



Analysis of sea surface temperature pattern, variability and their teleconnection with rainfall dynamics over the Gulf of Guinea

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Abstract

Spatial pattern and variability of sea surface temperature SST and their teleconnections with rainfall dynamics in the Gulf of Guinea (GOG) were examined in this study. SST and rainfall data of 50 years (1970–2022) were obtained from ERA5 and NOAA CPC at $0.25^\circ \times 0.25^\circ$ and $0.5^\circ \times 0.5^\circ$ spatial resolution from longitudes 10°W and 8°W , 6°W , 4°W , and 2°W and latitudes 15°N , 5°N , 3°N , 15°S , 5°S , and 3°S , distributed along the Gulf of Guinea (GOG) respectively. Analysis was further carried out on twelve rainfall gridded stations distributed along the Gulf of Guinea (GoG) for the characterization of the Rainfall-SST teleconnection across the region while the relationship between the rainfall-SST anomalies, seasonal, inter-annual, and decadal scales was carried out using correlation analyses and composites. Interpolation of the meteorological variables was carried out using Inverse Distance Weight (IDW) from the ArcGIS Spatial Analyst Tool, Ferret, and CDO which were further employed to generate the seasonal and decadal rainfall and SST maps and statistical analysis of the study area. The result of the decadal and seasonal analysis of SST variability from 1970–1980, 1980–1990, 1990–2000, 2000–2010, 2010–2020 and 2022 indicate that SST was highest from 2010 to 2020 at 28.91°C and fluctuated between (28.49°C) in the 1970–1980 and (28.08°C) for the 1980–1990 decade While the seasonal pattern of SST showed marked variability with March–April and May (MAM) recording 29.34°C with the lowest being in June–July–August (JJA) at 28.7°C . In terms of decadal analysis of rainfall, the period 2010–2020 recorded the highest amount of rainfall along the coast (3,145.5 mm–3,928.3 mm while 1970–1980 recorded the lowest amount of rainfall (2,650–3,310 mm). To investigate the teleconnection between of SST and rainfall dynamics, statistical analysis was used where the SST values were plotted against seasonal rainfall in 11 stations namely Abidjan, Banjul, Accra, Guinea, Conakry, Cotonou, Dakar Doula, Freetown, Lagos, Lome, and Monrovia. The outcome of the statistical analysis and Standardized Anomaly Index used indicate that Banjul, Cotonou, Dakar, and Doula exhibited statistically insignificant correlation at 0.05 confidence level while Abidjan, Accra, Lagos, Lome, Freetown, and Monrovia showed positive and statistically significant correlation. The spatial pattern of seasonal rainfall climatology categorized into DJF, MAM, JJA, and SON reveals that JJA and SON produced 80% of rainfall in the Coastal GOG followed by MAM. The study affirmed that warm and cold tongues exist in the GOG alongside positive teleconnection and that the spatial variability of SST observed in this study corresponds positively with the decadal and seasonal variability of rainfall.

1 Introduction

The ocean plays an important role in the earth's climate system owing to their large heat storage capacity with approximately 3.5 m of water containing as much energy as the entire atmosphere column (Deser et al. 2010). Similarly,

more than 70% of the entire Earth's surface is covered by the ocean and therefore exerts an enormous influence on boundary layer atmospheric processes (Siedler et al. 2013). Ocean circulation therefore has profound impacts on the mean state and variability of the climate system. This is evidenced in the meridional transport of heat to the poles from the equator and its loss to the atmosphere moderates the climate, particularly in the mid to high latitude. In addition, changes in equatorial upwelling and currents play a critical role in driving El Nino and La Nina phenomena and thus wield significant influence on global climate from inter-annual to decadal timescale as well as modulating the intensity of human-induced climate change (Kosaka and Xue 2016).

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The mechanism that accounts for the observed high and increasing SST anomalies emanates from the excessive solar radiation and heat that dominates the tropics. The surplus heat available in the tropics is then transported to higher latitudes through atmospheric and oceanic circulations which allows for interaction between the ocean and the atmosphere through deep atmospheric convection (Lubbecke et al. 2018). It is the coupled ocean–atmosphere interaction that influences the atmospheric wind field which in turn, strongly impacts sea surface temperature (SST) in the tropics, especially in the eastern equatorial Atlantic and Pacific, where it controls both the upwelling of cold water from below the sharp, shallow thermocline as well as the depth of the thermocline. SST anomalies in the tropics can thus have far-reaching effects on the climate system.

Scientist over the years has focused their attention on sea surface temperature anomalies in their effort to unravel the driving mechanism behind the observed change and variability of the West African precipitation system characterized by extreme rainfall with implications on severe floods and droughts in the region. (Vizy and Cook 2001, Paeth and Stuck 2004, Rodwell 2013 and Meynadier et al. 2016). This is premised on already established scientific reports that there exists a statistically significant relationship between sub-Saharan rainfall variability and global sea surface temperature pattern and distribution. The pioneering work of Lamb (1978) who was able to successfully link Saharan rainfall deficiency in 1960 to warm SST anomalies over the equatorial Atlantic and periods of normal and heavy rainfall to cold SSTA and vice versa attracted the attention of another scientist with keen interest in the African climate system. Lübbecke and McPhaden (2017) following previous investigations further asserts that the fluctuations in interannual and seasonal SST influence the winds and precipitation regime over South America, the Indian Ocean, the Sahel and even Europe as changes in ocean temperature and upwelling of nutrients have the propensity to affect the marine ecosystem. Lamb and Pepler (1992) in another study revealed a distinctive SSTA pattern over the Atlantic in comparison with the three driest years in Sub-Saharan Africa notably 1972, 1977 and 1984 since 1984 to rainfall climatology unfortunately the 1983 drought broke the pattern. The high SST anomalies of the Atlantic Ocean have been described as an “El Niño like” phenomenon in the eastern equatorial Atlantic and the Gulf of Guinea as the “El Merle (1980) and Hisard (1980). Other studies that have been carried out with respect to SST anomalies of the East Mode and rainfall variability over West Africa include (Vizy and Cook 2001, Paeth and Stuck 2004, Rodwell 2013 and Meynadier et al. 2016) in their various research findings linked were the historical droughts that characterized West Africa and recent flood frequencies to SST anomalies. Some of the notable historical droughts with devastating impact in West Africa are shown

in Table 1 below (Grist and Nicholson 2001; Odekunle and Eludoyin 2008).

Given the scale and intensification of extreme climate change impacts which are already manifesting in Africa owing to her vulnerability to human induce global warming and climate change and low adaptive capacity, West Africa the most populated regions in the continent of Africa and the world are projected to experience a reversal of their developmental gains that will result in loss of livelihoods and infrastructure damages (UNFCCC 2021). Furthermore, the coastal regions of the GOG have seen an upsurge in rainfall in recent years culminating in devastating floods with huge loss impact on critical economic systems and human lives. The death toll and infrastructure loss triggered by flooding indicate high level of vulnerability of the coastal regions of West Africa due mainly to extreme rainfall and ocean–atmosphere interaction (The World Bank 2020).

Arising from above, it has become imperative to investigate the influence of local SST anomalies of the gulf of Gulf of Guinea on rainfall dynamics over West Africa. This is aptly important as rainfall variability is a major meteorological parameter that is critical to human life and socio-economic systems in West Africa. Most of the region’s population is largely dependent on rain-fed agriculture and pastures for livestock and the water resources sector, thus making them highly vulnerable to rainfall fluctuations. Consequently, it has become pertinent to understand the pattern and variability of SST anomalies on rainfall dynamics over the Gulf of Guinea and this is the relevance of the study.

Evidence in the literature affirms that previous studies conducted on sea surface temperature and their influence on West African rainfall include Ginanni (2010) on the relationship between anomalies of sea surface temperature (SST), perturbations in the atmospheric circulation, and response in precipitation forms the physical basis of seasonal to

Table 1 Historical droughts and flood years over West Africa

Drought	Flood
1913	1946
1914	1950
1931	1952
1932	1953
1942	1954
1943	1955
1970	1957
1972	1958
1980	1966
1983	1996
1984	1980
1993	2012
2013	2018
2019	2020

interannual prediction where the focus was on large scale SST variability. Other scholars include Grist and Nicholson 2000 on the dynamic factors influencing rainfall variability in the Sahel in which soil moisture, wind, temperature, and other instability mechanisms a. The outcome of their study confirms that the weaker African easterly jet (AEJ) and stronger tropical easterly jet (TEJ) and their latitudinal location rather than intensity during wet years are some of the dynamic factors driving rainfall in the Sahel. Vizy and Cook 2001, Vizy and Cook 2001 focused their studies on the mechanism by which the Gulf of Guinea and Eastern North Atlantic Sea surface temperature anomalies influence African rainfall by employing GCM model simulations. The study like previous ones was on large-scale atmospheric circulation and moisture anomalies and its association with precipitation in the Gulf of Guinea and the Congo Basin. Deser et al. 2010 also adopted a global outlook in their studies of large-scale atmospheric circulation perturbation and their influence on SST variability, patterns, and mechanisms in different on both the Northern and Southern oceans. Others include Rowell 2013, Akinbobola et al. 2015 Odekunle and Eludoyin 2008 and Wainwright 2019 have also investigated at various times the influence of tropical Atlantic SST on African rainfall variability. However, most of these studies failed to demonstrate the teleconnection of SSTA and rainfall variability in coastal cities along the Gulf of Guinea and this is the relevance of the study.

2 Materials and methods

The study used SST and rainfall data of 50 years (1970–2022) from ERA5 and NOAA CPC at $0.25^0 \times 0.25^0$ and $0.5^0 \times 0.5^0$ resolutions from specific locations namely longitudes 20°W and 10°E and latitudes 15°N and 2°N along the gulf of Guinea obtained at <https://cds.climate.copernicus.eu/> and <https://iridl.ideo.columbia.edu/sources/noaa> as shown in Table 1 below. The inverse distance weighted (IDW) method of interpolation, ArcGIS spatial Analyst tool, Ferret, Panoply, and climate data operator CDO were used in the study to produce the spatial patterns of SST and rainfall variability at decadal and seasonal timescale covering decade 1 (1970–1980), Decade 2 (1980–1990), Decade 3 (1990–2000), Decade 4 (2000–2010), Decade 5 (Decade (2010–2020), and the year 2022 for the characterization of extreme events in West Africa within the study period (1970–2022) while December–February (DJF); March–May (MAM); June–August (JJA- summer), and September–November (SON- autumn) constitute the seasonal pattern for the Northern hemisphere while statistical and standardized anomaly index was used for the teleconnection analysis on twelve names namely Abidjan, Banjul, Accra, Guinea, Conakry, Cotonou, Dakar Doula, Freetown, Lagos, Lome, and Monrovia which are points

within the 0.25×0.25 grides of the datasets as the mid-point of the grid were extracted to form the said twelve points as shown in Fig. 1b. Secondly, the choice of the twelve points was based on their coastal locations within West Africa at the intersection of the land–ocean interface which forms the focus of this study as shown in Fig. 1b while Table 2 highlights the Rainfall characteristics of all the sampled points. Consequently, statistical tools involving means and averages were used to generate monthly, annual, and inter-seasonal rainfall and SST for the study period. The choice of the dataset is based on the spatial characteristics and resolution of ERA5 Copernicus data which has been widely used for rainfall studies in Africa. In addition, both ERA5 and NOAA CPC data have high reliability and are up-to-date for hourly, synoptic, daily, and monthly data fractions for trend and ocean/weather monitoring and forecast particularly for a data-sparse region like Africa (Table 3).

2.1 Standardized rainfall and SST anomaly

The Standardized Precipitation Index (SPI) developed by McKee et al (1993) was used to identify variations and fluctuations in the rainfall values, for regional climate change and for changes in rainfall distribution. The Short-term and long-term rainfall anomalies were plotted for annual and inter-seasonal variations. SP values with its corresponding categories as shown in Table 4 below give a better representation of abnormal wetness and dryness than the Palmer indices. Similarly, an SST value greater than $+0.5^{\circ}\text{C}$ or less than -0.5°C was considered abnormal. Sea Surface Temperature anomalies are a commonly used index of the frequency and magnitude of El Niño and La Niña events. The SPI table as shown below in Table 1 contains both negative and positive values with the negative values as rainfall anomalies while the positive values indicate normal rainfall incidents. The formula for computing the SPI values is expressed in Eq. 1 below.

The SPI equation is stated as follows

$$\text{SPI} = \frac{x - x'}{\phi} \quad (1)$$

x is the annual mean rainfall,

x' is the mean of the entire series.

ϕ is the standard deviation from the mean of the series.

Similarly, the Regression model was also used to examine the relationship between the two variables of interest (SST and Rainfall in all the stations considered in the study and establish a teleconnection. Linear Regression model can identify the cause and effect of one variable against the other. The formula for Linear Regression is given below:

$$y = mX + b \quad (2)$$

where Y = Dependent variable.

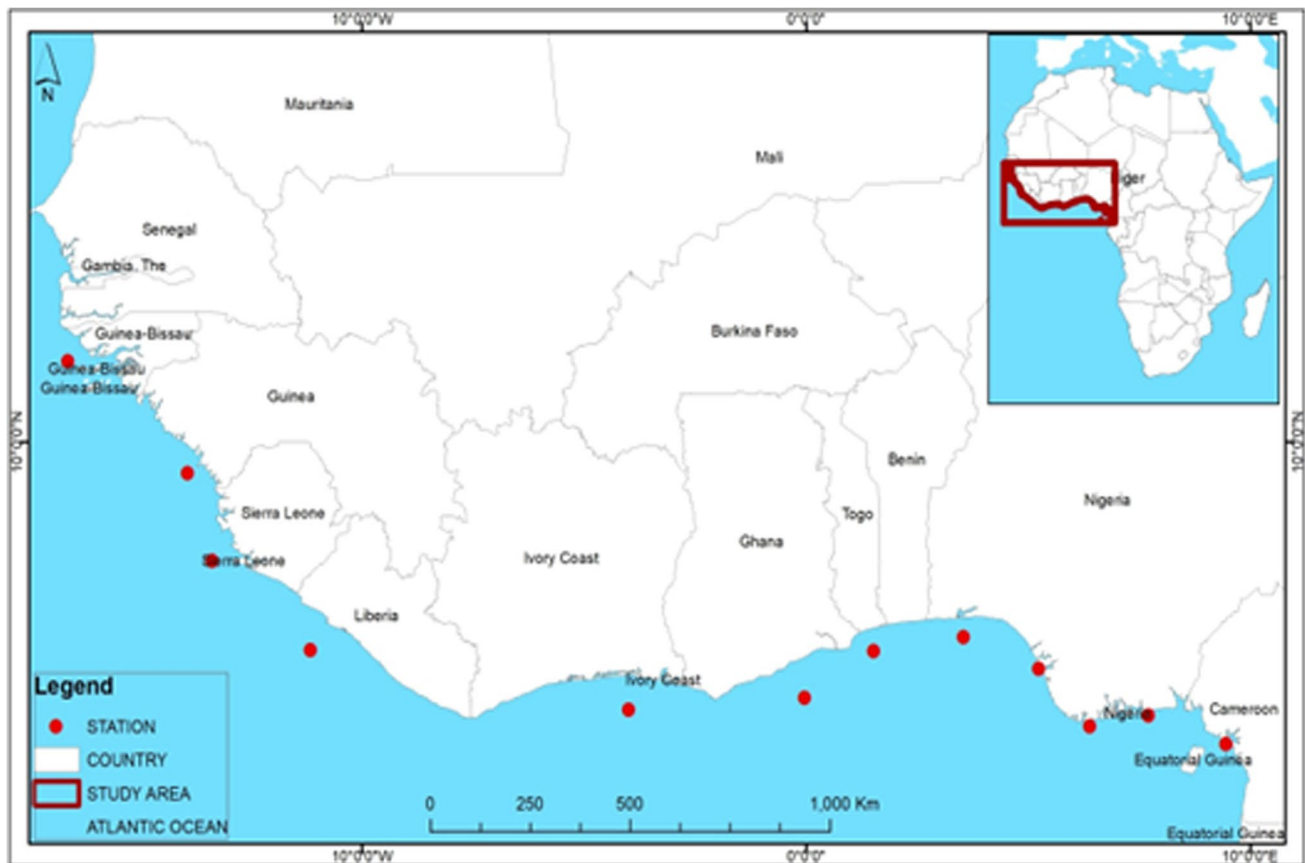


Fig. 1 a) Map of the Gulf of the Guinea showing study Area

Table 2 Historical datasets used in the study

Parameter	Source	Period	Coverage
ERA5 SST	https://cds.climate.copernicus.eu/	1970–2022	Monthly 0.25°×0.25°
NOAA CPC Rainfall	https://iridl.ldeo.columbia.edu/SOURCES/NOAA/	1970–2022	Monthly 0.5°×0.5°
NOAA SST	https://iridl.ldeo.columbia.edu/SOURCES/NOAA/	1970–2022	Monthly 0.5°×0.5°

- X Independent variable (Predictor).
M estimated slop.
b intercept.

