



Study of Recent Climate Variability in Guinean Coast: Case Study of Bingerville and La Mé in Côte D'Ivoire

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Abstract

Understanding and characterising climate change at a small scale is fundamental to face its impacts on local vulnerabilities and development projects. This study characterises climate parameters in the southern part of Côte d'Ivoire, more specifically in Bingerville and La Mé localities. Several methods were used to carry out the study, they include Nicholson's rainfall index, Gumbel's law and De Martonne's aridity index. The results show that the climate in this region has been subject to strong interannual variability, with a succession of dry and wet periods. Temporal analysis shows a long series of dry years over two decades (1991-2010), but a slight upturn over the decade 2010-2019. The seasonal behaviour of climatic parameters was highlighted in these localities. The results also showed that monthly temperatures and monthly relative humidity mean follow a similar pattern, but with a bias towards the January to March period in general. The surface winds in Bingerville are dominated by monsoon winds throughout the year, unlike the winds in La Mé, which are made up of monsoon and harmattan winds. Although the results of this study are important indicators for assessing climate risks, it is important to improve and strengthen observation systems in order to better characterise and update climate studies in these areas, with a view to help reduce the vulnerability of local populations.

Subject Areas

Atmospheric Sciences

Keywords

Climate, Monsoon, Vulnerability, Bingerville, La Mé

1. Introduction

The West African climate is influenced by local phenomena, the most relevant of which are the West African monsoon [1]-[6], the Harmattan and the Inter-Tropical Convergence Zone (ITCZ) displacement [7] [8], as well as convection phenomena. We also note the implications of tele-connected phenomena that impact tropical meteorology, namely the El Nino Phenomenon, the El Nino-Southern Oscillation (ENSO) movement [9]-[11] and the cold tongue in the Atlantic Ocean [12]-[15]. Understanding all these features throughout their variability and interactions is essential for understanding the West African climate in general and Côte d'Ivoire in particular [16].

However, the climate is facing persistent change both in time and space compared with pre-industrial times [17]-[20]. Studies have shown that the change in climate is a result of human activities. This is reflected, among other things, the recurrence of extreme weather events that impact the various sectors of activity in one way or another. According to Guilyardi *et al.* [21], human activities are responsible for global warming of between 0.8°C and 1.2°C, *i.e.* an average of around 1°C. This warming could reach 1.5°C between 2030 and 2052 if no measures are taken and the temperature continues to rise at the current rate. More specifically, the West African region is suffering the adverse effects of this climate upheaval. These effects have been highlighted in numerous climate change studies in West Africa [22]-[25]. These studies show that, for several decades now, West Africa has experienced a succession of dry climatic episodes alternating with rainy episodes, the intensity and spatial variation of which have become exceptional since 1970 [24] [26] [27]. More worrying, West Africa is experiencing faster global warming than the world average. Since the mid-1970s, temperatures have risen by 1°C to 3°C, especially in the Sahel [28]. Climate change scenarios indicate that the climate variability we are currently experiencing will amplify and intensify in this region. Droughts and floods will not only become more frequent but also more severe [29].

Like other countries, Côte d'Ivoire is no exception to this phenomenon [30]. The climate has fluctuated considerably since the 1950s [31] [32]. Indeed, the various climatic parameters are changing. In terms of rainfall, the 1950s and 1960s were relatively wet, while the 1970s to 1990s were dry. In general, rainfall has been particularly low since the 1980s compared with the 1951-1980 average [33]. In terms of temperature, Côte d'Ivoire has warmed by an average of 0.5°C since the

1980s [34]. Climate is the main factor conditioning socio-economic life in Côte d'Ivoire. Thus, several activities in rural areas are organised based on the climatic change. These include agriculture and transhumance livestock farming. However, with changes in the different seasons (dry and rainy) affecting socio-economic activities, climate studies need to be carried out constantly. Therefore, it seems necessary to study the evolution of climatic parameters [35] over recent decades in order to contribute to the updating of previous climate studies with a view to assist in the prevention and management of the socio-economic impacts of increasing extreme weather events. Thus, the general objective of this study is to characterise recent climatic variations in the southern part of Côte d'Ivoire, specifically in the localities of Bingerville [36] and Alépé, in a context of high climatic variability. Specifically, we will determine the interannual variability of rainfall and the return periods of extreme rainfall events, surface winds and relative humidity variability.

This paper is presented as follows. Firstly, the study area and the data used are presented in the first session, followed by the detail of applied methodology in the second session, then in the third session the results which are discussed.

2. Study Area and Data

2.1. Presentation of the Study Area

The study area includes the commune of Bingerville and Alépé, in the southern part of Côte d'Ivoire. Bingerville is a commune located in the east of the Abidjan district. Covering an area of 305 km², its natural boundaries are the Ebrié lagoon to the south and the Aghien and Potou lagoons to the north-west and north-east respectively. Alépé covers an area of 2.700 km² and is located 45 km from Abidjan (Figure 1).

The two communes are subject to the sub-equatorial climate, which is rather humid and has four seasons: a dry season, generally between december and march, a long rainy season from April to July, a short dry season from August to September and a short rainy season from October to November. In terms of vegetation, Bingerville is dominated by forest and perennial crops, notably oil palm plantation of Palmafrique Eloka, as well as reserves such as the botanical garden and the Dahlia reserve. Alépé where is located La Mé station is also characterised by its predominance of forests and oil palm plantation. It contains 82.422 hectares of dense forest, representing 31% of the area. Secondary forests also play an important role, with a total area of 75.483 hectares, or 28% of the prefecture. Crops and undifferentiated fallow land cover an area of 66.389 hectares, or 25% of the area. Rubber still remains the dominant perennial crop with an area of 21.059 hectares, or 8% [37].

2.2. Different Type of Data Used

The meteorological parameters analysed in this study are temperature, precipitation, humidity and wind, all measured on the ground. Two databases were used,

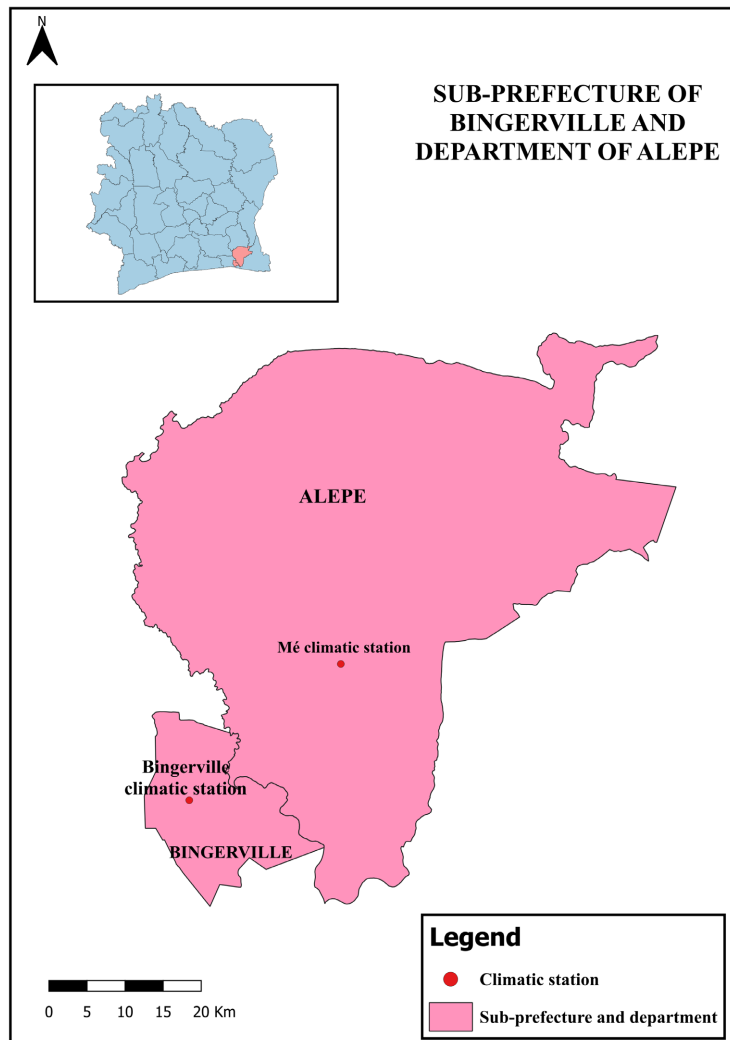


Figure 1. Map of the commune of Bingerville and Alépé where is located La Mé station.

