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RESEARCH

Variability and trends of the rainy season in West Africa with a special focus on Guinea-Bissau

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Abstract

This study provides a novel assessment of trends in rainy season behavior (1981–2020) in West Africa by analyzing high-resolution rainfall data from CHIRPS 2.0. Additionally, it presents the first comprehensive study of rainy season characteristics in Guinea-Bissau, based on an analysis of the country's available observational data, over the same period. The agronomic method was used to determine the rainfall onset, while the soil water balance was used to calculate the cessation of the rainy season. The findings indicate that the onset of the rainy season in West Africa progresses from south to north, beginning around 8°N in May and advancing to approximately 16°N by July and early August. The cessation of the rainy season follows an opposite, north-to-south trajectory, typically starting at 16°N in late September or early October and reaching 8°N by November and early December. This regional pattern is associated with the seasonal movements of the Intertropical Front. From 1981 to 2020, the onset, cessation, and duration of the rainy season in West Africa have exhibited significant variability. Although statistically significant trends are limited, these shifts still affect agricultural planning and crop planting schedules, underscoring the importance of continuous monitoring. The standard deviation in the onset of the rainy season ranges from 4 to 55 days, while the cessation shows less variability, spanning between 3 and 21 days. Meanwhile, the number of rainy days varies from 52 in the northern part of the study area to over 200 days in the southern regions. In Guinea-Bissau, rains typically start between 15–30 June each year, with notable differences between the northern and southern parts of the country. The average cessation occurs between the first and second weeks of November. Evolutionary trends suggest a slightly delayed onset of rainfall, with more stability in the cessation dates, leading to a slight reduction in the length of the rainy season.

1 Introduction

Ensuring global food security was one of the Sustainable Development Goals adopted by the United Nations (UN) in 2015. In this context, food production is under increasing pressure worldwide (FAO et al. 2023), particularly as the rain-fed agriculture practised by a large proportion of the population in West Africa faces significant challenges. This situation necessitates adaptation and mitigation measures to address the climate extremes that affect agricultural production (Agoungbome et al. 2023). Fluctuations in summer monsoon rainfall have substantial socio-economic consequences in Sub-Saharan Africa (Dombo et al. 2024). In this region, understanding the start and end dates of the rainy season, as well as its duration, is crucial for agricultural planning and the successful cultivation of staple cereals in many countries. (Akinseye et al. 2016; Laux et al. 2008) The uncertainty surrounding agricultural scheduling is heightened by the pronounced interannual variability of precipitation (Hippolyte et al. 2022; Mosunmola et al. 2020; Odenkunle 2004). Therefore, the proposal of an agricultural calendar based on determining the onset of the rainy season in different agricultural zones is a highly relevant approach, as it provides farmers with guidance for planning their activities throughout the agricultural season. For instance, sowing immediately after prolonged dry periods can disrupt seed germination and lead to the need for replanting, while water deficits during the flowering stage can severely reduce crop yields (Benoit 1977; Ndomba 2010). In response to issues

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surrounding the start of the rainy season and to support farmers in decision-making, various methods and criteria have been developed by researchers from different regions. These methods predominantly rely on daily rainfall data or soil variables (Odenkunle 2004; Roffe et al., 2020).

In West Africa, particularly in the Sahelian and Sudanian zones, the precipitation regime is unimodal, with a strong north–south gradient of increase in mean annual amount. Rainfall ranges from 150–600 mm in the Sahelian zone and 600–1200 mm in the Sudanian zone, which are below the typical range of 1200–2200 mm recorded in the Guinean zone (CILSS 2016; Nicholson 2013). The variations of the seasonal cycle of the general atmospheric circulation are the most consistent factor in the interannual variability of precipitation (Laux et al. 2007). The rainfall regime in the region is influenced by two primary fronts: the continental tropical front ("from the north"), characterised by dry Harmattan winds, and the maritime tropical front ("from the south"), together forming the zone known as the Intertropical Front (ITF) (e.g. Avenard & Michel 1982; Hall & Peyrill 2014; Leroux 1988). This front plays a crucial role in the formation of mesoscale convective systems in West Africa (Vizy & Cook 2018).

The ITF is a key feature of atmospheric circulation in West Africa (Djossou et al. 2017), undergoing latitudinal shifts throughout the annual cycle. In January, when it reaches its southernmost position, its average location lies just north of Guinea- Conakry, stretching parallel to the coast of the Gulf of Guinea and curving southeast into Cameroon, reaching the Equator. By August, its average position shifts to around Nouakchott, orienting northeastward and reaching 20°N, south of Atar (Koumare 2014; Lucio et al. 2012; Suraud 1954). Other factors influencing the activity of convective systems and the distribution of rainfall in the West African region are associated with the West African Westerly Jet (WAWJ), which brings in monsoonal flows carrying moisture from the tropical eastern Atlantic to the Sahelian region of West Africa during the rainy season (Pu & Cook 2010). Rainfall variability is also influenced by the activity of African easterly waves (AEWs) and large mesoscale convective systems (MCS) (Nicholson 2013), as well as by sea surface temperature (SST) variations in the Atlantic and the El Niño-Southern Oscillation (ENSO) (Koumare 2014).

According to Djossou et al. (2017), the onset of the rainy season in a given area typically occurs when the Intertropical Front (ITF) is located more than 400 km to the north. Monitoring the northward movement and position of the ITF across West Africa is therefore one of the most crucial elements for predicting the arrival of the rainy season in this region. An early onset of the rainy season is linked to stronger and earlier moisture transport northwards across West Africa, highlighting the significance of this factor in triggering the rainy season (Faye et al. 2023). Conversely, in West Africa, a delayed onset of the rainy season in a particular region can be attributed to latitudinal shifts in the ITF's position, with its northward movement being postponed (Benoit 1977; Lélé & Lamb 2010; Mensah et al. 2016). Similarly, an early end to the rainy season is associated with the ITF's rapid southward retreat after reaching its maximum latitude (Odenkunle 2004).

Among the criteria used to calculate the onset of the rainy season, based on daily rainfall records, notable approaches include: the agronomic criterion, which defines the onset of the rainy season based on a certain amount of rainfall recorded over consecutive days (e.g. Sivakumar 1988; Stern 1981); the climatic criterion, which is based on the occurrence of significant rainfall (> 1 mm) at 80% of stations within a 300 km radius (Balme et al. 2005; Djossou et al. 2017); and the hydrological criterion, which determines the start of the rainy season from the first rainfall event exceeding a specified threshold (0.5 mm, 2.5 mm, or 5 mm) (Balme et al. 2005). In the agronomic criterion, an additional qualifying condition is often applied to prevent false starts to the rainy season, such as ensuring that no dry spell of a specific duration occurs after the rainy season has begun.