2.2 The study area

The study area is the GOG region of the Atlantic Ocean (Fig. 1). The area lies between longitudes 10°W and 8°E and latitudes 5°N and 5°S, and thus, south of West Africa. The hydrography of the GOG is directly affected by five main currents, namely, Benguela, the South Equatorial, the Canary, the Counter Equatorial, and the Guinea Currents (Longhurst 1962) as shown below in Fig. 1a while

the sample points namely Abidjan, Accra, Banjul, Cotonou, Conakry, Dakar, Doula Freetown, Lagos, Lome, and Monrovia are shown in Fig. 1b. The tropical marine (mT) air mass and the tropical continental (cT) air mass are the two main wind currents that have the most impact on the climate of GOG and all of West Africa. The Equatorial Easterlies, a third wind current, is only significant over the continent of West Africa (Ojo 1977; Illoeje 1981). The southern high-pressure band off the coast of Namibia is where the mT air mass starts. On its path, the air mass takes up moisture over the South Atlantic Ocean, crosses the Equator, and then penetrates GOG and West Africa. The high-pressure area to the north of the Tropic of Cancer is where the cT air mass is found. It picks up little moisture along its path and is thus

Table 3 Rainfall characteristics of sampled stations

The bGulf of Guinea (Sampled Stations)	Rainfall Characteristics
Abidjan	75 inches (1,900 mm) of rainfall annually Two rainfall seasons (April-July) and (September-October)
Accra	29.4 inches (748 mm)
Banjul	81.55 mm (3.21 inches) of rainfall with an average of 72.64 rainy days
Conakry	3730 mm (146.9 inches) annually 1 mm (0 in) in the driest month (February) and 1142 mm (45 in) in the wettest one (August)
Cotonou	1308.3 mm (51.5 inches) annually. January is the driest month (9.2 mm) followed by June, the wettest month with 356 mm of rainfall
Dakar	The average rainfall of 500 mm, between the driest and wettest month is 182 mm. Rainfall begins in June, picking up in June with early cessation in October
Doula	The average rainfall received is 13,851.2 mm (12.6 inches) with 233 days of more than 0.1 mm rainfall annually. The driest month is August while the wettest month is August
Freetown	The average rainfall received annually is 2948.3 mm (116 inches), with 149 days of more than 0.1 mm rainfall. January is the driest month while the Wettest month is August
Lagos	The average rainfall received in Lagos Nigeria annually is 1506.6 mm (59.3 inches) with 121 days of more than 0.1 mm rainfall. January is the driest month with 13.2 mm followed by June the wettest month with 315 mm of rainfall
Lome	Lome receives an average of 949 mm or 97.1of rainfall annually with 88 days of rainfall more than 0.1 mm. The driest month is December with 0.3 mm while the wettest month is June with 271 mm of rainfall
Monrovia	Monrovia is a tropical monsoon climate with 4600 mm of average rainfall. And 182 rain days more than 0.1 mm. The driest month is January (0.4inches) followed by August the wettest month with 11.2inches of rainfall

Source: USAID 2013a

Table 4 The standardized precipitation index (McKee et al. 1993)

SPI Values	Categories
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-0.99 to 0.99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

dry. The two air masses (mT and cT) meet along a slanting surface called the Inter-tropical Discontinuity (ITD). The Equatorial Easterlies are rather erratic cool air masses, which come from the east and flow in the upper atmosphere along the ITD.

3 Results/discussion

The results of the spatiotemporal variability of SST and rainfall patterns are presented as follows.

It is well known that variations in sea surface temperatures (SSTs) are partly responsible for large anomalies of seasonal mean rainfall over many areas of Africa. Generally, as can be seen from Fig. 2 above. SST decreases westward and the northern parts with a

significant increase in the south and eastern axis of the Gulf of Guinea. The 1970 -1980 (Fig. 2a), 1980–1990, and 1990–2020 periods (Fig. 2b and c) were characterized by below-normal SST mean values across the Gulf of Guinea while substantial increase in SST was observed from 2000–2010, 2010–2022 and 2022 respectively (Fig. 2d-f) The anomalously low SST observed in the periods corresponds well with the periods of different drought episodes that characterized West Africa in the early 1970 and 1980s. The result further reveals that the Guinea coast has experienced accelerated and fluctuating SST increase over the study period leading to intensification of rainfall anomalies. A reversal of this narrative was observed in the Western flank with anomalously cold SST leading to reduced rainfall anomalies and drought. The result established in the study are in agreement with extensive studies conducted by Odekunle and Eludoyin 2008; Akinbobola et al. 2015, Rowell 2013; Vizy and Cook 2001 and Giannini 2016 on the contribution of sea surface anomalies on West African climate.

Furthermore, the pattern of decadal variation observed in this study confirms the influence of El-Nino on the warming of the tropical Atlantic Ocean and the continuous rise of SST of the GOG. An ENSO episode manifests through the appearance of SST anomalies, and this was evident in the analysis performed in the study.

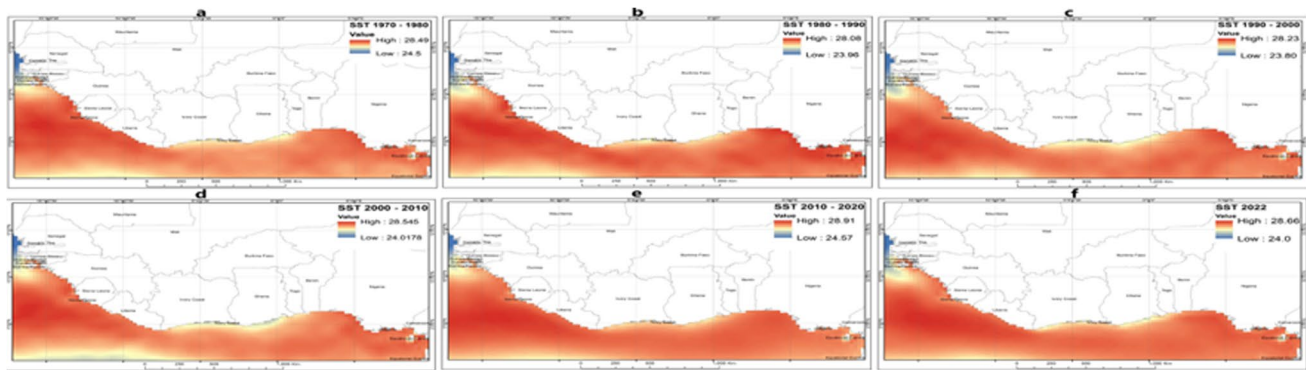


Fig. 2 Decadal pattern of SST variability: **a)** Climatological 1970–1980 **b)** 1980–1990 SST **c)** 1990–2000 SST **d)** 2000–2010 SST **e)** 2010–2020 SST and **f)** climatological 2022 SST

3.1 Seasonal pattern of SST variability

Seasonal pattern of SST variability was also conducted in the study and the result of the geospatial analysis as shown in Fig. 3 below revealed marked variability with June–July and August (JJA, Fig. 3b) recording the lowest (28.18 °C for the Guinean coast and 24.70 °C in the western Sahel) followed by 28.71 °C for the Guinean coast in fall months of December, January and February DJF (Fig. 3a) and 20.85 °C for the Western Sahel. Conversely, the spring months of March, April, and May MAM recorded the highest as shown in (Fig. 3c) given the variability values of 29.34 °C for the Guinean coast and 20.08 °C in the Sahel while the variability values for the fall months of September, October, and November SON exhibited 28.74 °C for the Guinean coast and 25.62 °C for the low rainfall region (Fig. 3d). Generally, the result of the seasonal pattern indicates that SST in the Guinean Coast was generally low in June, July, and August, JJA as shown in Figure 3b followed by September, October, and November (SON) in Figure 3d. Similarly, March, April and May MAM and December, January, and February (DJF) were characterized by high SST values as presented in Figure 3a and 3c. The anomalously cold SST observed in June July August, JJA and September, October November along the Guinea coast is attributed to the influence of coastal upwelling of cold water from below the sharp, shallow thermocline. The upwelling of nutrients has been reported to impact marine ecosystems negatively (Odekunle and Eludoyin 2008, Lubbeck et al. 2018).

3.2 Rainfall variability

Precipitation variability is one of the most important climate variables that impacts human activities, agriculture, and the environment in West Africa, particularly seasonal rainfall. Therefore, assessing rainfall patterns and variability is critical in managing climate risk and improving resilience.

The analysis of the decadal variability of rainfall was carried out in this study to ascertain the degree of interannual variability of rainfall in the Gulf of Guinea. Although the period of study is from 1970–2022, the analysis was divided into 4 phases namely 1970–1980, 1980–1990, 1990–2000, 2010–2020, and 2022 at ten years intervals as shown in Fig. 4 below.

The results of the geospatial analysis presented above provide an insight into the areas of low and high precipitation concentration with the Western Sahel characterized as a region of low and erratic rainfall. The variability values in the 1970–1980 decade as presented in Fig. 4a are shown in Table 2 below.

Rainfall distribution in five different decades of the Gulf of Guinea is shown in Table 2 with the 1970–1980 (Fig. 4a) recording the lowest rainfall concentration based on the variability values exhibited. There was however an upward trend in the 1980–1990 phase (Fig. 4b) as the variability values improved. In contrast, a reduction in the closing values of 1980–1990 was observed compared to the 1970–1980 era implying low rainfall in the rainfall-abundant regions of the study. 1990–2000 (Fig. 4c) was characterized by a remarkable improvement in rainfall as the variability increased from 21.4–691.4 to 2.071.5–3.371.4 mm. In comparison with the 1990–2000 decadal analysis, the 2000–2010 epoch (Fig. 4d) can be described as a decade of reduced rainfall as the variability values decreased from 21.4–691.4 to 13.9–687.2 mm. The result further indicates that the Western Sahel and the Guinean coast recorded significant improvement in rainfall in 2010–2020 (Fig. 4e) given the fact that the variability values were which is the highest in all the five 5 decades considered in the study (Table 5).

Arising from above, it's obvious that the GOG decadal rainfall pattern was characterized by a high degree of fluctuation and variability with 1970–1980 considered as the decade with the lowest rainfall concentration followed by the 1980–1990 phase. Finally, a cursory look at the 2022

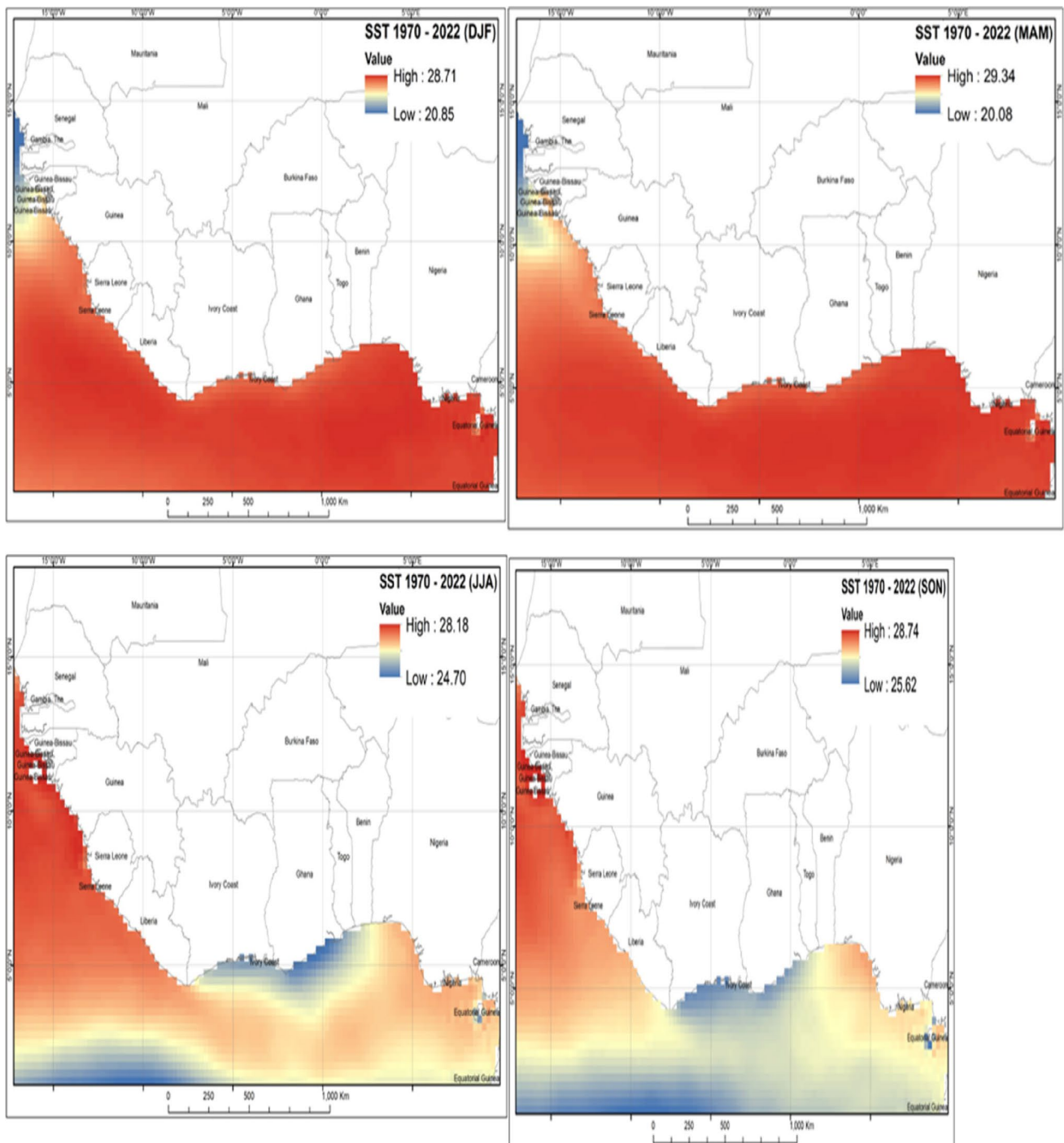


Fig. 3 Seasonal pattern of SST Variability: Climatological **a)** December-January- February SST **b)** June-July August SST **c)** March–April-May SST and **d)** September–October–November SST

analysis as presented in Fig. 4f reveals rainfall reduction in the dry regions as the mean annual contrasted from 21.7- 695.4 in 2010–2020 to 17.4- 659.8 mm in 2022. The rainfall-abundant regions also experienced a drastic reduction as maximum rainfall decreased from 2,7166–3.390.1 to 2557.2–3.229.6 mm in 2022.