namely data from La Mé meteorological station of CNRA (precipitation, humidity, temperature and wind for a 10-year period from 2010 to 2019) and ERA5-Land reanalysis data. It provides high-resolution hourly information on surface variables. The original ERA5-Land data are on a global grid at 0.1° (~ 9 km) of 10 m surface winds (horizontal component of the velocity noted velocity u_{10} and vertical component of the velocity noted vertical v_{10}) [38]. They cover a 39-year period from 1981 to 2019.

2.2.1. Relative Humidity Data

The monthly mean relative humidity was supplied directly by La Mé station. Relative humidity, on the other hand, was calculated from the ambient air temperature and dew point temperature produced by ERA5-Land using the following relationship:

$$Hr = 100 \frac{e_w(T_d)}{e_w(T)}, \quad (1)$$

$$\text{With } \begin{cases} T_d : \text{temperature de rosee} \\ T : \text{temperature de l'air} \\ e_w(T_d) : \text{pression partielle de vapeur d'eau contenue dans l'air} \\ e_w(T) : \text{pression partielle de vapeur saturante} \\ Hr : \text{humidite relative} \end{cases}$$

This means that

$$Hr = 100 \frac{\exp\left(\frac{17.62 * T_d}{T_d + 243.12}\right)}{\exp\left(\frac{17.62 * T}{T + 243.12}\right)}, \quad (2)$$

This equation is the one recommended by the World Meteorological Organisation for the saturation of air with respect to water [39].

2.2.2. Surface Wind Data

These are winds measured at 10 metres above the ground. Only the meteorological station at La Mé provided direct wind data. These wind data are daily data measured at time intervals of 6 h, 12 h and 18 h. The ERA5-Land re-analysis wind data are determined by the horizontal component u_{10} and the vertical component v_{10} . These components represent the direction from which the wind is blowing. To this end, the wind speed Ws and direction Wd are given by the following relationship:

$$Ws = \sqrt{u_{10}^2 + v_{10}^2}, \quad (3)$$

$$Wd = \begin{cases} -\arctan 2(u_{10}; v_{10}) * 180/\pi + 270, \text{ si } u_{10} > 0 \text{ et } v_{10} < 0 \\ 90 - \arctan 2(-u_{10}; -v_{10}) * 180/\pi, \text{ sinon} \end{cases} \quad (4)$$

These wind data from the ERA5-Land re-analysis are recorded at a time step of one hour.

3. Methodology

3.1. Temperature, Rainfall, Humidity and Wind Analysis

Data on air temperature, rainfall and relative humidity of Bingerville and La Mé station were analysed using descriptive statistics (mean values, cumulative totals) and graphical representations. This analysis was carried out using observation data from La Mé and ERA5-Land reanalysis data for Bingerville. This enabled us understanding the seasonal and interannual variability of temperature, rainfall and relative humidity over this region. Wind speed is also a parameter that influences rainfall in our area. The winds that blow in our area are mainly monsoon winds (south-west wind sector) and harmattan winds (north-east wind sector). In this work, we will consider the westerly winds, the south-westerly winds, the southerly winds and the south-easterly winds as monsoon winds, and the north-westerly winds, the northerly winds, the north-easterly winds and the easterly winds as harmattan winds. The speed or strength of the wind was estimated in

Beaufort.

3.2. Rainfall Anomalies

The Nicholson [40] rainfall index method was used to assess changes in rainfall over the years. This method has the advantage of highlighting wet and dry periods. For each of the rainfall stations selected, an interannual rainfall index was determined. It is defined as a reduced centred variable expressed by the equation:

$$I_i = \frac{X_i - \bar{X}}{S}, \quad (5)$$

X_i : annual rainfall value for year i

\bar{X} : interannual mean rainfall value over the period studied

S : interannual value of the standard deviation of rainfall over the period studied

In this study, the meteorological normal over the period 1981 to 2010 was used as the study period for the ERA5-Land data. However, for data from La Mé station, the entire 10-year series was used as the study period.

3.3. Characterisation of Extreme Rainfall

The return period is from a statistical point of view, the average duration of repeated events of the same intensity. The term is often used to characterise natural hazards such as earthquakes, floods, storms, wind speed, etc. In this work, Gumbel's law [41] was applied to daily rainfall amounts to characterise the return periods of extreme rainfall events in order to study the other parameters linked to this extreme rainfall. To sample the extreme rainfall, we used the Block Maxima Analysis (BMA) sampling method. It involves defining blocks of n realisations of the random variable X and taking the maximum within each block. The vector of maxima Z thus obtained contains $l = p/n$ realisations of the random variable Z :

$$\begin{aligned} Z &= \{Z_1, \dots, Z_l\} \\ &= \left\{ \max(X_1, \dots, X_n), \max(X_{n+1}, \dots, X_{2n}), \dots, \max(X_{p-n+1}, \dots, X_p) \right\} \end{aligned} \quad (6)$$

Gumbel's law is an important law used in the frequency analysis of extreme values (floods, extreme rainfall, wave heights). It belongs to the family of exponential laws, but specialists also refer to it as the Generalized Law of Extreme Values (G. E. V.), of which it is a special case. The Gumbel distribution is a distribution with 2 parameters a and b , both of the same dimension as x . It is defined for any value of x by its distribution function $F(x, a, b)$:

$$F(x) = \exp\left(-\exp\left(-\frac{x-a}{b}\right)\right), \quad (7)$$

Fitting consists of finding the parameters of a mathematical function so that it corresponds as closely as possible to an experimental curve. There are various methods of fitting: the graphical method (fitting by eye or using statistical regression), the method of moments, the method of maximum likelihood, etc. Although graphical fitting is an approximate method, it has the great advantage of providing a visual representation of the data and the fit. This is an essential aspect of the

judgement made on the adequacy between the law chosen and the data processed, whatever the fitting method used. It should be noted, however, that if only one point in the data is significantly offset from the others, the graphical method is difficult to use.

Graphical method (adjustment by eye or using statistical regression). It consists of making a judicious change of variables to reduce the adjustment to a simple linear regression, which is possible with Gumbel's law. We show that:

$$u = -\ln(-\ln(F(x))) \Leftrightarrow u = (X - a)/b, X = b \cdot u + a, \quad (8)$$

u Gumbel variable and $F(x)$ the probability of not exceeding. Essentially, therefore, it is a question of estimating the probability of not exceeding $F(x)$, which should be assigned to each x value. There are many formulas for estimating the distribution function using the empirical distribution. They are all based on sorting the series by increasing values, so that each value is assigned its rank i . Simulations have shown that for Gumbel's distribution, it makes sense to use Hazen's empirical distribution [41]:

$$F(x) = \frac{i - 0.5}{n}, \quad (9)$$

where i is the rank occupied by observation x and n is the size of the sample under consideration. a and b then represent, respectively, the y -intercept and the slope of the regression line adjusted by the least square's method. The return period is therefore given by the following relationship:

$$T = \frac{1}{1 - F(x)}, \quad (10)$$

The De Martonne aridity index is used in this study to determine how wet a month is during the course of a year. De Martonne's aridity index [42], denoted I_m is a parameter that can be used to distinguish between months considered to be dry and those considered to be wet during a given period. For a given month characterised by precipitation and average temperatures P (mm) and T ($^{\circ}$ C), respectively, De Martonne's aridity index is given by the following formula:

$$I_m = \frac{12 * P}{T + 10}, \quad (11)$$

Rainfall is multiplied by 12 to obtain an index value comparable to that of the annual index. These indices express drought but do not indicate when a month is really dry. Aridity increases as the value of the index decreases. At global level, De Martonne proposed six major types of macroclimate, ranging from arid desert zones ($I < 5$) to humid zones ($I > 40$) [43].

