HJHPD

HJ

Article

National Assessment of Climate-Derived Malaria Seasonality in Nigeria Using Daily AgERA5 Climate Data.

Zubairul Islam[1]*, Yakubu Joel Cherima[2], Usman Mohammad Ibrahim[3], Fauwzia Sanusi[4], Charles Adeiza Umar[5], Yonwul Jacqueline Dakyen[6], Kebiru Umoru[7]

Received: 07.02.2026
Revised: 12.05.2026
Accepted: 15.05.2026
Published: 18.05.2026

[1] Faculty of Environmental Sciences (FES), Hensard University, Bayelsa 56110, Nigeria; +91-9821405543; zubairul.Islam@hensarduniversity.edu.ng; ORCID: https://orcid.org/0000-0002-6591-2241

[2] Center for AI Accountability in Health NG, Federal Capital Territory, Nigeria; +234-7036244967; ycherima@gmail.com; ORCID: https://orcid.org/0009-0004-3724-9886

[3] Nigeria Centre for Disease Control and Prevention (NCDC), Nigeria; +234-8035563217; ibrahim.usman@ncdc.gov.ng; ORCID: https://orcid.org/0009-0009-9625-7671

[4] Kano State Primary Health Care Management Board, Kano State, Nigeria; +234-9031568154; fawzya2012@gmail.com; ORCID: https://orcid.org/0009-0001-2832-1864

[5] Health Strategy and Leadership (HSL) Inc., Nigeria; +234-7033262284; cumar@hslhealth.pro; ORCID: https://orcid.org/0009-0001-1469-7983

[6] Independent Public Health Researcher, Nigeria; ydakyen@yahoo.com; ORCID: https://orcid.org/0009-0006-7229-4943

[7] Faculty of Environmental Sciences (FES), Hensard University, Bayelsa 56110, Nigeria; +234-8062384808; kabiirchief@yahoo.com

* Correspondence: zubairul.Islam@hensarduniversity.edu.ng

Abstract

Malaria transmission is strongly influenced by climatic conditions that regulate mosquito survival, breeding habitat persistence, and parasite development. However, most large-scale malaria studies rely on monthly climate averages that may overlook short-term environmental variability relevant to transmission dynamics. This study aimed to characterize climate-derived malaria transmission windows and seasonality patterns across Nigeria via daily AgERA5 climatic observations for 2025. Daily rainfall, air temperature, relative humidity, dew point temperature, solar radiation, wind speed, and cloud cover data were processed for 774 local government areas (LGAs). Climate-suitable malaria days were identified via biologically informed thresholds that incorporate thermal suitability, atmospheric moisture, rainfall persistence, and humidity persistence. Season onset, cessation, duration, and fortnightly transmission dynamics were subsequently quantified and mapped. The results revealed substantial spatial heterogeneity in climatic suitability, with annual climate-suitable malaria days averaging 157.7 days across LGAs. Near-perennial climatic suitability (>180 days) occurred in 35.3% of LGAs and was concentrated in the humid coastal and Niger Delta regions, whereas northern Sahelian environments presented short and highly seasonal transmission windows. Climatic suitability expanded progressively during the wet season, reaching a national maximum during Fortnight 18, when 771 of 774 LGAs experienced favorable transmission conditions. These findings demonstrate that daily climate observations provide a robust framework for identifying malaria transmission windows and supporting climate-informed surveillance, preparedness, and intervention planning across environmentally diverse regions of Nigeria.

Keywords: malaria seasonality; climate suitability; AgERA5; transmission windows; Nigeria.

1. Introduction

Malaria remains one of the most significant vector-borne diseases worldwide, accounting for substantial morbidity, mortality, and socioeconomic losses, particularly in sub-Saharan Africa [1]. Despite considerable progress in malaria control over the past two decades through insecticide-treated nets, indoor residual spraying, rapid diagnostic testing, and artemisinin-based combination therapies, transmission remains persistent across many African countries [2,3]. Nigeria bears the largest malaria burden worldwide, contributing to approximately one quarter of global malaria cases and deaths, with marked spatial and temporal heterogeneity in transmission intensity across ecological zones [4,5]. Understanding the environmental factors that regulate malaria transmission dynamics is therefore essential for effective surveillance, preparedness, and targeted intervention planning.

Climate is widely recognized as one of the primary determinants of malaria transmission because it directly influences mosquito survival, breeding habitat availability, biting activity, and parasite development rates [6,7]. Temperature affects both mosquito longevity and the extrinsic incubation period of *Plasmodium falciparum*, whereas rainfall governs the creation and persistence of larval habitats. Relative humidity, dew point temperature, cloud cover, solar radiation, and wind conditions further influence mosquito survival and dispersal potential [8–10]. Consequently, variations in climatic conditions can alter both the duration and geographical extent of malaria transmission seasons.

Numerous studies have investigated climate–malaria relationships via monthly or seasonal climatic averages derived from meteorological observations, satellite products, or reanalysis datasets [11–13]. These studies have demonstrated significant associations between rainfall, temperature, humidity, and malaria incidence at local and regional scales. However, monthly averages often mask short-term climatic fluctuations that are critical for mosquito breeding, adult survival, and parasite development [14]. Malaria transmission is driven by cumulative environmental conditions operating over periods of days to weeks rather than calendar months, suggesting that daily climatic observations may provide a more realistic representation of transmission suitability [15].

Recent advances in climate reanalysis products have enabled the development of high-temporal-resolution environmental indicators for infectious disease applications. Daily datasets offer opportunities to identify transmission windows, the onset and cessation of climatically suitable conditions, and the seasonal persistence of favorable environments [16,17]. Nevertheless, relatively few studies have translated daily climate information into nationally consistent malaria seasonality indicators across large and climatically diverse countries such as Nigeria. Existing national assessments often rely on long-term malaria prevalence surfaces or broad ecological classifications, which provide limited information on the timing and duration of climate suitability throughout the year [18,19].

Nigeria presents an ideal setting for investigating climate-driven malaria seasonality because of its pronounced climatic gradients. The country spans humid coastal ecosystems, rainforest regions, Guinea and Sudan savannas, and semiarid Sahelian environments, resulting in substantial spatial variability in rainfall regimes, temperature patterns, atmospheric moisture, and seasonal duration [20]. These climatic contrasts are expected to produce considerable differences in malaria transmission windows between southern coastal states, central transitional zones, and northern semiarid regions. Quantifying these differences is essential for optimizing the timing of surveillance activities, seasonal malaria interventions, and resource allocation.

This study therefore developed a climate-based malaria seasonality framework using daily AgERA5 climatic observations for 2025. Specifically, this study aimed to (i) derive local government area (LGA)-level malaria transmission windows across Nigeria via daily rainfall, temperature, relative humidity, dew point temperature, solar radiation, cloud cover, and wind speed indicators and (ii) characterize the onset, duration, cessation, and spatial variability of climate-suitable malaria seasons while classifying LGAs into distinct malaria seasonality regimes. To achieve these objectives, daily climatic variables were integrated to identify climate-suitable malaria transmission days across all Nigerian LGAs. This study further quantified the onset, duration, cessation, and fortnightly progression of climate-suitable conditions and classified LGAs into malaria seasonality regimes. The results provide the first national-scale assessment of climate-derived malaria transmission windows on the basis exclusively of daily environmental suitability indicators and offer a reproducible framework for supporting climate-informed malaria surveillance and early warning systems in Nigeria.

2. Materials and methods

2.1 Study area

The study was conducted across Nigeria, the most populous country in Africa, which extends from approximately 4°N to 14°N latitude and 3°E to 15°E longitude (Figure 1).

Figure 1. Location and extent of Nigeria.

Nigeria encompasses a wide range of climatic zones, ranging from humid coastal and mangrove ecosystems in southern China to semiarid and Sahelian environments in northern China. The annual rainfall varies from more than 3,000 mm in parts of the Niger Delta and southeastern region to less than 500 mm in the far north region. The mean annual temperatures generally range between 24°C and 32°C, whereas the relative humidity decreases progressively from the southern coastal belt toward the northern interior. These pronounced climatic gradients create substantial spatial variation in the environmental suitability for malaria transmission.

The analysis was undertaken at the local government area (LGA) level via national administrative boundaries. A total of 774 LGAs were examined to characterize the spatial and temporal patterns of climate seasonality and malaria-relevant climatic suitability during 2025.

2.2 Study Design and Analytical Workflow

This study adopted a spatially explicit climate–seasonality framework to evaluate the environmental conditions associated with malaria transmission across Nigeria. The workflow consisted of two complementary objectives.

Objective 1 quantified monthly and daily climatic variability across Nigerian LGAs via AgERA5 climate data. Daily observations were aggregated to monthly climatologies and subsequently used to derive rainfall, temperature, humidity, dew point, solar radiation, cloud cover, and wind-related seasonality metrics.