The low rainfall variability values shown in the decadal analysis are indicative of drought vulnerability that dominated West Africa. There was however rapid improvement and recovery in rainfall in 1990–2000 while 2000–2010 witnessed reduced rainfall. The 2010–2020 was characterized by increased rainfall both on the Sahel and the Guinean

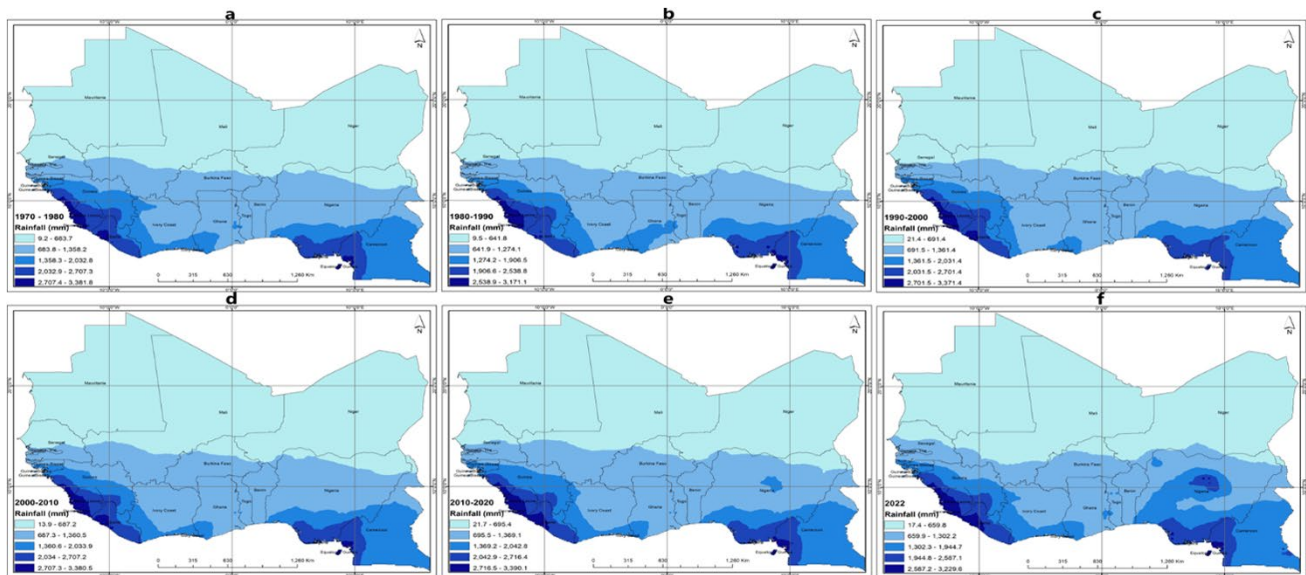


Fig. 4 Decadal pattern of rainfall variability: a-1970-1980; b-1980-1990; c-1990-2000; d-2000-2010; e-2010-2020; f-2022

Table 5 Decadal rainfall variability values(mm)

1970–1980	1980–1990	1990–2000	2000–2010	2010–2020
9.2–6–683.7	9.5–641.8	21.4–691.4	13.9–687.2	21.7–695.4
683.8–1,358.2	641.8–1,274.1	691.5–1,361.4	687.3–1,360.5	695.5–1,369.1
1,358.3–2,032.8	1,274.2–1,908.5	1,361.5–2,031.4	1,360.6–2,033.9	1,369.2–2,042.8
2,032.9–2,707.3	1,908.6–2,538.8	2,031.5–2,701	2,034–2,707.2	2,042.9–2,716.4
2,707.4–3,381.8	2,538.9–3,171.1	2,071.5–3,371.4	2,707.3–3,38.5	2716–3,390.1

coast followed by the year 2022. The increased rainfall observed in 2010–2020 and 2022 are indicative of wet years and flood risk in the study domain.

3.3 Seasonal pattern of rainfall variability

In many hydro-climatological investigations, precipitation is a crucial meteorological parameter that determines regional and global climate change risks (Soltani et al. 2016). Evidently, precipitation is very critical in the land surface-water balance studies as it replenishes soil moisture, supports vegetation growth and, given its role in replenishing soil moisture, supports vegetation growth, and in keeping surface flows and groundwater resources and serving as a link between atmospheric and land surface processes (Alimonti et al. 2017; Sarkar et al. 2021 and Abed-Elmdoust 2016). Therefore, seasonal pattern of rainfall variability assessment and distribution is imperative in mitigating against the impact of climate change and improving resilience to extreme weather events. The benefits of analyzing seasonal rainfall variability cannot be overemphasized given its role in climate risk management in the agricultural and water resources sectors.

The outcome of the geospatial analysis conducted on seasonal patterns of rainfall variability as shown in Fig. 5 above indicates almost total dryness along the West African Sahel given the variability values of 0–23.5 for DJF in Fig. 5a. In the coastal regions, rainfall ranged from 47.2 to 70.6 to 117.7 mm. Although this is the peak of the dry season, the coastal regions experience rainfall at any time of the year. March April and May MAM (Fig. 5b) represents the commencement of the rainy season in most parts of West Africa which accounts for the high variability values from 0.4–50.2 mm to 199.6–249.2 mm in the coastal regions.

The overall improvement of rainfall in the JJA (Fig. 5c) as demonstrated in Table 6 is directly associated with the peak of the rainy season in West Africa. JJA is also characterized by increased flash floods in many regions in West Africa as shown by the high variability values in Table 6 above. However, rainfall continues to improve in the coastal regions particularly Nigeria, Sierre Leon, Liberia, and Cameroun, with 3.1.4–392.8 mm as maximum rainfall for the months of September–October and November (SON, as shown in (Fig. 5d) with September as the peak of the rainy

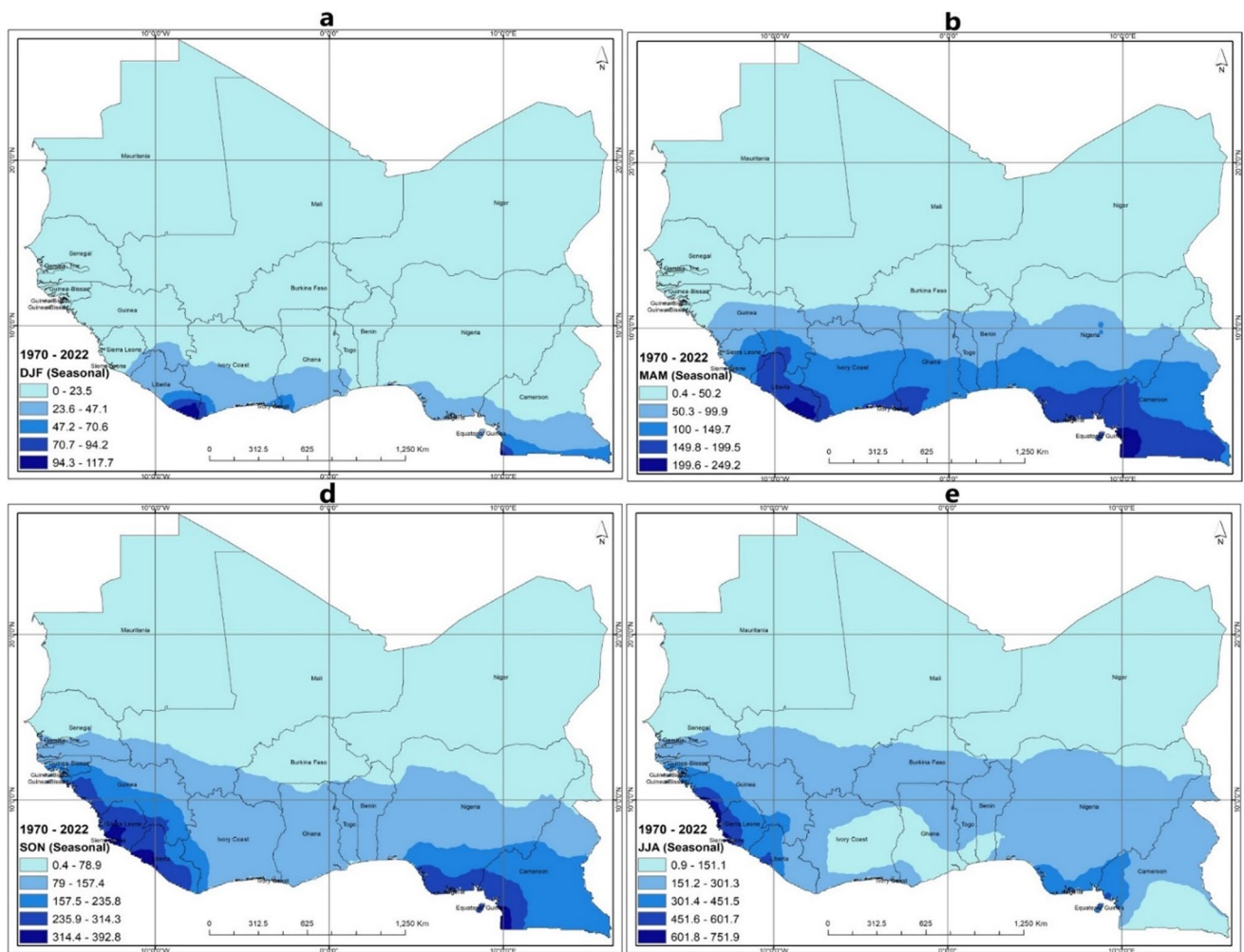


Fig. 5 Seasonal pattern of rainfall variability over the Gulf of Guinea: a: DJF; b: MAM; c: JJA; d: SON

Table 6 Seasonal pattern rainfall variability values(mm)

December-January and February DJF	March April May MAM	June July and August JJA	September October and November SON
0–23.5	0.4–50.2	0.9–151.1	0.4–78.9
23.6–47.1	50.3–99.9	151.2–301.3	79–157.4
47.2–70.6	100–149.7	301.4–451.5	151.5–235.8
70.7–94.2	149.8–199.5	451.5–601.7	235.9–314.3
94.3–117.7	199.6–249.2	601.8–751.9	314.4–392.8

season, the reversal was what played out in the Western Sahel, further reduction in rainfall was experienced given the fact that the variability value of 0.9–151 mm recorded previously in JJA further decreased to 0.4–78.9 mm. In West Africa, SON is normally the transition from the wet to the dry season.

3.4 Statistical analysis of sst-rainfall teleconnection in West Africa

Statistical analysis of annual sea surface SST and rainfall teleconnection of the sample points namely Abidjan, Accra, Banjul, Conakry, Cotonou, Dakar, Doula, Monrovia,

Freetown, Lome, and Lagos located along the Gulf of Guinea was carried out using standardized SST anomalies and Regression analysis for the study period 1970–2022 starting with Abidjan in that order. It is important to

emphasize that the ERA5 dataset was used for the teleconnection analysis.

The standardized SST and rainfall anomaly and Regression analysis for Abidjan as shown below in Fig. 6 indicates

Fig. 6 Regression and Standardized Anomaly Index of SST-Rainfall teleconnection in for Abidjan Cote'd Ivoire

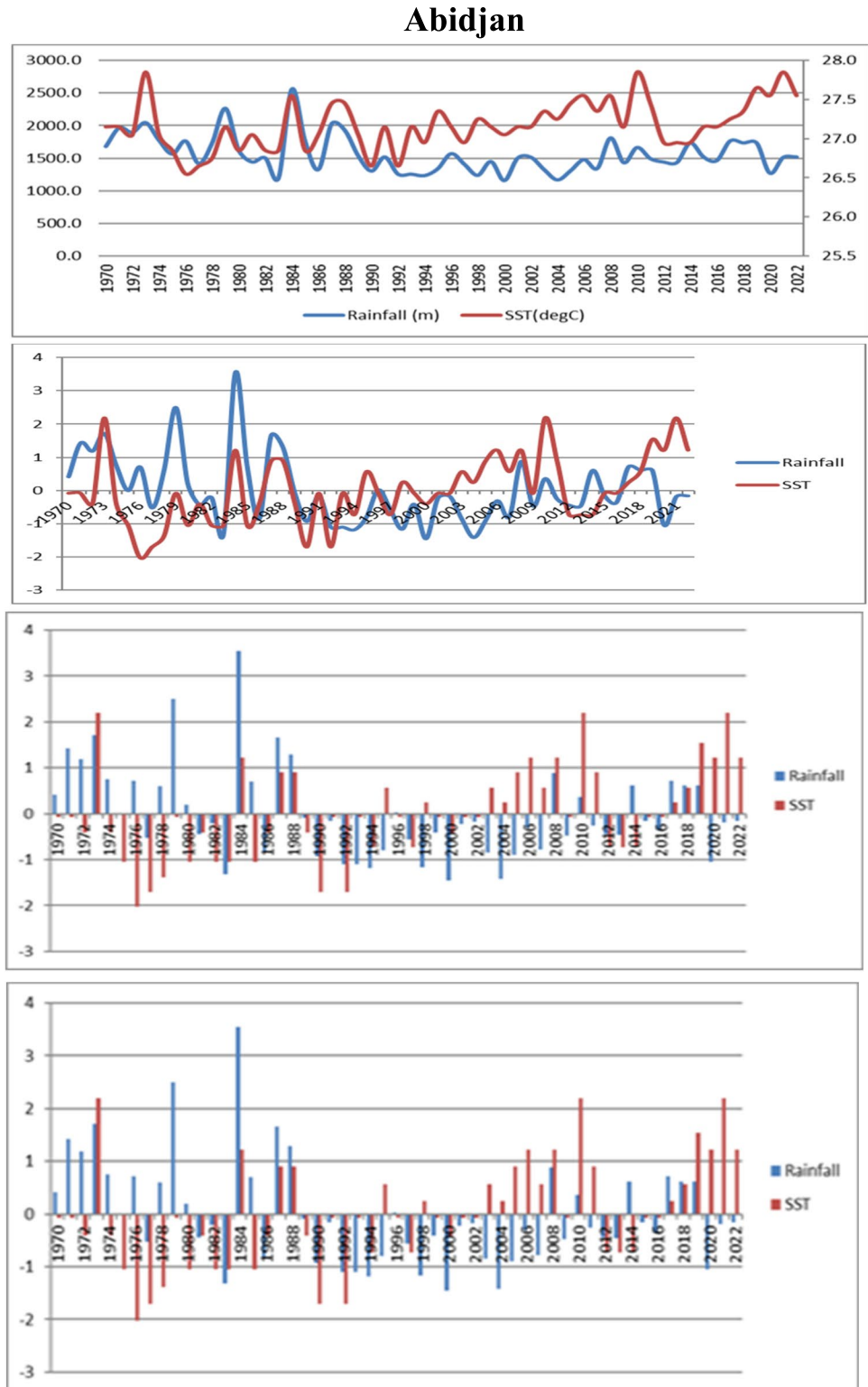
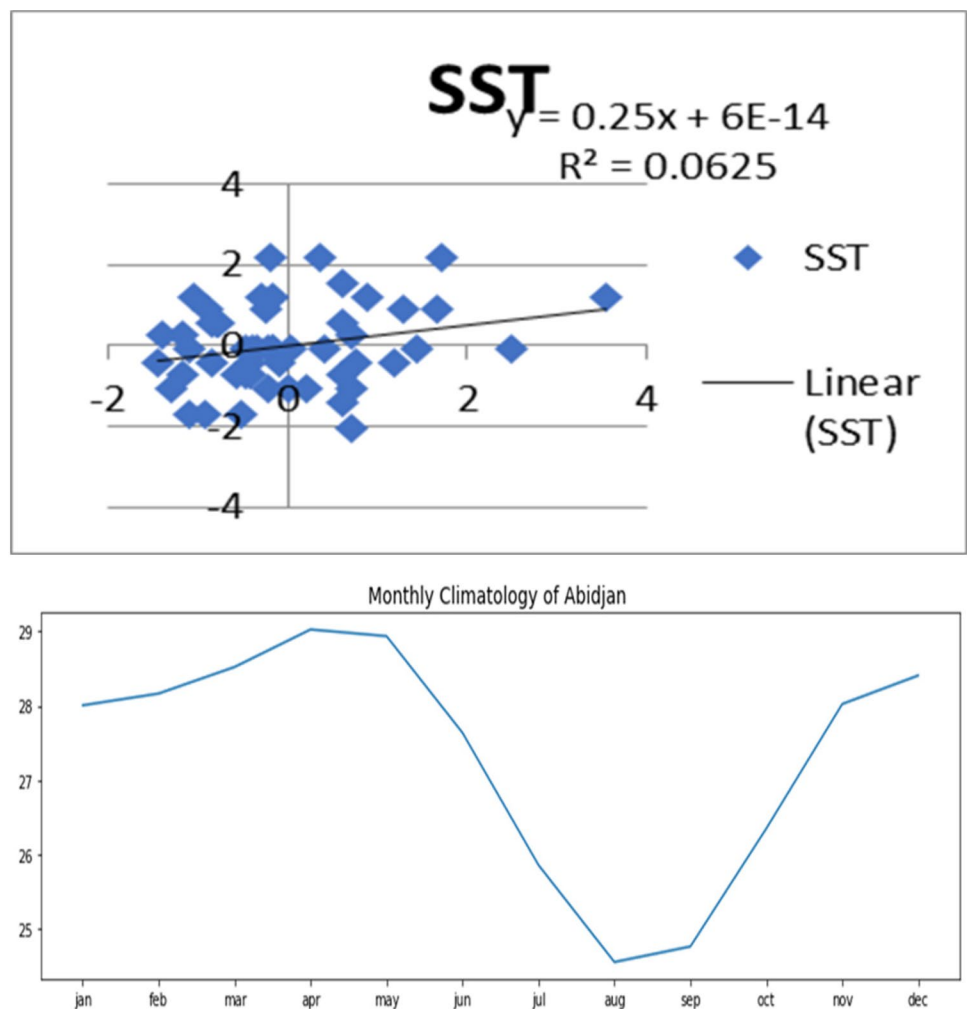


Fig. 6 (continued)



that the early 1970s and 1980 had negative SST values indicative of anomalously low SST with implication on rainfall while positive SST observed late in 2000 signifies warm tongue which could also positively influence rainfall in the station. The model summary result of the regression analysis was however positive with a coefficient of determination of $R^2=0.0625$. The standardized rainfall anomaly agrees with the trend analysis as negative SST was recorded in the late 1970s while positive SST values were observed from 2020–2022 indicative of increasing rainfall. The analysis of the monthly SST climatology further revealed that SST increased in the winter and spring months of January, February, March, April, and May while a downward and anomalously low was recorded in the summer months of June, July, August, and September which lends credence to the decadal and seasonal SST pattern earlier presented.