4. Results and Discussion

4.1. Results

4.1.1. Seasonal and Interannual Rainfall Variability

Rainfall at Bingerville station is marked by remarkable interannual variability,

with a succession of dry (rainfall amount under the normal) and wet (rainfall amount over the normal) periods. The first decade, from 1981 to 1990, was relatively wet, with slight deficits in 1983, 1986 and 1990. From 1991 onwards, there was a long dry period spanning two decades, with a few surpluses in 1991, 1996, 1999, 2009 and 2010. The following decade, from 2011 to 2020, saw a great inter-annual variability in rainfall. With an average annual rainfall of 1779 mm, compared with 1709 mm and 1685 mm for the previous decades of 1991-2000 and 2001-2010 respectively. It is relatively wetter than the two previous decades, highlighting an increase in rainfall in the period from 2011 to 2020 (**Table 1**). During the decade 2011-2020, Bingerville has experienced dry years such as 2011, 2012, 2013, 2015, 2017 and 2020 (dry years), as well as wet years such as 2015, 2017, 2018 and 2019 (wet years). Also marked by strong interannual variability, La Mé station has experienced dry years such as 2012, 2013, 2015, 2016 and 2018, as well as wet years such as 2010, 2011, 2014, 2017 and a period from 2019 to 2022.

Table 1. Average annual rainfall over the different decades from 1981 to 2020 in Bingerville.

Decade	Annual average (mm)
1981-1990	2006
1991-2000	1709
2001-2010	1685
2011-2020	1779
Climate normals (1981-2010)	1800

There are two main rainy seasons in Bingerville: the rainy season and the dry season. The rainy season generally begins in April and ends in November. There are two peaks one in June and the second in October (the June peak is higher than the October peak), with a break in August. The dry season begins in December, coinciding with the onset of the harmattan and ends in March. **Figure 2** shows the monthly rainfall at Bingerville for the periods 1981 to 1990, 1991 to 2000, 2001 to 2010, 2011 to 2020 and La Mé station for the period 2011 to 2022. The first decade (1981-1990) was a surplus decade, with monthly rainfall amounts higher than those of the monthly climate normal, except for the rainfall amounts in February and November, which were very close to those of the climatic normal. During the second decade (1991-2000) in Bingerville, monthly rainfall amounts were relatively close to normal monthly amounts for all months except August and September. The rainfall amounts in August and September were fairly low compared with the climatic normal, with a difference of 20 mm and 40 mm respectively.

The following decade (2001-2010), the one with the most deficits, saw a fall in the amount of monthly rainfall compared with the climate normal in general. We noted that may, September and October, they all received slightly more rain than normal. Contrary to over months which had a negative anomaly, the lowest being march with a rainfall value of -25.6 mm. The month with the highest anomaly is September, with a rainfall value of 7 mm.

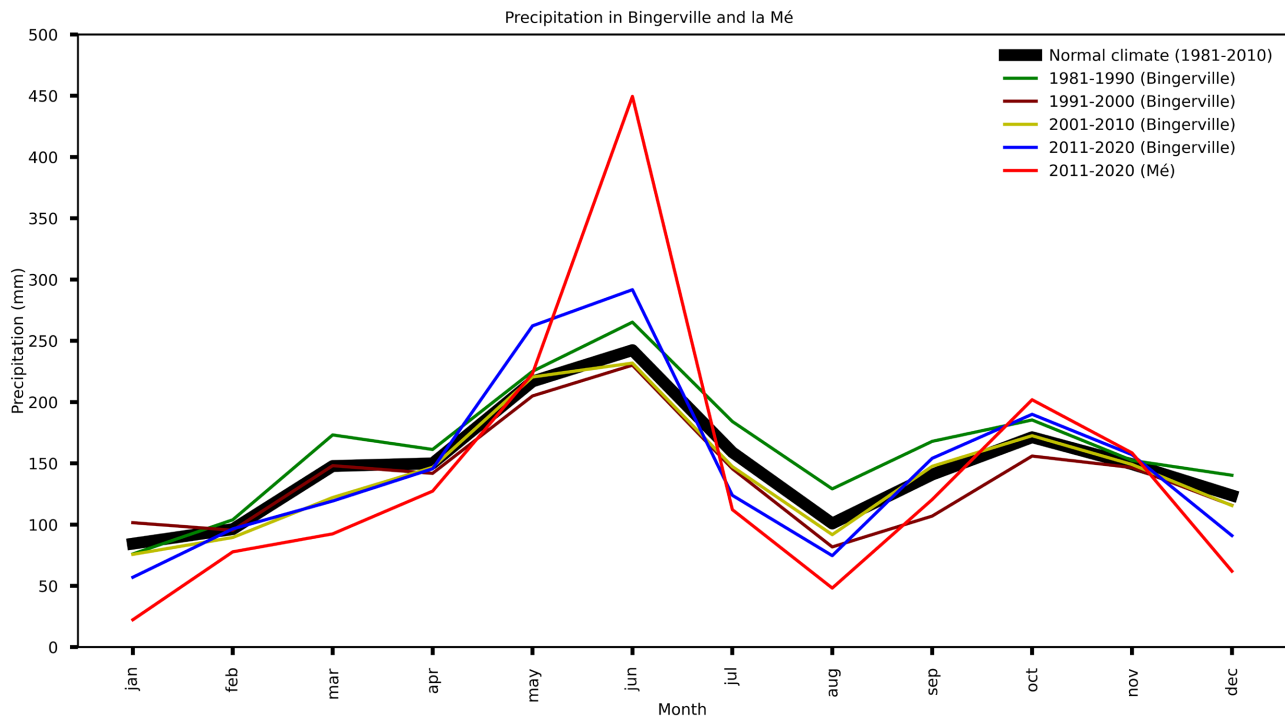


Figure 2. Rainfall seasonal mean averaged other different decades at Bingerville and La Mé.

Monthly rainfall amounts over the last decade (2011-2020) are relatively lower than normal monthly amounts during the dry season and higher during the wet seasons, with the exception of august. Monthly rainfall for the May-June-July period of this decade is the highest, with a cumulative total of 677.8 mm compared with 615.3 mm for the climatic normal. For the September-October-November period, the cumulative rainfall was 501 mm compared with 461.8 mm. This shows that despite the fact that this decade was slightly deficient (**Table 1**), the rainy season was very wet.

La Mé station also has two major seasons: the rainy season and the dry season. These two seasons have the same temporary characteristics, *i.e.* the start of the dry season in December, its end in March and then the rainy season which begins in April and ends in November, with peaks also in June and October, and a decrease in august (**Figure 2**). In terms of rainfall, La Mé decade received less rain than the Bingerville decade (1695.63 mm for the Mé and 1779 mm for Bingerville: annual average). In fact, the dry season at La Mé station was less wet than that of Bingerville over the period from 2011 to 2020. For the rainy season, only the months of June and October at La Mé station were wetter than those in Bingerville.

