical mean, with a maximum anomaly of +0.16 in the period of 2041–2044. This suggests that more

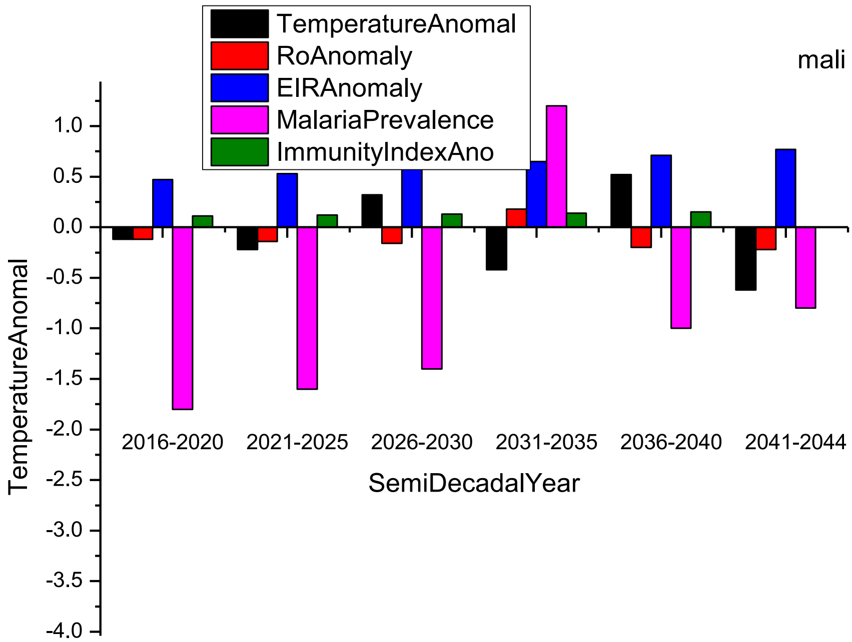

Figure 7. Graphical representation of forecast temperature anomaly against related climatic parameters in semi-decadal year in Mali (2016–2044).

people are developing immunity to malaria over time. This may be due to factors such as improved healthcare, better access to antimalarial drugs, or changes in the environment. The negative temperature anomaly may also be contributing to the increase in the Immunity Index, as mosquitoes that transmit malaria may be less active in cooler temperatures.

3.3. Niger

Figure 8 provides a comprehensive overview of the yearly fluctuations of several key parameters in Niger between 1985 and 2015. This graphical representation is instrumental in understanding the influence of rainfall and temperature on malaria indices. Rainfall in the region shows dramatic fluctuations over the studied period. Starting at a moderate level in the late 1980s, there is a slight decrease in the early 1990s, followed by a significant increase in the late 1990s, marking a wetter period. This is followed by a drop in the early 2000s, then another substantial rise in the late 2000s, peaking in the early 2010s. These variations in rainfall significantly impact the habitats of disease vectors such as mosquitoes, which are highly sensitive to changes in moisture levels. Surface temperatures during the critical months of July, August, and September (JAS) remain relatively stable, with no clear trend over the studied period, except for a noticeable drop in the early 1990s. This stability might suggest a lesser impact on disease transmission and immunity. However, even slight temperature variations can significantly influence vector behavior and disease dynamics, particularly in areas with limited resources. The reproduction number (Ro), which measures how contagious a disease is, and the entomological inoculation rate (EIR), indicating disease transmission risk, both exhibit fluctuations over time. From the late 1980s to the early 2000s, Ro values are negative, indicating limited transmission. However, the period from the early 2010s sees a positive Ro for the first time, suggesting an increase in disease spread, possibly due to increased rainfall creating optimal conditions for mosquito breeding. Conversely, EIR values remain negative throughout the period but show an increasing trend during higher rainfall periods, reflecting a complex interplay between climatic conditions and malaria transmission.