Other criteria include those proposed by Hippolyte et al. (2022), Ndomba (2010), and Odenkunle (2004), who define the start of the rainy season as the date when 7–8% of the total annual rainfall has been accumulated. Similarly, Chukwudi et al. (2017) in Nigeria use a threshold of 51 mm to define the onset of the rainy season. Benoit (1977) proposed a criterion based on the soil water balance, where the rainy season begins when precipitation equals or exceeds half of the potential evapotranspiration (ET), provided there is no dry spell longer than five consecutive days after this date. Ilunga & Mugiraneza (2006) also base their criterion on the relationship between rainfall and potential evapotranspiration (ET), considering the start of sowing to occur when rainfall exceeds ET, with no dry spell longer than five days, as this period is critical for seed germination.

In West Africa, most studies on the onset of the rainy season have been based on agronomic criteria, with slight variations in the rainfall thresholds recorded over a given period (e.g. Agoungbome et al. 2023; Balme et al. 2005; Descroix et al. 2015; Dodd & Jolliffe 2001; Marteau et al. 2009, 2010; Mensah et al. 2016; Sivakumar 1988, 1991; Stern 1981). In this study, the agronomic method mentioned above was chosen to determine the onset date of the rainy season, due to its proven effectiveness in West Africa and its ease of application.

The objectives of this paper are: 1) to analyse long-term trends and variability in the onset, cessation, and duration of the rainy season across West Africa using high-resolution CHIRPS 2.0 data (1981–2020); 2) Conduct a detailed assessment of rainy season characteristics in Guinea-Bissau based on available observational data to identify specific patterns and variability over the same period; 3) ultimately providing insights into seasonal rainfall changes to help farmers and policymakers optimise crop selection, planting schedules, and risk management strategies.

2 Data and Methods

2.1 Study area

This study focuses on the regions located between latitudes 8°N—16°N and longitudes 17°W—0°W, covering the Sahelian zone (approximately 12°− 16°N) and the Sudanian zone (approximately 8°− 12°N) of West Africa (Kouassi et al. 2010), encompassing the territories of the Republic of Guinea-Bissau (RGB), Senegal, The Gambia, southern and southwestern Mali, southernmost Mauritania, Burkina Faso, Guinea-Conakry, northern Sierra Leone, Côte d'Ivoire, and Ghana (Fig. 1, left). These territories are situated in a band within the intertropical zone, characterized by a unimodal rainfall regime (Liebmann et al. 2012), with the rainy season occurring mainly during the boreal summer, from May to November, depending on the specific regions.

The current research includes a case study focused on Guinea-Bissau, a country with a population of approximately two million people and an area of 37,500 km^2. The landscape is characterised by large estuaries, mangrove forests, and extensive rice fields. Guinea-Bissau has a tropical climate, classified as tropical savannah (Aw) according to the Köppen climate classification, with a rainy season during the summer and a dry season in the winter. The country's climatic conditions are highly favourable for rice cultivation, receiving an average of 1,500 to 2,500 mm of rainfall over a six-month period. As a low-income nation, rice is a staple of the population's diet and plays a vital role in food security. With an estimated per capita consumption of 125 kg per year, rice cultivation is crucial for both income generation and subsistence for a significant portion of the population (Mendes & Fragoso 2024).

2.2 Data

The sequence of procedures undertaken in this study, including the extraction, organisation, and statistical and graphical treatment of the data, is detailed in the next section.

2.2.1 CHIRPS (2.0) dataset

The CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) version 2.0 dataset (Funk et al. 2014) was used to conduct a regional analysis covering the study areas in West Africa (Fig. 1, left image). This dataset provides daily precipitation records by combining satellite estimates with ground-based observations from weather stations. The suitability of the CHIRPS 2.0 dataset for estimating daily rainfall over tropical African regions has been assessed in several studies (e.g., Nkunzimana et al., 2020; Mekonnen et al., 2023), demonstrating that it outperforms other similar satellite-observation blended datasets. The available data in NetCDF file format includes two spatial resolutions: 0.05° and 0.25° (latitude × longitude). Considering computational and storage constraints, the 0.25°

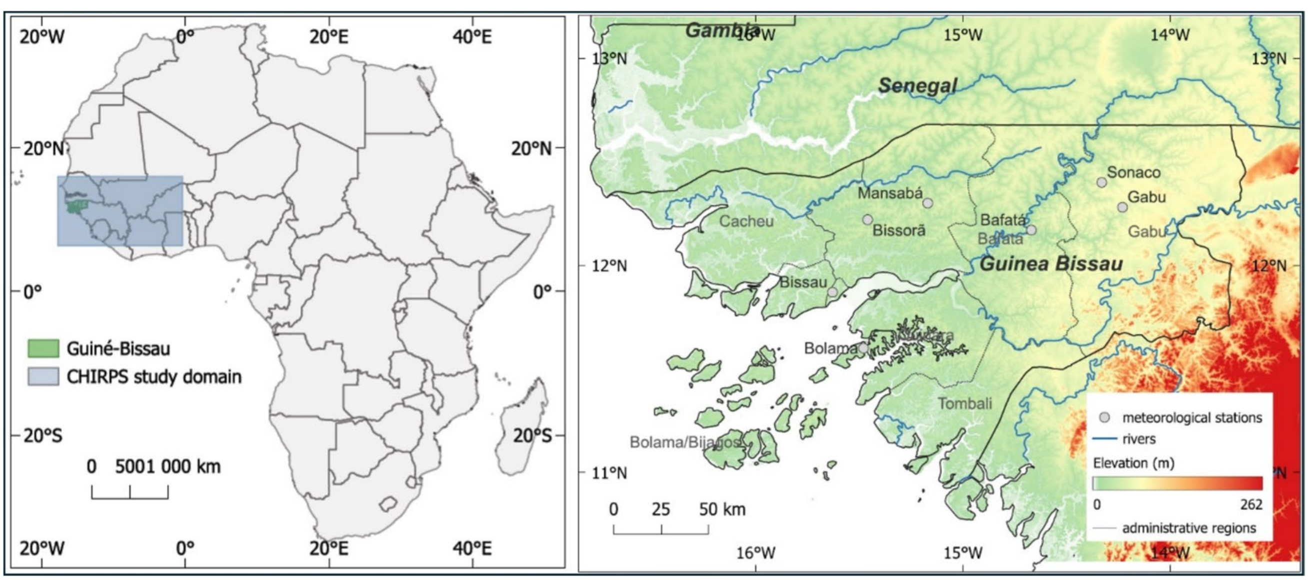

Fig. 1 Study area. Left map: West Africa, and domain of the CHIRPS 2.0 dataset used in the study);Right map: Guinea-Bissau territory and national meteorological stations used in the study

resolution was selected, as it remains a high-resolution dataset suitable for geospatial analysis of phenomena such as rainy season characteristics. Daily precipitation series were extracted for the West Africa domain shown in Fig. 1, enabling an assessment of long-term variability, particularly in terms of temporal variance and trends over the past 40 years (1981–2020).

2.2.2 Guinea-Bissau meteorological stations

The precipitation observation data used in this study was sourced from the database of the National Institute of Meteorology of Guinea-Bissau, covering the country's main meteorological stations and rain gauges. These consist of the longest available daily precipitation series, spanning the period from 1981 to 2020 although some years are missing from the series for certain locations, as indicated in Table 1. Incomplete or missing years within the collected series were excluded to ensure the reliability of the results. The quality control and homogeneity testing of the precipitation series from these stations were conducted in a previous study (Mendes & Fragoso 2024), allowing their selection for the current research.