4.1.2. Return Frequencies of Exceptional Rainfall Events

The Gumbel variable and the return period are shown respectively in **Figure 3(a)** and **Figure 3(b)**. Referring to the international classification of extreme events [44], **Figure 3(b)** shows that daily rainfall amount of 98 mm, 103 mm and 132 mm respectively represent the thresholds for abnormal (6-year return period), very abnormal (10-year return period) and exceptional (30-year return period)

events. **Table 2** shows some extreme daily rainfall events with their return periods. For instance, the rainfall of 14 May 2014, with a rainfall amount of 138.1 mm, was exceptional, meaning that it had a 1 over 30 chance or a 3.33% probability of occurring. There were also some very abnormal rainfalls (return period about 10 years), including the rains of 3 October 2011, 15 July 1996 and 18 August 1987, with rainfall of 103.2 mm, 108.9 mm and 131.3 mm respectively. Daily rainfall on 10 October 1984 and 16 June 2016 are abnormal, with rainfall amounts of 99.7 mm and 102.7 mm respectively. These abnormal rainfall events have a return period of more than 5 years, *i.e.* a probability of 20%.

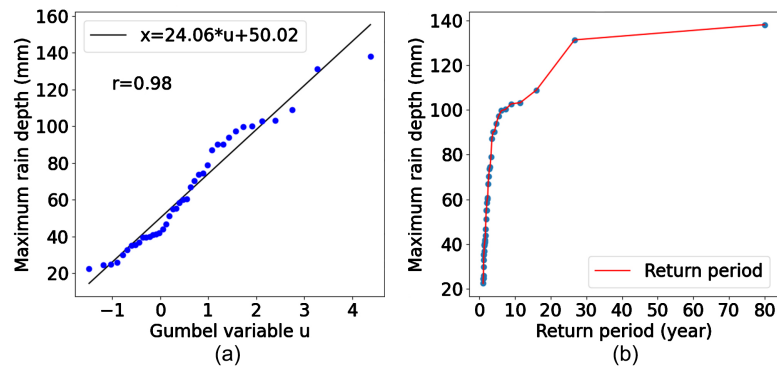


Figure 3. Linear regression line and rainfall return period at Bingerville.

Table 2. Return frequency of maximum daily rainfall at Bingerville.

Date	Quantity (mm)	Return period (year)	Qualification
10 October 1984	102.7	8.89	Abnormal
18 August 1987	131.3	26.66	Very abnormal
15 July 1996	108.9	16	Very abnormal
13 October 2011	103.2	11.43	Very abnormal
9 May 2014	138.1	80	Exceptional
14 June 2016	99.7	6.15	Abnormal

4.1.3. Analysis of Seasonal Rainfall Variability in Wet and Dry Years

During the period from 2010 to 2019, La Mé station experienced interannual variability in rainfall. There were five years with rainfall over the normal. We refer to as wet_year, including 2010, 2011, 2014, 2017 and 2019, and five years with rainfall less than normal we refer as dry_year, such as 2012, 2013, 2015, 2016 and 2018. **Figure 4** shows the variability of rainfall in wet_years **Figures 4(a)-(e)** and dry_years **Figures 4(f)-(j)**. It is arranged from left to right show the least wet to wettest years and least dry to driest. It can be seen that the rainy season in wet years at La Mé station generally begins in April and ends in November, with a marked break in August. In dry years, however, the rainy season starts in May. There is therefore a delay in the rainy season in dry years.

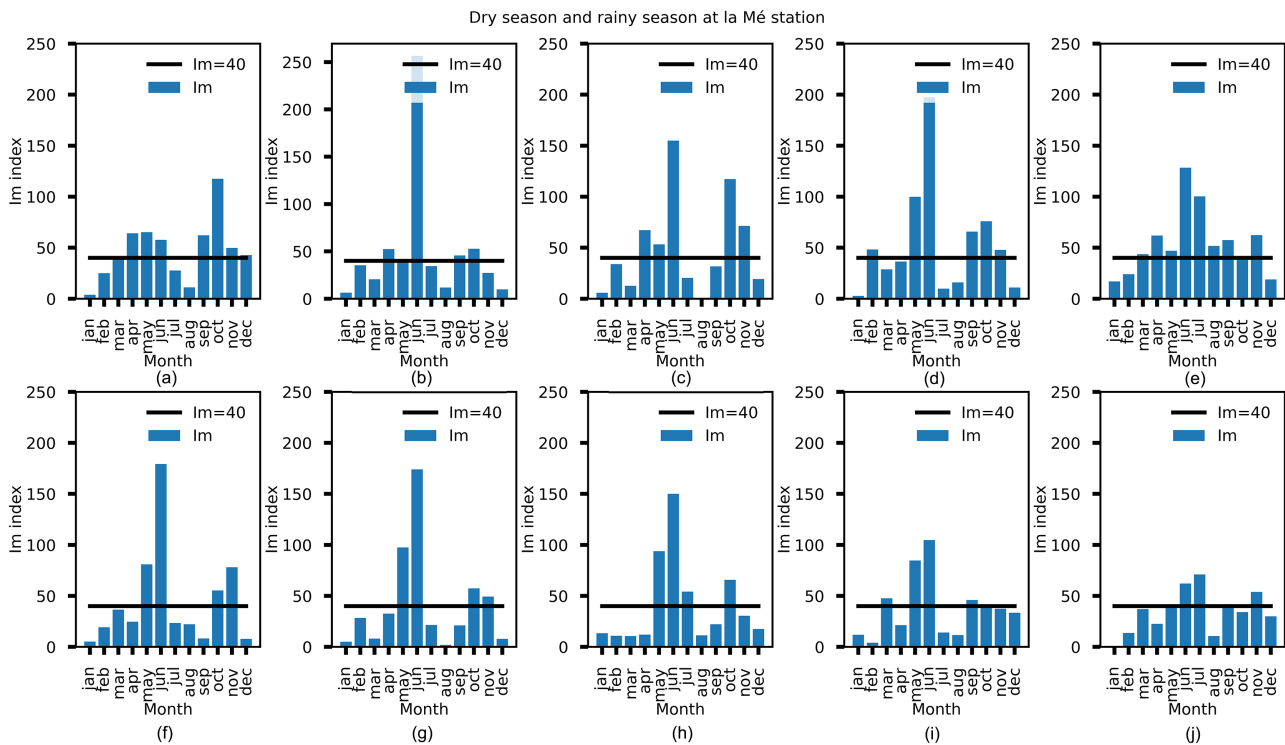


Figure 4. Rainy season in wet and dry years at La Mé. (a) Wet year 2019; (b) Wet year 2014; (c) Wet year 2017; (d) Wet year 2011; (e) Wet year 2010; (f) Dry year 2015; (g) Dry year 2012; (h) Dry year 2018; (i) Dry year 2016; (j) Dry year 2013.

As La Mé station, Bingerville has experienced interannual variability in rainfall from 2010 to 2019. There were five years with rainfall over the normal. We refer to as wet_year, including 2010, 2014, 2017, 2018 and 2019, and five years with rainfall less than normal we refer as dry_year, such as 2011, 2012, 2013, 2015 and 2016. **Figure 5** also shows the variability of rainfall in wet_years **Figures 5(a)-(e)** and dry_years **Figures 5(f)-(j)**. However, in Bingerville the data show that the rainy season begins in April and ends in November both in wet_years and dry_years.

4.1.4. Analysis of Temperature and Relative Humidity in Wet and Dry Years

Average monthly temperatures at La Mé station range from 25.4°C (august) to 28.9°C (march). In Bingerville, they range from 25.2°C (august) to 27.1°C (march). The maximum monthly averages over the period 2010 to 2019, in Bingerville as well as in La Mé station, are generally observed during March. Temperatures are high overall, but very little throughout the year. Temperatures in wet (**Figures 6(a)-(e)**) and dry (**Figures 6(f)-(j)**) years show no major distinction at Bingerville, unlike La Mé station (**Figures 7(a)-(j)**), which shows a slight rise in temperature in the dry season.