Objective 2 translated daily climatic conditions into malaria-relevant environmental suitability indicators. Climate-suitable malaria days were identified via threshold-based combinations of temperature, moisture availability, humidity persistence, and rainfall conditions. The derived indicators included the number of climate-suitable malaria days, season onset and cessation timing, season duration, fortnightly suitability dynamics, and spatial classification of malaria climatic regimes.

The analytical framework integrated raster processing, zonal statistics extraction, temporal aggregation, seasonality assessment, and geospatial visualization to characterize national-scale malaria-relevant climate patterns.

2.3 Data Sources

The primary climatic dataset consisted of the AgERA5 agro-meteorological reanalysis product for 2025. Daily gridded datasets were obtained for seven climatic variables: precipitation flux, air temperature at 2 m, relative humidity at 2 m, dew point temperature at 2 m, solar radiation flux, cloud cover, and wind speed at 10 m.

Administrative boundaries for Nigerian LGAs and states were obtained from national administrative shapefiles and projected to the WGS84 geographic coordinate system. Climate rasters were processed individually and converted into monthly raster products before the extraction of zonal statistics for each LGA.

The selected variables were chosen because they represent the principal environmental controls on malaria transmission, influencing mosquito survival, larval habitat persistence, vector development rates, and parasite development processes.

2.4 Data analysis

2.4.1 Characterization of Climate Seasonality Across Nigerian LGAs

The daily AgERA5 climatic variables, including precipitation, air temperature, relative humidity, dew point temperature, solar radiation, wind speed, and cloud cover, were processed to characterize climate seasonality across Nigeria during 2025. Daily raster layers were aggregated to monthly climatologies, where monthly rainfall was calculated as the cumulative sum of daily precipitation:

$$P_m = \sum_{d=1}^{n} P_d \tag{1}$$

where P_m represents the monthly rainfall and where P_d denotes the daily precipitation.

The monthly averages for temperature, relative humidity, dew point temperature, solar radiation, wind speed, and cloud cover were calculated as follows:

$$X_m = \frac{1}{n}\sum_{d=1}^{n} X_d \tag{2}$$

where X_d is the daily value of climate variable X.

Area-weighted zonal statistics were extracted for all 774 Nigerian local government areas (LGAs) via exact polygon–raster intersections. The resulting database contained daily and monthly climatic information for each administrative unit.

Rainfall seasonality was quantified via annual rainfall totals, rainy-day frequency, rainfall onset, cessation, and season length. Rainfall onset was identified as the first day satisfying:

$$\sum_{i=d}^{d+6} I(P_i \geq 1) \geq 3 \tag{3}$$

where I is an indicator function equal to one when the rainfall exceeds 1 mm and zero otherwise. Rainfall cessation was determined via the same persistence criterion in reverse chronological order. The rainfall season length was computed as follows:

$$RSL = DOY_{cessation} - DOY_{onset} + 1 \tag{4}$$

where DOY denotes the day of the year.

Thermal suitability was quantified as the number of days within the temperature range favorable for malaria transmission:

$$TSD = \sum I(22 \leq T_d \leq 32) \tag{5}$$

where T_d represents the daily air temperature.

Humidity conditions were assessed on the basis of the number of humid days:

$$HD = \sum I(RH_d \geq 60) \tag{6}$$

where RH_d represents the daily relative humidity.

The outputs of Objective 1 included daily climate databases, monthly climate raster data, monthly climatological maps, and LGA-level summaries of rainfall, temperature, humidity, dew point temperature, solar radiation, wind speed, and cloud cover.

2.4.2 Climate-derived malaria seasonality assessment

Daily climatic observations were translated into malaria-relevant environmental suitability indicators via biologically informed climatic thresholds. To account for the lagged effects of rainfall and moisture persistence on mosquito breeding habitats, rolling climatic windows were calculated.

The fourteen-day cumulative rainfall was computed as follows:

$$R_{14}(d) = \sum_{i=d-13}^{d} P_i \tag{7}$$

The number of rainy days within the preceding fourteen days was calculated as follows:

$$RD_{14}(d) = \sum_{i=d-13}^{d} I(P_i \geq 1) \tag{8}$$

Humidity persistence was represented by the number of humid days during the preceding seven days:

$$HD_7(d) = \sum_{i=d-6}^{d} I(RH_i \geq 60) \tag{9}$$

A daily climate suitability indicator was then defined. A day was classified as climatically suitable for malaria transmission when all of the following conditions were simultaneously satisfied:

$$\mathrm{MCS}_d = \begin{cases} 1, & \text{if } 22 \leq T_d \leq 32 \\ & \wedge\, (RH_d \geq 60 \text{ or } DP_d \geq 18) \\ & \wedge\, (R_{14}(d) \geq 10 \text{ or } RD_{14}(d) \geq 2) \\ & \wedge\, HD_7(d) \geq 4 \\ & \wedge\, T_d < 35 \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

where DP_d denotes the dew point temperature.

The daily malaria climate suitability function was expressed as follows:

$$MCS_d = \begin{cases} 1, & \text{if all conditions are satisfied} \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

The annual number of climate-suitable malaria days for each LGA was calculated as follows:

$$CMD = \sum_{d=1}^{365} MC\,S_d \quad (12)$$

Season onset was defined as the first day for which at least five climate-suitable days occurred within a moving fourteen-day window:

$$\sum_{i=d}^{d+13} MC\,S_i \geq 5 \quad (13)$$

Season cessation was identified as the final day satisfying the same criterion. The climate-suitable season duration was subsequently calculated as follows:

$$SD = DOY_{end} - DOY_{start} + 1 \quad (14)$$

To examine intra-annual seasonality, the year was divided into 26 fortnights:

$$FN = \left\lceil \frac{DOY}{14} \right\rceil \quad (15)$$

and fortnightly suitability was calculated as follows:

$$FS_j = \sum_{d \in FN_j} MC\,S_d \quad (16)$$

National-scale suitability dynamics were assessed by calculating the number of LGAs exhibiting at least one climate-suitable malaria day within each fortnight.

Finally, the LGAs were classified into six malaria seasonality regimes on the basis of annual climate-suitable malaria days: very short suitability (≤30 days), short suitability (31–60 days), moderate suitability (61–90 days), long suitability (91–120 days), very long suitability (121–180 days), and near-perennial suitability (>180 days). These classes were used to map spatial variations in malaria climatic suitability and transmission seasonality across Nigeria during 2025.

3. Results

3.1. Climate Characteristics of Nigeria

The climatic patterns observed across Nigeria during 2025 revealed substantial spatial heterogeneity in moisture availability, thermal conditions, atmospheric humidity, solar energy, wind dynamics, and cloud cover. A pronounced south–north gradient was evident across all the climatic variables. The coastal and Niger Delta states were characterized by high rainfall, elevated relative humidity, high dew point temperatures, and persistent cloud cover, reflecting strong maritime and monsoonal influences. In contrast, the northern state featured higher temperatures, greater solar radiation, lower atmospheric moisture, and reduced cloud cover. These contrasting climatic regimes delineate distinct environmental zones across Nigeria and provide the climatic foundation for understanding the spatial differences in malaria seasonality examined in subsequent sections.

3.1.1. Monthly Rainfall Distribution

Figure 3 shows the monthly rainfall distribution across Nigeria during 2025. Rainfall exhibited a pronounced latitudinal gradient, with the highest precipitation concentrated in the southern coastal and rainforest belts. Moderate rainfall conditions extended through Abia, Delta, Imo, Ebonyi, and Anambra States, whereas the northern Sahelian states experienced substantially lower precipitation and a shorter wet season. Spatially, rainfall expanded northward from April onward, reaching maximum coverage during July–September before retreating southward toward the end of the year.