2.3 Mapping average annual precipitation

Using appropriate CDO operators (Climate Data Operators, program available at https://code.mpimet.mpg.de/projects/cdo), the annual rainfall totals for the period 1981–2020 were calculated, followed by the computation of the average annual value for this climatological period to illustrate the regional rainfall pattern of West Africa. Panoply software (freely available at https://www.giss.nasa.gov/tools/panoply/) was used to produce this representation.

2.4 Calculation of onset and cessation dates of rainy season

The start date of the rainy season (Julian day) was determined using two criteria. From 1 May onwards, a specific day was defined as the onset of the rainy season if: (i) the recorded rainfall over one or two consecutive days totalled 20 mm or more, and (ii) there was no dry spell lasting more than seven days within the following 30 days (Akinseye et al. 2016; Ati et al. 2002; Balme et al. 2005; Marteau et al. 2009, 2010; Paiva 1997; Pereira et al. 2009; Sivakumar 1988). This agronomic criterion, proposed by Sivakumar (1988), was based on observations and studies conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, Sahel) in Niger. False start dates are those followed by dry periods lasting seven days or more, which can be detrimental to crop establishment.

The cessation date of the rainy season (Julian day) was determined using the water balance criterion between precipitation and evaporation. The cessation of the rainy season was defined from September onwards, when the water balance between soil moisture and evaporation fell below 0.05 mm, assuming a daily evaporation rate of 5 mm in soil with an available water capacity of 70 mm (Dekoula et al. 2018; Stern et al. 2006; Yao et al. 2020). For the specific case of Guinea-Bissau, the evaporation rate was set at 4 mm, corresponding to the observed daily average during October and November, in the country's three main regions, adopting the threshold estimated in a prior study (Samuel et., 2019).

The duration of the rainy season was calculated as the difference between the end date and the start date of the same rainy season, both defined in Julian days, using 1 st January as the reference point.

All calculations were performed using Python and the Climate Data Operators (CDO) program for NetCDF-format data (CHIRPS 2.0), while the precipitation series from meteorological stations in Guinea-Bissau were processed using the Instat + tool (versions 3.036 and R-Instat (Akinseye et al. 2016; Attoumane et al. 2022; Dekoula et al. 2018; Kadyampakeni et al. 2017; A. M. Kouassi et al. 2018; Sivakumar 1988; Stern et al., n.d., 2006; Yao et al. 2020). Instat + is a statistical analysis tool developed by the Met Office Statistical Services Centre (UK). Microsoft Office Excel was also used for graph creation and rainfall data processing.

Spatial modelling and interpolation techniques were performed using Panoply software (version 5.5.5), specifically the inverse distance weighting method, enabling the construction of various maps representing spatial rainfall patterns and characterisation of the rainy season, including the

Table 1 Main meteorological stations of Guinea-Bissau, and characteristics of the daily precipitation observation series

Station	Latitude	Longitude	Altitude	Period	Years with missing data
Mansabá	– 15,17	12,30	43	1981–2020	2000
Bissorã	– 15,46	12,22	10	1981–2020	1981,1996, 2003 and 2011
Bissau	– 15,63	11,87	20	1981–2020	1998
Bolama	– 15,48	11,60	20	1981–2020	-
Bafatá	– 14,67	12,17	43	1981–2020	-
Gabu	– 14,23	12,28	83	1981–2020	1998
Sonaco	– 14,31	12,24	54	1981–2020	2001

onset and cessation dates, duration, and related variability and trend parameters.

2.5 Trend analysis of onset and cessation dates of the rainy season

To assess the temporal trends in the onset date, cessation date, and duration of the rainy season, the non-parametric Mann–Kendall test was applied. This test has been widely used in various studies, such as Reis et al. (2020) and Santos et al. (2019). To evaluate the magnitude of the trends, Sen's slope estimator was used (Rathnayaka et al. 2021; Sen 1968), through the MAKESENS tool, available for download at https://en-beta.ilmatieteenlaitos.fi/makesens. This tool incorporates the parameters necessary to calculate the Mann–Kendall test under the null (H0) or alternative (Ha) hypothesis at a 5% significance level, as well as the trend magnitude using Sen's slope estimator. Trend variation is considered significant when the obtained p-value is ≤ 0.05; otherwise, it is not considered significant. While the Makesens tool was used for the Guinea-Bissau precipitation series, Python codes implementing the Mann–Kendall test and Sen´s slope estimator calculation were used regarding the CHIRPS precipitation data over the West African study domain.

3 Results

3.1 West Africa region

The mean annual precipitation (1981- 2020) in the West African region reveals a clear increasing gradient from north to south between latitudes 17°N and 12°N (Fig. 2). Additionally, an increase in rainfall is observed from northeast to southwest, particularly south of latitude 12°N. The annual average ranges from 230 mm in the northernmost part of the study area, progressively increasing both to the south and southwest, reaching a maximum of ≈3,500 mm in the southwestern extremity of the study area (Fig. 2).

In the studied region of West Africa, the onset of the rainy season is closely linked to the latitudinal movement of the Intertropical Front (ITF), which shifts northward during the rainy season and southward during the boreal winter, marking the end of the rainy period, as illustrated in Fig. 3 (A and B).

Fig. 3 A shows the average on the onset day of the rainy season, progressing from early May to early August. The colours transition from blue in the south to red in the north, indicating an earlier onset in southern regions and a later onset as one moves northward.

The onset of the rainy season (Fig. 3A) varies across regions, starting early in the southern regions (8°N–10°N) around early May (5 th–17 th May), gradually shifting to mid to late June (10 th–22nd June) in the central regions (10°N–12°N), and occurring the latest in the northern regions (12°N–14°N and beyond) around mid-July to early August (3rd–8 th August). During this period, the region receives the moist monsoon air from the Gulf of Guinea.

Regarding the Cessation of the Rainy Season, illustrated on Fig. 3 B, progressing from mid-September to mid-December. The transition from blue to red colours indicates an earlier end in the north and a later end in the south.