The data also show that La Mé station generally has a higher surface temperature than Bingerville station throughout the year and during period 2010-2019 this can be seen in **Figure 8** from panel **Figures 8(a)-(j)**. Also, the annual variability

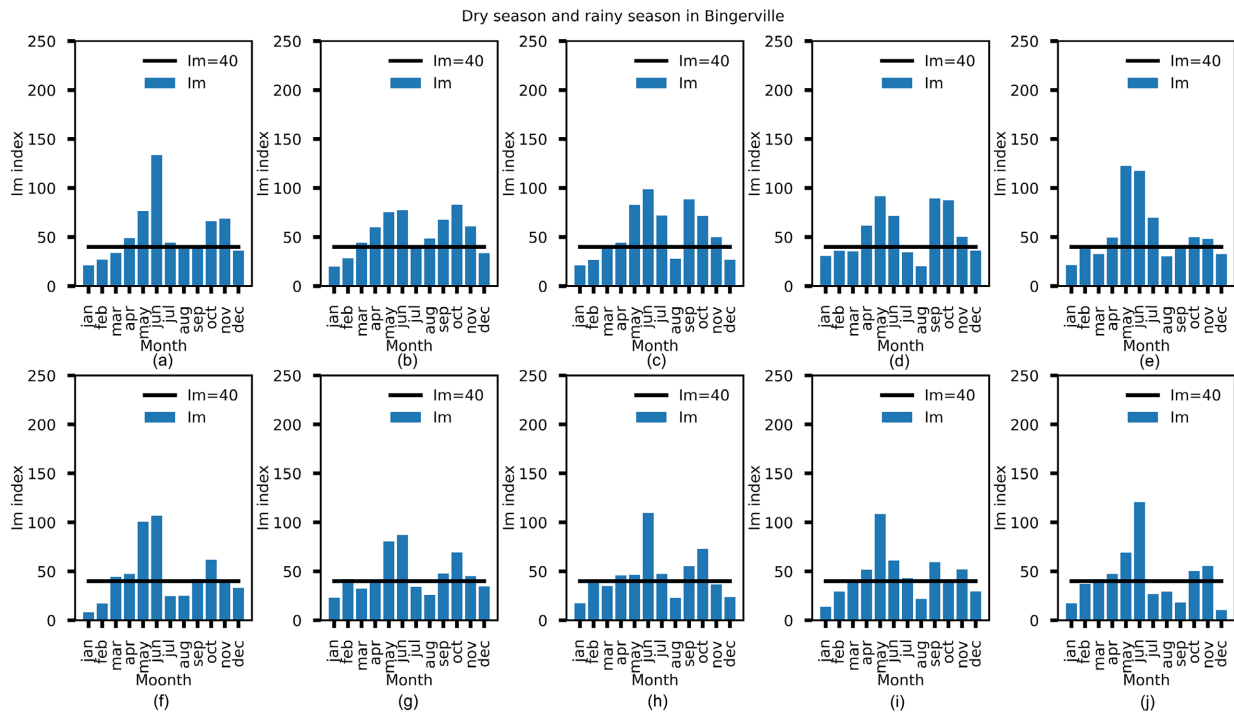


Figure 5. Rainy season in wet and dry years in Bingerville. (a) Wet year 2017; (b) Wet year 2010; (c) Wet year 2018; (d) Wet year 2019; (e) Wet year 2014; (f) Dry year 2016; (g) Dry year 2012; (h) Dry year 2011; (i) Dry year 2013; (j) Dry year 2015.

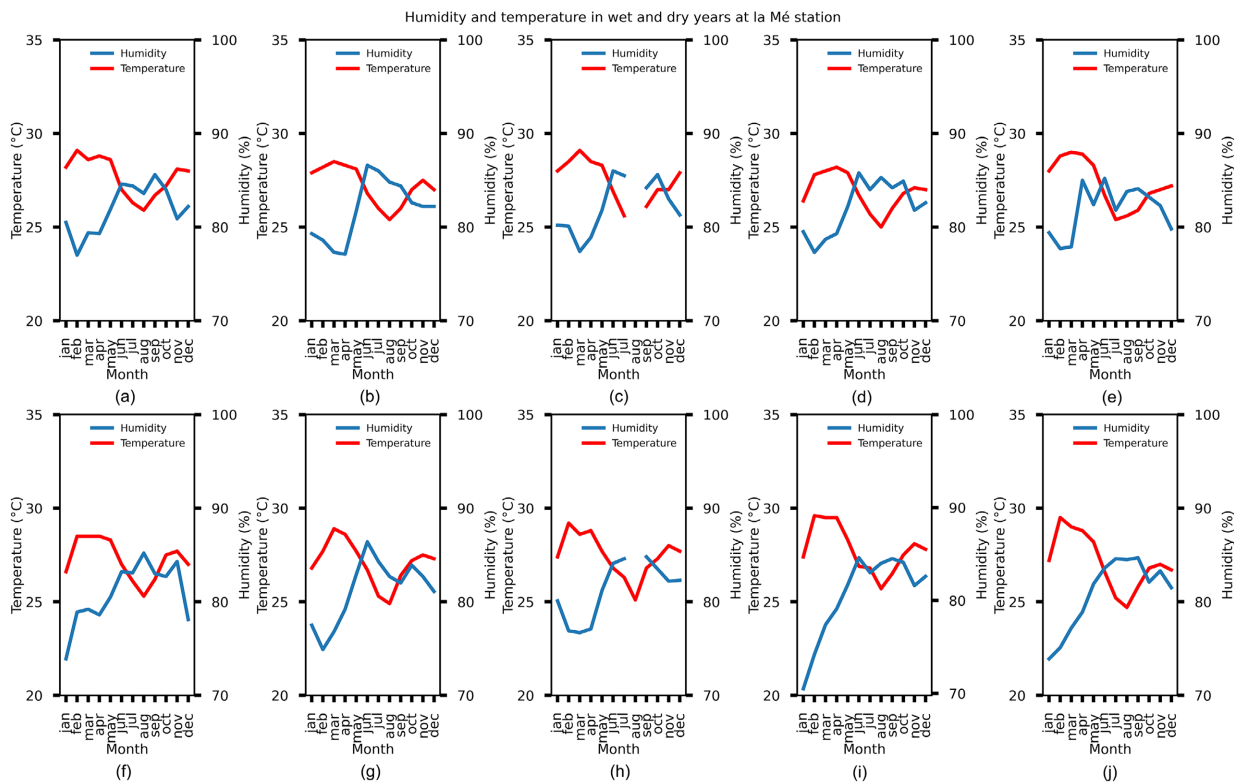


Figure 6. Seasonal variability of temperature and humidity in wet and dry years at La Mé. (a) Wet year 2019; (b) Wet year 2014; (c) Wet year 2017; (d) Wet year 2011; (e) Wet year 2010; (f) Dry year 2015; (g) Dry year 2012; (h) Dry year 2018; (i) Dry year 2016; (j) Dry year 2013.

