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**Special Collection:**
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**Key Points:**

- Malaria peaks May–August; rainfall and humidity increase cases, while higher temperatures reduce incidence
- Northern zone shows strongest rainfall–humidity effects; children under five are most climate sensitive
- Climate-based early warning systems can improve malaria prediction and targeted control strategies

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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# Impact of Seasonal Meteorological Variability on Malaria Incidence in Côte d'Ivoire: A Retrospective Study (2021–2023)

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**Abstract** Metrological variations strongly influence malaria transmission by affecting mosquito breeding and survival. Côte d'Ivoire, located within a tropical climate zone, is particularly vulnerable to metrological variations that can alter disease patterns. This study aimed to assess the relationship between meteorological variations of temperature, precipitation, relative humidity and malaria incidence in Côte d'Ivoire from 2021 to 2023. This was a retrospective ecological time-series study that used data from the National Malaria Control Program (NMCP) and meteorological data from SODEXAM. Monthly data was analyzed by ecological zones and age groups. Pearson's correlation and multiple linear regression models were used to examine associations between metrological variation factors and malaria incidence. Malaria incidence peaked during the rainy season (May–August) across all regions, with children under five representing 39% of total cases. Precipitation and relative humidity were positively and significantly correlated with malaria incidence ($r = 0.583$–$0.698$, $p < 0.05$), while temperature showed a significant negative correlation ($r = -0.539$ to $-0.600$, $p < 0.05$). Interaction analysis revealed that the effect of precipitation and humidity was strongest in the northern zone, where malaria transmission risk increased significantly ($\beta = 22.51$, $p = 0.01$). Malaria transmission in Côte d'Ivoire is strongly associated with metrological variability, particularly rainfall and humidity. Elevated precipitation and humidity increase malaria morbidity, whereas high temperatures above 28°C suppress transmission. Integrating meteorological surveillance into malaria early warning systems can improve prediction and control strategies, especially among vulnerable populations such as children under five.

**Plain Language Summary** Changes in weather conditions such as temperature, rainfall, and humidity can affect how malaria spreads by influencing mosquito breeding and survival. This study examined how these weather factors were associated with malaria cases in Côte d'Ivoire between 2021 and 2023 using national malaria surveillance data combined with meteorological records. We analyzed patterns across different ecological zones and age groups to identify who is most affected by climate-related changes. Malaria cases increased during cooler and wetter months, particularly from May to August, when rainfall and humidity were highest, and declined during hotter, drier periods when temperatures exceeded 28°C. Children under 5 years of age accounted for 39% of reported cases and showed the strongest response to rainfall and humidity, indicating greater vulnerability to climate conditions than older age groups. The strongest weather-related effects were observed in the northern and central regions of the country. These findings show that malaria transmission in Côte d'Ivoire is closely linked to rainfall and humidity. Monitoring weather patterns can help anticipate malaria outbreaks and support timely public health actions to protect vulnerable populations, especially young children.

## 1. Introduction

Worldwide, the emergence, resurgence, and distribution of infectious diseases are increasingly influenced by climate variability and global warming (Epstein, 2001). The World Health Organization (WHO) and the Intergovernmental Panel on Climate Change (IPCC) emphasized in the Sixth Assessment Report that adaptation to rising global temperatures will become progressively difficult, as climate-related risks appear earlier and intensify more rapidly than previously projected (WHO, 2023). Approximately 3.6 billion people currently live in regions highly vulnerable to metrological disruptions, and between 2030 and 2050, an estimated additional 250,000

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deaths per year are expected to result from malaria, diarrheal, malnutrition, and heat stress attributable to seasonal variability change (WHO, 2023).

In 2023, global temperatures reached their highest level since instrumental records began in 1850, with the annual mean temperature rising to 14.98°C–0.17°C higher than the previous record in 2016 and 1.48°C above pre-industrial levels (Copernicus, 2024). Due to its geographical location, economic dependence on climate-sensitive sectors, and limited adaptive capacity, Côte d'Ivoire ranks among the nations most exposed to the adverse effects of global warming (Bank, 2023). National records indicate an average temperature rise of 0.5–0.8°C between 1970 and 2000, with projections suggesting further increases in temperature variability, irregular precipitation, and more frequent extreme events by 2050 especially in the northern regions (Fiches, 2024).

Malaria remains one of the most prevalent vector-borne diseases in tropical and subtropical regions and continues to represent a major public health challenge despite decades of control efforts (Raghavendra et al., 2011). It was reported an estimated 608,000 malaria deaths in 2022 compared with 610,000 in 2021, alongside 244 million cases worldwide, of which 94% occurred in the African Region (WHO, 2023). Côte d'Ivoire alone recorded 7,328,427 malaria cases in 2021 (Gouamene et al., 2024). Despite sustained national investments, supported by the President's Malaria Initiative (PMI) and the Global Fund, malaria remains endemic with continuous transmission that peaks during rainy seasons (Fiches, 2024). The prevalence among children under five also increased from 18% in 2011 to 26% in 2021, according to the preliminary Demographic and Health Survey results (Observatory, 2022).