Malaria prevalence shows a steady increase from the late 1980s to the early 2000s, followed by a significant rise in the early 2010s, correlating with increased rainfall and a positive Ro. This sharp rise in prevalence could indicate a resurgence in transmission or improved detection and reporting mechanisms. Meanwhile, the immunity index, which starts high in the late 1980s, drops significantly over the years, reaching its lowest point in the early 2000s before fluctuating slightly but remaining low through the 2010s. This decline in immunity could be due to

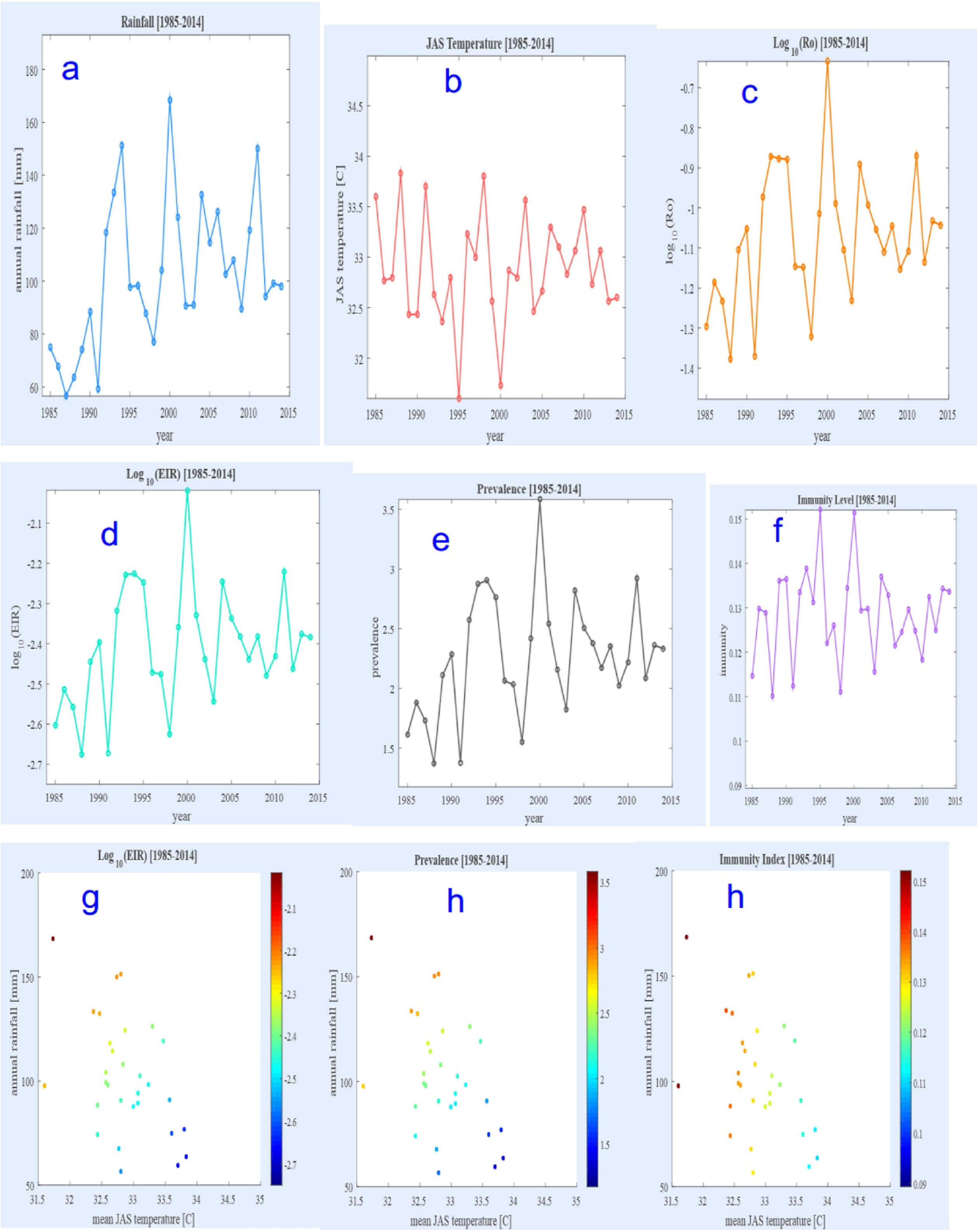

Figure 8. Illustrates the yearly fluctuations of six parameters in Niger between 1985 and 2015, namely rainfall, surface temperature during July, August, and September (JAS), the entomological inoculation rate (EIR), prevalence rate, and immunity level (a–f). Additionally, it shows the influence of rainfall and temperature on three malaria indices (g–i) (Source-http://eltahir.info/).