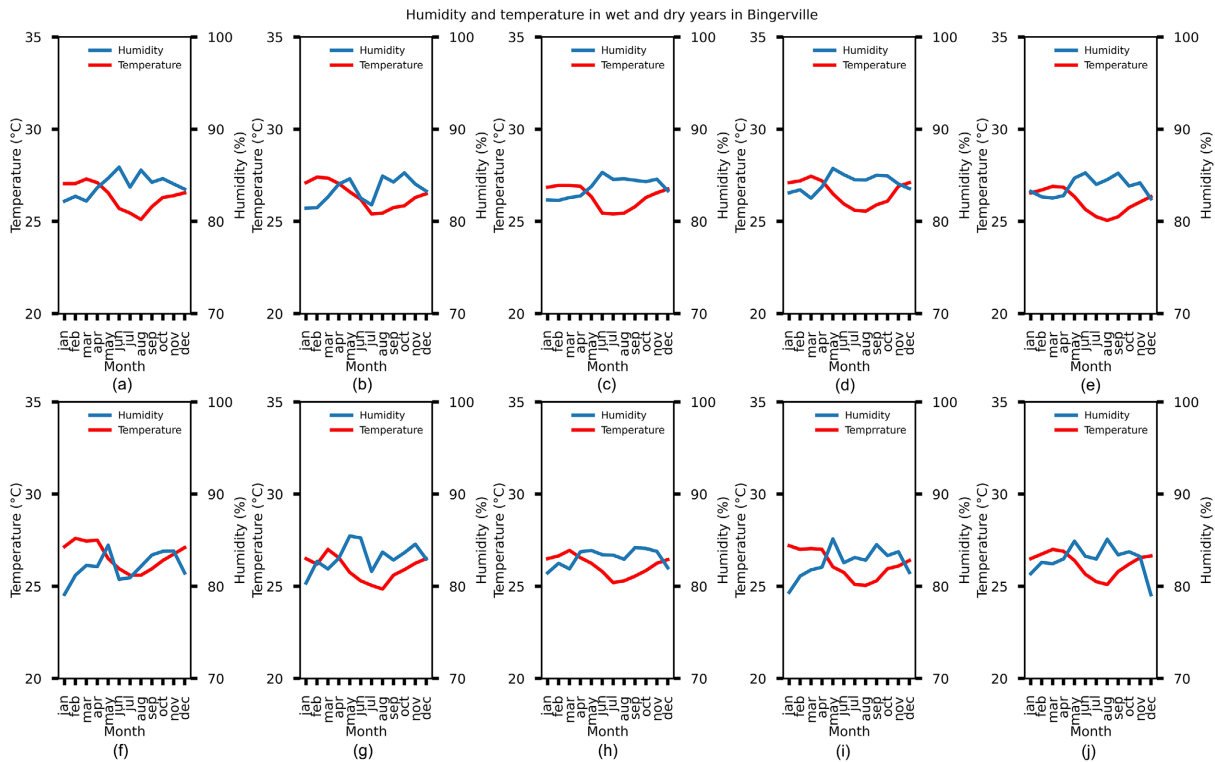


Figure 7. Seasonal variability of temperature and humidity in wet and dry years in Bingerville. (a) Wet year 2017; (b) Wet year 2010; (c) Wet year 2018; (d) Wet year 2019; (e) Wet year 2014; (f) Dry year 2016; (g) Dry year 2012; (h) Dry year 2011; (i) Dry year 2013; (j) Dry year 2015.

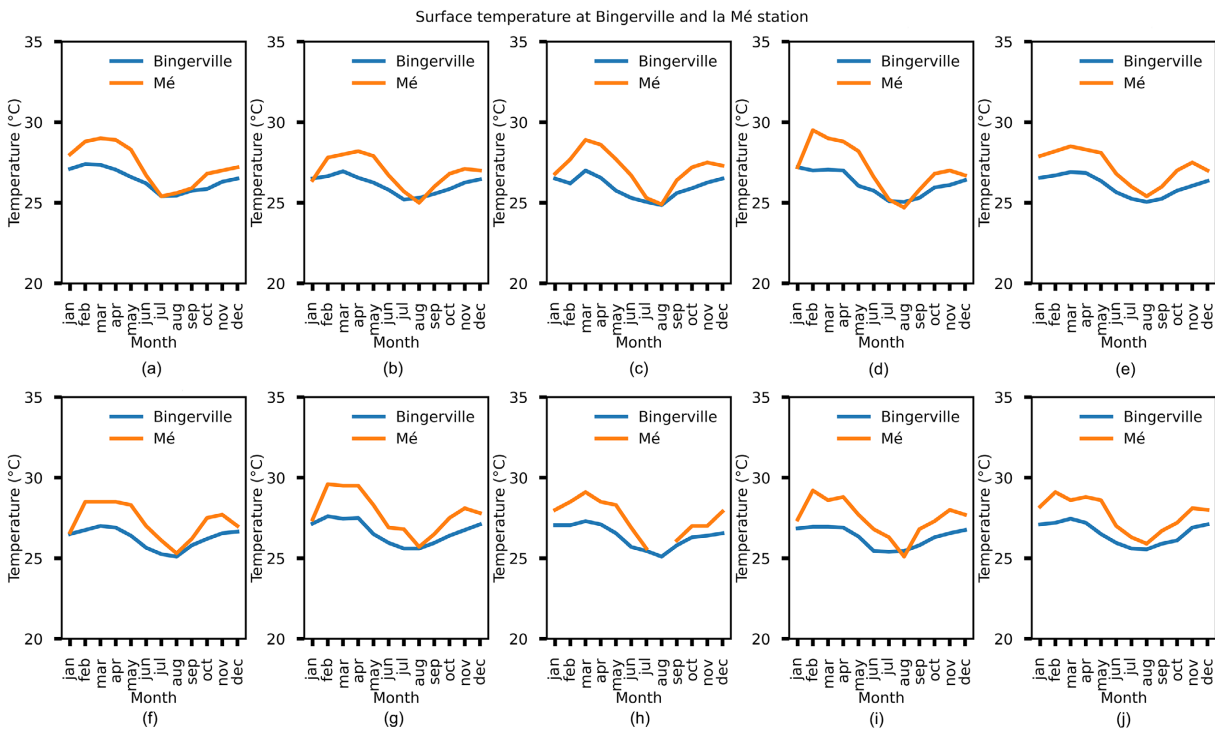


Figure 8. Seasonal temperature variability at Bingerville and La Mé station. (a) 2010; (b) 2011; (c) 2012; (d) 2013; (e) 2014; (f) 2015; (g) 2016; (h) 2017; (i) 2018; (j) 2019.

in the temperature cycle is more marked at La Mé than in Bingerville. When it comes to monthly relative humidity, for the same period 2010 to 2019 at Bingerville it varies between 81.4% in January and 84.8% in August. Over la Mé station, it ranges from 77.5% in January to 85.2% in August. We notice that relative humidity is in general above 70% and varies relatively widely throughout the year. However, the relative humidity in Bingerville is somewhat different from that of La Mé station. In fact, Bingerville records higher relative humidity values than those at La Mé station from January to May in most cases, except 2010 when the relative humidity at Bingerville is higher than at La Mé station from January to April. From June onwards, it can be seen that the monthly relative humidity is very close until December (Figures 9(a)-(j)). In terms of wet and dry years, there is quite remarkable seasonal variability in relative humidity. At La Mé station, wet years have higher relative humidity values than dry years, more specifically from January to April (Figure 9). On the other hand, at Bingerville, wet and dry years generally show fairly similar seasonal variations in humidity. However, the months of January and December in dry years have slightly lower relative humidity than January and December in wet years (relative humidity of January and December in wet years greater than 82%; relative humidity in dry years between 78% and 81%, except for December 2012 and 2011).