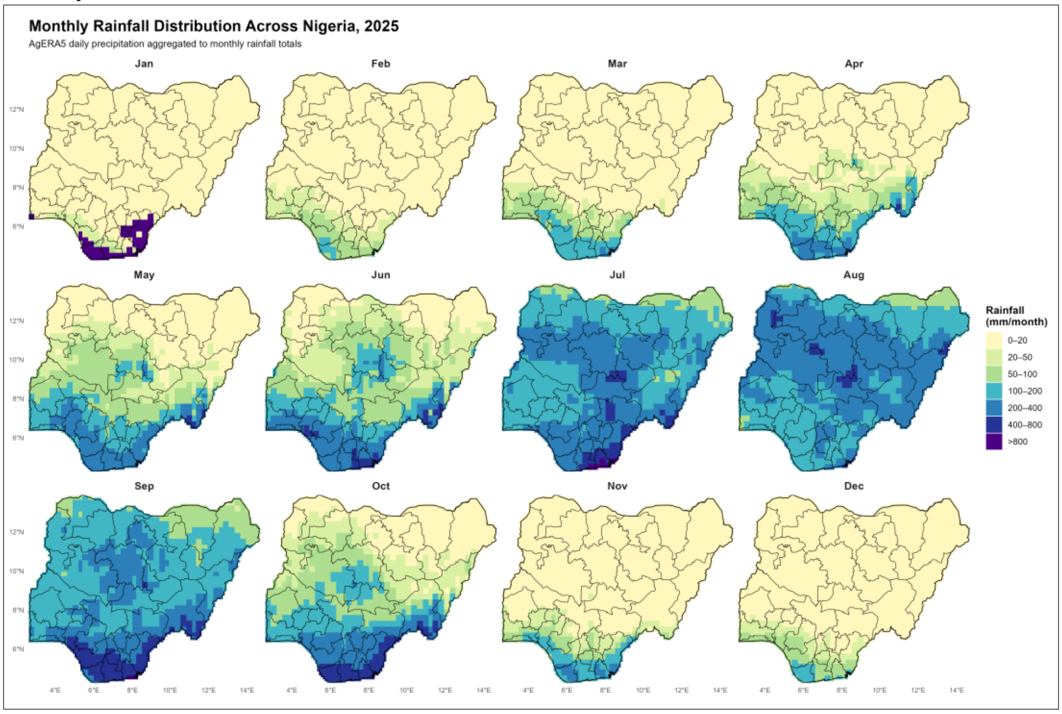

Figure 2. Monthly rainfall distribution across Nigeria in 2025 derived from AgERA5 daily precipitation data aggregated to monthly totals (mm $month^{-1}$).

3.1.2. Monthly air temperature distribution

Figure 4 presents the monthly distribution of the mean air temperature across Nigeria. The mean temperatures exhibited marked spatial variability, ranging from cooler conditions in the southern coastal states and elevated terrains to persistently high temperatures across the northern interior. Kebbi, Sokoto, Benue, Nasarawa, and Borno recorded the highest annual temperatures, highlighting the influence of continentality and semiarid climatic conditions. The peak temperatures occurred during the late dry season preceding the onset of the monsoon, whereas a modest decline was observed during the rainy season due to increased cloud cover and evaporative cooling. The temperature distribution delineates a clear thermal gradient from the humid southern state to the arid northern state, which has important implications for vector development and parasite maturation rates.

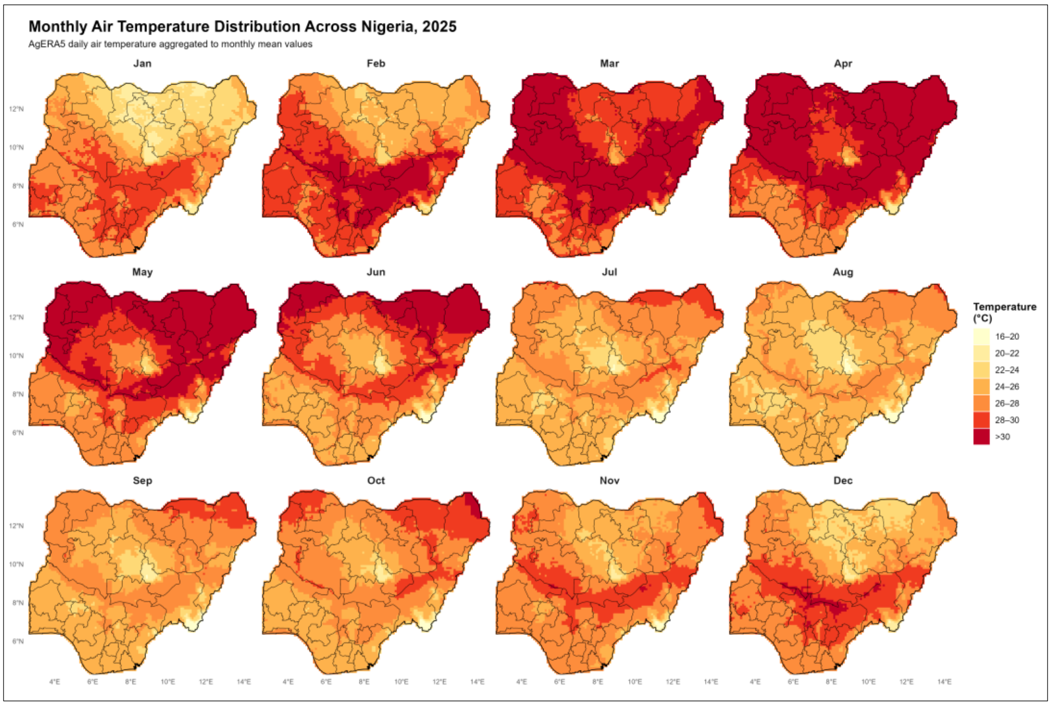

Figure 3. Monthly air temperature distribution across Nigeria in 2025 derived from AgERA5 daily mean 2-m air temperature observations (°C).

3.1.3. Monthly relative humidity distribution

Figure 5 shows the spatial distribution of relative humidity across Nigeria.

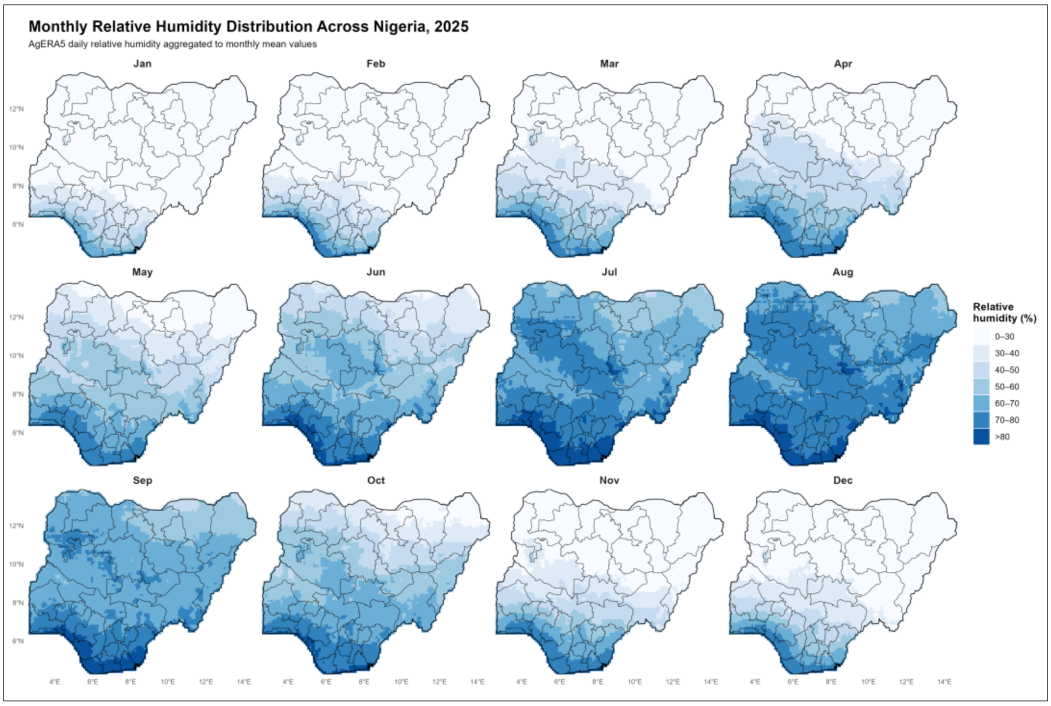

Figure 4. Monthly relative humidity distributions across Nigeria in 2025 derived from AgERA5 daily 2-m relative humidity observations (%).

Relative humidity increased substantially during the rainy season, with annual mean values highest in Bayelsa, Rivers, Akwa Ibom, Lagos, and Delta States. These coastal and deltaic regions remained under persistent maritime influence, resulting in prolonged periods of atmospheric moisture. In contrast, the northern Sahelian states experienced considerably lower humidity levels, particularly during the dry season, when continental air masses dominated. The strong seasonal and spatial variabilities in humidity closely mirrored the rainfall pattern and highlighted the importance of atmospheric moisture in sustaining favorable environmental conditions for mosquito survival and malaria transmission.

3.1.4. Monthly Dew Point Temperature Distribution

Figure 6 shows the spatial distribution of the dew point temperature, which serves as a direct indicator of the atmospheric moisture content.