The end of the rainy season varies regionally, occurring earliest in the northern regions (14°N and above) around mid to late September (19 th–29 th September), shifting to

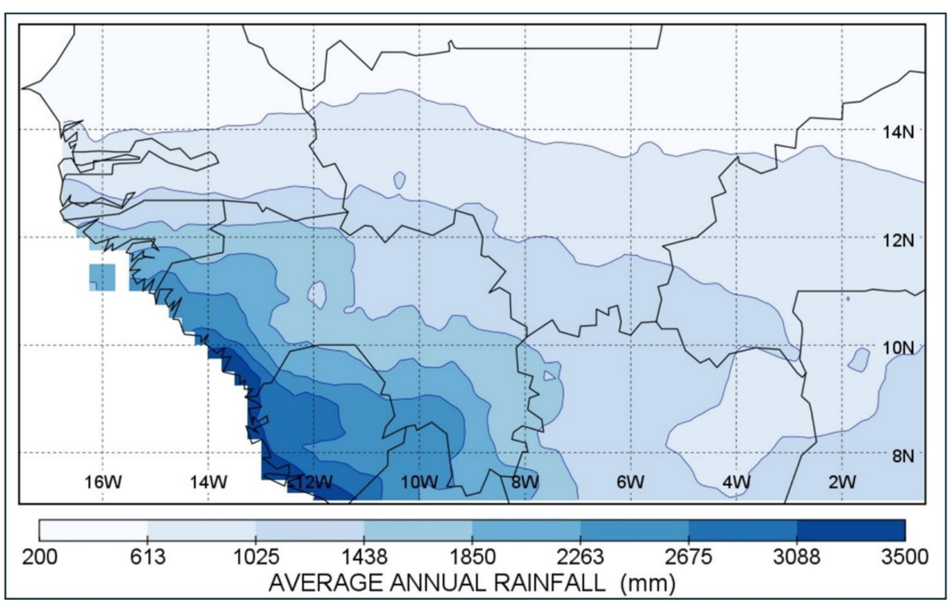

Fig. 2 Mean annual precipitation (1981–2020) in West Africa. Data source: CHIRPS 2.0

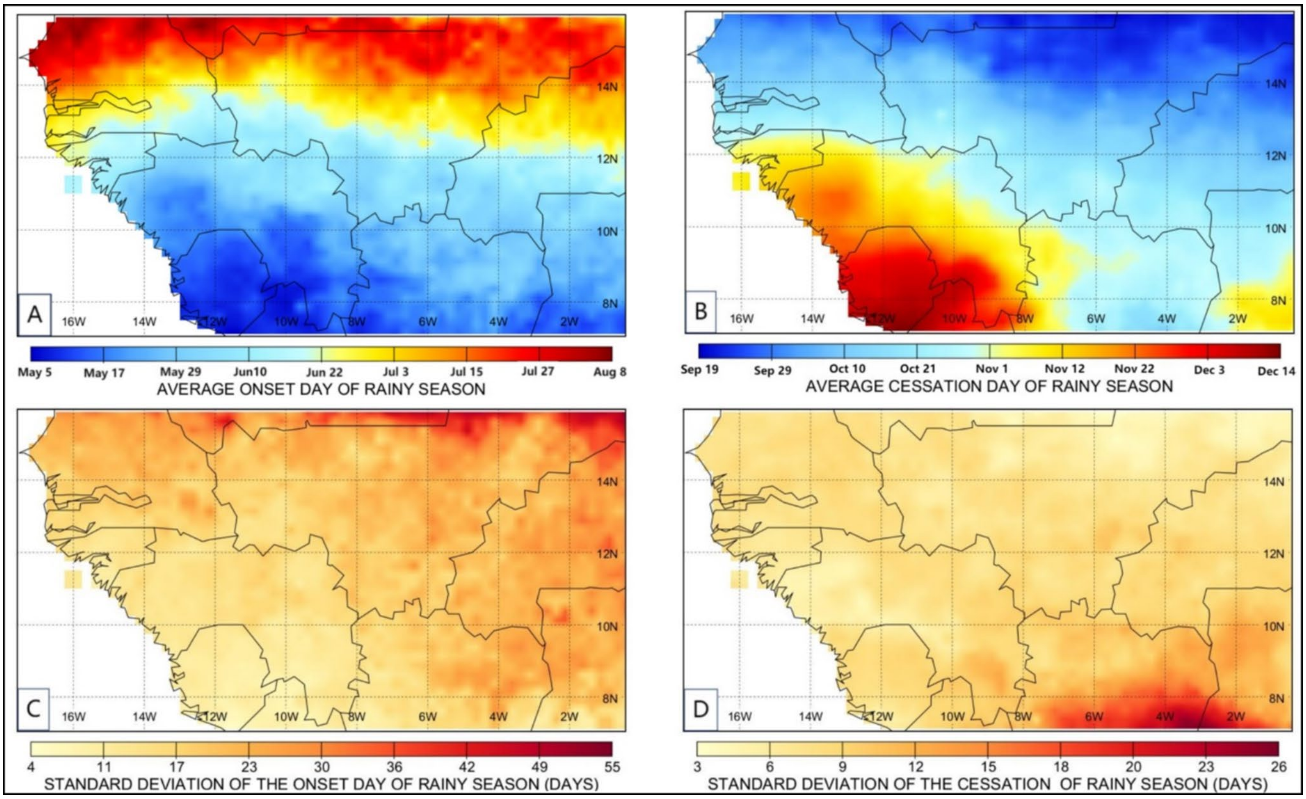

Fig. 3 Mean dates of the onset (A) and cessation (B) of the rainy season in Julian days and its standard deviation (C and D, respectively), in West Africa (1981–2020)

between October and early November (10 th October–1 st November) in the central regions (10°N–12°N), and persisting the longest in the southern regions (below 10°N), where it ends between mid-November and early December (22nd November–14 th December).

This cessation pattern is influenced by the southward retreat of the ITD, and the increasing dominance of dry Harmattan winds from the Sahara.

The standard deviation of the onset day of the rainy season Fig. 4C, ranging from 4 to 55 days. Higher values (darker red shades) indicate greater variability, whereas lower values (lighter shades) indicate more consistency.

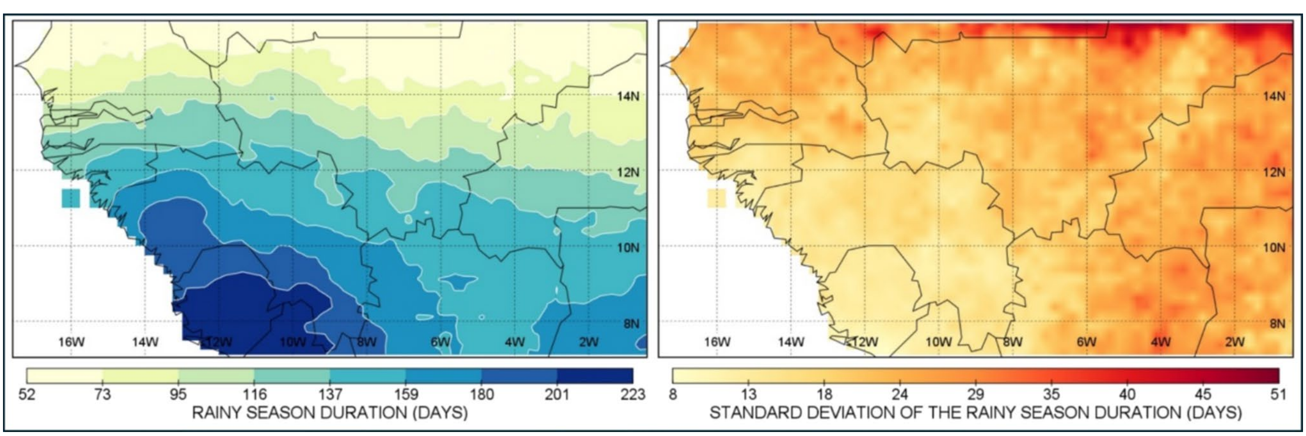

Fig. 4 Average duration of the rainy season in days (left) and its standard deviation (right), in the period 1981–2020

The onset of the rainy season exhibits varying degrees of variability across regions, with the highest variability in the northern regions (above 12°N), where it fluctuates significantly from year to year with a standard deviation exceeding 50 days. In the central regions (10°N–12°N), the variability is moderate, with standard deviations ranging from 23 to 42 days (Fig. 3C). Meanwhile, the southern regions (below 10°N) experience the most stable onset, with standard deviations as low as 4–11 days.