Meteorological or seasonal variations amplifies the risk of emerging and re-emerging infectious diseases through their effects on temperature, precipitation, and humidity factors that directly influence the life cycles of vectors and pathogens. Africa's most vulnerable regions are already experiencing the compounded burden of climate change and vector-borne diseases (Doumbia et al., 2023; Khormi & Kumar, 2016). Several studies have demonstrated that temperature, precipitation, relative humidity, and wind dynamics critically determine the breeding, survival, and transmission efficiency of *Anopheles* mosquitoes and *Plasmodium* parasites (Adja et al., 2011; Agusto et al., 2015; Gatore Sinigirira et al., 2025; Jatta et al., 2021; Mohamed, 2001; Mohammadkhani et al., 2016). Atmospheric changes in temperature and rainfall can trigger outbreaks by creating favorable conditions for mosquito proliferation (Craig et al., 1999; Diouf et al., 2020). Rainfall replenishes larval habitats, while high temperatures accelerate parasite development within vectors. However, excessive rainfall may wash away breeding sites, while low humidity limits adult mosquito survival (Gatore Sinigirira et al., 2025; Hwang et al., 2016; Jatta et al., 2021).

The IPCC projects that if control strategies are not adapted, climate-related expansion of vector-borne diseases such as malaria, dengue, West Nile virus, and Lyme disease will continue throughout the next century (Graffy et al., 2024; Jatta et al., 2021; Mabaso et al., 2005; Yamba et al., 2023). In Côte d'Ivoire, rising temperatures, changing rainfall regimes, and extreme weather events are expected to alter malaria distribution and transmission intensity (Bank, 2023; Gouamene et al., 2024; M'Bra et al., 2018). As malaria has been one of the leading causes of morbidity and mortality in the past decade, these environmental shifts pose a significant public health threat (Observatory, 2022). Thus, this retrospective time series study, aimed to examine the relationship between metrological variations related indicators and malaria incidence in Côte d'Ivoire from 2021 to 2023, thereby contributing to a better understanding of climate-sensitive health outcomes and informing future adaptation and disease-surveillance strategies.

## 2. Methods

### 2.1. Study Design, Data Sources, and Population

This retrospective descriptive study examined the association between metrological variation parameters and malaria incidence in Côte d'Ivoire from January 2021 to December 2023. Data were obtained from two primary national sources: the National Malaria Control Program (NMCP) for malaria morbidity data and the Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM) for meteorological observations.

Malaria case data were compiled monthly across multiple health districts, representing all major ecological zones of Côte d'Ivoire. The NMCP data set included laboratory-confirmed malaria cases recorded through health facilities' surveillance systems. Meteorological data from SODEXAM provided monthly averages of temperature (°C), precipitation (mm), and relative humidity (%) for the same period and corresponding regions. A multistage (cluster) sampling approach was used to ensure geographical representation across administrative regions, combining urban and rural sites from four ecological zones: Northern savanna (North land), Central plateau (Middle land), Western highlands (Mountain areas), and Southern littoral (Coastal area).

### 2.2. Variables

The primary outcome variable in this study was the number of laboratory-confirmed malaria cases that using rapid diagnostic tests (RDTs) and/or microscopy according to NMCP surveillance protocols reported monthly in each region of Côte d'Ivoire; clinically suspected cases were excluded. The main explanatory variables were the meteorological parameters namely, temperature (°C), precipitation (mm), and relative humidity (%), which represent key metrological determinants influencing malaria transmission. In addition to these environmental factors, sociodemographic variables such as age group and ecological zone were included to account for population-level variations in exposure and vulnerability.

The age group variable was categorized into three strata: children under 5 years (<5 years), individuals aged 5 years and above (≥5 years), and all ages combined. The ecological zone variable classified the study area into four distinct geographical and metrological regions: North land, Middle land, Mountain areas, and Coastal area. These classifications reflect the environmental diversity of Côte d'Ivoire and its influence on malaria transmission dynamics. Collectively, these variables allowed for the analysis of how changes in temperature, precipitation, and humidity correlate with malaria incidence across different age groups and ecological settings.

### 2.3. Statistical Analysis

Data management and statistical analyses were conducted using RStudio (R version 4.3.0). Descriptive statistics summarized malaria morbidity and meteorological characteristics. Quantitative variables were presented as means ± standard deviations (SDs) and visually represented using time-series plots to display trends in temperature, precipitation, humidity, and malaria incidence across months and years. The relationship between metrological indicators and malaria cases was initially examined using Pearson's correlation coefficients ($r$) to determine the direction and strength of associations. Simple linear regression was performed to estimate the individual effects of each metrological parameter (temperature, precipitation, and humidity) on malaria incidence. Subsequently, multiple linear regression models were constructed to assess the combined and interactive effects of the three meteorological factors on malaria transmission. Model diagnostics were conducted to confirm linearity, normality, and absence of multicollinearity. Statistical significance was defined at $p < 0.05$.

## 3. Results

### 3.1. General Characteristics of Malaria and Weather Parameters

Between 2021 and 2023, Côte d'Ivoire exhibited pronounced seasonal variability in temperature, precipitation, and relative humidity. The warmest conditions were observed from February to April, with mean maximum temperatures exceeding 28°C from January through May, corresponding to the dry season. In contrast, cooler temperatures below 28°C prevailed during the rainy season from June to September. Spatially, temperature patterns were relatively stable in the northern zone, while greater variability was observed in the Middle-Land (25.6–29.4°C) and Mountain regions (24.8–27.9°C). Coastal areas showed limited seasonal fluctuation, with the highest average temperatures recorded in February (Figure S1 in Supporting Information S1).

### 3.2. Metrological Variations in Precipitation, Humidity, and Temperature

Figure 1 presents precipitation patterns, indicating that rainfall peaked between May and August, particularly in the northern and mountainous regions, with the central and coastal zones experiencing earlier and more gradual increases starting in June. The highest rainfall averages were recorded in June 2021 (253 mm), June 2022 (261.2 mm), and June 2023 (342.8 mm), whereas the lowest precipitation occurred in December and January.