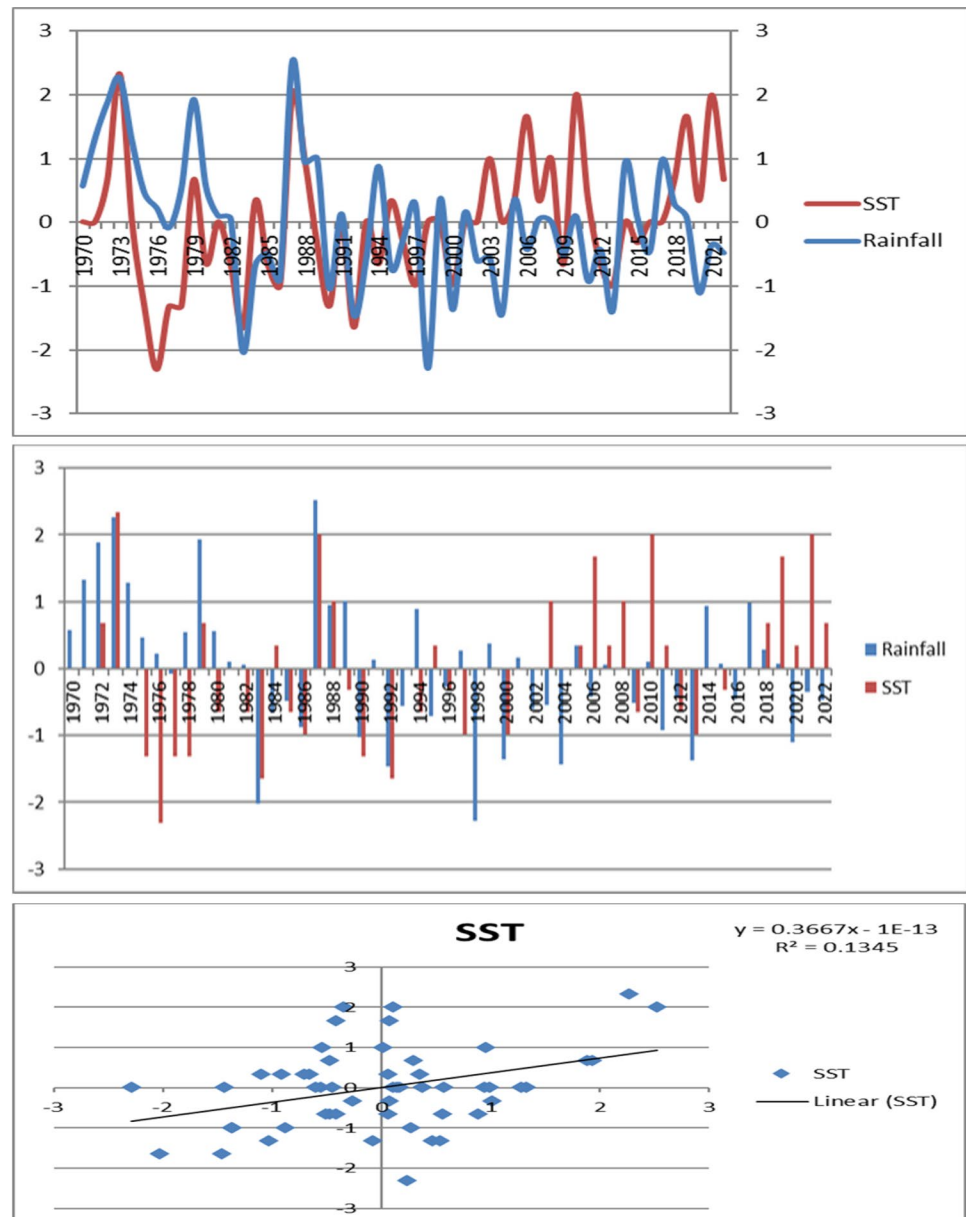
In Accra Ghana, the trend analysis indicates negative SST in 1976–1979 with a corresponding impact on rainfall during the period. Similarly, rainfall anomaly was recorded in 1997 implying anomalous SST. Furthermore, the positive rainfall trend that characterized the station from early 2000

to 2022 represents an increased rainfall trend. The summary result of the regression model indicates a statistically significant relation given the coefficient of determination $R^2=0.1345$ as ($P < 0.05$) as shown in Fig. 7d above. The monthly climatology plot in Fig. 7e shows anomalously low SST in the summer months of June, July, and August.

The trend analysis for Cotonou in Benin as shown in Fig. 8a above reveals a significant decrease in both SST and rainfall in 1970 and 1980 decade which indicates the influence of SST on rainfall in the Guinean coast. However, an upward SST trend was observed in early 2000 before decreasing sharply again in 2014 and 2016. The summary result of the regression analysis in Fig. 7d indicates a weak and statistically insignificant given the coefficient of determination $R^2=0.0151$ ($P < 0.05$). The monthly climatology in Fig. 7e shows again anomalously low SST in June, July, August, and September.

Marked temporal annual variability continues for both SST and rainfall as shown in Fig. 9. SST was all time low in 1972–1974 before accelerating in 1984 with a corresponding increase from early 2020 as shown in

Fig. 7 Regression and Standardized Anomaly Index of SST-Rainfall teleconnection for Accra Ghana



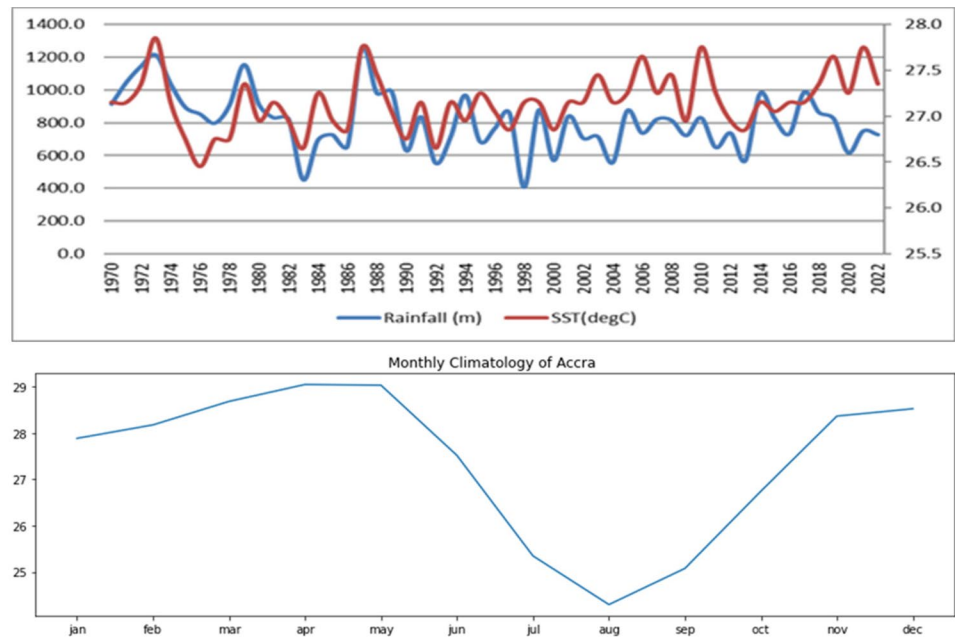
(Figs. 9b and c). Rainfall fluctuates all through the period recording its lowest in 1984 and from 2002–2009 before showing signs of recovery in 2001. The regression result indicates a weak correlation coefficient of (0.00266) in Fig. 9e which is not statistically significant at a 0.05 confidence level ($p < 0.05$). The monthly climatology in Fig. 7e shows again anomalously low SST in June, July, August, and September.

In Fig. 10 above, significant variation in both SST and rainfall was observed all the period of study in Dakar. The result further indicates a rapid downward trend in rainfall. As shown in Fig. 10a. The standardized SST and rainfall anomaly computed for Dakar as shown in Figs. 10b and c indicates that the early 1970s and 1980 were characterized

by SST anomalies indicative of decreased SST and erratic rainfall and dryness while positive SST was observed late in 2000 while the positive values are considered upward trend of rainfall. The model summary result of the regression analysis in Fig. 10d revealed a weak and insignificant correlation of 0.006 at a 0.05 confidence level ($p < 0.05$). This implies that other variables outside the regression model could be responsible for the observed variability in rainfall in the SST. The monthly SST climatology showed anomalously low SST in the summer months of June, July, and September thus agreeing with the SST and rainfall seasonal analysis as shown in Fig. 10e above.

The trend analysis for Monrovia in Liberia reveals decreasing SST in 1976, 1994, 1990, 1992, 2008–2014 while

Fig. 7 (continued)



the increasing trend was recorded in 1972 and 1974, 2010, 2020, and 2022 as shown in Fig. 11b and c below. Rainfall anomaly recorded in 2012–2014 which corresponds to anomalous SST. Again, the analysis showed marked inter-annual variability in both meteorological variables. The standardized SST and rainfall analysis indicate negative SST and rainfall in 1972 and 2008 implying anomalously dry years. However positive SST was recorded for the period 2018–2022. The summary result of the regression analysis as shown in Fig. 11d indicates a coefficient of determination $R^2=0.092$ was statistically significant at 0.05 significance level which we can infer that SSTA can be used as an explanatory variable in predicting rainfall in the station while the monthly climatology of the mean SST shows that SST was anomalously low in July August and December as captured in Fig. 11e

The trend analysis for Conakry in Guinea reveals decreasing SST in the 1970s and 1990s while the upward trend was observed in early 2000 and late 2000, The station exhibited the same trend observed in other cities along the West African coast considered in this study characterized by abnormally low SST in the 1970s and 80 which correspond well with declining rainfall as shown in Fig. 12a. The SST and rainfall anomaly indicates that 1974–1976 and later 1994 were periods of decreasing rainfall and dryness as shown in Fig. 12b and c, although increasing trend of SST and rainfall was observed from 2018–2022. The summary result of the regression analysis indicates a coefficient of determination $R^2=0.007$ which is insignificant at 0.05 as shown in Fig. 12d. The monthly climatology plot indicates anomalously low SST in January February and March before peaking up in April, May, June July. Anomalously low SST

was observe in August and September while November and December were associated with an increase in SST as shown in Fig. 12e.

The SST and rainfall trend analysis for Doula Cameron as shown in Fig. 13a above reveals spatial variation for both SST and rainfall. The standardized rainfall anomaly indicates that 1974 and 1976 were years in which SST was negative as shown in Fig. 13b and c. However, 2002 -2006 were also periods of positive SST while abnormal rainfall was also recorded in 2018. The regression model shows a downward and negative slop with a coefficient of determination $R^2=0.08$ as shown in Fig. 13d which is statistically insignificant at 0.05 confidence level while the monthly climatology shows downward slop in the months of June, July, August, and September as captured in Fig. 13e

The result of the SST rainfall teleconnection for Freetown Sierre Leon as shown in Fig. 14a revealed spatial variability with anomalously dry conditions from 1993 to 1994 as rainfall was negative (Fig. 14b and c). Increasing SST was also observed from 2003 to 2012 with corresponding upward trend in rainfall. The summary regression model shows a positive correlation with an upward slop of 0.0683 as coefficient of determination which is statistically significant at 0.05 confidence level as captured in Fig. 14d while the monthly climatology of shows anomalously low SST in the months of February with a peak in March, April May. The summer months June July and August were characterized by anomalously low SST while the fall months of October, November and December were associated with high SST.

The statistical analysis of rainfall and SST teleconnection conducted for Lagos Nigeria as shown in Fig. 15a above exhibited the same pattern and trend of SST and rainfall

Contonou

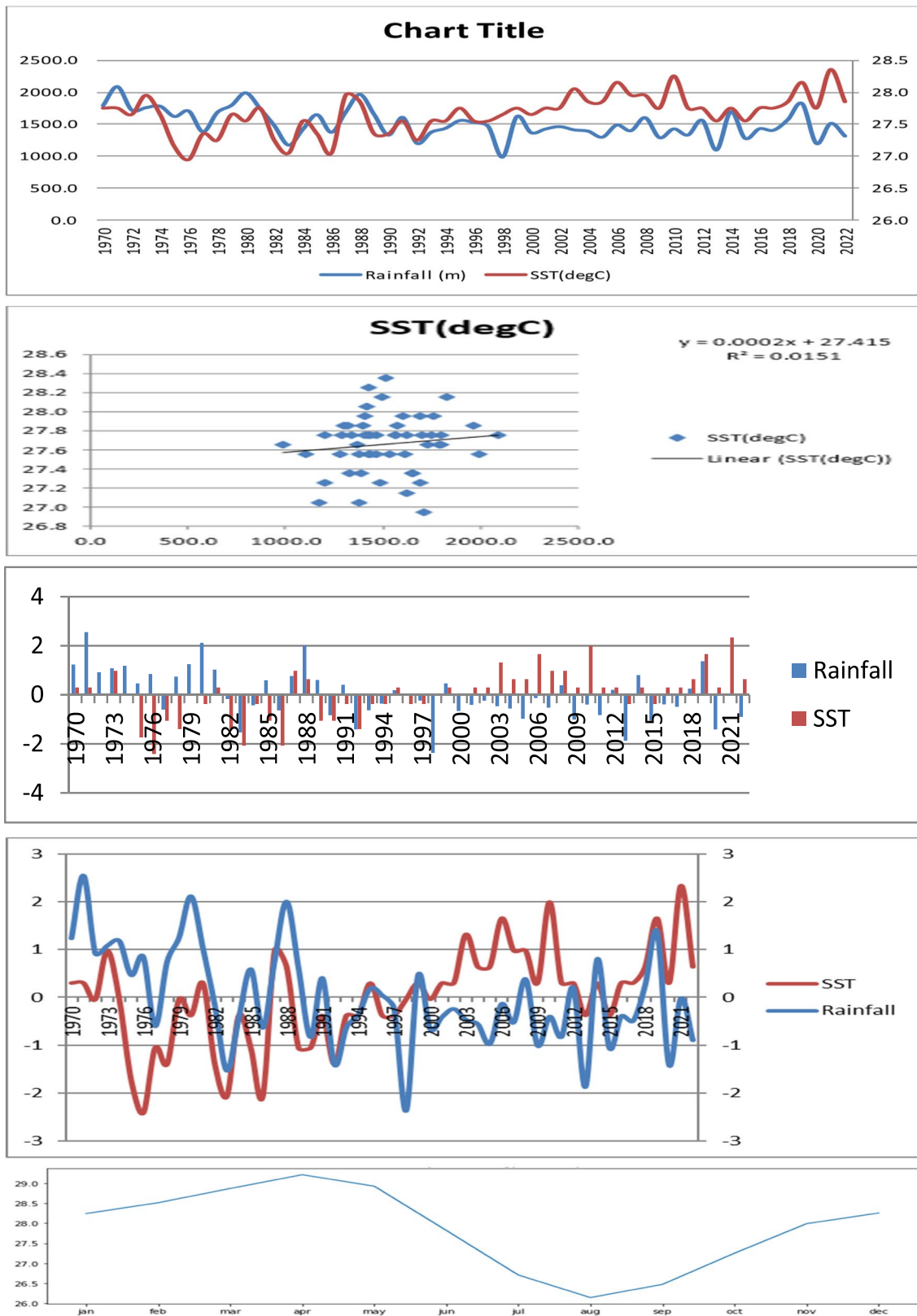
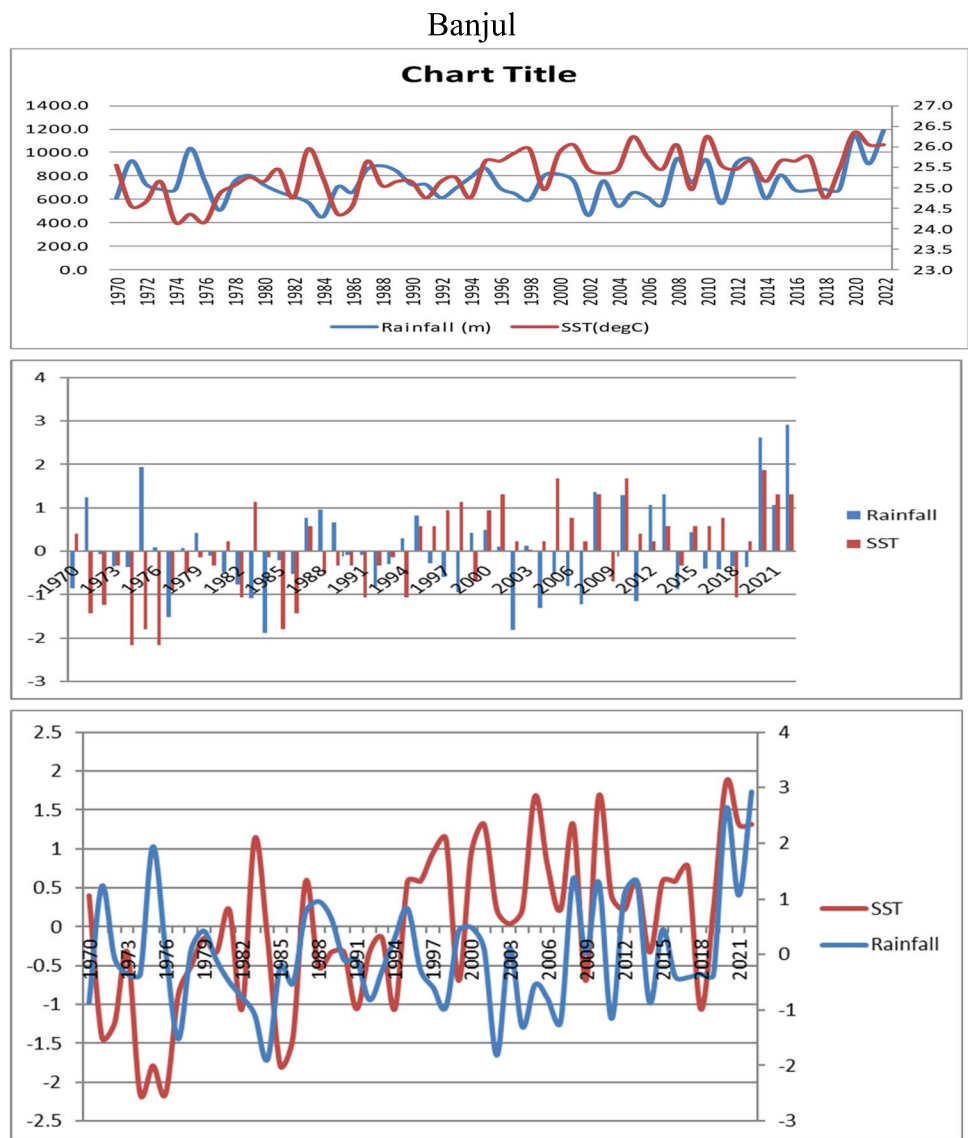