The standard deviation of the cessation day of the rainy season (Fig. 3D) ranges from 4 to 26 days.The end of the rainy season exhibits varying degrees of variability across regions, with the highest variability in the southern regions (below 10°N) and coastal areas, where standard deviations reach up to 23–26 days. The moderate variability in the central regions (10°N–12°N), with standard deviations ranging from 12 to 18 days and the lowest variability in the northern regions (above 12°N), where the cessation of rainfall is more predictable, with standard deviations as low as 4–7 days.

The onset and cessation of the rainy season in West Africa exhibit a latitudinal gradient, closely linked to the movement of the ITD. The onset progresses from south to north, while the cessation moves from north to south. Variability in these transitions is higher in the north for the onset and in the south for the cessation, indicating regional differences in climatic stability and interannual rainfall variability.

The duration of the rainy season across the study area (Fig. 4), which covers a large portion of West Africa typified by a unimodal rainfall regime, varies significantly from north to south follows a clear latitudinal gradient.

In the southernmost regions near the coast, particularly in Guinea, Sierra Leone, and Liberia, the rainy season lasts the longest, exceeding 200 days in some areas; however, as one moves northward, the duration progressively decreases, with the rainy season lasting approximately 100 to 150 days around 10°N latitude, further shortening to 50 to 100 days in the Sahel region (between 12°N and 16°N), and becoming very brief in the northernmost parts, near the Sahara Desert, where it lasts less than 75 days.

For the standard deviation of the rainy season duration (Fig. 4), areas with higher standard deviation (depicted in darker red and orange shades) indicate greater interannual variability, meaning the start and end of the rainy season fluctuate significantly from year to year, with the highest variability observed in the northern regions, particularly near the Sahel and the southern Sahara, where standard deviations range between 35 and 51 days, suggesting significant uncertainty in rainfall timing; however, moving southward, the variability gradually decreases, with standard deviations mostly between 8 and 25 days, while the coastal regions, where the rainy season is longest, exhibit the lowest variability (light yellow shades), implying a more predictable rainy season.

In genera (Fig. 4)l, the rainy season is longest in the southern coastal areas and shortest in the northern semi-arid regions, its variability is highest in the north, particularly in the Sahel, and lowest in the south, where the rainy season is more consistent from year to year.

The trends in the onset, cessation, and duration of the rainy season in the West African region exhibit significant variability, as illustrated in Fig. 5.

The onset date trends (Fig. 5A) vary across the region, with some areas experiencing an earlier onset while others show delays.

In certain parts of the western Sahel, including Senegal, southern Mauritania, and portions of Mali and Burkina Faso, there is a slight tendency for the rainy season to begin earlier, with an advance of approximately 3 to 8 days per decade. Similarly, northern regions of Ghana, Côte d'Ivoire, Sierra Leone, and southern Guinea, also show a trend toward an earlier onset. Conversely, large interior areas, such as central Mali, Burkina Faso, northern Guinea, and the southern and eastern regions of Guinea-Bissau, exhibit a delayed onset, with shifts ranging from 0 to 9 days per decade. The most pronounced delays are observed in Burkina Faso and some parts of Côte d'Ivoire and Mali.

Although the evolutionary trends in the onset of the rainy season that reach statistical significance (p-value < 0.05; Fig. 5B) are limited and almost residual, the observed variations remain highly relevant for agricultural planning. Even minor shifts of a few days per decade introduce considerable uncertainty in crop planting schedules, emphasizing the importance of closely monitoring these changes despite their lack of strong statistical significance.

The trends in the cessation of the rainy season (Fig. 5 C and D) across West Africa exhibit mixed patterns, with some regions experiencing an earlier end while others see an extension of the rainy season. In the central and western Sahel, particularly in Mali and eastern Burkina Faso, signs of an earlier cessation suggest a potential shortening of the rainy season. Similarly, northeastern Guinea and extreme northern Côte d'Ivoire show slight tendencies toward an earlier end.

Conversely, the southernmost parts of the study domain, especially coastal regions in Liberia, Côte d'Ivoire, and Ghana, exhibit a trend toward a later cessation, indicating a possible extension of the rainy season. Further north, the patterns are more variable, with some areas experiencing an earlier end while others see a prolonged rainy season. The southern regions, however, generally tend to experience a later cessation, reinforcing the trend of a lengthening wet season in these areas.

Although statistically significant trends (p-value < 0.05; Fig. 5D) in the cessation date are limited, these variations remain highly relevant for agricultural activities. Even minor shifts of a few days per decade introduce considerable