As illustrated in Figure 2, relative humidity progressively increased from April to September each year, reaching its highest levels between July and September 2021–2022 and in August 2023. Figure 3 demonstrates an inverse

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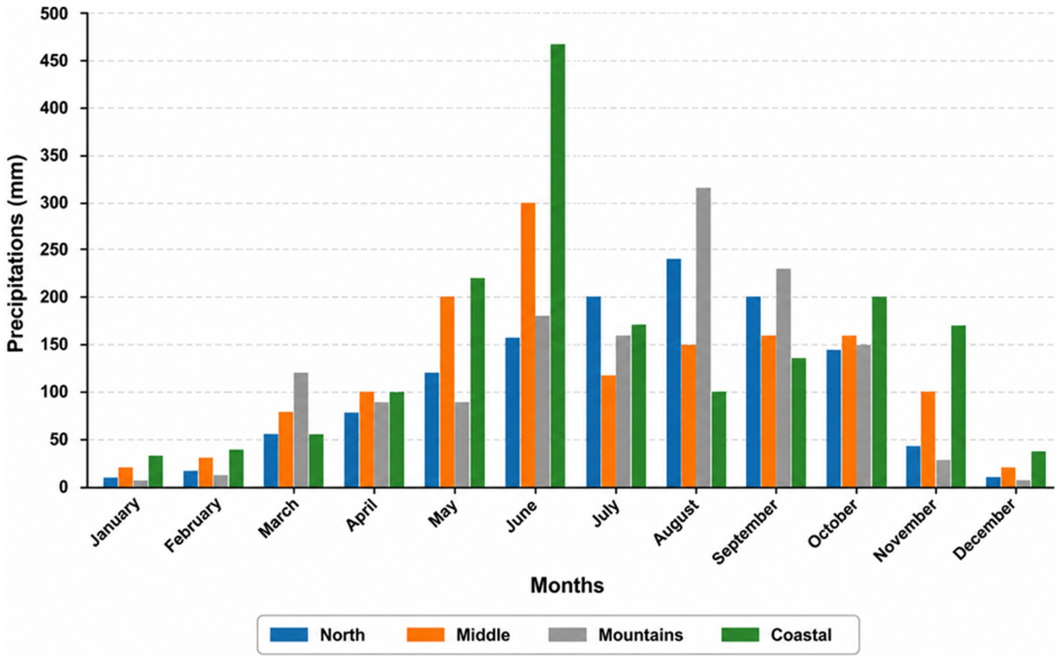