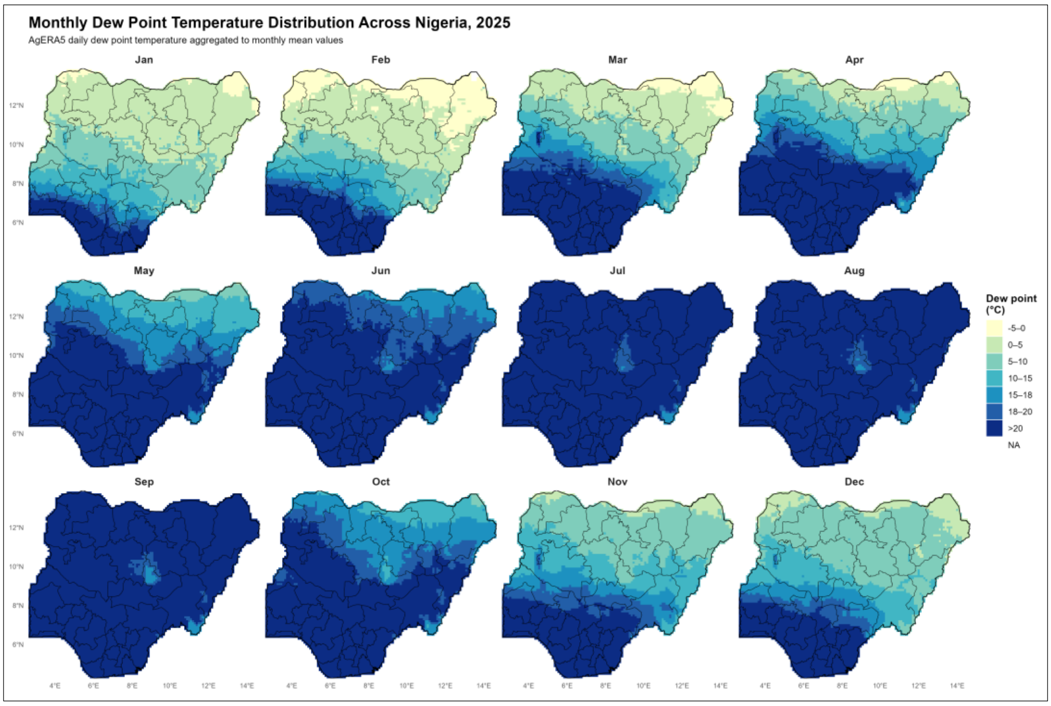

Figure 5. Monthly dew point temperature distribution across Nigeria in 2025 derived from AgERA5 daily 2-m dew point temperature observations (°C).

The highest annual mean dew point temperatures were recorded in Lagos (23.91°C), Bayelsa (23.82°C), Rivers (23.80°C), Akwa Ibom (23.59°C), and Delta (23.58°C). Elevated dew point temperatures were also observed across Ogun, Abia, Imo, Edo, and Anambra States. In contrast, substantially lower dew point temperatures characterize northern Nigeria, particularly during the dry season. The spatial pattern closely mirrored that of relative humidity and rainfall, confirming the concentration of atmospheric moisture within southern Nigeria and the Niger Delta region.

3.1.5. Monthly Solar Radiation Distribution

Figure 7 presents the spatial distribution of solar radiation across Nigeria.

The highest annual mean solar radiation values occurred in Jigawa (1.97×10^6), Yobe (1.97×10^6), Katsina (1.95×10^6), Kano (1.95×10^6), and Borno (1.93×10^6), reflecting the prevalence of clear skies and low atmospheric moisture across northern Nigeria. High radiation levels were also observed in Bauchi, Sokoto, Zamfara, Gombe, and Adamawa states. Conversely, lower solar radiation characterized the humid southern states, where persistent cloud cover and monsoonal activity reduced incoming solar energy. The inverse relationship between solar radiation and rainfall was particularly evident during the wet season, when cloud development substantially suppressed radiation levels across southern and central Nigeria.

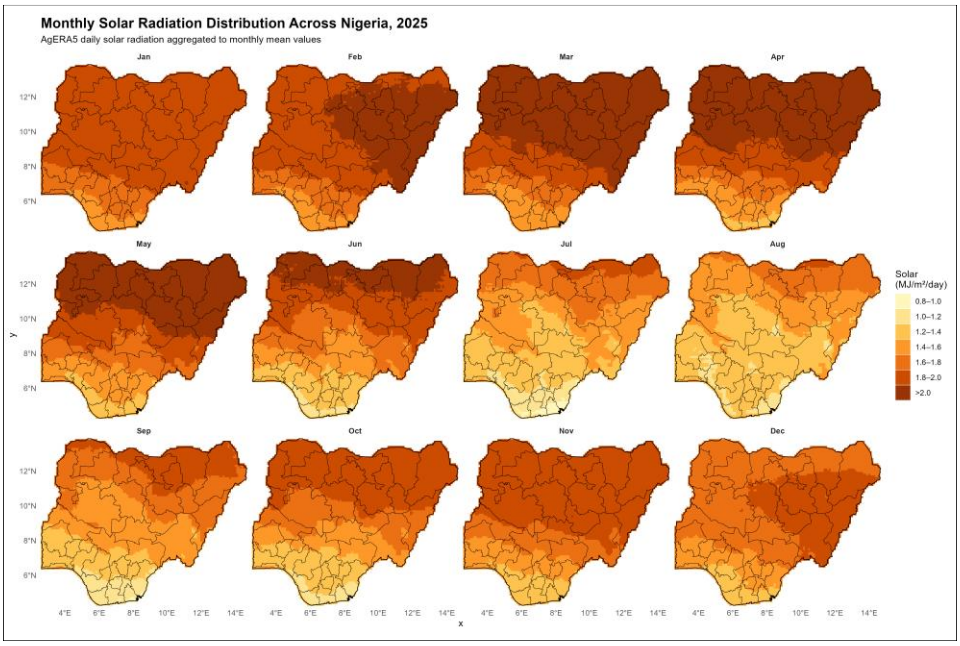

Figure 6. Monthly solar radiation distribution across Nigeria in 2025 derived from AgERA5 daily solar radiation flux observations (MJ m^{-2} day^{-1}).

3.1.6. Monthly Wind Speed Distribution

Figure 8 shows the spatial distribution of the wind speed across Nigeria.

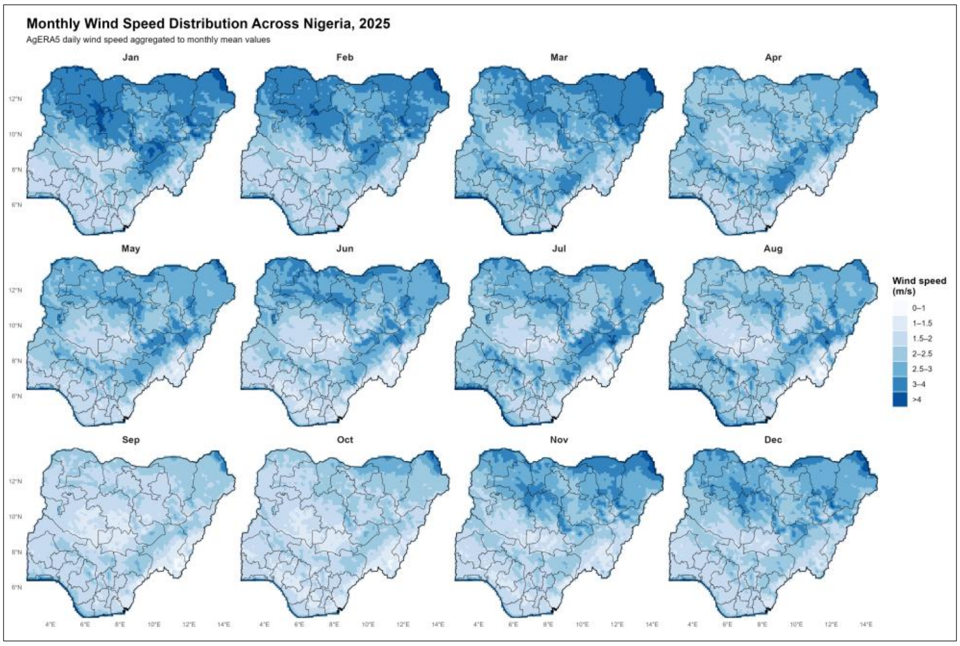

Figure 7. Monthly wind speed distribution across Nigeria in 2025 derived from AgERA5 daily mean 10-m wind speed observations (m s^{-1}).

The highest annual mean wind speeds occurred in Lagos (3.04 m s^{-1}), followed by Yobe (2.86 m s^{-1}), Borno (2.83 m s^{-1}), Katsina (2.82 m s^{-1}), and Sokoto (2.77 m s^{-1}). Elevated wind speeds were also observed in Zamfara, Gombe, Jigawa, Plateau, and Kano States. The relatively high values in Lagos reflect the influence of coastal air circulation, whereas the northern states are strongly influenced by Harmattan and regional atmospheric circulation systems. Although the seasonal variations were less pronounced than those observed for rainfall and humidity, the wind speed clearly differed across coastal, plateau, and northern arid environments.