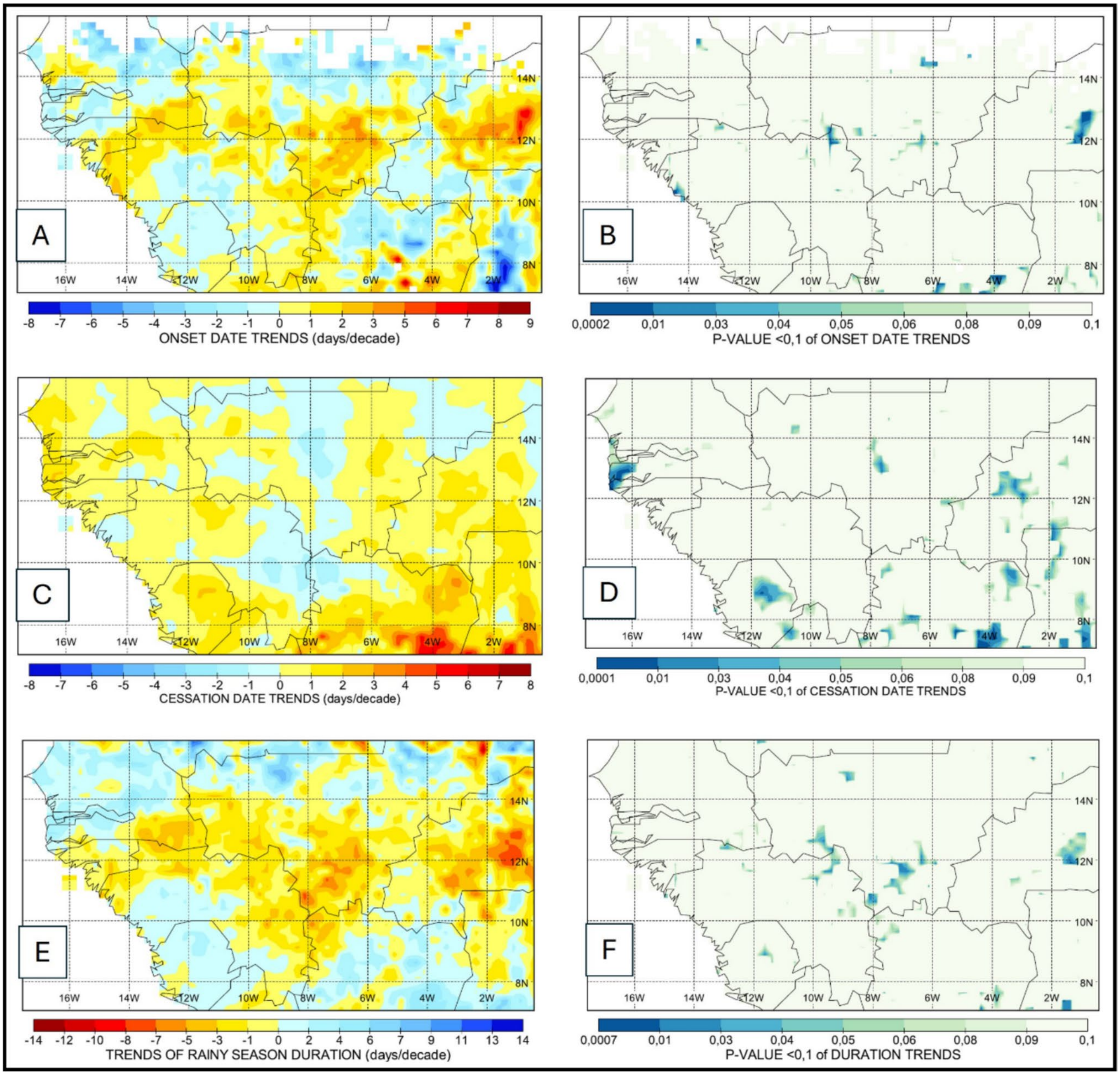

Fig. 5 Trends of the onset (A), cessation (B) and duration (C) of the rainy season in West Africa

uncertainty in crop production, underscoring the importance of monitoring these changes despite their lack of strong statistical significance.

The trends in the duration of the rainy season (Fig. 5E) reflect the combined effects of changes in both onset and cessation dates, revealing significant regional variations across West Africa. In some areas, the rainy season is becoming shorter, while in others, it is lengthening. Notable reductions in the length of the rainy season, ranging from 3 to 14 days per decade, are observed in eastern Senegal, northern Guinea, southern Guinea-Bissau, Mali, and Burkina Faso. Additionally, northern Ghana and western Côte d'Ivoire exhibit shortening trends, likely influenced by both a later onset and an earlier cessation. In contrast, coastal areas, particularly in southern Guinea, Serra Leoa, and extreme north of Liberia show a trend toward a longer rainy season. A similar pattern is observed in the northernmost regions of Senegal, Mauritania, and Mali, where the rainy season is also extending. The northern part of the study area exhibits the greatest variability, with alternating regions of shorter and longer rainy seasons. In contrast, southernmost countries display a more consistent increase in the duration of rainfall.

Although statistically significant trends ($p\text{-value} < 0.05$; Fig. 5F) in the length of the rainy season are quite limited, these variations remain highly relevant for agricultural activities. Even minor changes of a few days per decade introduce considerable uncertainty in agricultural production, emphasizing the need for continuous monitoring despite the lack of strong statistical significance.

3.2 Guinea-Bissau case study

Average annual rainfall in Guinea-Bissau varies from 1,000 mm to 2,000 mm, depending on the region. The southern area, including the regions of Tombali, Quinará, and the Bijagós archipelago, experiences the highest levels of rainfall in the country, compared to the northern and eastern regions. Two clear gradients are observed, with rainfall increasing from north to south and from east to the coastal areas. In the south, average annual precipitation can reach up to 2,000 mm, while the central area, including the Autonomous Sector of Bissau, southern Oio and Bafatá, as well as the southern and eastern parts of the Cacheu region, receives between 1,300 and 1,500 mm annually. In contrast, the northernmost areas of Cacheu, northern Oio and Bafatá, and the Gabu region receive less rainfall, ranging from 1,000 to 1,200 mm per year, as illustrated in Fig. 6.

Generally, across the main regions of the country, the rainy season typically begins in June, though there are exceptional cases of very early starts in May or significantly later starts in July. The rainy season first begins in the southern region of the country, followed by the central and eastern areas, and lastly in the northern regions of Oio and Cacheu. The average onset date for the rainy season in the south is 15 June, corresponding to Julian day 166, with significant interannual variability, expressed by a standard deviation of 16 days. The earliest recorded start dates in the time series occur in May, from the third week onwards, while the latest are observed in July. In the regions corresponding to the Autonomous Sector of Bissau (in the centre of the country), the eastern regions of Bafatá and Gabu, and the northern region of Oio, the average onset of the rainy season falls between 21 and 30 June, with an estimated standard deviation of 13 to 20 days, indicating greater variability compared to the southern region. The earliest observed start dates in the series occurred in May, while the latest ranged between July and August, as shown in Table 2.

The average end date of the rainy season typically falls between 1 and 9 November, beginning in the northern and eastern regions of Cacheu, Oio, Gabu, and Bafatá, before moving to the central areas and, lastly, the southern region. The average standard deviation for the end of the rainy season is between 9 and 10 days, indicating less interannual variability compared to the start of the season. An early end to the rains can be observed as early as October, while the latest end dates can occur during the third week of November, and, on rare occasions, in early December in the south, as detailed in Table 3.

The duration of the rainy season varies greatly from year to year. Analysis of the climatological data under study revealed that the average length of the rainy season in Guinea-Bissau ranges from 123 to 148 days. The regions of Cacheu, Oio, Gabu, and Bafatá experience the shortest rainy season, lasting between 124 and 132 days, while in the central and southern parts of the country, the average duration is longer, ranging from 141 to 143 days. The standard deviation across the territory is between 16 and 25 days, as shown in Table 4.