**Figure 1.** Monthly average precipitation (2021–2023).

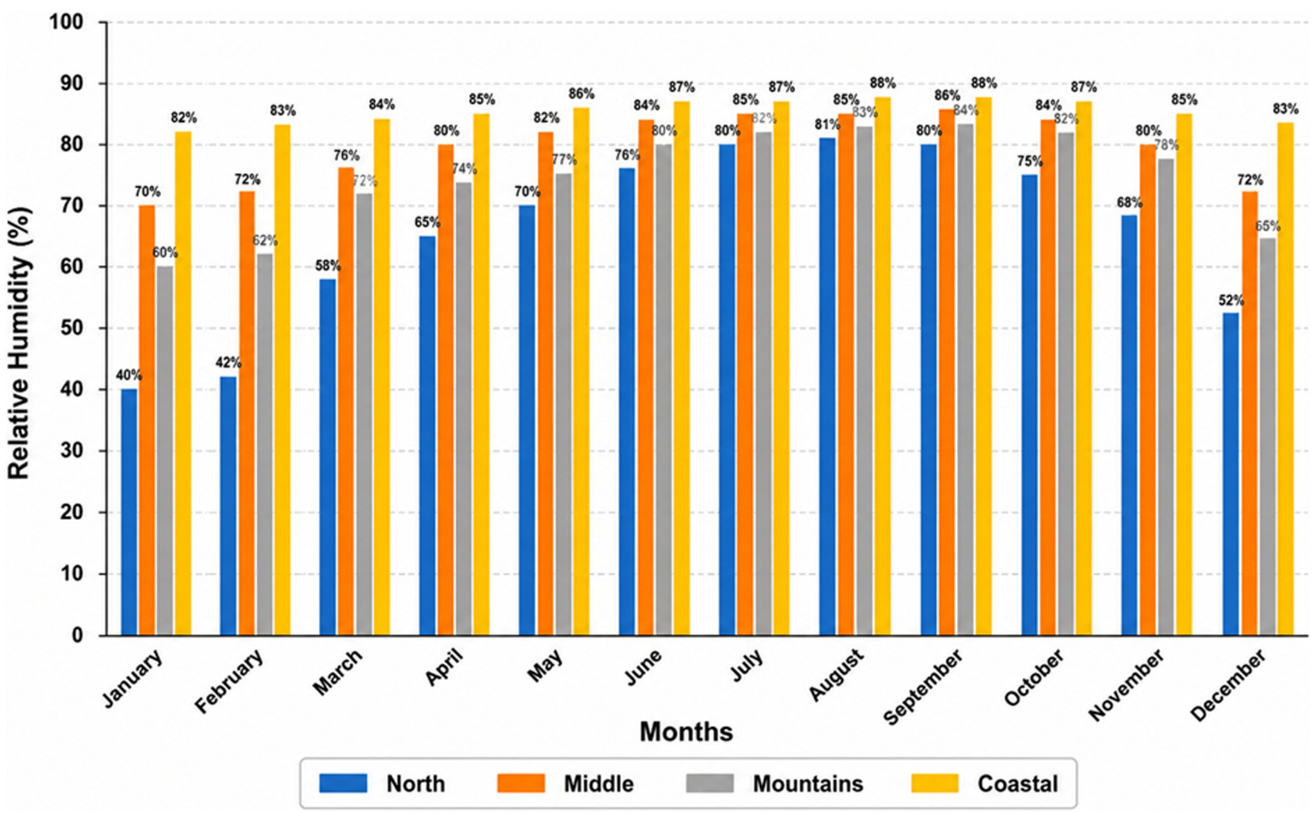


**Figure 2.** Monthly average humidity (2021–2023).

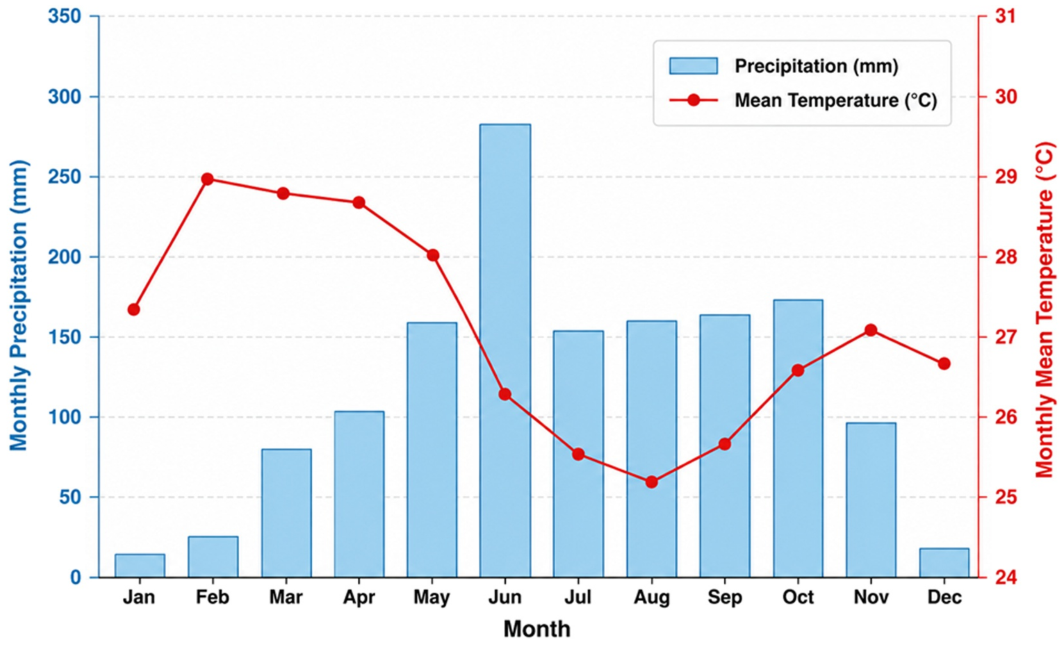


**Figure 3.** Relative inverse relationship between temperature and precipitation.

relationship between temperature and precipitation: low temperatures coincided with high rainfall during May–August, whereas higher temperatures were observed in the dry months.

The age distribution of malaria cases is indicating that children under 5 years represented 39% of all confirmed malaria cases, while individuals aged 5 years and older accounted for 61% and temporal trends in malaria morbidity, showing a marked increase in cases from May to August corresponding with peak rainfall followed by a decline in September and a moderate resurgence toward the year's end (Figures S2 and S3 in Supporting Information S1).

### 3.3. Association Between Malaria Cases and Weather Indicators

Correlation analyses revealed significant associations between metrological parameters and malaria incidence across all age groups. Among children under 5 years, malaria cases correlated positively with precipitation ($r = 0.583$, $p < 0.05$) and humidity ($r = 0.698$, $p < 0.05$), but negatively with temperature ($r = -0.539$, $p < 0.05$) (Table 1).

In individuals aged 5 years and above, malaria showed a similar pattern, with positive correlations with precipitation ($r = 0.509$, $p < 0.05$) and humidity ($r = 0.591$, $p < 0.05$), and a significant negative correlation with temperature ($r = -0.600$, $p < 0.05$) (Table 2). When considering all ages combined, malaria incidence remained significantly and positively associated with precipitation ($r = 0.536$, $p < 0.05$) and humidity ($r = 0.633$, $p < 0.05$), while maintaining a negative correlation with temperature ($r = -0.576$, $p < 0.05$) (Table 3).

**Table 1**
*Correlation Between Average Weather Indicators and Malaria Cases in Children Under 5 Years*

| Variables | Malaria <5 years | Precipitation (mm) | Humidity (%) | Temperature (°C) |
|---|---|---|---|---|
| Malaria <5 years | 1.000 | | | |
| Precipitation (mm) | 0.583* | 1.000 | | |
| Humidity (%) | 0.698** | 0.851** | 1.000 | |
| Temperature (°C) | −0.539** | −0.292 | −0.315 | 1.000 |

*Note*. $P < 0.001$*; $p < 0.05$**.

**Table 2**
*Correlation Between Average Weather Indicators and Malaria Cases in Individuals Aged 5 Years and Above, Côte d'Ivoire (2021–2023)*

| Variables | Malaria ≥5 years | Precipitation (mm) | Humidity (%) | Temperature (°C) |
|---|---|---|---|---|
| Malaria ≥5 years | 1.000 | | | |
| Precipitation (mm) | 0.509** | 1.000 | | |
| Humidity (%) | 0.591** | 0.851** | 1.000 | |
| Temperature (°C) | −0.600** | −0.292 | −0.315 | 1.000 |

*Note*. **$p < 0.05$.