Fig. 8 Regression analysis and Standardized Anomaly index of SST-Rainfall Teleconnection over Banjul

Fig. 9 SST and Rainfall trend analysis Banjul Gambia



like other coastal cities in West Africa. SST was anomalously low as captured in Fig. 15b and c in 1974–1976 and later assumed an upward trend from 2004–2022 implying periods of increased wet years. The summary regression statistics was positive with a coefficient of determination of $R^2=0.0848$ at 0.05 confidence level indicating a statistically significant relationship and teleconnection as shown in Fig. 15d while the monthly climatology in Fig. 15e shows that SST was anomalously low in the months of June, July, August, and September corresponding well with the decadal and seasonal SST pattern earlier explained. This explains why SST can be used as explanatory variable to predict rainfall variability in the summer months of June, July, August and September in Lagos Nigeria and across West Africa.

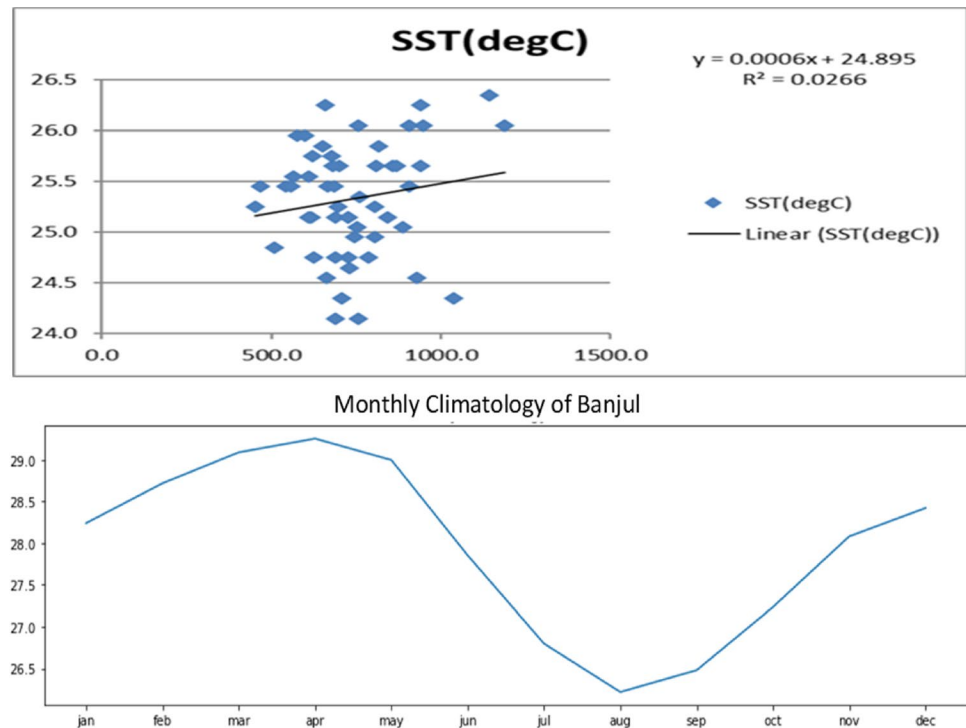
The result of the trend analysis for Lome as presented in Fig. 16 above indicates that 1974–1978 were anomalously dry years as SST was negative. Also, abnormal rainfall was

observed from 1996–1998 implying increased drought episodes. However, there was an upward SST and a progressing SST trend from 2018–2022. The summary regression output showed a positive correlation at insignificant at $r=0.0043$. The monthly climatology reveals anomalously low SST in June, July, August, and September with peaks in March, April, May, October, November, and December.

The composites of the SST anomaly, wet and dry years over the Gulf of Guinea is shown in the table below.

The table above summarizes wet and dry years over the Gulf of Guinea and the accompanying years of SST anomaly showing the influence of ENSO events which could be disastrous to the water resources and the agricultural sectors in the study domain. The Wet years as shown in Table 7 are years of El Nino which is associated with warmer SST anomaly over the gulf of gulf of Guinea and driven by ENSO in the central and Pacific. The resultant effect manifests in

Fig. 9 (continued)



wetter years experienced in West Africa while La Nina conditions favor Cold SST anomalies resulting in drier and sort rains years as demonstrated in the various statistical analyses. The outcome of this analysis as shown in this study is consistent with previous studies conducted by (Akinsanola et al. 2018; Biao and Alamous 2018).

4 Discussion of findings

4.1 Decadal SST variability

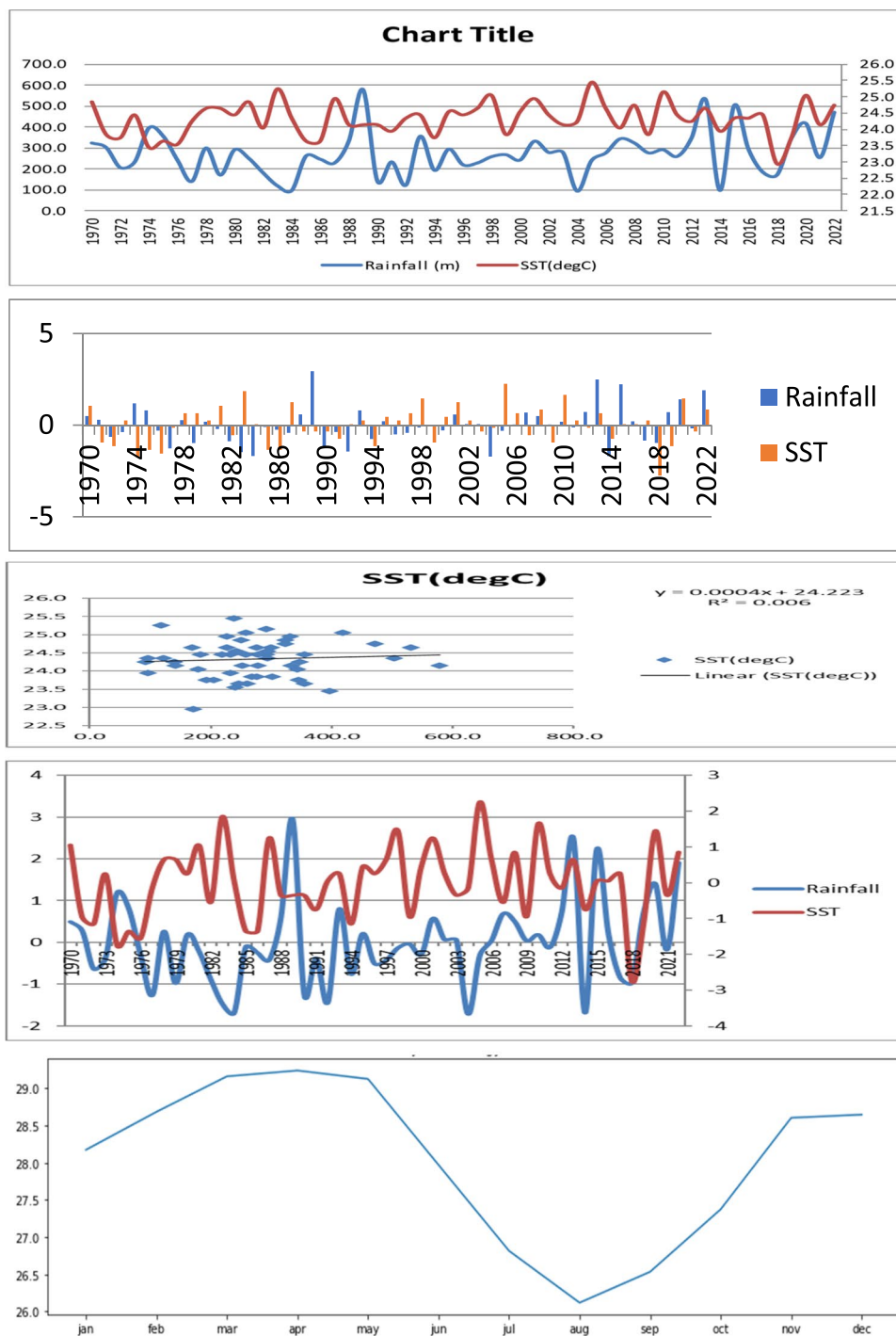
It is well known that variations in sea surface temperatures (SSTs) are partly responsible for large anomalies of seasonal mean rainfall over many areas of Africa. Knowledge of these teleconnections is increasingly used to provide probabilistic predictions of such rainfall anomalies, to help vulnerable African communities, and assist national resource management (Lubbecke et al. 2018). The outcome of the decadal analysis of SST variability in the Gulf of Guinea was generally on the increase with 2010–2020 as the period with the highest warming followed by 2022 (28.91 °C) while the decade with the lowest SST was 1980–1990 followed by the decade of 1990–2000 phase. with consecutive increases.

Generally, SST decreases westward and the northern parts with a significant increase in the south and Eastern axis of the Gulf of Guinea. The 1970 -1980 and the 1990 periods are associated with low SST which corresponds well with

the periods of different drought episodes that characterized West Africa in the early 1970s and 1980s. The dominant variability of SST is seasonal. Studies has shown that SST anomaly arises from several mechanisms at different time-scales and that Inter-annual SSTA variability at a given location tends to be greater for some months of the year than for others, and also varies from place to place (Czaja 2004). The warming trend shown in this study is consistent with other studies made during the satellite era (1979–2012) as cited in the Intergovernmental Panel on Climate Change (IPCC 2022 special report Ocean. Seas and cryosphere).

The result further shows that coastal SST has increased rapidly over the study period leading to intensification of rainfall anomalies while cold SST dominates the Western part leading to reduced rainfall and drought. Extensive studies conducted by Odekunle and Eludoyin 2008; Akinbobola et al. 2015, Rodwell 2013; Vizy and Cook 2001 and Giannini 2016 affirmed the existence of interannual variability of SST and its attendant influence on the regional climate system of the Guinean Coast and the Sahel. Furthermore, the pattern of decadal variability observed in this study confirms the influence of El-Nino phenomenon on the tropical Atlantic Ocean and the continuous rise of SST of the GOG. The warming pattern demonstrated in this study An ENSO episode established in this study is a robust response to anthropogenic induced climate change with significant impact on the climate system.

Fig. 10 SST and rainfall trend and anomaly for Dakar

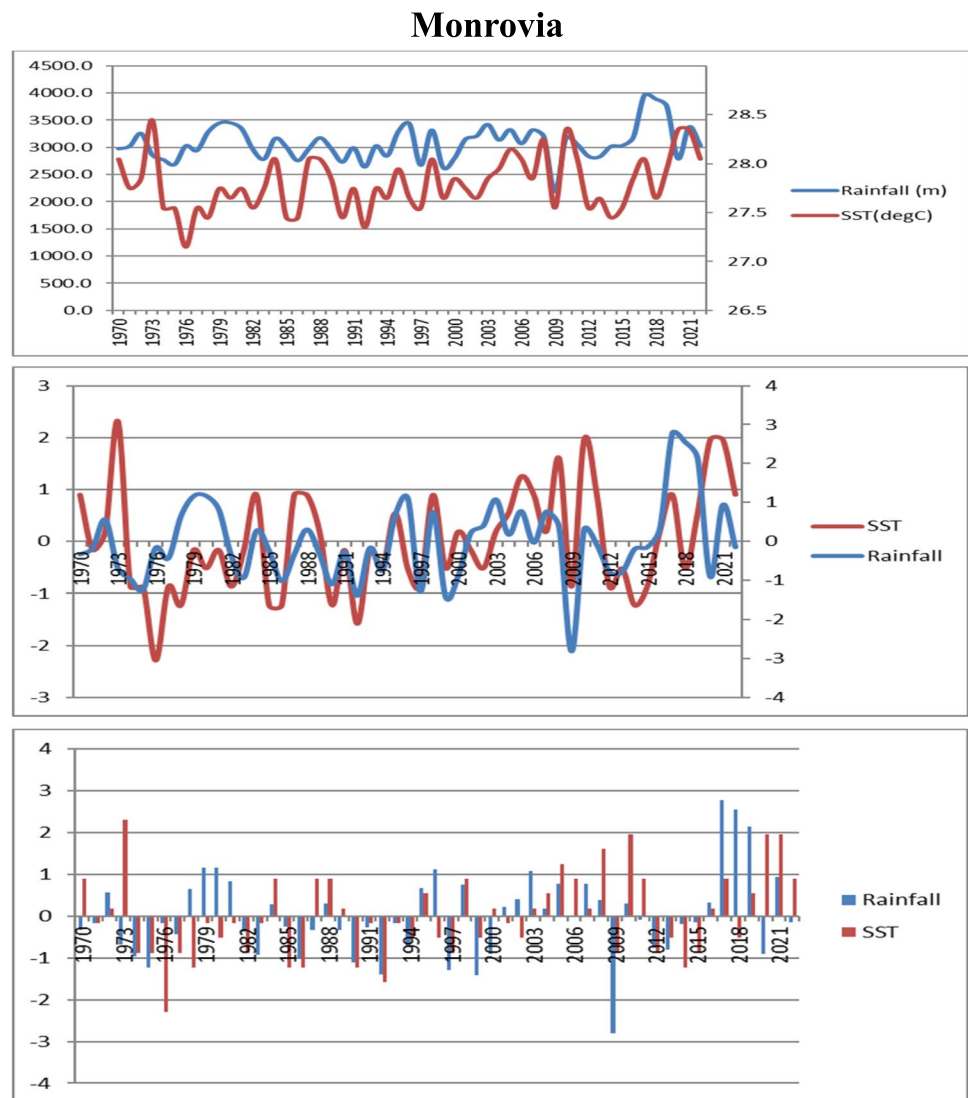


4.2 Seasonal SST variability

The analysis of the seasonal pattern of SST variability conducted in this study indicates anomalously low SST (28.18 °C and 2o) for the summer months of June July and August, JJA 29.34°C, 28.71 °C and 28.74°C for March