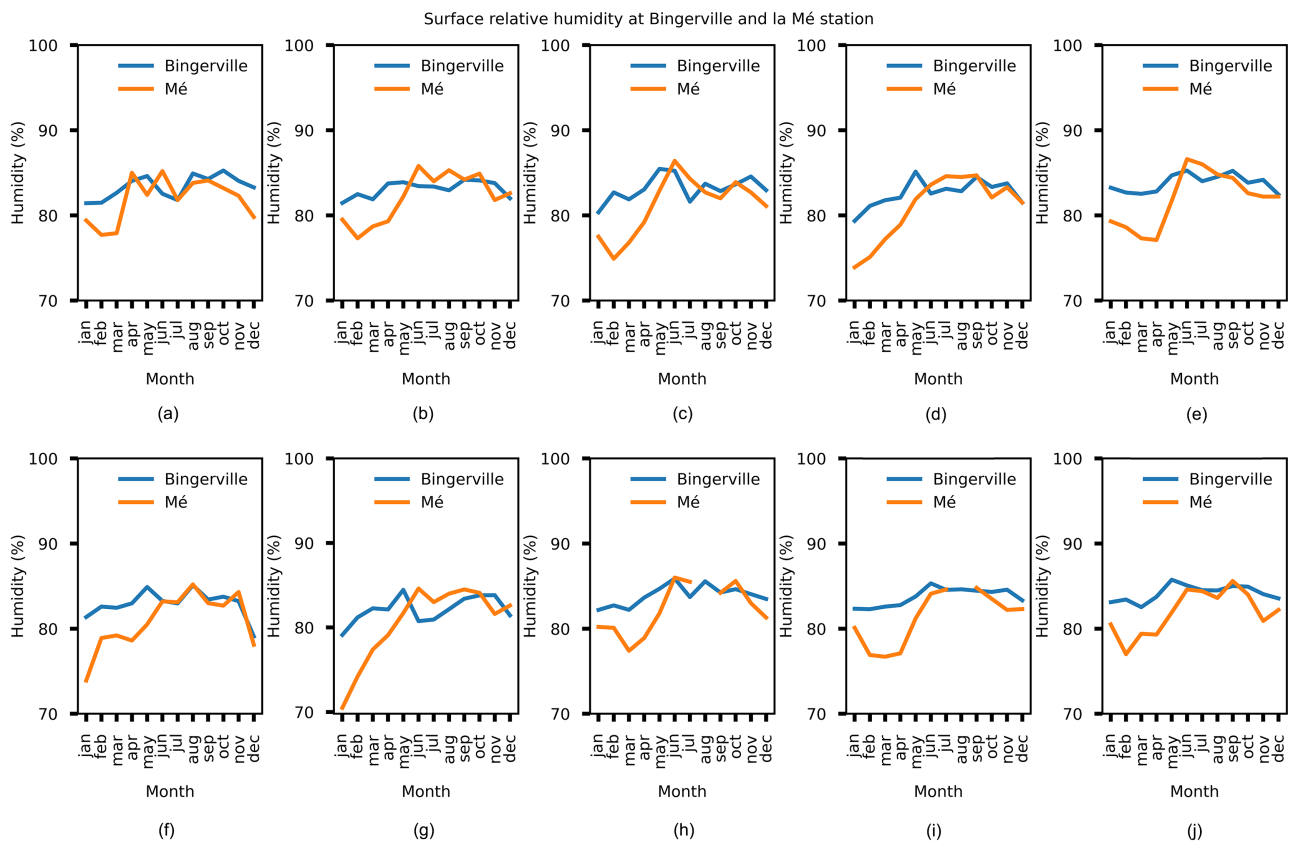


Figure 9. Seasonal relative humidity variability observed in Bingerville and La Mé station. (a) 2010; (b) 2011; (c) 2012; (d) 2013; (e) 2014; (f) 2015; (g) 2016; (h) 2017; (i) 2018; (j) 2019.

4.1.5. Analysis of Winds in Wet and Dry Years

Focus is made on two periods of the year December, January, February and March (DJFM) we refer to as dry season and April, may, June and July (AMJJ) we refer to as wet season. Then based on the previous defined wet_years and dry_years the winds have been characterised throughout the wind rose. Thus, the wind rose for Bingerville (not shown in this paper) shows that over the period 2010-2019, the winds blowing in this area are predominantly southwesterlies. In fact, more than 80% of the winds blow almost all year (in both the DJFM and AMJJ) in this direction. However, these winds decrease in intensity during DJFM (fewer light breezes: moderate winds). At La Mé station, the winds are fairly varied. Winds come from several directions throughout the year and some are very low. On average, La Mé station records almost 59.8% monsoon winds, around 11.1% calm winds and 30.1% harmattan winds during DJFM (Figure 10, from panel Figures 10(a)-(j)) followed by 49.7% monsoon winds in AMJJ (Figure 11, from panel Figures 11(a)-(j)), 15.4% calm winds and 34.9% harmattan winds, showing a decrease in monsoon winds in the dry season. Winds in wet and dry years at Bingerville and at La Mé station do not show any significant particularities in terms of speed or direction.

4.2. Discussion

This study highlights the interannual variability of rainfall in Bingerville and La Mé. The results show that there are strong interannual variability in rainfall in Bingerville and La Mé, as well as a succession of dry and wet periods. Bingerville experienced significant dry spells over two decades, from 1991 to 2010. These dry

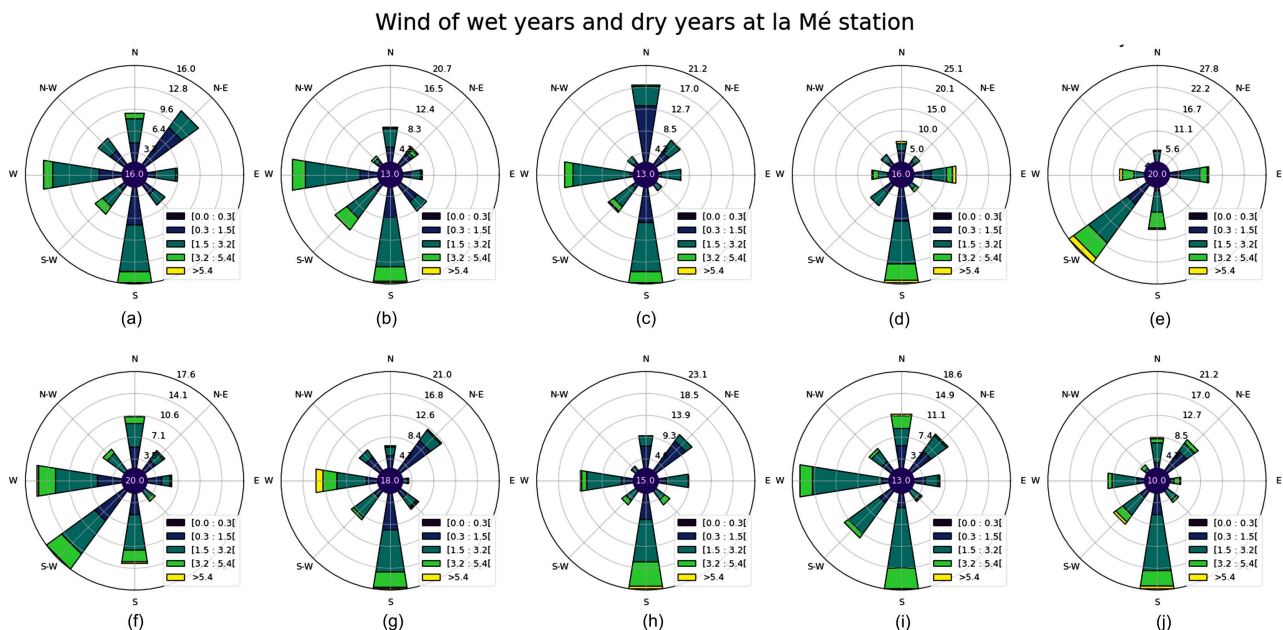


Figure 10. Wind rose of wet and dry year from December to March at La Mé station. (a) Wet year: DJFM 2019; (b) Wet year: DJFM 2014; (c) Wet year: DJFM 2017; (d) Wet year: DJFM 2011; (e) Wet year: DJFM 2010; (f) Dry year: DJFM 2015; (g) Dry year: DJFM 2012; (h) Dry year: DJFM 2018; (i) Dry year: DJFM 2016; (j) Dry year: DJFM 2013.