Overall, precipitation was strongly and positively correlated with humidity ($r = 0.851$, $p < 0.05$), indicating that increased rainfall led to higher relative humidity. Conversely, precipitation and temperature were inversely related ($r = -0.292$, $p > 0.05$), suggesting that higher rainfall periods coincided with cooler conditions. A similar negative and non-significant association was noted between humidity and temperature ($r = -0.315$, $p > 0.05$).

### 3.4. Evolution of Malaria and Meteorological Parameters

An inverse relationship between temperature and malaria incidence presented in Figure 4. As temperatures decreased from May to August, malaria cases increased sharply, peaking during cooler months. When temperatures rose above 28°C from September onward, malaria incidence declined. This confirms that malaria transmission in Côte d'Ivoire is higher during cooler, wetter periods and lower during hotter, dry months.

#### 3.4.1. Monthly Precipitation and Malaria Incidence in Côte d'Ivoire

Malaria incidence rose sharply from April to July, coinciding with increased rainfall and peaking in June, when precipitation reached its highest level (~290 mm). As rainfall declined after August, malaria incidence also gradually decreased (Figure 5). This pattern demonstrates a strong positive correlation between precipitation and malaria incidence, confirming that rainfall enhances mosquito breeding and transmission during the rainy season.

#### 3.4.2. Monthly Mean Humidity and Malaria Incidence in Côte d'Ivoire

Both humidity and malaria incidence rose progressively from March to July, peaking between July and August when relative humidity exceeded 85% (Figure 6). As humidity declined after September, malaria incidence also decreased. This pattern indicates a strong positive relationship between humidity and malaria transmission, showing that higher atmospheric moisture favors mosquito survival and malaria spread during the rainy season.

### 3.5. Correlation Coefficients Between Malaria Cases and Weather Indicators

Table 4 shows that across all age groups and ecological zones, temperature was negatively correlated with malaria incidence, while precipitation and humidity were positively correlated, with most associations statistically significant ($p < 0.05$). The strongest correlations were observed in the Middle and Northern zones, where lower temperatures and higher rainfall and humidity were consistently linked to increased malaria cases. In contrast, the Mountain and Coastal zones showed weaker or non-significant associations, suggesting less metrological influence on transmission.

**Table 3**
*Correlation Between Average Weather Indicators and Malaria Cases (All Ages), Côte d'Ivoire (2021–2023)*

| Variables | Malaria (all ages) | Precipitation (mm) | Humidity (%) | Temperature (°C) |
|---|---|---|---|---|
| Malaria (All Ages) | 1.000 | | | |
| Precipitation (mm) | 0.536** | 1.000 | | |
| Humidity (%) | 0.633** | 0.851** | 1.000 | |
| Temperature (°C) | −0.576** | −0.292 | −0.315 | 1.000 |

*Note*. **$p < 0.05$.

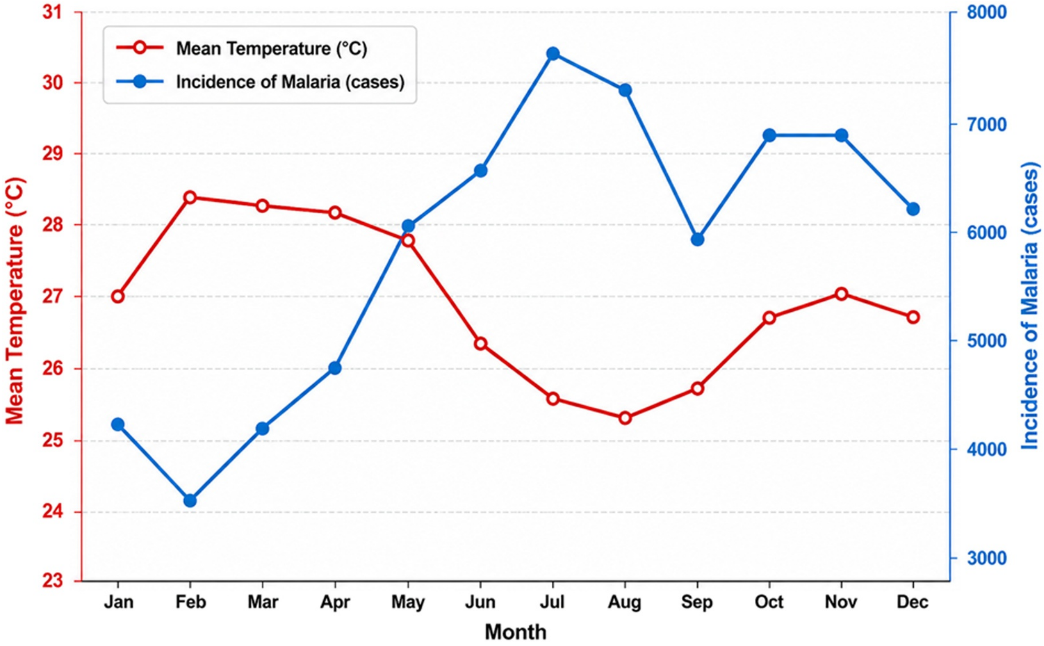


**Figure 4.** Distribution of inverse relationship between temperature and malaria incidence.

### 3.6. Subgroup Analysis: Interaction of Precipitation and Humidity With Malaria by Age Group

Results from the multiple regression analysis examining the interaction between precipitation and humidity by ecological zone and age group are summarized in Table 5. In the northern zone, the interaction effect was positive and statistically significant across all groups: children under 5 years ($\beta = 8.56$, $p = 0.01$), individuals aged 5 years