April May, MAM, December, January February DJF, and September, October November SON respectively for the Guinean Coast. In the Southwestern flank bordering the Sahel region, the variability values are 20.08°C for MAM, 20.85°C for DJF while JJA recorded 24.7 °C and SON 25.82°C over the Guinean Coast in the months of July

Fig. 11 Regression and Standardized Anomaly Index analysis of SST-Rainfall teleconnection SST-Rainfall for Monrovia

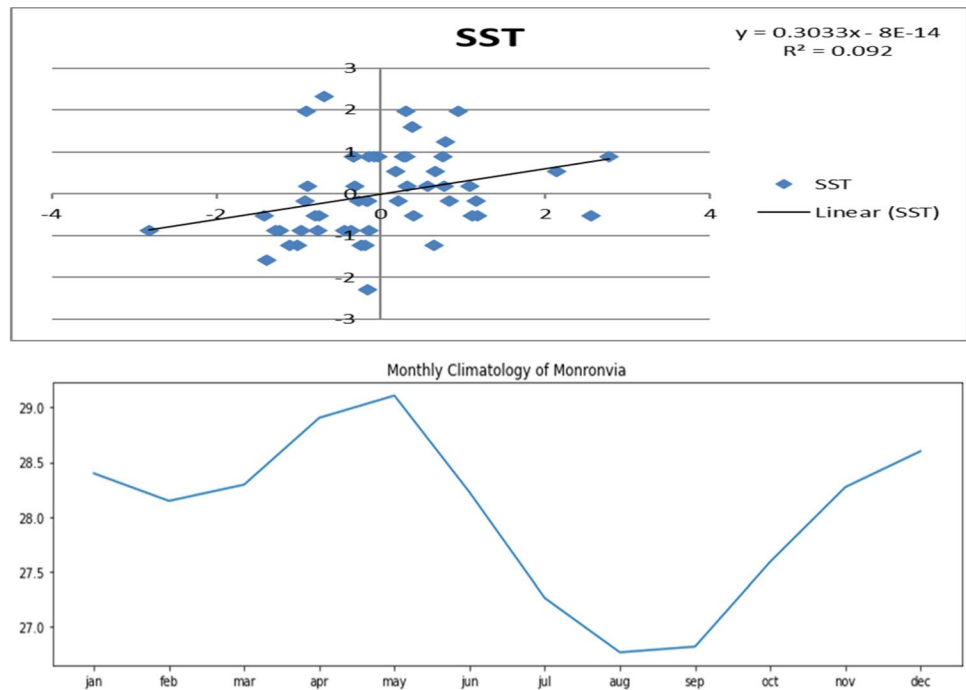


and August and highest in March, April and March MAM followed by December, January and February DJF and September, October, and November SON respectively. The anomalously cold SST observed in the months of June July August, JJA and September, October November along the Guinea coast is attributed to the influence of coastal upwelling. The coastal upwelling is associated to gyre circulation and the Guinean current in the North South equatorial current in the south. What is not clear however is the mechanism that drives the cold water which is the focus of ongoing scientific investigation as previous studies are yet to fully resolve teleconnection between local winds and upwelling effect (Odekunle and Eludoyin 2008; Rowell 2013).

The observed SST pattern demonstrated in this study indicates that the anomalously cold SST emanates from the advection of cold upwelled water that flows from the south equatorial current and the northward extension of the

cold Benguela current that develops into an equatorial current during the summer leading to a shoaling of the Thermocline near the northern coast of the GOG and is what triggers the upwelling effect. The outcome of the decadal and seasonal SST anomalies in this study agrees with the explanation espoused above as causative factor responsible for the anomalously cold SST observed in the JJA and SON. The observed seasonal pattern of SST shown in this study corroborates earlier studies conducted by the Mercator operational oceanographer in 2006 cited in Odekunle and Eludoyin 2008, Rowell 2013 and Vizy and Cook in 2001, Dippe et al. (2018) reports that the cold tongue in the summer months of June, July and August manifest due to the northward migration of the inter tropical convergence Zone ITCZ and its interaction with the south trade winds which in turn leads to the shoaling of the thermocline. It is this process that gives rise to the development of upwelling phenomenon that persist up to September.

Fig. 11 (continued)



Furthermore, the pattern of the decadal and seasonal SST variability observed in the study lends credence to the much-publicized anthropogenic induced global warming as stated in the (IPCC 2022 WG II 4R6 report). The study revealed that between 1970–2022, SST increased by an average of 0.5° with 2010–2020 as the decade with the highest SST variability values.

4.3 Decadal pattern of rainfall variability

Precipitation variability is an important climate factor that impacts human activities, agriculture, and the environment in West Africa. The outcome of the decadal rainfall variability from 1970–1980 shows a maximum of 2.707.4–3.81 mm with Nigeria, Cameroon, Guinea, Sierre-Leon, and Liberia as areas of major concentration. Area with latitude 20° N constitute the low rainfall region. In the second decade, 1980–1990, was characterized by a period of high rainfall variability as significant reduction in rainfall was observed declining from 2.7074–3.381.8 mm in the 1970–1980 phase to 1.906.6–2.538.8 mm in the 1980–1990 phase. The pattern of rainfall variation observed in the 1980–1990 era synchronized well with the decadal pattern of SST in 1980–1990. In the discussion on SST pattern, mention was made of anomalously low SST between 1970–1980 and 1980–1990. Remarkably, the anomalously low SST reported for the first and second decade correspond well with the rainfall variability of the 1980 decade thus providing further insight on the SST rainfall teleconnection over the Gulf of Guinea which is the motivation for the study.

The pattern of SST-rainfall teleconnection revealed in this study supports previous studies by Rodwell 2013; Vizy and Cook 2001; Vizy and Cook 2001; Nicholson 2013; Akinbobola 2015 and Meynadler et al. 2016 on recent air–sea coupling of West Africa Precipitation.

Rainfall variability for the period 1990–2000 witnessed remarkable improvement in both the Sahel and the Guinean coast. The variability values increased from a minimum of 21.4–691.4 mm to 2.7101.5–3.371.4 mm with areas of high concentration been around Sierre Leone, Liberia, Nigeria and the borders with Equatorial Guinea. The Western Sahel from Senegal experienced rainfall recovery as the variability values increased from 9.5–641.6 mm in the preceding phase (1980–1990). The improvement in rainfall recorded this period is in response to accelerated ocean warming evidenced by SST over the tropical Atlantic during the period of 1990–2000.

The 2000–2010 decade was also characterized by intense rainfall in the Guinean coast as the variability values increased to 2.707–3.380.5 mm. The high rainfall recorded this period could be attributed to increased SST, topography, and the West Africa Monsoon WAM and the position of the ITCZ as previously reported by (Akinsanola and Zhou 2019, Grist and Nicholson 2001). Conversely, the regions around the Western Sahel experienced rainfall reduction with values ranging from 13.0–687.2 mm. The observed decline in rainfall in the Western Sahel could be explained by the weaker easterly jet (TEJ) and weaker low level southerly monsoon flow, equatorial Westerlies, and the position of

Conakry

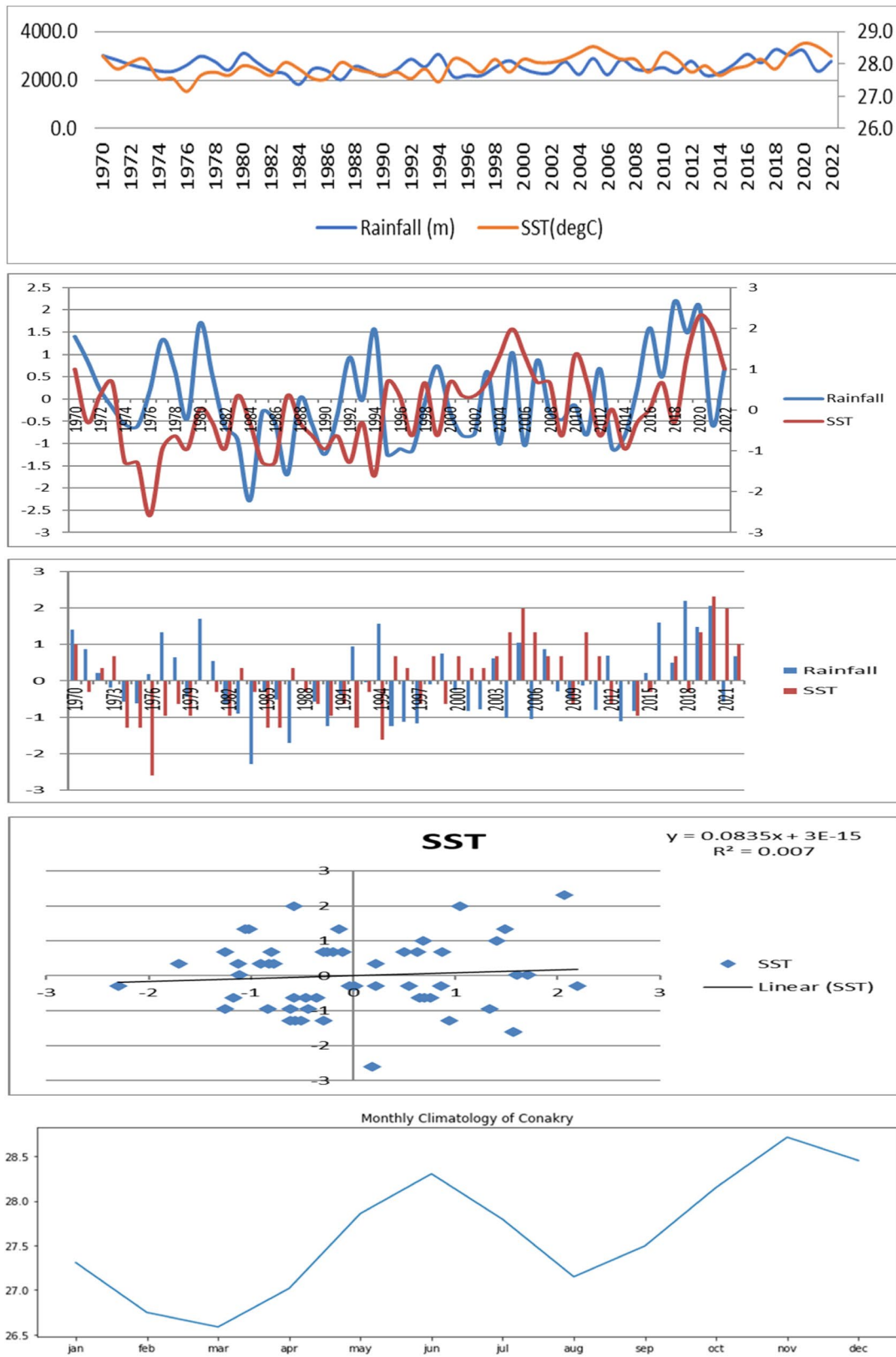


Fig. 12 Regression and Standardized Anomaly Index analysis of SST-Rainfall teleconnection SST and Rainfall for Analysis Conakry Guinea

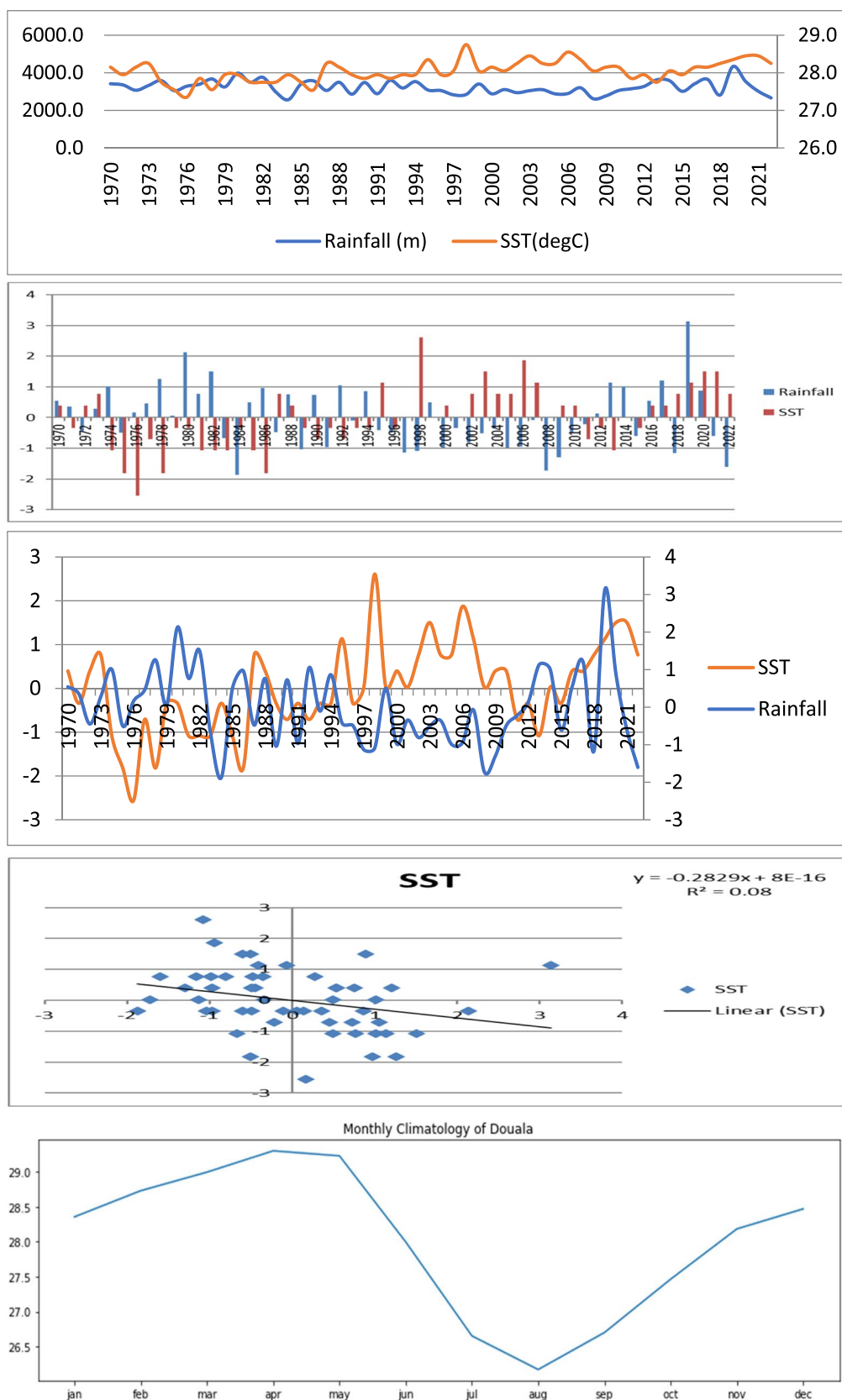


Fig. 13 Regression and Standardized Anomaly Index analysis of SST-Rainfall Teleconnection for Doula, Cameroon