Table 5
Climate Data and Malaria Transmission Indices for Niger, 1985–2016 (Source-http://eltahir.info/)

Semi-decadal year	Rainfall (mm)	Temperature	Ro	EIR	Prevalence	Immunity index
1985–1990	228.67	30.02	−0.25	−1.57	4.50	1.53
1991–1995	212,00	26.62	−0.14	−1.37	5.04	0.778
1996–2000	256.60	30.24	−0.24	−1.38	5.18	0.174
2001–2005	210.00	30.24	−0.23	−1.34	5.44	0.17
2006–2010	298.00	30.48	−0.08	−1.34	5.36	0.205
2011–2015	369.40	30.04	0.29	−1.06	8.16	0.28

various factors, including changes in vector control strategies, population movements, or changes in malaria strains. In summary, Figure 3.0 reveals the intricate and evolving balance between environmental factors and public health in Niger. Higher rainfall periods are linked to higher malaria transmission, as reflected in the Ro and prevalence rates, while stable temperatures play a supporting role. Understanding this balance is crucial for developing effective strategies to manage and mitigate disease risks in the face of changing climate patterns. This period's climatic and disease dynamics narrative highlights the delicate interplay between nature and health, emphasizing the need for adaptive and resilient public health strategies.

Table 5 provides a detailed data set spanning three decades, capturing the interplay between climate variables (rainfall and temperature) and malaria transmission indices (Ro, EIR, prevalence, and immunity index) in Niger from 1985 to 2015. This period saw significant variations in climatic conditions, which in turn influenced malaria dynamics in the region. Between 1985 and 2015, Niger experienced a dynamic interplay of climate and disease indicators, each influencing the other in subtle yet significant ways. The region's rainfall pattern exhibits dramatic fluctuations, with notable increases from the late 1980s, peaking around 1996–2000, and then again from 2006 to 2015, followed by periods of decline. These shifts in rainfall significantly impacted the habitats of disease vectors like mosquitoes, which are highly sensitive to changes in moisture levels (Table 5).

Surface temperatures during the critical months of July, August, and September (JAS) remained relatively stable, with no clear trend over the studied period, except for a noticeable drop in 1991–1995. While this stability might suggest a lesser impact on disease transmission and immunity, even slight temperature variations can significantly influence vector behavior and disease dynamics, particularly in areas with limited resources. The reproduction number (Ro), which measures how contagious a disease is, and the entomological inoculation rate (EIR), indicating disease transmission risk, both exhibited fluctuations over time. From 1985 to 2005, Ro values were negative, indicating limited transmission. However, the period from 2011 to 2015 saw a positive Ro for the first time, suggesting an increase in disease spread, possibly due to increased rainfall creating optimal conditions for mosquito breeding. Conversely, EIR values remained negative throughout, but the highest transmission intensity was noted in 2011–2015, reflecting a complex interplay between climatic conditions and malaria transmission (Tables 6 and 7).

Malaria prevalence showed a steady increase from 1985 to 2005, followed by a significant rise to 8.16 in 2011–2015, correlating with increased rainfall and a positive Ro. This sharp rise in prevalence could indicate a resurgence in transmission or improved detection and reporting mechanisms. Meanwhile, the immunity index,

Table 6
Temperature and Related Parameters Anomalies in Niger (1985–2015) (Source-http://eltahir.info/)

Semi-decadal year	Temperature anomaly	Ro anomaly	EIR anomaly	Prevalence anomaly	Immunity index anomaly
1985–1990	0.22	−0.1233	−0.255	−0.883	1.06
1991–1995	−3.18	−0.0133	0.025	−0.343	0.308
1996–2000	0.44	−0.1133	−0.065	−0.203	−0.296
2001–2005	0.44	−0.1033	−0.025	0.057	−0.300
2006–2010	0.68	0.0573	−0.025	−0.043	−0.265
2011–2015	0.24	0.4167	0.255	2.777	−0.234

Table 7
Forecast Climatic Data and Malaria Transmission Indices for Niger (2016–2044)