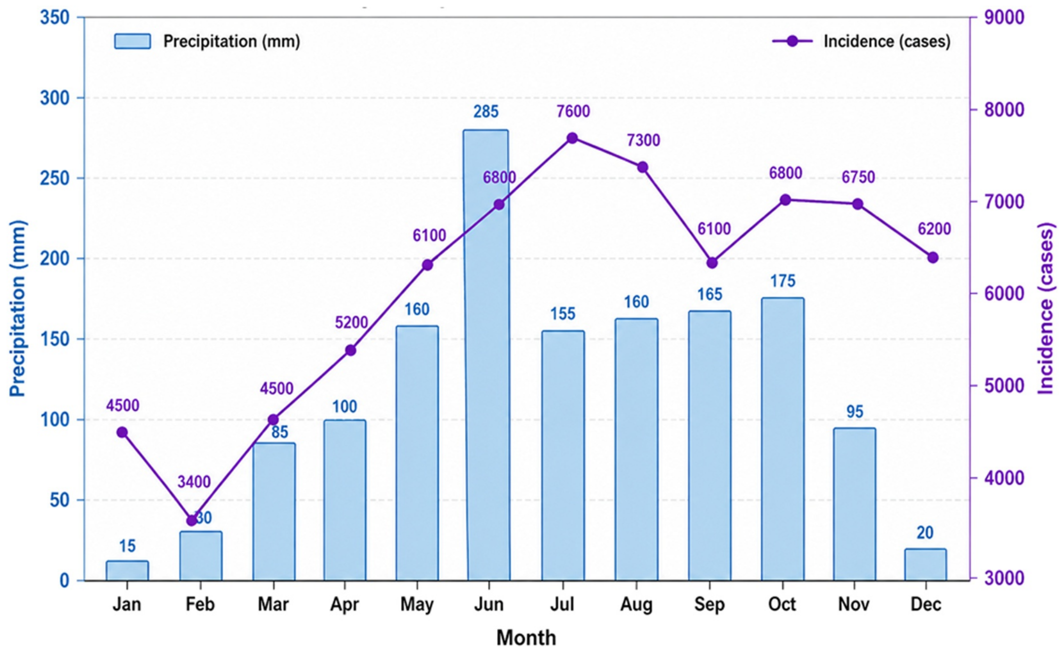


**Figure 5.** Distribution of inverse relationship between monthly precipitation and malaria incidence.

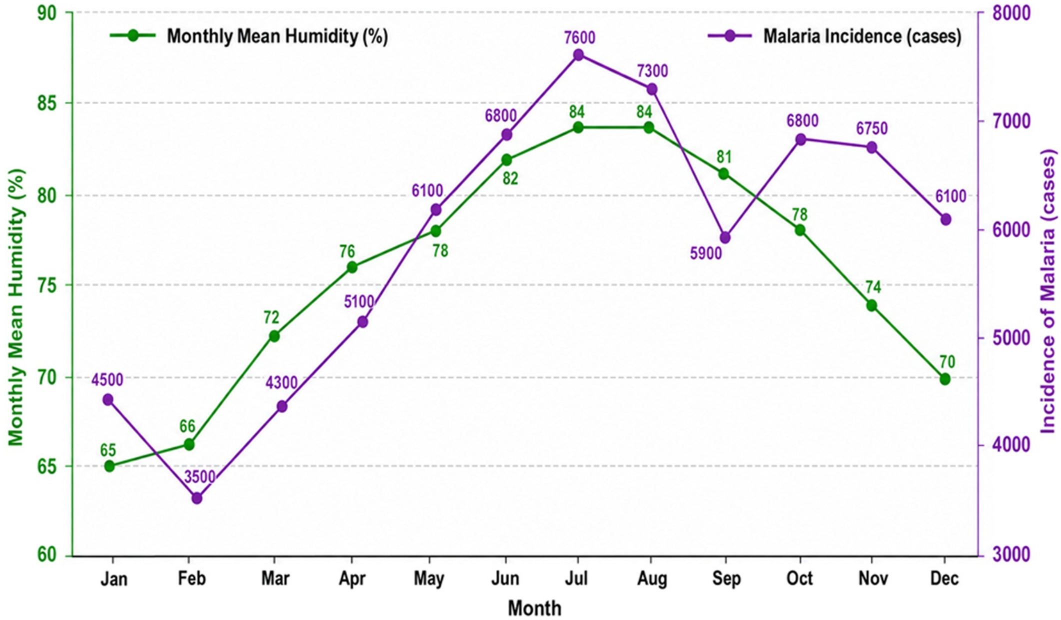


**Figure 6.** Distribution of inverse relationship between humidity and malaria incidence.

and above ($\beta = 13.95$, $p = 0.02$), and all ages combined ($\beta = 22.51$, $p = 0.01$). This finding indicates that the combined influence of rainfall and humidity significantly increases malaria incidence in the northern region. In contrast, the interaction effects were negative or non-significant in the Middle-Land, Mountain, and Coastal zones, suggesting that metrological interactions in these regions exert less consistent or weaker effects on malaria transmission. The adjusted $R^2$ values ranged from 0.11 to 0.80, confirming variable model strength across ecological zones.