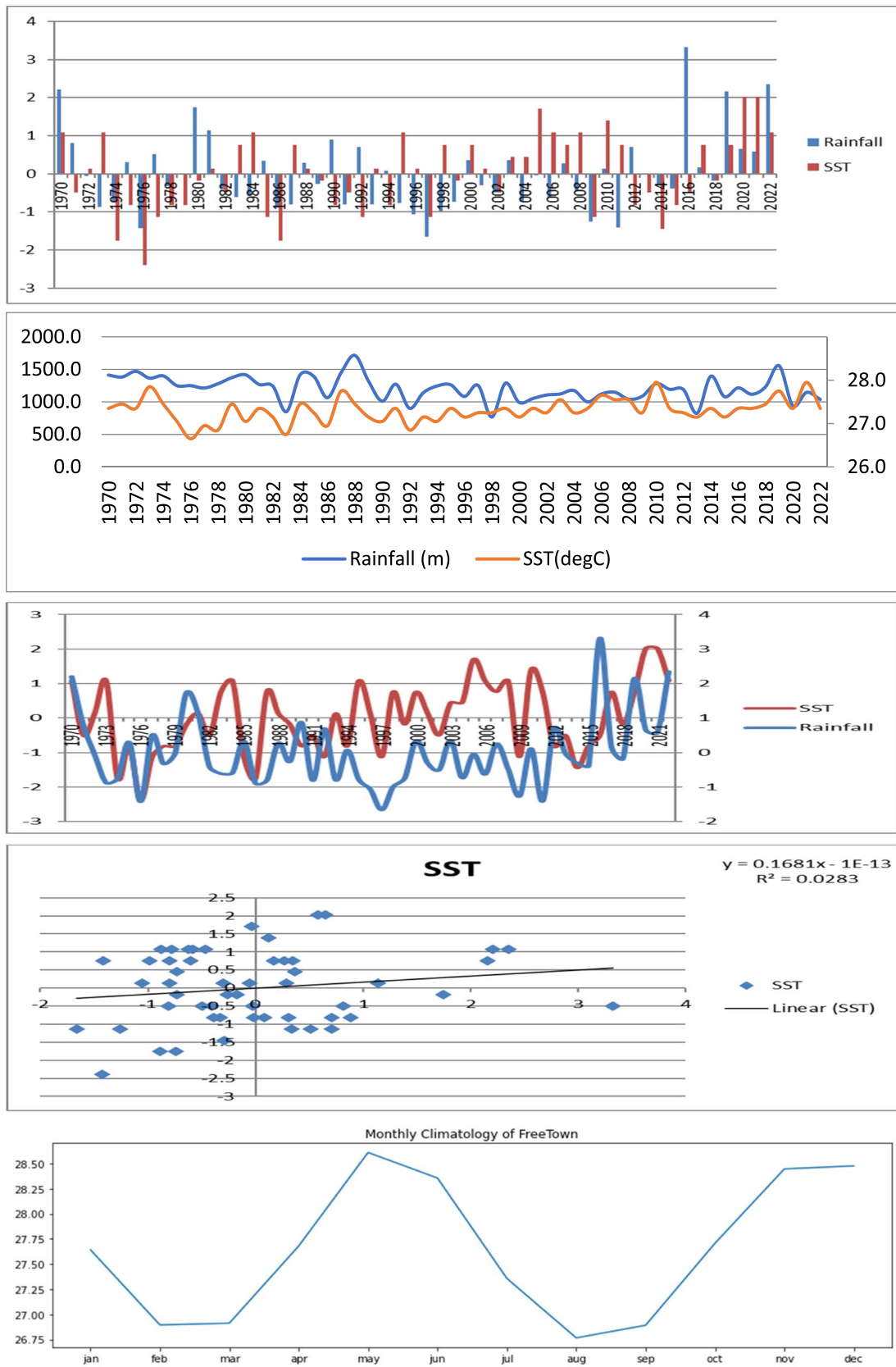
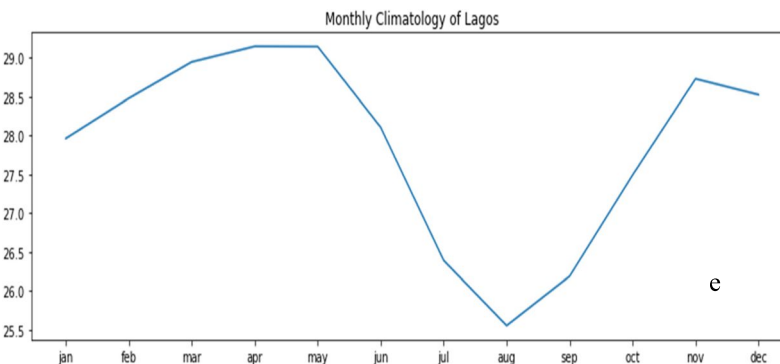
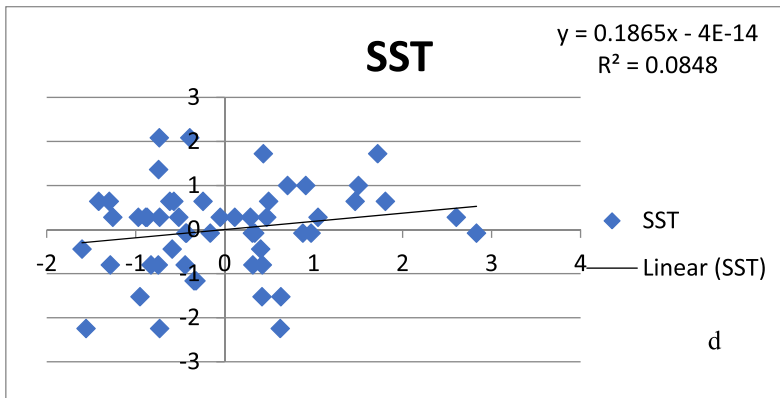
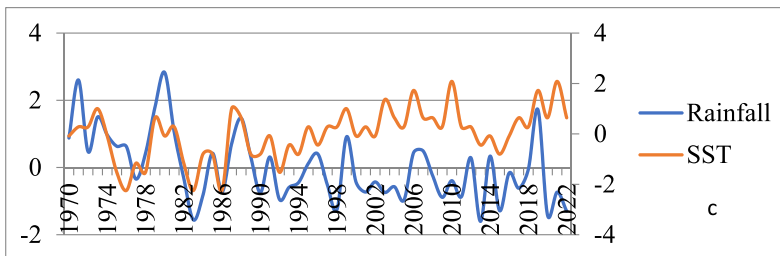
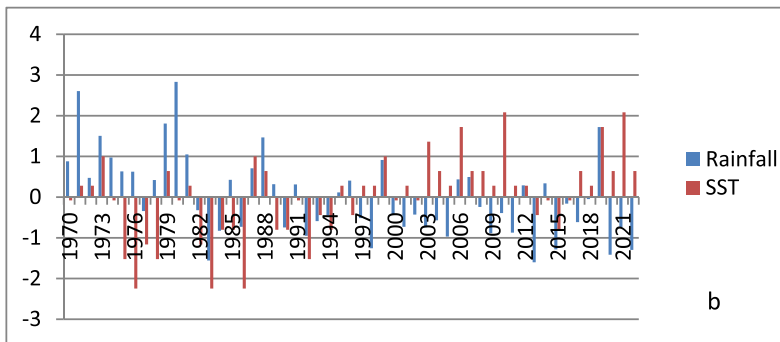
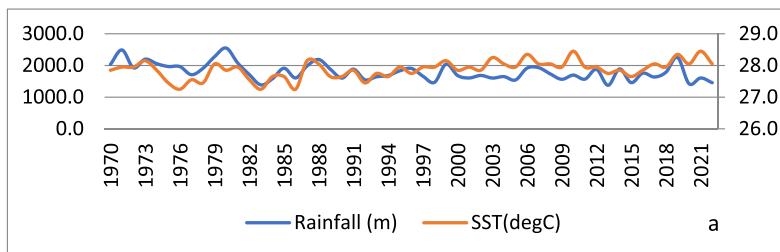


Fig. 14 Regression and Standardized Anomaly Index o analysis of SST-Rainfall teleconnection SST-Rainfall for FreeTown

Fig. 15 Regression and Standardized Anomaly Index of SST-Rainfall Teleconnection over Lagos Nigeria

Lagos Nigeria



Lome

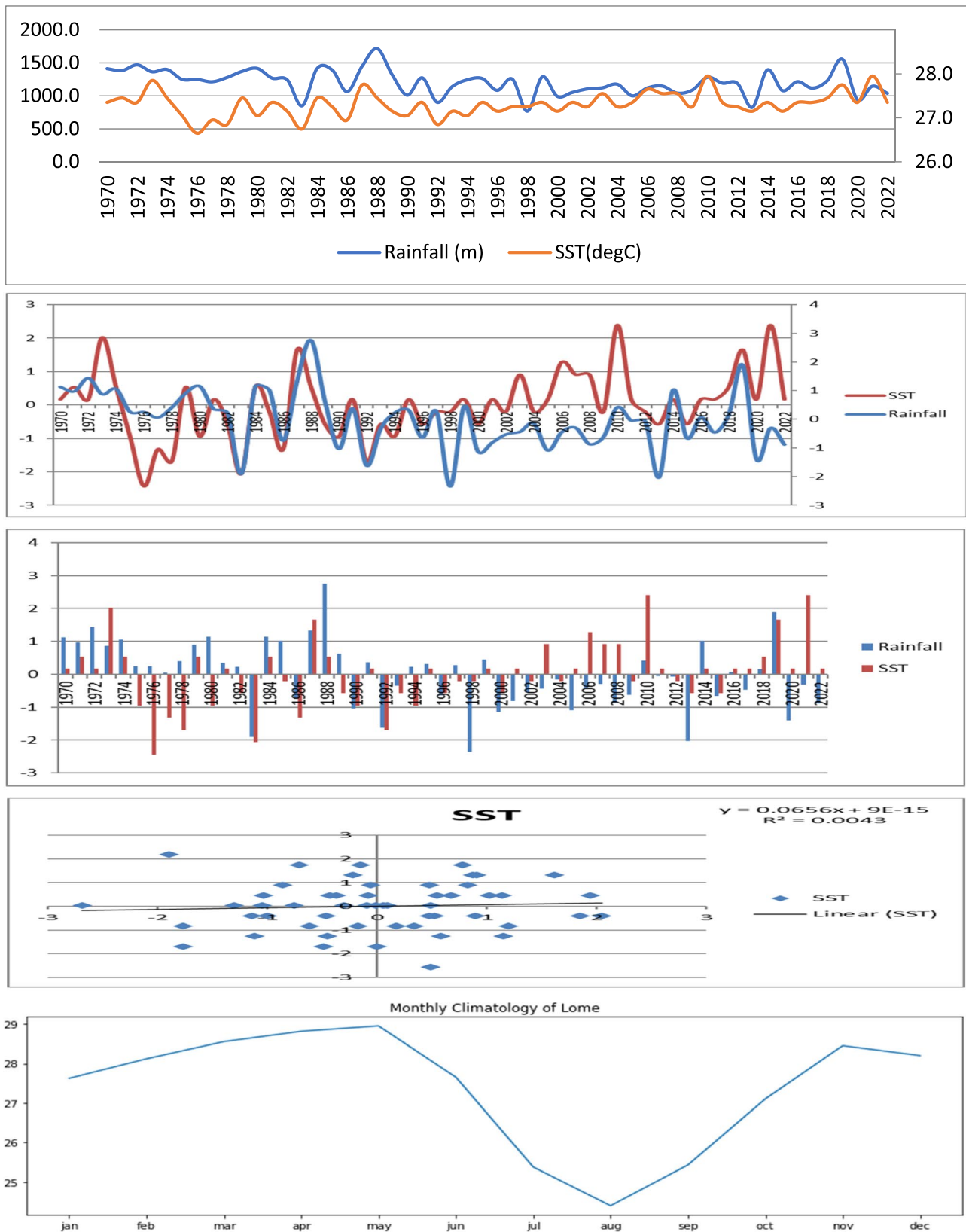


Fig. 16 Regression and Standardized Anomaly Index calculation of SST-Rainfall teleconnection a SST-Rainfall trend anal over

Table 7 Rainfall and SST years of anomaly

STATIONS	DRY YEARS	WET YEARS	SST ANOMALY
Abijan	1973,1976,1978,1994,199,2004	1985,1997, 1972,1976,1990,	1976,1978,1992,2000,2010, 2020
Accra	1984,1990,1998,2000, 2012,2020	1986	1972.1976,1984,1994, 2002,2006, 2010,2020
Banjul	1976,184,2002,2004,2006	1974,1988,2008,	1974.1976,1986
Monrovia	1973 1997,2009,	1979,1996,2018, 1976,1981	2010,2020,2022, 2018
Doula	1988,2021	1973,2004	1976.1979,2010,2021, 2016, 2018
Conakry,	1985, 1987	1979,1984,2015	1976, 1994,2005.2018,2021
Cotonou	1982,1997,2009, 2012,2018	1979,1988,2018	1976,1979,1982,2003, 2006, 2006,2009,2018 2021
Dakar	1978,1982,1984,1998, 200, 2014	1974, 1988,2012, 2014, 2020, 2022	1974,1976,1986, 2018, 2004, 2006, 2010,2020
Freetown	1976,1997,2009	2015,2018,2021	1976,1985.2003, 2006, 2015
Lagos	1982, 1997.2012,2015	1979,2018	1976,1985,2006,2021
Lome	1982, 1991, 1997,2012	1973,1988,2018	1973,1976,1979,1985, 2003,2009

the ITCZ that significantly modulates the inter annual rainfall variability in West Africa as stated by (Nicholson 2013).

Therefore, the increased precipitation variability reproduced in this study can trigger reduce agricultural yields as shown by (Rowhani et al. 2011). Also, precipitation variability as demonstrated in this study is strongly connected to extreme wet and dry events, floods, and droughts, which pose great threats to the environment and society, and can also have devastating consequences on ecosystems, food supplies, and economies at the local and regional which is in agreement with (Easterling et al. 2000).

The analysis revealed that the period 2010–2020 was also characterized by increased rainfall as the variability values increased from 21.7–695.5 along latitude 12° (Western Sahel) to 695.5–1.369.1–2.042.6. 2.7166.5–3.390.1 in the Guinean coast. This represents a significant increase compared to the preceding decade of 200–2010, However, the year 2022 experienced rainfall reduction as the variability values of 2.587.2–3.220.6 were lower as against 2010–2020. The decline observed in 2022 corresponds to lower SST in 2022. The pattern of rainfall variability could be linked top internal variability of the Atlantic Multidecadal Variability (AMV), previously known as the Atlantic Multidecadal Oscillation (AMO) (Zhang and Delworth 2006) The AMV is a basin-wide SST variability pattern with its strongest signal located in the North Atlantic. The pattern of decadal SST analysis produced in this study agrees with empirical studies conducted by (Bertnttelle 2023, Ting et al. 2011, Williams et al. 2022, and Zhang et al. 2021) that AMO exerts a significant influence on the climate of adjoining continents including rainfall over West Africa.

4.4 Seasonal pattern of rainfall variability

The seasonal pattern of rainfall variability from 1970–2022 was categorized into December-January–February DJF, March–April-May MAM, June-July and August JJA and September, October and November SON.

Findings from the spatial analysis indicate high seasonal variability with September–October and November SON recoding high rainfall intensity as the variability values increase from 0.4–76.9 mm in the Western Sahel 79–157.4 mm, 157.5–235.8 and 235.9–314.3 mm been the maximum. This further affirms that the rainy season in West Africa peaks up in September, October, and November SON, followed by June-July and August JJA and March, April, and May MAM respectively. Conversely, the seasonal distribution of rainfall in the Western Sahel was poor, particularly in the months of SON which could be devastating to crops and pasture development, particularly in Northern parts of Senegal, Southern Mauritania, Central and Northern Mali, Northern Nigeria, Niger and the lake Chad Basin. This finding agrees with the World Food Program (WFP 2021).

Significant rainfall deficits were also observed in JJA across the coastal Guinea regions of Ghana, eastern Cameroon, Northern Nigeria, Burkina Faso, Togo, and Benin. The phenomenon of reduced rainfall in the months of JJA is called the little Dry season LDS. The Little Dry Season LDS associated with anomalously low SST in the months of JJA and the southward migration of the tropical rain belt ITCZ all contributed to the high variability of rainfall during this season (Adejuwon and Odekunle 2006, Odekunle and Eludoyin 2008, Chineke et al. 2020, Paker and Diop-Kane 2017 and Wainwright et al. 2019. The length and severity of the LDS could be detrimental to crop productivity and

pasture which are the major source of livelihoods in West Africa. The seasonal variability of rainfall further indicates that JJA and SON account for 80% of total rainfall in West Africa which is attributed to WASM, a critical aspect of the West Africa Monsoon (Akintomide and Zhou 2019).