Semi-decadal year	Temperature	Ro	EIR	Prevalence	Immunity index
2016–2020	29.61	−0.02	−0.91	8.46	0.286
2021–2025	29.18	−0.13	−0.71	9.00	0.201
2026–2030	28.75	−0.24	−0.51	9.54	0.117
2031–2035	28.32	−0.35	−0.31	10.08	0.033
2036–2040	27.89	−0.46	−0.11	10.62	−0.051
2041–2044	27.46	−0.57	0.09	11.16	−0.135

which began at 1.53 in 1985–1990, dropped significantly over the years, reaching its lowest in the 1996–2005 period before fluctuating slightly but remaining low through 2015. This decline in immunity could be due to various factors, including changes in vector control strategies, population movements, or changes in malaria strains. In summary, the data from 1985 to 2015 reveals the intricate and evolving balance between environmental factors and public health in Niger. Rainfall increases were linked to higher malaria transmission, as reflected in the Ro and prevalence rates, while stable temperatures played a supporting role. Understanding this balance is crucial for developing effective strategies to manage and mitigate disease risks in the face of changing climate patterns. This period's climatic and disease dynamics narrative highlights the delicate interplay between nature and health, emphasizing the need for adaptive and resilient public health strategies.

The graph depicted in Figure 9 illustrates the anomalies of temperature, Ro, EIR, prevalence, and immunity for different semi-decadal years in Niger. Based on the temperature anomaly data, it can be observed that from 1985 to 1990, the temperature was 0.22°C above the anticipated value. Subsequently, the temperature anomaly fluctuated between negative and positive values, reaching a maximum of 0.68°C from 2006 to 2010. The temperature anomaly demonstrated a fluctuating pattern over the years, with a negative anomaly in 1991–1995 and a positive anomaly in all the other years.

The Ro anomaly data indicated a decreasing trend from 1985 to 1990 to 1991–1995, followed by a fluctuating pattern with no clear correlation. The EIR anomaly also displayed a fluctuating trend with no distinct correlation. Similarly, the prevalence anomaly showed a decreasing trend from 1985 to 1990 to 1991–1995, followed by a fluctuating trend with no clear correlation. The immunity index anomaly also exhibited a decreasing trend from 1985 to 1990 to 1991–1995, followed by a fluctuating pattern with no distinct correlation (Table 6). Regarding the impact of temperature anomaly on the other anomalies, the Ro anomaly data demonstrated a negative correlation

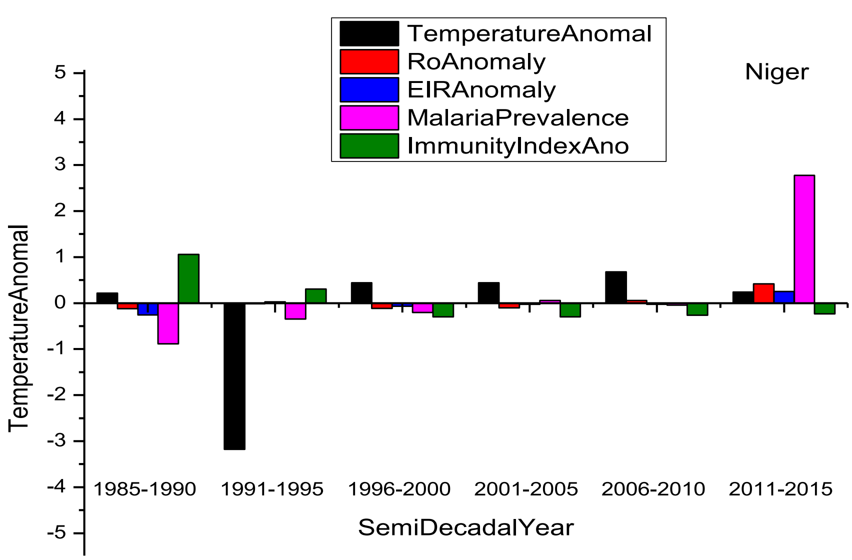

Figure 9. Temperature anomaly against related climatic parameters in semi-decadal year in Niger.

with the temperature anomaly, indicating that as the temperature increased, the Ro anomaly decreased, and vice versa. On the other hand, the EIR anomaly displayed a mixed correlation with no clear pattern. The prevalence anomaly exhibited a positive correlation with the temperature anomaly, signifying that as the temperature increased, the prevalence anomaly also increased, and vice versa. The immunity index anomaly also displayed a mixed correlation with no clear pattern.