3.1.7. Monthly Cloud Cover Distribution

Figure 9 shows the spatial distribution of cloud cover across Nigeria. The highest annual mean cloud cover was observed in Akwa Ibom (78.18%), Rivers (77.13%), Imo (76.26%), Abia (76.25%), and Bayelsa (76.01%). High cloud cover conditions also characterize the Cross River, Osun, Ondo, Delta, and Anambra states. These regions correspond closely with the principal rainfall and humidity zones of southern Nigeria. Cloud cover increased markedly during the monsoon period and remained elevated throughout the wet season, particularly across the coastal and rainforest regions. In contrast, northern Nigeria experienced lower cloud cover percentages associated with drier atmospheric conditions and enhanced solar radiation. The strong spatial correspondence between cloud cover, rainfall, relative humidity, and dew point temperature highlights the integrated climatic controls governing moisture availability across Nigeria.

3.2 Climate-Derived Malaria Seasonality and Transmission Suitability Across Nigeria

3.2.1 Distribution of climate-suitable malaria days

The climate suitability analysis revealed substantial spatial variability in malaria-conducive environmental conditions across Nigeria during 2025 (Figure 8).

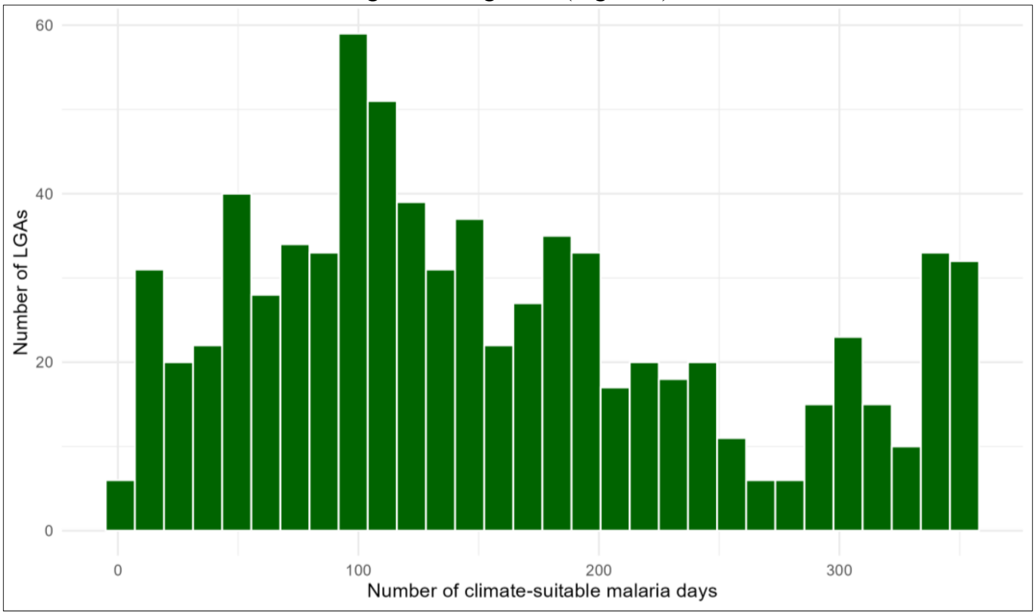

Figure 8. Distribution of annual climate-suitable malaria days across Nigerian LGAs in 2025 derived from daily AgERA5 climate data.

Across 774 LGAs, the mean number of climate-suitable malaria days was 157.7 days yr^{-1}, with a median of 137.5 days yr^{-1} and a maximum of 352 days yr^{-1}, indicating that several locations experienced near-year-round climatic suitability for malaria transmission. The coefficient of variation was 61.9%, demonstrating pronounced geographical heterogeneity in transmission potential.

More than one-third of all LGAs (35.3%) were classified as having near-perennial suitability (>180 days), whereas an additional 21.8% experienced very long suitability periods (121–180 days). In contrast, only 7.1% of the LGAs presented very short suitable periods (≤30 days). Overall, over 57% of Nigerian LGAs experienced climatic conditions favorable for malaria transmission for more than four months of the year, highlighting the extensive environmental support for malaria persistence across the country.

3.2.2 National Fortnightly Expansion of Climatic Transmission Conditions

The temporal progression of climatic suitability clearly showed a seasonal expansion and contraction pattern (Figure 9).

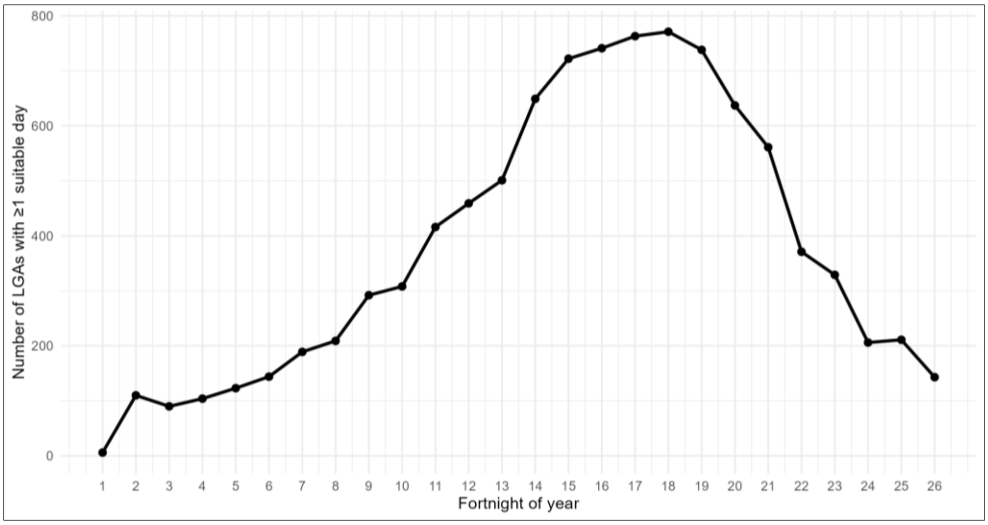

Figure 9. National fortnightly expansion and contraction of climate-suitable malaria conditions across Nigeria during 2025.

Climate-suitable conditions were already present during the first fortnight of the year (**FN01**), indicating persistent suitability in southern Nigeria. The number of LGAs exhibiting suitable conditions increased progressively and reached a national maximum during **FN18**, when **771 of 774 LGAs (99.6%)** experienced at least one climate-suitable day within the fortnight.

The peak fortnight coincided with an average of **13.4 suitable days per LGA**, suggesting widespread and sustained environmental support for mosquito survival and parasite development. Suitable conditions remained detectable until the final fortnight (**FN26**), demonstrating that climatic suitability for malaria transmission occurred throughout the year somewhere within the country, although with strong regional differences in timing and duration.

3.2.3 Timing of Malaria Season Onset

The onset of climate-suitable malaria conditions varied considerably among LGAs (Figure 10).

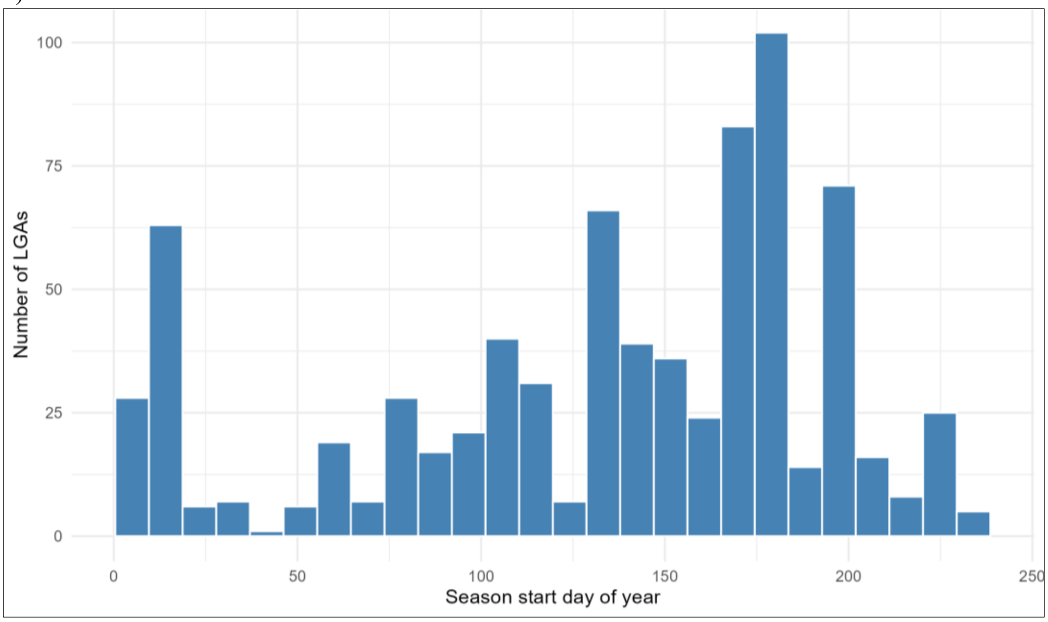

Figure 10. Distribution of climate-suitable malaria season onset dates (day of year) across Nigerian LGAs in 2025.

Sustained climatic suitability was identified in 770 LGAs, whereas only four LGAs failed to exhibit a persistent suitable season. The earliest season onset occurred on Day 5 of the year, whereas the latest onset occurred on Day 234.