The anomalously low SST also increases static stability over the Gulf of Guinea region leading to the suppression of convective-producing rainfall. Findings from the decadal and seasonal distribution of rainfall reveal that mean annual rainfall in West Africa was generally zonal with rainfall amount decreasing from the coast to the inland regions. The results of the analysis performed here are consistent with previous studies that rainfall intensity is dominant along the Guinea coast in West Africa (Nicholson 2003, Afesimama et al. 2006, Gbobaniyi et al. 2013 and Akinsanola et al. 2006). Palmer et al. 2023 was emphatic of the role of seasonal rainfall to the health and economic prosperity of the West Africa sub-region and such disruptions to the rainfall cycle could result in wide range economic and environmental impacts.

Furthermore, the results of the analysis on spatial variability of SST and rainfall anomalies demonstrated in this study lend s credence to previous studies that SST is believed to be strongly influenced by the interannual variability of the West African Moonson (Caminade and Terray 2010; Folland et al. 1986; Losada et al. 2001; Palmer 1986; Rodríguez-Fonseca et al. 2011; Zhang and Delworth 2006. Additional observational data carried out on the SST pattern of the South Atlantic Ocean indicates that the SST anomalies in the tropical Atlantic are associated with the ENSO phenomenon which reinforces previous studies by Nnamchi and Li 2011, Cheneke et al 2020, Rohli and Vega 2017.

4.5 Rainfall and SST anomalies

The outcome of both rainfall and SST regression analysis and the Standardized anomalies conducted in the study revealed fluctuating and progressive increases in both SST and rainfall in the study domain from 1970–2022. This agrees with previous studies that SST fluctuation is more pronounced in the coastal regions and arises from dynamic features such as Kelvin waves and Tropical Instability Waves (TIWs) in the equatorial Pacific Ocean. (Bulgin, et al. 2020). The regression analysis further indicates a weak and insignificant coefficient of relationship for Banjul, Conakry, Cotonou, Dakar, and Doula while the positive and significant relationship was established in Abidjan, Accra, Lome, Freetown Monrovia, and Lagos. The weak correlation exhibited by some of the coastal stations demonstrates the fact that precipitation in the coastal regions are also influenced by other processes such as coastal topography, thunderstorms, as well as prevailing wind and tropospheric stability which corroborates Akinbobola et al. 2015.

The standardized rainfall and SST anomaly carried out reveals composite wet and dry years with anomalously low SST years more pronounced in the 1970 and early 1980 across all the stations. The SST anomaly captured in this study is in direct response to various ENSO episodes as evidenced by years of below and abnormal SST and rainfall variability. Similarly, plots of the SST monthly climatology revealed that SST was anomalously low in the summer months of June, July, August, and September before peaking up in the fall months of October, November and December as this was evident across all the stations except Conakry. The SST monthly variability is greatest in summer than winter which is associated when the marked layer of the ocean significantly responds to its internal forcing. This is partly linked to the El Nino Southern Oscillation (ENSO), which is the largest mode of SSTA variability involving remote teleconnections mediated by ENSO influences on atmospheric circulation (Deser et al. 2010).

5 Conclusion

The study has examined sea surface temperature spatial pattern, variability, and the teleconnection with rainfall dynamics over the Gulf of Guinea from 1970–2022. In achieving this, both NOAA CPC and ERA5 data sets were used for analysis of decadal and seasonal variability for both SST and rainfall using ten year moving average for both SST and rainfall while three-month interval was used for the seasonal analysis. To establish the teleconnection of SST response to rainfall, statistical analysis were employed for trend, anomaly and linear regression for Abidjan, Accra, Cotonou, Dakar, Doula, Banjul, Lome, Freetown, Conakry, Lagos and Monrovia with results showing increasing trend, weak and insignificant relationship in Banjul, Dakar, Doula, Conakry, and Cotonou which are clear signals that other processes such as prevailing winds, coastal topography and thunderstorms could play a part. The monthly SST climatology indicates that June, July, August, and September are the months where SST is anomalously low in all the stations considered except Conakry thus agreeing with previous studies that SST monthly variability depends on the location though the changes are much greater in the summer months than winter thus further providing lucid explanation to rainfall variability during the summer months in West Africa.

In view of the forgoing, the study concludes that the spatial variability of SST established in this study has enormous implication on rainfall dynamics and the West African climate system. The anomalously low SST established in the study indicates that coastal regions will experience below normal rainfall in the months of JJA, and SON irrespective of its geographical location in the coast. Coastal upwelling has been implicated as the causative mechanism for the

anomalously low SST thus driving erratic rainfall in mid-summer giving rise to the phenomenon of Little Dry Season LDS. The study also revealed that SST decreases westward and increases along the coast.

The rainfall variability analysis also indicates that 2010–2020 recorded the highest concentration of rainfall. The pattern of the SST observed may create north–south rainfall dichotomy, a situation in which when precipitation is below normal in the Sahel it will tend to be above normal rainfall in the Guinean coast. The study further affirms that the general increase in the SST of the GOG in the 52 years of the study period (1970–2022) may lead to a dipole structure of rainfall changes over West Africa and the intensification of extremes and a further reduction of the average severity of the LDS by creating the moisture-laden wind more buoyant in terms of moisture and energy and thus in agreement with Chineke et al, 2020

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Authors contribution The first author conducted the research including the geospatial and statistical analysis and preparation of the manuscript as part of his postdoctoral research fellowship while the second author hosted the fellow and supervised the researcher in his Lab in the School of Natural Resources, university of Missouri Columbia. The manuscript was revised by both authors.

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Declarations

Competing interests The authors declare that there is no competing interest.

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References

- Abed-Elmdoust A, Miri MA, Singh A (2016) Reorganization of river networks under changing spatiotemporal precipitation patterns: An optimal channel network approach. *Water Resource Res* 52:8845–8860. <https://doi.org/10.1002/2015WR018391>
- Adejuwon JO, Odekunle TO (2006) Variability and the severity of the “Little Dry Season” in Southwestern Nigeria. *J Clim* 19(3):483–493
- Afiesimama EA, Pal JS, Abiodun BJ, Gutowski WJ, Adedoyin A (2006) Simulation of West African monsoon using RegCM3 part I: model validation and inter-annual variability. *Theor Appl Climatol* 93:245–261
- Akinbobola A, Oluleye A, Balogun IA (2015) Impact of sea surface temperature over East Mole and South Atlantic Ocean on Rainfall pattern over the coastal status of Nigeria. *Br J Appl Sci Technol* 6(5):463–476
- Akinsanola AA, Zhou W (2019) Ensemble-based CMIP5 simulations of West African summer monsoon rainfall: current climate and future changes. *Theoret Appl Climatol* 136:1021–1031. <https://doi.org/10.1007/s00704-018-2516-3>
- Akinsanola AAA, Ajayi VO, Adejare AT, Adeyemi OE, Gbode E, Ogunjobi RO, Nikulin G, Abolade AT (2018) Evaluation of rainfall simulations over West Africa in a dynamically down-scaled CMIP5 global circulation models. *J Theor Appl Climatol* 132:437–450
- Alimonti G, Mariani L, Prodi F et al (2016) RETRACTED ARTICLE: A. critical assessment of extreme events trends in times of global warming. *Eur Phys J plus* 137:112. <https://doi.org/10.1140/epjp/s13360-021-02243-9>
- Bertnttelle E (2023) Understanding West African Monsoon variability: Insights from modeling at past warm climates. Published PhD thesis. Department of Physical geography, Stockholm University Sweden
- Biao EI, Alamou EA (2018) Stochastic Modeling of Daily Rainfall for Decision Making in Water Management in Benin (West Africa). *Res Ad Environ Sci* 1:12–21. Available from: https://www.researchgate.net/publication/329097257_Stochastic_Modelling_of_Daily_Rainfall_for_Decision_Making_in_Water_Management_in_Benin_West_Africa. Accessed 19 Nov 2023
- Bulgin CE, Merchant CJ, Ferreira D (2020) Tendencies, variability and persistence of sea surface temperature anomalies. *Sci Rep* 10(1):7986
- Intergovernmental Panel on Climate Change (IPCC) (2022) Climate Change: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, p 3056. <https://doi.org/10.1017/9781009325844>
- Caminade C, Terray L (2010) Twentieth century Sahel rainfall variability as simulated by the ARPEGE AGCM, and future changes. *Clim Dyn* 35:75–94
- Chineke TC, Jagtap SS, Nwofor O (2020) West African monsoon: is the August break “breaking” in the eastern humid zone of Southern Nigeria? *Clim Change* 103(3–4):555–570
- Deser C, Alexander MA, Xie SP, Phillips AS (2010) Sea surface temperature variability: patterns and mechanism. *Ann Rev Mar Sci* 2(1):115–143
- Easterling DR, Gerald AM, Camille P et al (200) Climate extremes: Observations, modeling, and impacts. *Science* 289:2068–2074. <https://doi.org/10.1126/science.289.5487.2068>
- Folland S (1986) Rainfall and worldwide sea temperatures, 1901–85. *Nature* 319:402–403
- Gbobaniyi E, Sarr A, Sylla MB, Diallo I et al (2013) Climatology, annual cycle and interannual variability of precipitation and

- temperature in CORDEX simulations over West Africa. *Int J Climatol* 34(7):2241–2257. <https://doi.org/10.1002/joc.3834>
- Ginanini A (2010) The influence of sea surface temperature on Africa climate system. ECMWF-Seminar on predictability in the European and Atlantic regions. International Research Institute for climate and society. The Earth institute at Columbia University. Palisades NY, USA
- Grist JP, Nicholson SE (2001) A study of the dynamic factors influencing the rainfall variability in the West African Sahel. Department of Meteorology, The Florida State University Tallahassee Florida. *J Clim: Amer Meteorol Soc* 14(7):1337–1359
- Iloje NPA (2021) New geography of Nigeria. Longman: Great Britain 1981, 25. Intergovernmental Panel on Climate Change (IPCC). Climate Change: The Physical Scientific Basis. Available online: <http://www.ipcc.ch>. Accessed 8 Jun 2021
- Kosaka Y, Xie SP (2016) The tropical Pacific as Key peacemaker of the variable rates of global warming. *Nat Geo Sci* 9(9):669–673
- Lamb PJ, Pepler RA (1992) Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought. Vol.5. <https://api.semanticscholar.org/CorpusID:129029352>
- Lamb PJ (1978) Case Studies of Tropical Atlantic Surface Circulation Patterns during Recent Sub-Saharan Weather Anomalies: 1967 and 1968. *Monthly Weather Review*, 106:482–491. [https://doi.org/10.1175/1520-0493\(1978\)106<0482:CSOTAS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1978)106<0482:CSOTAS>2.0.CO;2)
- Longhurst ARA (1962) Review of the Oceanography of the Gulf of Guinea. *Bull IFAN* 24:633–663
- Losada T, Rodríguez-Fonseca B, Polo I, Janicot S, Gervois S, Chauvin F, Ruti P (2001) Tropical response to the Atlantic Equatorial mode: AGCM multi model approach. *Clim Dyn* 35(1):45–52
- Lübbecke JF, McPhaden MJA (2017) Comparative stability analysis of Atlantic and Pacific Niño modes. *J Clim* 26:5965–5980. <https://doi.org/10.1175/JCLI-D-12-00758.1>
- Lübbecke JF, Belen-Fonseca BR, Richter I, Martín-Rey M, Losada T, Polo I, Keenlyside NS (2018) Equatorial Atlantic Variability Modes, Mechanisms, and Global Teleconnections. *Wires Wiley J Interdiscip Rev* 9(4):e527
- McKee TB, Doesken NJ, Kleist J (1993) Drought Monitoring with multiple time scales. *Proc Ninth Conf App Climatol Dallas TX Amer Meteor Soc* 233–236
- Meynadier R, Coetlogon G, Leballeur ML, Eymard L, Janicot, (2016) Seasonal influence of sea surface temperature on the atmospheric and precipitation in the eastern equatorial Atlantic. *Springer* 47:1127–1142
- Nicholson SE (2003) Comments on the south Indian convergence zone and interannual rainfall variability over south Africa and the question of ENSO's influence on Southern Africa. *J Clim* 6:1463–1466
- Nicholson SE (2013) The West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorol* 2013:453521. <https://doi.org/10.1155/2013/453521>
- Nnamchi HC, Li J, Anyadike RNC (2011) Does a dipole mode really exist in the South Atlantic Ocean? *J Geophys Res: Atmos* 116:1–15. <https://doi.org/10.1029/2010JD01557>
- Odekunle TO, Eludoyin AO (2008) Sea surface temperature pattern and its implication on rainfall variability over the Gulf of Guinea. *Int J Climatol* 28(11):1507–1517
- Ojo O (1977) *The Climates of West Africa*. Heinemann, London, p 219
- Paeth H, Stuck J (2004) The West African dipole in rainfall and its forcing mechanism in global and regional climate models. *Mausam* 55:561–582
- Palmer PI, Wainwright CM, Dong B, Maidment RI, Wheeler KG, Gedney N, Hickman JE, Madani N, Folwell SS, Abdo G, Allan RP, Emily Black CL, Feng L, Gudoshava M, Haines K, Huntingford C, Kilavi M, Lunt MF, Shaaban A, Turner AG (2023) Drivers and impacts of Eastern African rainfall variability. *Nat Rev; Earth Environ* 4:254–27
- Parker D, Diop-Kane M (2017) *Meteorology of tropical West Africa: the forecaster's handbook*. Wiley, New York
- Rodríguez-Fonseca B, Janicot S, Mohino E, Losada T, Bader J, Caminade C, Joly M (2011) Interannual and decadal SST-. Forced responses of the West African monsoon. *Atmos Sci Lett* 12(1):67–74
- Rodwell DP (2013) Stimulating SST teleconnections to Africa: What is the state of the Art?. Met Office, Hadley Center, Fritz Roy Exeter, United Kingdom
- Rohli RV, Vega AJ (2017) *Climatology*, 4th Ed. Jones and Bartlett, p 466
- Sarkar A, Saha S, Sarkar D, Mondal P (2021) Variability and trend analysis of the rainfall of the past 119 (1901–2019) years using statistical techniques: A case study of Uttar Dinajpur, India. *J Clim Chang* 7:49–61. <https://doi.org/10.3233/jcc210011>
- Siedler G, Griffies SM, Gould J, Church JA (2013) Ocean circulation and climate: a 21st century perspective. Academic. Press
- Soltani M, Laux P, Kunstmann H et al (2016) Assessment of climate variations in temperature and precipitation extreme events over Iran. *Theor Appl Climatol* 126:775–795. <https://doi.org/10.1007/s00704-015-1609-5>
- UNFCCC (2021) United Nations Climate Change Bonn Germany
- Ting M, Y. Kushnir R, Seager C Li (2011) Robust features of atlantic multi-decadal variability and its climate impacts, *Geophys. Res. Lett.*, 38 L17705. <https://doi.org/10.1029/2011GL048712>
- USAID (2013) Climate risk in West Africa: Regional risk profile. 20523 Washington DC, <https://www.usaid.gov>. Accessed 15 Mar 2024
- Vizy EK, Cook KH (2001) Mechanism by which Gulf of Guinea and Eastern North Atlantic Sea surface temperature Anomalies can influence African Rainfall. *J Clim Amer Meteorol Soc* 14(5):795–821
- Williams CJR, Lunt DJ, Salzmann U, Reichgelt T, Inglis GN, Greenwood DR, Chan WL, Abe-Ouchi A, Donnadiou Y, Hutchinson DK, de Boer AM, Ladant JB, Morozova PA, Niezgodzki I, Knorr G, Steinig S, Zhang Z, Zhu J, Huber M, Otto-Bliesner BL (2022) African 2022. Hydroclimate During the Early Eocene From the Deep MIP Simulations. *Paleoceanography Paleoclimatol* 37:e2022PA004419. <https://doi.org/10.1029/2022PA004419>
- World Bank African Region (2020) The next Generation Africa Climate Business Plan. Ramping Up Development Centered Climate Action. World Bank, Washington DC. <https://openknowledge.worldbank.org/bitstream/handle/10986/34098/34098.pdf>
- World Food Program WFP (2021) The2021 rainy season in review. Vam Food Analysis. World food program Regional Bureau, Dakar. <https://reliefweb.int/sites/reliefweb.int/files/resources/WFP-0000133543.pdf>
- Zhang R, Delworth TL (2006) Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophys Res Lett* 33:1–5. <https://doi.org/10.1029/2006GL026267>
- Zhang L, Zhao J, Kug J-S, Geng X, Xu H, Luo J, Zhan R (2021) Pacific warming pattern diversity modulated by Indo-Pacific sea surface temperature gradient. *Geophysical Research Letters*, 48, e2021GL095516. <https://doi.org/10.1029/2021GL095516>

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