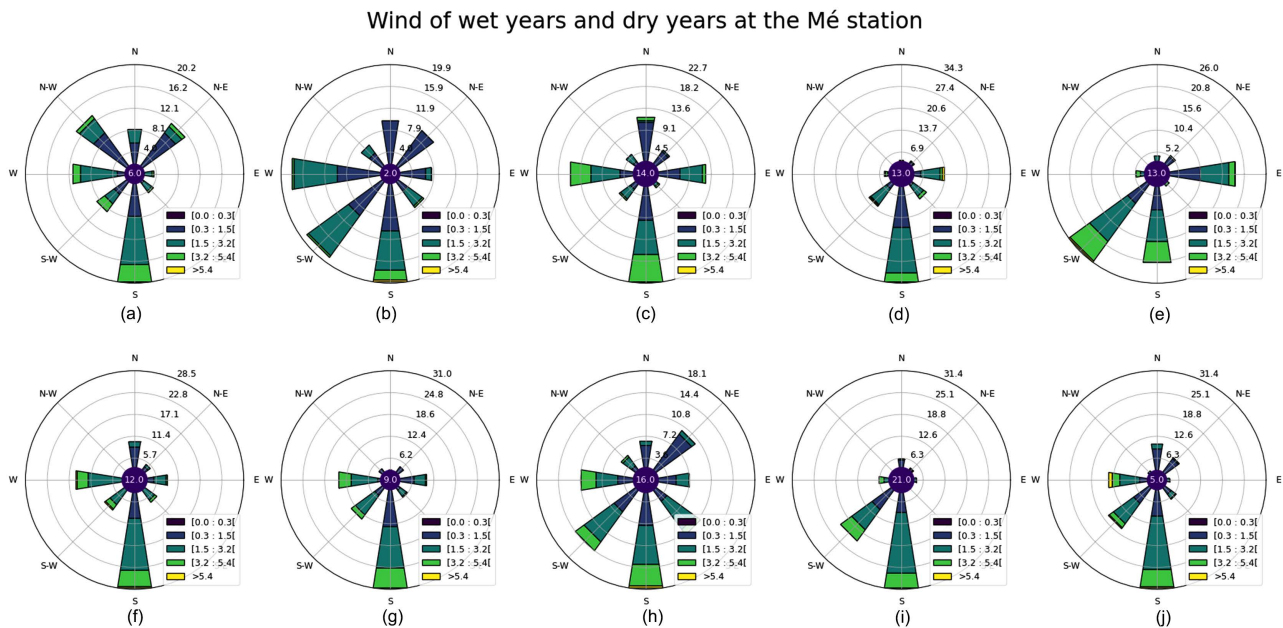


Figure 11. Wind rose of wet and dry year from April to July at La Mé station. (a) Wet year: AMJJ 2019; (b) Wet year: AMJJ 2014; (c) Wet year: AMJJ 2017; (d) Wet year: AMJJ 2011; (e) Wet year: AMJJ 2010; (f) Dry year: AMJJ 2015; (g) Dry year: AMJJ 2012; (h) Dry year: AMJJ 2018; (i) Dry year: AMJJ 2016; (j) Dry year: AMJJ 2013.

periods can be interpreted as manifestations of the great drought that occurred in West Africa from the late 1960s and mid-1990s [45]-[48]. This rainfall deficit has also been highlighted in Côte d'Ivoire by a number of authors [49] [50]. For the decade from 2011 to 2019, there will be alternating dry and wet years. This succession of dry and wet years can be observed in some regions and is marked by extreme daily rainfall events such as abnormal rainfall events on 13 October 2013 and 14 June 2016, exceptional rainfall events on 14 May 2014, showing a slight upturn in rainfall during this decade. It is mainly accompanied with flooding which cause many losses and damages in Abidjan and surrounding. This finding agrees with the research done by Kouame *et al.* [51] and Dos Santos *et al.* [52] who found an increase in flooding events over the past two decades in Abidjan. According to them floods have increased since 2009, with a high death toll, with an estimated average of 13 deaths each year, and affecting also many other cities. In La Mé region, the exceptional rainfall events can affect the agriculture by exacerbating erosion phenomenon with the loss of crops nutrients in the soil, this could lead to soil impoverishment. It could also lead to an increase of post-harvest losses. According to Kpanou *et al.* [53] in the rural zone, flooding caused by extreme rainfall disrupts agricultural activities and is liable to the destruction of crops. As for the characterisation of meteorological parameters in Bingerville and La Mé, the results showed that the monthly temperatures in La Mé are higher than those in Bingerville but have lower relative humidity values, particularly in DJFM. As far as it concerns the surface wind, the results also show that the winds in Bingerville are more intense than those in La Mé, these winds are specifically southwesterlies which are the monsoon winds (50% to 60% of winds) blowing throughout

the year toward the land therefore at the two localities. This finding is consistent with those of Coulibaly *et al.* [54] who found that southwesterly monsoon winds are dominant for the entire day all year round in the coastal zones. However, the sea breeze can be stronger in Bingerville than La Mé based on the latitudinal position of the two localities in relation to the sea in the southern part of Côte d'Ivoire. The gradient of penetration over land is affected by many constraints. The behaviour of these winds in the two regions could be influenced by local factors. Vautard *et al.* [55] recently analysed meteorological data measuring surface winds, confirming a slowing trend in the northern hemisphere. It seems that, to a certain extent, forests can slow down winds, and desertification can exacerbate them. Where forests have regained ground, wind strength decreases (by 5% to 15%) the stronger the wind. This may therefore explain the drop in the intensity of monsoon winds. Also, the behaviour of these winds in the two regions may be caused by the latitudinal position of these two regions. Consequently, this reduction in monsoon winds in La Mé favours a reduction in relative humidity and an increase in temperature. Probably, the harmattan wind, being hot and dry, reduces relative humidity in La Mé and increases its temperature. This shows the impact of the monsoon wind on temperature and relative humidity in our area. Thus, the decrease in relative humidity and the increase in temperature favour a fall in rainfall, more generally in the period from December to March. In terms of wet and dry years, La Mé is marked by a particular variation in temperature, the start of the rainy season and relative humidity. In fact, the dry seasons during the dry years in this region have higher temperatures than the wet years but lower relative humidity values. The rainy seasons in dry years also lag behind those in wet years.

5. Conclusion

This study shows that over the last forty years, Bingerville has experienced considerable climatic variability, with a succession of consecutive dry years and consecutive wet years. Analysis of the time series at measurement points shows that rainfall in Bingerville experienced a long period of drought from 1991 to 2010 and a slight upturn over the decade 2010-2019. This is characterised by the recurrence of the abnormal rainfall events causing more flooding in the southern area. Inter-seasonal analysis of climatic parameters in Bingerville and La Mé also shows that temperature monthly mean and relative humidity monthly mean show similar trends, but are skewed more precisely towards the January-March period in general. As far as winds are concerned, Bingerville is dominated by monsoon winds throughout the year, unlike the winds in La Mé, which are made up of monsoon and harmattan winds, which can be explained by local factors in the region that can influence the climate in this zone. La Mé is marked by specific variations in temperature, rainy season and relative humidity. In fact, the dry season in dry years in this region has higher temperatures than wet years, but relative humidity values decrease. The rainy season in dry years starts late contrary to the rainy season in wet years where we noticed an early rainfall. The results of this study

provide an important database for assessing both climate risks and vulnerability to climate change. In this context, observation systems need to be improved and strengthened in order to obtain reliable and sufficient data to better characterise climate change and make accurate forecasts that will help us to better adapt to the likely adverse effects of climate change.

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Conflicts of Interest

The authors declare no conflicts of interest.

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