The Ro anomaly data suggests a negative correlation between temperature and Ro anomaly. In the periods of 1985–1990 and 1996–2000, the Ro value decreased as the temperature increased. However, in the 2011–2015 period, when the temperature anomaly was positive, the Ro anomaly was also positive, indicating that as the temperature increased, so did the Ro value. The EIR anomaly data suggested a mixed correlation between temperature and EIR anomaly. In the periods of 1985–1990 and 1991–1995, as the temperature increased, the EIR value decreased. But in the 2011–2015 period, as the temperature increased, the EIR value increased. The prevalence anomaly data also demonstrated a mixed correlation between temperature and prevalence anomaly. In the periods of 1985–1990 and 1991–1995, as the temperature increased, the prevalence value decreased. However, in the 2011–2015 period, as the temperature increased, the prevalence value increased. The immunity index anomaly data indicated a mixed correlation between temperature and immunity index anomaly. In the periods of 1985–1990 and 1996–2000, as the temperature increased, the immunity index value increased. However, in the subsequent periods, the immunity index value decreased as the temperature increased. The trends in the data suggest that temperature has a mixed effect on the different parameters, with Ro, EIR, and prevalence displaying mixed correlations with temperature, while the immunity index shows a more consistent correlation with temperature in the periods of 1985–1990 and 1996–2000. The data highlights the importance of understanding the complex relationship between temperature and disease transmission, particularly in regions like Niger where diseases such as malaria are prevalent. The mixed correlations suggest that the relationship between temperature and disease transmission is complex and may depend on other factors such as humidity, rainfall, and human behavior. Therefore, further research is required to better understand this relationship and its implications for public health in Niger.

The implications of these findings on the health of people in Niger are that temperature anomalies have a significant impact on the spread of infectious diseases. The negative correlation between temperature anomaly and Ro anomaly suggests that as the temperature increases, the spread of diseases like malaria may decrease. This may be due to a decrease in mosquito populations or a decrease in their lifespan, both of which would limit the transmission of malaria. However, the positive correlation between temperature anomaly and prevalence anomaly suggests that as the temperature increases, the prevalence of diseases like malaria may increase. This could be due to factors such as increased breeding of mosquitoes or increased exposure to mosquitoes by people.

The temperature anomaly in Niger has a significant effect on the anomalies of Ro, EIR, prevalence, and immunity, which are all important factors in understanding the health outcomes of people in the country. However, it's important to note that this relationship may not hold for all diseases and there may be other factors at play. Based on the trends in the data from 1985 to 2015, it's difficult to make accurate predictions for the years 2016–2044 (Table 7). However, if the trends from the previous year's continue, it is possible that there could be an increase in disease prevalence and a decrease in immunity index if temperatures continue to rise. Overall, the implications of these findings for the health of people in Niger are complex and multifaceted. While higher temperatures could decrease the transmission potential of some diseases and reduce the number of infectious mosquito bites, they could also lead to an increase in disease prevalence and a decrease in the strength of the population's immune system. Public health officials and policymakers in Niger need to consider these factors when making decisions about disease prevention and treatment (Mordecai et al., 2013).

4. Conclusion

In this study, it was discovered that in Niger, malaria had a low to moderate potential to spread. The results showed that the mosquito bite rates are relatively low but the population's immunity levels are relatively low, which make them susceptible to diseases like malaria, dengue among others and the disease was relatively widespread. High temperatures may increase the prevalence of diseases like malaria, dengue, and yellow fever, which are transmitted by mosquitoes and other vectors. This can lead to increased morbidity and mortality rates, especially among vulnerable populations like children and pregnant women. The temperature anomaly in Niger has a significant effect on the anomalies of Ro, EIR, prevalence, and immunity, which are all important factors in understanding the health outcomes of people in the country. However, it's important to note that this relationship may not hold for all diseases and there may be other factors at play. Public health officials and policymakers in Niger need to consider these factors when making decisions about disease prevention and treatment.

In Nigeria, the values of EIR do not show any apparent trend with temperature, the reproduction number (Ro) suggested moderate spread tendency of the disease. The implications of these different parameter values depend on the parameter in question. For instance, higher rainfall and temperature can lead to more favorable breeding conditions for mosquitoes, increasing the transmission of malaria. There is no clear pattern between temperature anomaly and the other anomalies.