Regarding trends in the rainy season across different regions of Guinea-Bissau from 1981 to 2020, as illustrated

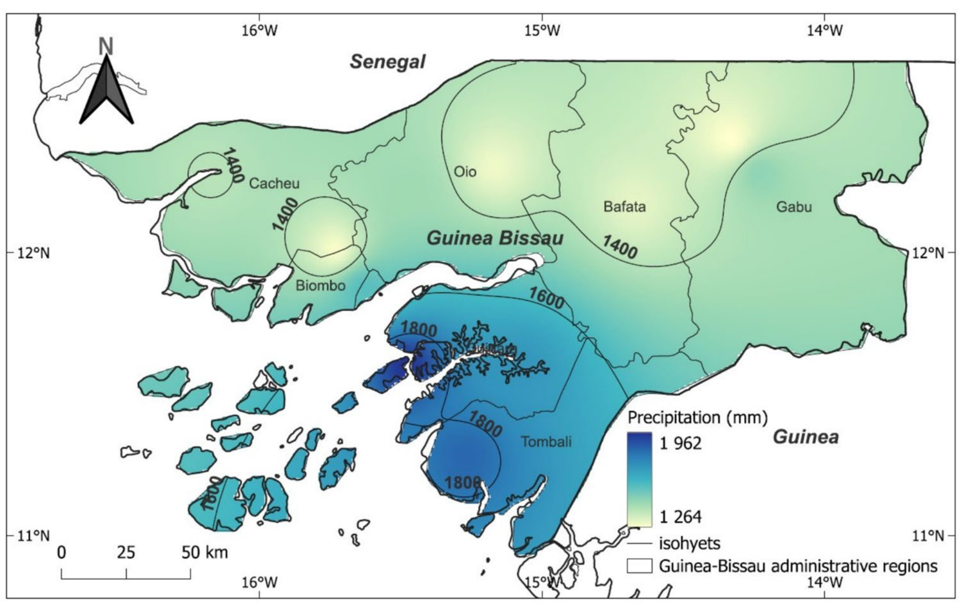

Fig. 6 Mean annual precipitation in Guinea-Bissau (1981–2020)

Table 2 Characterization of the variability of the onset date of the rainy season in Guinea-Bissau, in the period 1981–2020

Station	Mean date	Latest date	Earliest date	Median date	Standard deviation (days)
Bissorã	30/Jun	12/Aug	19/May	29/Jun	17
Mansabá	30/Jun	09/Aug	30/May	27/Jun	18
Bafatá	23/Jun	14/Aug	07/May	23/Jun	20
Sonaco	28/Jun	09/Aug	07/May	30/Jun	20
Gabu	27/Jun	30/Jul	29/May	27/Jun	17
Bissau-Obs	21/Jun	22/Jul	07/May	22/Jun	13
Bolama	15/Jun	22/Jul	28/May	15/Jun	16

Table 3 Characterization of the variability of the cessation date of the rainy season in Guinea-Bissau, in the period 1981–2020

Station	Mean date	Latest date	Earliest date	Median date	Standard deviation (days)
Bissorã	03/Nov	21/Nov	03/Oct	04/Nov	10
Mansabá	01/Nov	23/Nov	12/Oct	03/Nov	9
Bafatá	02/Nov	12/Dez	15/Oct	03/Nov	10
Sonaco	03/Nov	23/Nov	15/Oct	04/Nov	10
Gabu	03/Nov	24/Nov	12/Oct	05/Nov	9
Bissau-Obs	09/Nov	25/Nov	24/Oct	09/Nov	9
Bolama	05/Nov	23/Nov	19/Oct	05/Nov	9

Table 4 Characterization of the variability of the rainy season duration in Guinea-Bissau, in the period 1981–2020

Station	Mean duration	Longest duration	Shortest duration	Median duration	Standard deviation (days)
Bissorã	126	176	83	126	20
Mansabá	124	174	74	129	23
Bafatá	132	183	73	132	18
Sonaco	128	188	69	127	25
Gabu	129	160	91	132	16
Bissau	141	172	114	142	16
Bolama	143	185	116	142	19

in Fig. 7 it can be observed that in the northern region (Oio), the rainy season tends to start progressively later, particularly in Bissorã and Bafatá, where a delayed start of 5 and 4 days per decade has been recorded, respectively (statistically significant, in both cases). In the Autonomous Sector of Bissau and Bolama, there is a slight delay in the start of the season, around 3 days per decade, and a slightly delayed end, which keeps the length of the rainy period practically stable in these locations. In the eastern region, which includes Bafatá and Gabu, a late start of 3 to 5 days per decade is noticeable, particularly in Sonaco and Bafatá, while Gabu shows a more stable situation. As for the end of the rainy season, both Bafatá and Sonaco maintain a stable pattern, although there is a reduction in the season's length in Sonaco (2 days per decade) and in Bafatá (4 days per decade). In contrast, in Gabu, the end of the rainy season tends to be slightly later, with an increase in the season's length of 2 days per decade.

Overall, the onset dates of the rainy season display greater interannual variability than the end dates. As a result, the duration of the rainy season naturally reflects the combined behaviour of these two parameters, as illustrated in Fig. 7.

4 Discussion

This study offers new and expanded insights into the evolution of rainy season patterns in West Africa over the past 40 years, utilizing one of the most reliable high-resolution precipitation datasets available. While previous studies have primarily focused on other regions of Africa or specific countries, this research represents the first comprehensive regional assessment of rainy season behavior in West Africa based on an in-depth analysis of the CHIRPS 2.0 database. The present study confirmed that annual rainfall distribution exhibits strong regional contrasts in West Africa, with a marked gradient of increasing rainfall from north to south, combined with an even stronger increasing gradient from east to west at latitudes lower than 12ºN. The Sahelian zone receives less rainfall, in contrast to the Sudanian zone, which