**Table 4**
*Correlation Coefficients Between Meteorological Parameters and Malaria Incidence by Age Group and Ecological Zone, Côte d'Ivoire (2021–2023)*

| Age group/Zone | Temp (°C) | p | Precip (mm) | p | Humidity (%) | p |
|---|---|---|---|---|---|---|
| Malaria <5 years | | | | | | |
| North | −0.68 | 0.01 | 0.67 | 0.01 | 0.80 | 0.001 |
| Middle | −0.75 | 0.004 | 0.61 | 0.03 | 0.83 | 0.006 |
| Mountains | −0.06 | 0.84 | 0.41 | 0.18 | 0.69 | 0.01 |
| Coastal | −0.57 | 0.05 | 0.46 | 0.13 | 0.56 | 0.05 |
| Malaria ≥5 years | | | | | | |
| North | −0.68 | 0.01 | 0.63 | 0.02 | 0.75 | 0.004 |
| Middle | −0.81 | 0.001 | 0.60 | 0.03 | 0.80 | 0.001 |
| Mountains | −0.60 | 0.03 | 0.38 | 0.22 | 0.52 | 0.07 |
| Coastal | −0.73 | 0.007 | 0.39 | 0.20 | 0.54 | 0.06 |
| Malaria (All Ages) | | | | | | |
| North | −0.68 | 0.01 | 0.65 | 0.02 | 0.77 | 0.003 |
| Middle | −0.78 | 0.02 | 0.61 | 0.03 | 0.82 | 0.001 |
| Mountains | −0.31 | 0.31 | 0.42 | 0.16 | 0.68 | 0.01 |
| Coastal | −0.68 | 0.01 | 0.42 | 0.16 | 0.56 | 0.05 |

*Note*. Temp, temperature; Precip, precipitation.

**Table 5**
*Interaction Between Precipitation and Humidity on Malaria Cases by Age Group and Ecological Zone, Côte d'Ivoire (2021–2023)*

| Group/Zone | Coefficient (precipitation × humidity) | Adjusted $R^2$ | *p*-value |
|---|---|---|---|
| Malaria <5 years | | | |
| North | 8.56 | 0.80 | 0.01 |
| Middle | −5.77 | 0.59 | 0.78 |
| Mountains | −1.80 | 0.45 | 0.47 |
| Coastal | −31.27 | 0.24 | 0.33 |
| Malaria ≥5 years | | | |
| North | 13.95 | 0.72 | 0.02 |
| Middle | 3.48 | 0.51 | 0.90 |
| Mountains | 3.40 | 0.23 | 0.17 |
| Coastal | −35.02 | 0.11 | 0.55 |
| Malaria (All Ages) | | | |
| North | 22.51 | 0.76 | 0.01 |
| Middle | −2.29 | 0.96 | 0.96 |
| Mountains | 2.04 | 0.59 | 0.59 |
| Coastal | −67.23 | 0.45 | 0.45 |

*Note*. Temp = Temperature; Precip = Precipitation; Humid = Humidity.

## 4. Discussion

From 2021 to 2023, malaria incidence in Côte d'Ivoire followed a clear seasonal pattern, peaking between May and August especially in July before declining in September and showing moderate resurgence in October and November. This pattern aligns with the seasonal rise in rainfall and humidity, which create optimal conditions for mosquito breeding and parasite development. Similar findings were observed that 62% of malaria cases occurred during the rainy season compared with 38% during the dry season (Hajison et al., 2017; Lauderdale et al., 2014; Yamba et al., 2023). Increased rainfall contributes to the formation of stagnant water pools that serve as larval habitats, while elevated humidity enhances mosquito survival and transmission efficiency.

Regional variation was also evident, particularly in the northern zones, where malaria cases remained high into October, corresponding with the end of the rainy season. This may reflect residual breeding sites that persist when heavy rains prevent their destruction (Bal et al., 2025; Yao et al., 2024). Comparable results were reported in Senegal, found that most malaria-related deaths occurred between August and December, peaking in October (Etard et al., 2003). These temporal dynamics reinforce the importance of vector-control interventions immediately after rainfall peaks, before the onset of the dry season.

The persistence of malaria transmission into the post-rainy period has also been linked to incomplete destruction of breeding habitats and the lag effect of rainfall on mosquito life cycles (Epstein, 2001; Gatore Sinigirira et al., 2025). Studies in Ethiopia and The Gambia confirm that mosquito density, longevity, and biting rates are significantly higher during the wet season, whereas vector survival and transmission potential decrease markedly during dry months (Adja et al., 2011; Jatta et al., 2021; Mohamed, 2001; Teklehaimanot et al., 2004). Such findings demonstrate how precipitation and humidity remain critical drivers of malaria seasonality across West Africa (Diouf et al., 2020; Doumbia et al., 2023).

Rainfall was consistently found to have a strong positive correlation with malaria incidence in this study, a result supported by multiple regional and international analyses. Prior studies observed that both temperature and precipitation significantly affect malaria prevalence globally (Graffy et al., 2024; Raghavendra et al., 2011), with precipitation exerting a stronger effect in Africa. In Ghana, Krefis et al. reported that rainfall levels could predict malaria incidence with a 9-week lag (Krefis et al., 2011), while other studies demonstrated that rainfall serves as a major predictor of malaria cases in India (Kumar et al., 2020; Lauderdale et al., 2014; Raghavendra et al., 2011). These findings confirm the pivotal role of rainfall in vector proliferation and malaria transmission.