In Mali, while there is no clear trend in most of the parameters over time, the effect of temperature on disease transmission and immunity is complex and depends on several factors. This suggests that the effect of temperature on disease transmission is not straightforward and may depend on other factors such as rainfall and humidity. These temperature anomalies can have significant implications for the health of people in Mali. For example, increased EIR can lead to a higher incidence of mosquito-borne diseases such as malaria, which is a major public health problem in Mali. Changes in disease prevalence and immunity can also have significant implications for public health, affecting the burden of disease and the effectiveness of disease control measures such as vaccination programs. Therefore, health authorities in Mali must closely monitor temperature anomalies and their effects on disease transmission and take appropriate measures to mitigate the impact on public health. The implications of these changes in Ro, EIR, prevalence, and immunity index on the health of people in Mali are complex and depend on a range of factors. On the one hand, the decrease in Ro and prevalence suggests that fewer people are being infected with malaria, which is a positive development for public health. On the other hand, the increase in EIR suggests that the risk of malaria infection is increasing, which is a negative development for public health.

Generally, based on the trends in the data from 1985 to 2015, it's difficult to make accurate predictions for the years 2016–2044. However, if the trends from the previous years continue, it is possible that there could be an increase in disease prevalence and a decrease in immunity index if temperatures continue to rise. Therefore, it is crucial to promote public health education and awareness campaigns to encourage the use of preventive measures like insecticide-treated bed nets, vaccination, and prompt treatment of infections.

5. Recommendations

The comprehensive data analysis of Nigeria, Mali, and Niger from 1985 to 2015 provides critical insights into the interplay between climate variables and malaria transmission indices. This analysis highlights the intricate relationships between rainfall, surface temperature, and key malaria metrics, such as the Entomological Inoculation Rate (EIR), reproduction number (Ro), prevalence rate, and immunity level. Based on the findings, the following recommendations are proposed:

Firstly, it is essential to strengthen vector control measures during high rainfall periods. Increased rainfall in certain periods correlated with higher malaria prevalence and EIR values in Nigeria. Similarly, in Mali, rainfall peaks were associated with fluctuating Ro and EIR values, indicating increased malaria transmission risk during wetter periods. In Niger, dramatic fluctuations in rainfall correlated with a positive Ro and increased malaria prevalence. Therefore, it is recommended to intensify vector control efforts, such as distributing insecticide-treated bed nets and conducting indoor residual spraying, particularly during and after high rainfall periods to mitigate mosquito breeding and malaria transmission.

Secondly, implementing temperature-responsive malaria control strategies is crucial. Higher surface temperatures during certain months in Nigeria are linked to increased mosquito activity and malaria transmission. Mali showed temperature anomalies correlated with increased EIR during higher temperatures, while in Niger, stable temperatures with occasional drops still impacted malaria dynamics. Developing adaptive malaria control strategies that consider temperature variations is essential. Enhancing early warning systems and ensuring rapid response capabilities to manage malaria outbreaks effectively during periods of higher temperatures is recommended.

Accurate and timely data collection on malaria incidence, climate variables, and vector behavior is crucial for effective malaria control and prevention in all three countries. Strengthening health surveillance systems to improve data accuracy and reporting frequency will enable better tracking of malaria trends and more informed decision-making. This enhancement in surveillance and reporting mechanisms will ensure that health authorities can respond promptly to any changes in malaria transmission patterns.

Promoting public health education and community engagement is another vital recommendation. Community awareness and participation are crucial for successful malaria control. Public health campaigns should educate communities about the importance of vector control measures, the proper use of bed nets, and seeking prompt medical treatment for malaria symptoms. Engaging local leaders and community groups will ensure widespread adoption of preventative practices, making the efforts more effective.

Improving healthcare access and boosting immunity are also recommended. The immunity index indicated varying levels of population immunity to malaria in Nigeria, while fluctuations in the immunity index in Mali highlighted the need for consistent healthcare access. In Niger, the immunity index showed a significant decline over the years. Enhancing access to healthcare services, particularly in rural and underserved areas, is essential. Focus on improving vaccination coverage, nutritional status, and the availability of antimalarial treatments to boost population immunity and reduce susceptibility to malaria.

Lastly, adaptation to climate change is necessary for all three countries. Climate change is expected to exacerbate the variability in rainfall and temperature, impacting malaria transmission dynamics. Developing climate-resilient malaria control programs that incorporate predictive modeling and scenario planning is essential. Collaborating with meteorological services to integrate climate forecasts into malaria prevention strategies will ensure that the countries are better prepared for the future impacts of climate change on malaria transmission. By implementing these recommendations, Nigeria, Mali, and Niger can better manage the impact of climate variability on malaria transmission, ultimately reducing the burden of malaria and improving public health outcomes in these regions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data is available at Bomblies et al. (2008).

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