Nationally, the mean onset date was day 132.9 (mid-May), with a median onset of day 146 (late May). The interquartile range extended from Day 98 to Day 178, indicating that most LGAs entered climatically suitable malaria seasons between early April and late June. The large standard deviation (62.2 days) further confirms substantial geographical variability in transmission season initiation across the ecological zones.

3.2.4 Duration of Climatically Suitable Malaria Seasons

Marked differences were observed in the duration of climate-suitable malaria seasons among LGAs (Figure 11). The mean duration was 178.7 days, corresponding to approximately six months of suitable transmission conditions annually. However, the season duration ranged from 0 to 361 days, illustrating a transition from highly seasonal environments in the northern Sahel to nearly perennial suitability in the humid coastal belt.

The median duration was 159.5 days, whereas the upper quartile exceeded 245 days, indicating that one quarter of Nigerian LGAs experienced more than eight months of favorable climatic conditions. The observed standard deviation (97.1 days) highlights strong environmental gradients controlling malaria seasonality throughout the country.

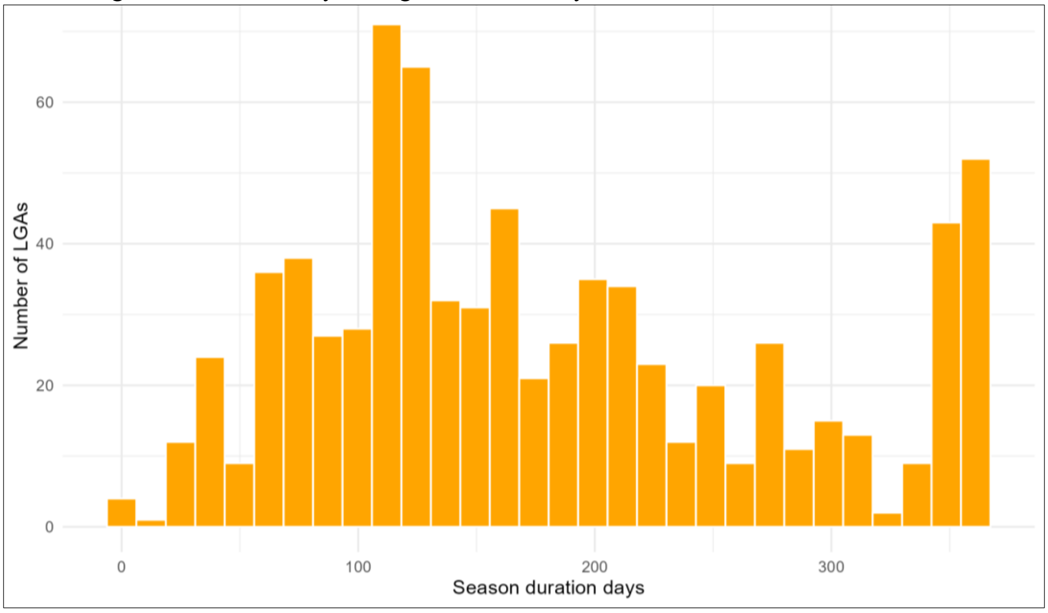

Figure 11. Distribution of climate-suitable malaria season durations across Nigerian LGAs in 2025.

3.2.5 Spatial distribution of climate-suitable malaria days

Strong north–south contrasts were evident in the spatial distribution of climate suitability (Figure 12). The highest suitability levels were concentrated within humid coastal and Niger Delta states. Bayelsa State recorded the highest average suitability (346.3 days yr^{-1}) and the longest average suitable season (357 days), followed by Lagos (336.8 days), Rivers (329.7 days), Akwa Ibom (313.6 days), and Delta (294.9 days).

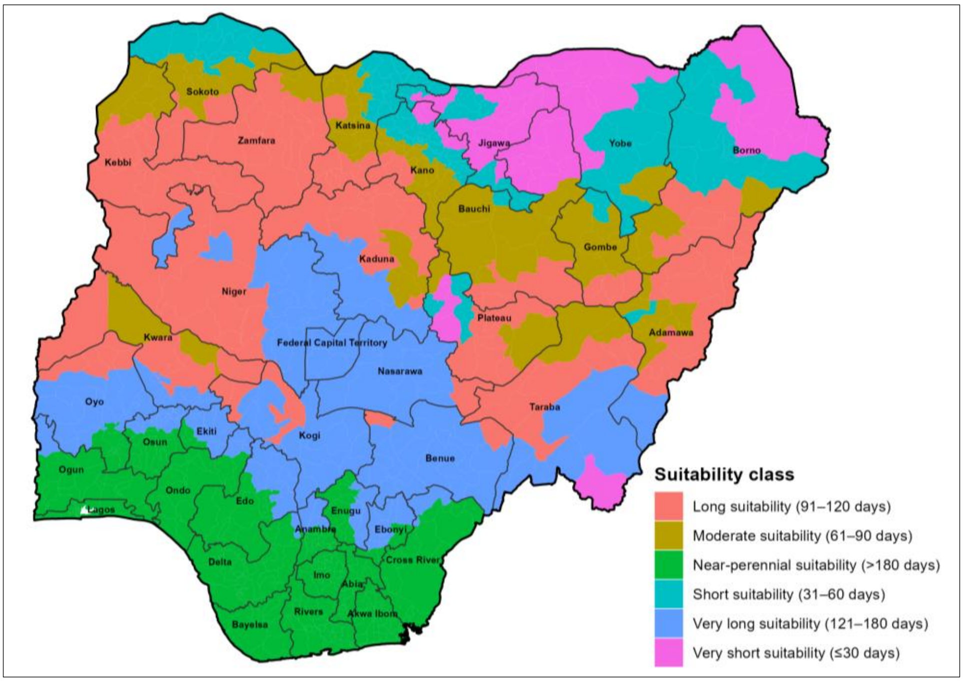

Figure 12. Spatial distribution of climate-suitable malaria day classes across Nigerian LGAs in 2025.

Other southern states exhibiting prolonged climatic suitability included Ogun, Abia, Cross River, Ondo, and Imo, all averaging more than 230 suitable days annually. These states generally presented season durations exceeding 250 days and season onset dates occurring within the first three months of the year. In contrast, the lowest suitability values occurred within the Sudan and Sahel ecological zones. Jigawa State presented the lowest mean suitability (25.9 days yr^{-1}), followed by Yobe (30.0 days), Borno (50.7 days), Bauchi (52.5 days), and Kano (58.0 days). These states experienced substantially delayed season onset, typically between Day 189 and Day 215, and much shorter suitable periods ranging from approximately 46--82 days.

3.2.6 Regional Differences in Malaria Season Onset

The onset of climate-suitable malaria seasons exhibited clear geographical progression patterns across Nigeria (Figure 13).

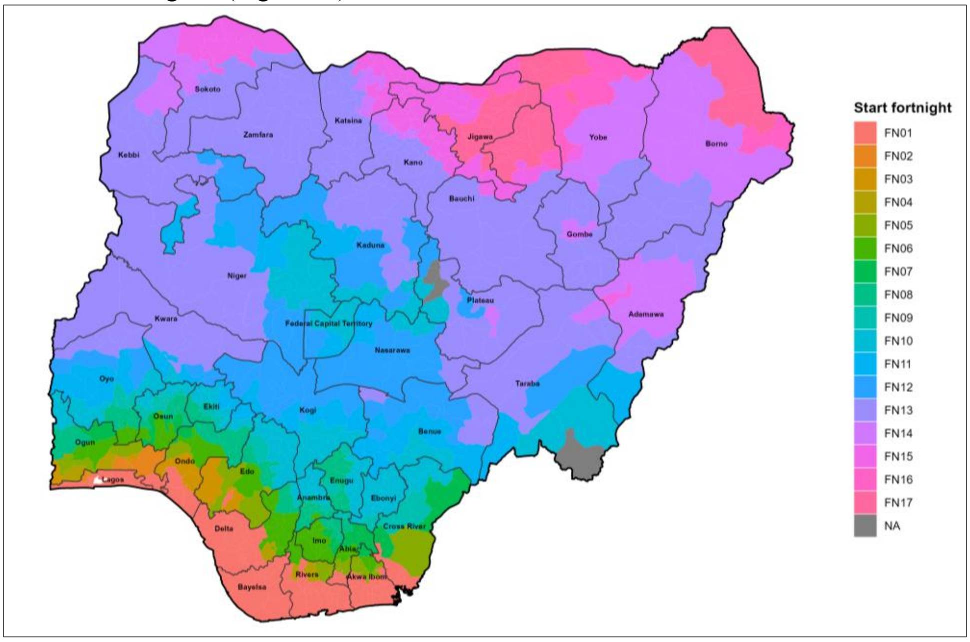

Figure 13. Spatial pattern of climate-suitable malaria season onset fortnights across Nigerian LGAs in 2025

Coastal states experienced the earliest season initiation, with Bayelsa entering climatically suitable conditions during FN02, followed by Lagos (FN03) and Rivers (FN06). Most of the Niger Delta and southeastern states reached peak climatic suitability between FN09 and FN11, corresponding to the onset and intensification of the West African monsoon.