In contrast, temperature showed a significant negative correlation with malaria incidence in Côte d'Ivoire. As temperatures exceeded 28°C during the dry season, both parasite development and adult mosquito survival declined. Moderate temperatures between 16°C and 28°C favor saprogenic development and transmission, while excessive heat shortens mosquito lifespan and disrupts parasite maturation (Agusto et al., 2015; Craig et al., 1999; Doumbia et al., 2023; M'Bra et al., 2018; Yamba et al., 2023). Although some studies in Asia reported positive associations between temperature and malaria (Khormi & Kumar, 2016; Liu et al., 2024)., Studies from China have shown that malaria transmission responds to short-term temperature changes with a delayed effect. In Shuchen, a significant positive relationship was observed between monthly malaria incidence and minimum temperature with a 1-month lag (Bi et al., 2003; Khormi & Kumar, 2016; Liu et al., 2024). Consistently, other study reported in a temperate region that both minimum and maximum temperatures were positively associated with monthly malaria incidence (Hwang et al., 2016), also exhibiting a 1-month lag, and that a 1°C increase in minimum temperature led to an estimated 12%–16% rise in cases, with minimum temperature exerting a stronger influence than maximum temperature, these differences likely reflect regional metrological baselines and vector adaptation thresholds.

This study also revealed that correlations between malaria and metrological variables were stronger among children under 5 years, consistent with studies found young children to be the most affected group in high-transmission settings (Li et al., 2013; Liu et al., 2024). The heightened vulnerability of this population underscores the importance of incorporating meteorological indicators into child-health surveillance systems. Children constituted the most affected population group, with those under 5 years of age experiencing the highest malaria incidence compared with other age categories (Liu et al., 2024). In high-transmission settings, young children carry the greatest burden of malaria and are simultaneously exposed to multiple comorbid conditions (Brooker et al., 2017), including anemia, malnutrition, genetic disorders, and a range of parasitic, viral, and bacterial infections.

The present study found a significant interaction between precipitation and humidity, particularly in the northern zone, where higher humidity amplified the impact of rainfall on malaria transmission. This aligns with findings from Mozambique, where Zacarias and Andersson highlighted humidity as a key determinant of malaria spread (Zacarias & Andersson, 2011), and with broader analyses showing that humidity ranks above temperature and precipitation in predicting malaria risk (Santos-Vega et al., 2022). Similar associations have been noted in India, emphasized that changes in humidity and hydrological planning could influence urban malaria transmission (Bal et al., 2025). Humidity exerted a particularly strong influence on malaria transmission. High relative humidity increases mosquito longevity and biting frequency, extending opportunities for parasite transmission. A study demonstrated that *Anopheles gambiae s.s.* survives best at 60%–100% relative humidity (Mohamed, 2001), while Hajison et al. confirmed that humidity, temperature, and rainfall jointly determine breeding site productivity (Hajison et al., 2017).

Overall, the results confirm that rainfall and humidity are strong, positive predictors of malaria incidence, while excessive temperature suppresses transmission. These interactions highlight the sensitivity of malaria epidemiology to climate variability and underscore the need for climate-based early warning systems.

## 5. Limitations

This study has several limitations. First, the analysis was constrained using retrospective secondary data sets, which limited inclusion of additional determinants such as socioeconomic status, entomological data, vegetation indices, and wind patterns that also influence malaria transmission. Second, lag effects between meteorological variables and malaria incidence (e.g., 0–2 months related to mosquito breeding and parasite development) were not formally modeled and therefore could not be assessed in this study. Third, Meteorological data were aggregated at the regional level, preventing differentiation between urban and rural microclimates. Also, this study does not consider COVID 19 related impact or information due to the scope of the study objectives. Furthermore, the observational design precludes establishing causal inference, and potential reporting inconsistencies in health surveillance data cannot be ruled out.

### 5.1. Policy Implications

Given the demonstrated influence of metrological variations on malaria transmission, Côte d'Ivoire's malaria-control programs should incorporate meteorological monitoring into routine surveillance. Strengthening collaboration between the National Malaria Control Program and meteorological services (e.g., SODEXAM) would enable climate-based alert systems to predict transmission peaks and guide vector-control interventions. Tailored strategies should prioritize vulnerable groups, especially children under five and residents of northern zones with high rainfall–humidity interactions. Policymakers should also invest in community-level education, environmental sanitation, and early response infrastructure to mitigate malaria risks under changing metrological variations. Integrating these findings into national adaptation frameworks will enhance resilience against vector-borne diseases amid ongoing climate change.

## 6. Conclusion

Malaria incidence in Côte d'Ivoire remains closely linked to seasonal metrological variability. Precipitation and relative humidity showed strong, positive associations with malaria morbidity, particularly among children under five, while higher temperatures were inversely related to case counts. These findings suggest that increased rainfall and humidity foster mosquito breeding and transmission, whereas extreme heat reduces vector survival. Integrated surveillance of meteorological and epidemiological indicators is therefore essential to anticipate outbreaks and strengthen malaria control. Although climate plays a major role, malaria trends are also influenced by factors such as vector-control measures, environmental management, and healthcare access. Developing predictive models that integrate climate and public-health data could support early warning systems and inform national malaria elimination strategies.

## Informed Consent Statement

Not applicable.

## Conflict of Interest

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

## Availability Statement

The malaria incidence data used in this study are available in the National Malaria Control Program (NMCP) Côte d'Ivoire Malaria Data set (2021–2023), archived at [https://www.severemalaria.org/countries/la-cote-divoire].

The meteorological data from SODEXAM (temperature, precipitation, humidity) are available through the Côte d'Ivoire Climate and Weather Data set (2021–2023) https://sodexam.com.

Data processing and statistical analyses were conducted using R version 4.3.1. All data sets and code comply with AGU's Open Research and FAIR Data standards and are freely available for verification and reuse. No new software or physical samples were created as part of this research. All data and generated is openly accessible and cited (https://sodexam.com) in the AGU's Open Research section.

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