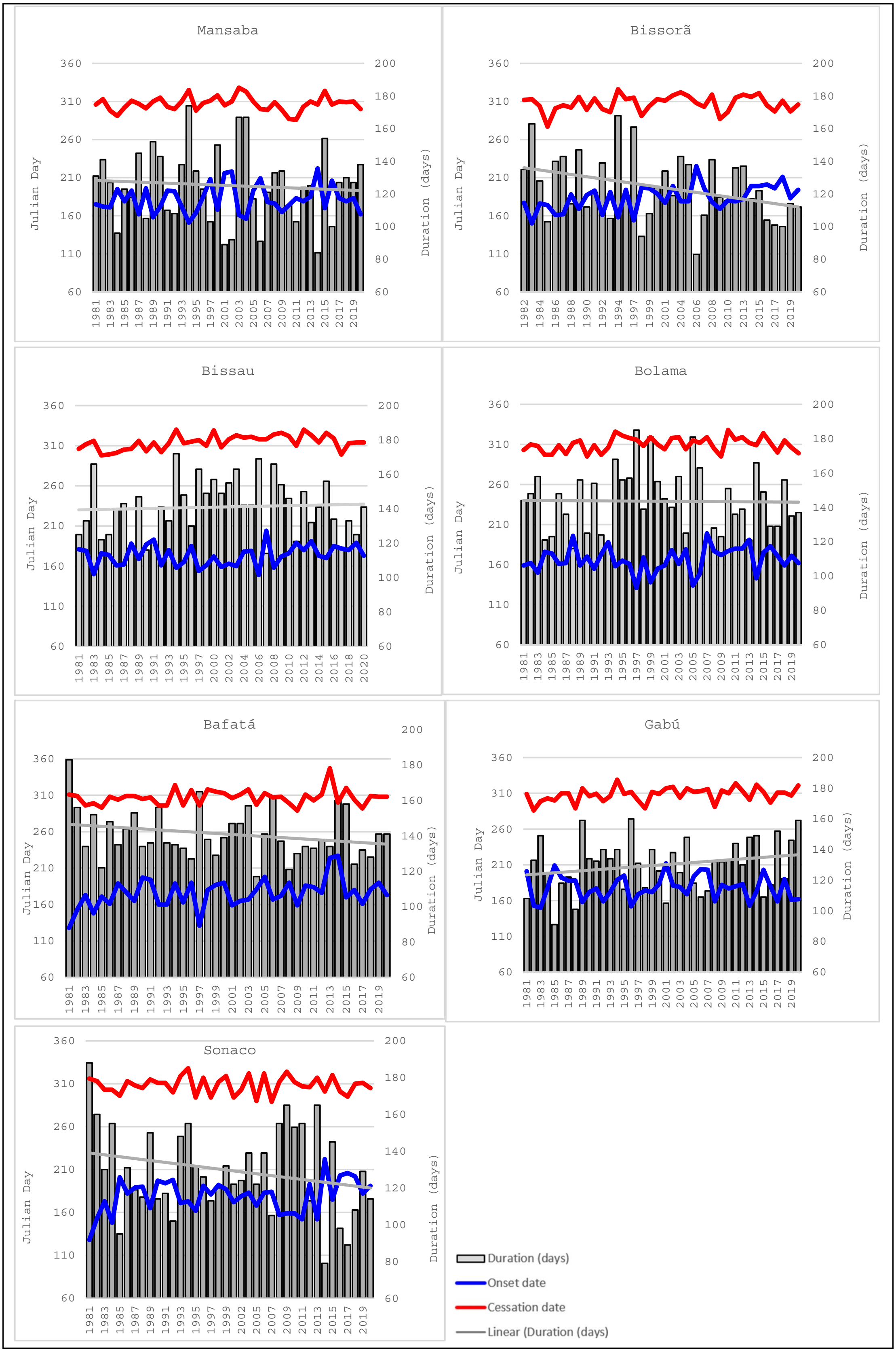

Fig. 7 Trends on start, cessation and duration of the rainy season in Guinea-Bissau, period 1981–2020

enjoys relatively abundant precipitation. This disparity is linked to the shorter duration of the rainy season in the Sahel, due to the later arrival of the Intertropical Front (ITF) and its earlier retreat from north to south (Lélé & Lamb 2010; Mensah et al. 2016; Odenkunle 2004). The findings of Diatta et al. (2020), which analysed spatial variation and precipitation trends using the CHIRPS dataset, also demonstrated this general gradient of increasing rainfall from the Sahelian zone in the north towards the southern Guinea coast of West Africa.

The results of this study demonstrated that the onset and end of the rainy season vary according to an alternating pattern South-North and North–South across most of West Africa, characterised by a unimodal rainfall regime. This involves a progression from south to north marking the onset of the rainy season, followed by a north-to-south shift signalling its end. Thus, the rainy season begins between latitudes 8ºN and 10ºN in May, followed by latitudes 10ºN to 12ºN from June, and finally, by July to early August, it reaches latitudes around 15ºN in the study area.

These findings align with previous research, but it should be emphasised that this study is the first, based on observational data, to provide evidence of the timing and interannual variability of the rainy season specifically within the territory of Guinea-Bissau.A similar study by Vellinga et al. (2013) on the onset of the West African monsoon indicates that the monsoon begins in May along the Atlantic coastal belt, followed by June, and later July in the Sahelian regions, a sequence associated with the northward movement of the Intertropical Front (ITF). Similarly, the findings of Rauch et al. (2019) in a study on the seasonal prediction of the rainy season's onset in West Africa, and those of Liebmann et al. (2012) on African rainfall seasonality, also demonstrated the south-to-north progression of the rainy season from May to July in the region. Additionally, Descroix et al. (2015) also confirmed that the rainy season starts in July in northern Senegal, while Akinseye et al. (2016), in their study on Mali, estimated the average onset of the rainy season to occur between June and July, varying between latitudes 11ºN and 15ºN, with a progression from south to north.

The findings of this research also corroborate those of Dunning et al. (2016) on the onset and cessation of rainfall in West Africa, highlighting a south-to-north progression of the rainy season from May to July across different latitudes. Regarding the cessation of rainfall in the same region, the results align with those authors, who identified September and October as the months marking the end of the rainy season, beginning at latitudes 16º–15ºN and progressing southwards to latitudes 14ºN–11ºN between October and November.

Another key finding of this study relates to the duration of the rainy season in the Sahelian band, which spans northern Senegal, southern Mauritania, and southwestern Mali. It was shown a variation in the average length of the rainy season between latitudes 14ºN and 11ºN, confirming Akinseye et al. (2016) findings on the increasing duration of the rainy season from north to south in Mali.

Overall, the onset dates of the rainy season show greater variability compared to the end dates in most of the studied regions. This is consistent with the findings of Kouassi et al. (2018), in a similar study on the Bandama River basin in Côte d'Ivoire, where the onset dates of the rainy season exhibited greater variability than its cessation dates.

In the case of Guinea-Bissau, the results indicate significant variability in the onset of the rainy season, with a trend towards increasingly delayed starts, while the end of the season remains relatively stable in most of the stations studied. These findings provide new relevant insights on the rainy season behaviour in Guinea Bissau, expanding the results of previous works (e.g. Mendes 2017; Mendes and Fragoso 2023, 2024).

5 Conclusion

The onset, cessation, and duration of the rainy season in West Africa were analyzed using CHIRPS data (1981–2020) for regions with a single annual rainy season, while in Guinea-Bissau, the analysis relied also on daily precipitation records from various meteorological and rain gauge stations over the same period. Understanding these seasonal patterns is essential for farmers in selecting suitable crop varieties and minimizing risks.

In West Africa, the rainy season typically begins in May at latitudes between 8ºN and 10ºN, progresses northward to 11ºN–13ºN by June, and finally reaches 14ºN and beyond in July, following the movement of the Intertropical Front (ITF). In Guinea-Bissau, the onset dates show greater variability than the cessation dates, with more than 75% of stations indicating a trend toward later starts, though the magnitude varies. On average, the rainy season begins in the third or last weeks of June, with the earliest occurrences in May (rare) and the latest in July, occasionally extending into August.

The cessation of the rainy season starts in September and October in northernmost areas, including northern Senegal, southern Mauritania, and southwestern Mali, then shifts southward between October and early November at latitudes 13ºN–11ºN, and finally concludes between 8ºN–10ºN in November. In Guinea-Bissau, the rainy season typically ends in early November, with the earliest cessation occurring between the third and last weeks of October.

The duration of the rainy season varies significantly across the region, varying between 50 days in the north of studies zones (above 15ºN) and 200 days in years in the southernmost regions near the coast. In Guinea-Bissau, it ranges from 124 to 135 days in the northern (Cacheu, Oio) and eastern (Bafatá, Gabu) regions, while in the central (Bissau) and southern (Bolama, Quinara, Tombali) regions, it exceeds 140 days, reaching up to 180 days in exceptionally wet years. A late onset combined with an early cessation can significantly shorten the rainy season, disrupting agricultural activities. By integrating this information with seasonal forecasts from key West African climate centers (AGRHYMET—CCR-AOS and ACMAD), farmers can make informed decisions about cropping cycles, reducing yield losses while maximizing production.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflicts of interest The authors declare no competing interests.

Ethics approval Not applicable.

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