The peak suitability occurred later in northern China, reflecting delayed rainfall onset and shorter humid periods. This systematic shift in seasonal timing demonstrates how climatic controls govern malaria transmission opportunities across Nigeria, producing a continuum from near-perennial transmission environments in the southern region to highly seasonal transmission regimes in the semiarid northern region. The observed fortnightly progression provides a detailed climatic framework for targeted region-specific malaria surveillance and intervention schedules.

4. Discussion

This study provides a national-scale assessment of the suitability of climate-derived malaria transmission across Nigeria via daily AgERA5 climatic observations. By integrating rainfall, temperature, relative humidity, dew point temperature, and moisture persistence indicators, the analysis identified substantial spatial and temporal heterogeneity in climate suitability for malaria transmission across the country's diverse ecological zones. The results demonstrate that malaria-relevant climatic conditions vary considerably among Nigerian LGAs, producing distinct transmission windows that range from highly seasonal environments in the northern Sahel to near-perennial suitability in the humid coastal and Niger Delta regions.

The strong north–south gradient observed in climate-suitable malaria days is consistent with the ecological controls governing malaria transmission across West Africa. LGAs located within Bayelsa, Rivers, Akwa Ibom, Delta, and other southern states presented the highest numbers of climate-suitable malaria days and the longest transmission seasons. These areas are characterized by persistent humidity, prolonged rainfall seasons, elevated dew point temperatures, and reduced thermal stress, all of which promote mosquito survival and the continuous availability of breeding habitats. Similar relationships between atmospheric moisture and malaria persistence have been documented across tropical Africa, where humidity and rainfall are frequently identified as dominant drivers of vector abundance and transmission intensity [21–23].

Conversely, northern states such as Jigawa, Yobe, Borno, Kano, and Bauchi presented substantially fewer climate-suitable malaria days and shorter transmission windows. Although temperatures in these regions are generally favorable for parasite development, limited rainfall, prolonged dry seasons, and lower atmospheric moisture constrain mosquito survival and breeding habitat persistence. This finding supports previous observations that malaria transmission in semiarid environments is limited primarily by moisture availability rather than temperature alone [24,25]. The results therefore reinforce the hypothesis that climatic suitability in Nigeria is controlled by the interaction between thermal conditions and moisture persistence rather than by individual climate variables acting independently.

Notably, there is substantial variation in the timing of season onset across the country. Climatically suitable conditions emerged earliest within coastal and Niger Delta environments and progressively expanded northward following the seasonal migration of the West African monsoon. The observed progression closely corresponds with established rainfall climatology across West Africa, where monsoonal rainfall advances from the Gulf of Guinea toward the Sahel during the wet season [26,27]. This spatial progression suggests that malaria early warning systems should incorporate regional differences in season onset rather than rely on uniform national intervention schedules.

The fortnightly suitability analysis further demonstrated that climate conditions favorable for malaria transmission expanded rapidly during the wet season, eventually encompassing almost all LGAs during peak transmission periods. These findings support previous studies emphasizing the importance of short-term climatic variability in determining malaria transmission dynamics

[28,29]. Unlike conventional analyses based on monthly averages, the daily framework adopted here captures transient environmental conditions that are directly relevant to mosquito breeding, adult survival, and parasite development. Consequently, the climate-suitable malaria day metric provides a more biologically meaningful representation of transmission opportunities than monthly climatic summaries do.

The identification of near-perennial climatic suitability in several southern states has important public health implications. In such environments, malaria transmission may remain possible throughout much of the year, reducing the effectiveness of intervention strategies designed around short seasonal transmission periods. In contrast, the highly seasonal conditions observed across northern Nigeria may provide opportunities for more precisely timed interventions, including seasonal malaria chemoprevention, intensified surveillance, and targeted vector control activities. Similar conclusions have been reported in studies demonstrating that intervention effectiveness can be substantially improved when interventions are aligned with local climatic transmission windows [30,31].

From a methodological perspective, this study demonstrates the utility of daily AgERA5 climate products for malaria seasonality assessment at the national scale. Most previous climate–malaria studies have relied on monthly climatologies, long-term averages, or coarse ecological classifications [32,33]. By incorporating rolling rainfall accumulations, humidity persistence, and daily suitability thresholds, the present framework captures dynamic environmental processes that more closely reflect the biological requirements of malaria vectors. The approach is computationally reproducible and can be readily transferred to other malaria-endemic countries where daily climate reanalysis datasets are available.

Several limitations should nevertheless be acknowledged. First, the analysis evaluated climatic suitability rather than actual malaria transmission. Malaria occurrence is influenced by numerous nonclimatic factors, including vector control interventions, human behavior, health-care access, land-use change, socioeconomic conditions, vector species composition, and acquired immunity [34,35]. Second, the suitability thresholds applied in this study were derived from broadly accepted biological ranges and may vary among ecological settings and vector populations. Third, the analysis was conducted for a single year (2025), which may not fully capture the interannual variability associated with large-scale climate oscillations and extreme weather events.

Future research should extend this framework to multiyear climate records to quantify long-term variability in malaria transmission windows and evaluate the influence of climate anomalies on season onset, duration, and suitability intensity. The integration of climate-derived suitability metrics with malaria prevalence data, health facility surveillance records, vector abundance observations, and population exposure datasets would further improve the understanding of how environmental suitability translates into realized transmission patterns. The incorporation of machine learning approaches and climate projection scenarios could also facilitate the development of operational malaria early warning systems capable of supporting climate-informed disease control strategies under future environmental change.

Overall, the results demonstrate that daily climate observations can provide valuable insights into the spatial and temporal organization of malaria transmission suitability across Nigeria. The derived transmission windows, seasonality classes, and onset patterns offer a robust climatic foundation for strengthening malaria surveillance, improving intervention timing, and supporting climate-informed public health decision-making.

Data availability statement: The data used in this study are open to access as follows:

The climatic datasets used in this study were obtained from the AgERA5 agro-meteorological reanalysis product provided by the Copernicus Climate Change Service (C3S) through the Climate Data Store (CDS) and are publicly available at https://cds.climate.copernicus.eu/datasets/sis-agro-meteorological-indicators. The dataset includes daily gridded observations of precipitation flux, air temperature at 2 m, relative humidity at 2 m, dew point temperature at 2 m, solar radiation flux, cloud cover, and wind speed at 10 m.
Administrative boundary data for Nigerian states and Local Government Areas (LGAs) were obtained from the Humanitarian Data Exchange (HDX) Common Operational Datasets (COD) administrative boundaries repository, available at https://data.humdata.org/dataset/cod-ab-nga.

Author Contributions: Conceptualization, Z.I.; methodology, Z.I. and Y.J.C.; software, Z.I.; validatAuthor Contributions: Conceptualization, Z.I.; methodology, Z.I., Y.J.C., and U.M.I.; software, Z.I.; validation, Z.I., Y.J.C., and C.A.U.; formal analysis, Z.I.; investigation, Z.I., Y.J.C., U.M.I., F.S., C.A.U., Y.J.D., and K.U.; data curation, Z.I., U.M.I., and F.S.; visualization, Z.I.; writing—original draft preparation, Z.I.; writing—review and editing, Y.J.C., U.M.I., F.S., C.A.U., Y.J.D., and K.U.; supervision, Z.I.; project administration, Z.I.; resources, Y.J.C., U.M.I., F.S., C.A.U., Y.J.D., and K.U. All authors have read and agreed to the published version of the manuscript.ion, Z.I., Y.J.C., and E.N.; formal analysis, Z.I.; investigation, Z.I., Y.J.C., E.N., M.M., U.S., and A.M.; data curation, Z.I., M.M., and E.N.; visualization, Z.I.; writing—original draft preparation, Z.I.; writing—review and editing, Y.J.C., E.N., M.M., U.S., and A.M.; supervision, Z.I.; project administrati Z.I.; resources, Y.J.C., E.N., M.M., U.S., and A.M. All the authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Informed Consent Statement

Not applicable.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	
DP	Dew Point Temperature
MPI	Moisture Persistence Index
TSD	Thermal Suitability Days
TSI	Thermal Suitability Index
CSV	Comma-Separated Values
GIS	Geographic Information System
ECMWF	European Centre for Medium-Range Weather Forecasts
C3S	Copernicus Climate Change Service
SD	Season Duration
R14	Fourteen-Day Cumulative Rainfall

References

1. World Health Organization (WHO). World Malaria Report 2024. Geneva: World Health Organization; 2024.
2. Bhatt, S.; Weiss, D.J.; Cameron, E.; Bisanzio, D.; Mappin, B.; Dalrymple, U.; Battle, K.E.; Moyes, C.L.; Henry, A.; Eckhoff, P.A.; et al. The effect of malaria control on Plasmodium falciparum in Africa between 2000 and 2015. Nature. 2015, 526, 207–211. 10.1038/nature15535
3. Noor, A.M.; Kinyoki, D.K.; Mundia, C.W.; Kabaria, C.W.; Mutua, J.W.; Alegana, V.A.; Fall, I.S.; Snow, R.W. The changing risk of Plasmodium falciparum malaria infection in Africa: 2000–2010. Lancet. 2014, 383, 1739–1747. 10.1016/S0140-6736(13)62566-0
4. World Health Organization (WHO). World Malaria Report 2023. Geneva: World Health Organization; 2023.
5. National Malaria Elimination Programme (NMEP); National Population Commission (NPC); National Bureau of Statistics (NBS); ICF International. Nigeria Malaria Indicator Survey 2021. Abuja, Nigeria; 2022.
6. Mordecai, E.A.; Cohen, J.M.; Evans, M.V.; Gudapati, P.; Johnson, L.R.; Lippi, C.A.; Miazgowicz, K.; Murdock, C.C.; Rohr, J.R.; Ryan, S.J.; et al. Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. PLoS Neglected Tropical Diseases. 2017, 11, e0005568. DOI:10.1371/journal.pntd.0005568
7. Parham, P.E.; Michael, E. Modeling the effects of weather and climate change on malaria transmission. Environmental Health Perspectives. 2010, 118, 620–626. DOI:10.1289/ehp.0901256
8. Craig, M.H.; Snow, R.W.; le Sueur, D. A climate-based distribution model of malaria transmission in sub-Saharan Africa. Parasitology Today. 1999, 15, 105–111. DOI:10.1016/s0169-4758(99)01396-4
9. Gething, P.W.; Smith, D.L.; Patil, A.P.; Tatem, A.J.; Snow, R.W.; Hay, S.I. Climate change and the global malaria recession. Nature. 2010, 465, 342–345. DOI:10.1038/nature09098
10. Caminade, C.; Kovats, S.; Rocklov, J.; Tompkins, A.M.; Morse, A.P.; Colón-González, F.J.; Stenlund, H.; Martens, P.; Lloyd, S.J. Impact of climate change on global malaria distribution. Proceedings of the National Academy of Sciences. 2014, 111, 3286–3291.
11. Pascual, M.; Ahumada, J.A.; Chaves, L.F.; Rodo, X.; Bouma, M. Malaria resurgence in the East African highlands: temperature trends revisited. Proceedings of the National Academy of Sciences. 2006, 103, 5829–5834.
12. Zhou, G.; Minakawa, N.; Githeko, A.K.; Yan, G. Association between climate variability and malaria epidemics in the East African highlands. Proceedings of the National Academy of Sciences. 2004, 101, 2375–2380.
13. Tompkins, A.M.; Ermert, V. A regional-scale, high-resolution dynamical malaria model that accounts for population density, climate and surface hydrology. Malaria Journal. 2013, 12, 65. https://doi.org/10.1186/1475-2875-12-65
14. Bomblies, A. Modeling the role of rainfall patterns in seasonal malaria transmission. Climatic Change. 2012, 112, 673–685. https://doi.org/10.1007/s10584-011-0230-6
15. Paaijmans, K.P.; Read, A.F.; Thomas, M.B. Understanding the link between malaria risk and climate. Proceedings of the National Academy of Sciences. 2009, 106, 13844–13849. https://doi.org/10.1073/pnas.0903423106
16. Boogaard, H.; de Wit, A.; te Roller, J.; van Diepen, K.; van Kraalingen, D.; Supit, I.; van den Wijngaart, R.; Boersma, L. AgERA5: a global climate dataset for agricultural applications. Earth System Science Data. 2020, 12, 479–494. https://doi.org/2073-4433/16/3/263
17. Copernicus Climate Change Service (C3S). AgERA5: Agrometeorological Indicators from ERA5. European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK; 2024.
18. Weiss, D.J.; Lucas, T.C.D.; Nguyen, M.; Nandi, A.K.; Bisanzio, D.; Battle, K.E.; Cameron, E.; Twohig, K.A.; Pfeffer, D.A.; Rozier, J.A.; et al. Mapping the global prevalence, incidence, and mortality of Plasmodium falciparum, 2000–2017. Lancet. 2019, 394, 322–331. DOI: 10.1016/S0140-6736(25)00038-8
19. Snow, R.W.; Sartorius, B.; Kyalo, D.; Maina, J.; Amratia, P.; Mundia, C.W.; Bejon, P.; Noor, A.M. The prevalence of Plasmodium falciparum in sub-Saharan Africa since 1900. Nature. 2017, 550, 515–518. doi: 10.1038/nature24059
20. Nicholson, S.E. The climate of tropical Africa. Cambridge University Press, Cambridge, UK; 2018.
21. Molineaux, L. The Epidemiology of Human Malaria as an Explanation of Its Distribution, Including Some Implications for Its Control; World Health Organization: Geneva, Switzerland, 1988.
22. Lindsay, S.W.; Birley, M.H. Climate change and malaria transmission. Ann. Trop. Med. Parasitol. 1996, 90, 573–588. DOI: 10.1080/00034983.1996.11813087
23. Ryan, S.J.; Lippi, C.A.; Zermoglio, F. Shifting transmission risk for malaria in Africa under climate change: A framework for planning and intervention. Nat. Clim. Chang. 2020, 10, 217–225. DOI: 10.1186/s12936-020-03224-6

24. Ermert, V.; Fink, A.H.; Morse, A.P.; Paeth, H. The impact of regional climate change on malaria risk due to greenhouse forcing and land-use changes in tropical Africa. Clim. Change 2012, 112, 573–595. doi: 10.1289/ehp.1103681
25. Yamana, T.K.; Bomblies, A.; Eltahir, E.A.B. Climate change unlikely to increase malaria burden in West Africa. Nat. Clim. Chang. 2016, 6, 1009–1013. DOI:10.1038/nclimate3085
26. Sultan, B.; Janicot, S. The West African monsoon dynamics. Part II: The "preonset" and "onset" of the summer monsoon. J. Clim. 2003, 16, 3407–3427. DOI:10.1175/1520-0442(2003)016<3407:TWAMDP>2.0.CO;2
27. Nicholson, S.E. The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorol. 2013, 2013, 453521. https://doi.org/10.1155/2013/453521
28. Thomson, M.C.; Connor, S.J.; Milligan, P.; Flasse, S.P. Mapping malaria risk in Africa: What can satellite data contribute? Parasitol. Today, 1997, 13, 313–318. https://doi.org/10.1016/S0169475897010971
29. Teklehaimanot, H.D.; Lipsitch, M.; Teklehaimanot, A.; Schwartz, J. Weather-based prediction of Plasmodium falciparum malaria in epidemic-prone regions of Ethiopia. Nature 2004, 430, 576. DOI: 10.1186/1475-2875-3-41
30. Cairns, M.; Roca-Feltrer, A.; Garske, T.; Wilson, A.L.; Diallo, D.; Milligan, P.J.; Ghani, A.C.; Greenwood, B.M. Estimating the potential public health impact of seasonal malaria chemoprevention in African children. Nat. Commun. 2012, 3, 881. DOI: 10.1038/ncomms1879
31. Penny, M.A.; Verity, R.; Bever, C.A.; Sauboin, C.; Galactionova, K.; Flasche, S.; White, L.J. Public health impact and cost-effectiveness of the RTS,S/AS01 malaria vaccine: A systematic comparison of predictions from four mathematical models. Lancet Glob. Health 2016, 4, e227–e235. DOI: 10.1016/S0140-6736(15)00725-4
32. Hay, S.I.; Guerra, C.A.; Tatem, A.J.; Noor, A.M.; Snow, R.W. The global distribution and population at risk of malaria: Past, present, and future. Lancet Infect. Dis. 2004, 4, 327–336. DOI: 10.1016/S1473-3099(04)01043-6
33. Tatem, A.J.; Smith, D.L. International population movements and regional Plasmodium falciparum malaria elimination strategies. Proc. Natl. Acad. Sci. USA 2010, 107, 12222–12227. DOI: 10.1073/pnas.1002971107
34. Noor, A.M.; Mutheu, J.J.; Tatem, A.J.; Hay, S.I.; Snow, R.W. Insecticide-treated net coverage in Africa: Mapping progress in 2000–2007. Lancet 2009, 373, 58–67. DOI: 10.1016/S0140-6736(08)61596-2
35. Cohen, J.M.; Smith, D.L.; Cotter, C.; Ward, A.; Yamey, G.; Sabot, O.J.; Moonen, B. Malaria resurgence: A systematic review and assessment of its causes. PLoS ONE 2012, 7, e29434. DOI: 10.1186/1475-2875-11-122