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RESEARCH ARTICLE

Assessing recovery and change in West Africa's rainfall regime from a 161-year record

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The Sahel region is known for the multi-decadal occurrence of severe drought that commenced in the late 1960s. A still open question is whether or not the region's rainfall has returned to "normal." This paper provides a compelling answer to that question by examining the longest and most comprehensive gauge series for the region ever published. It extends from 1854 to 2014 and is based on 602 gauge records. A comparative series for the Guinea Coast region to the south is also presented, as the two regions collectively provide insight into the long-term variability of the West African monsoon. In contrast to many previous studies, here the question of recovery and regime change is not restricted to the core of the Sahelian rainy season (July–September), but is separately discussed also for the coastal phase (April–May), transition phase (June), Sahelian phase (July–September) and the second transition phase (October–November) of the West African monsoon. These analyses suggest that full recovery from the droughts of the 1970s and 1980s has not occurred that a major change in the rainfall regime occurred around 1968 and that since that time large-scale teleconnections have also changed markedly. The shift post-1968 is evident in all phases of the monsoon except the coastal phase, in which a change to drier conditions occurred a decade later. Overall, recovery has been greater in the east than in the west, creating a change in the climatological east–west rainfall gradient. The drier post-1968 conditions appear to be associated with a general weakening of the intensity of the West African monsoon and only a small southwards displacement of the rainfall maximum. These changes have strong implications for the future of this region and for seasonal prediction.

KEYWORDS
climatic variability, drought, Guinea Coast, inter-annual variability, multi-decadal variability, rainfall, Sahel, teleconnections

1 | INTRODUCTION

The occurrence of severe drought in the West African Sahel in the early 1970s and throughout most of the 1980s has been well established. Whether or not the rainfall regime subsequently recovered has been a controversial issue. Numerous sources demonstrate that Sahel rainfall increased after the severe years of the 1980s (Ali and Lebel, 2009; Lebel and Ali, 2009; Mahé and Paturel, 2009; Giannini, 2015; Sanogo *et al.,* 2015). On the other hand, many authors (e.g., Nicholson *et al.,* 2000; L'Hôte *et al.,* 2002; L'Hote *et al.,* 2003) concluded that drought continued through the 1990s, even though rainfall had increased. Other sources claimed that the region was entering a more humid period (e.g., Ozer *et al.,* 2003). Complicating the issue was the fact that "recovery" showed strong geographical variations and that a handful of very wet years occurred during what was a relatively dry post-1980 interval

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(Nicholson, 2005; Lebel and Ali, 2009; Dieppois *et al.*, 2013; 2014; Diatta and Finkc, 2014; Hastenrath and Polzin, 2014). In some years, devastating flood conditions were reported (Ozer *et al.*, 2003; Paeth *et al.*, 2011), consistent with the recent increase in extreme rainfall events (Panthou *et al.*, 2014; Sanogo *et al.*, 2015). Fontaine *et al.* (2011) concluded that deep convection significantly increased since the mid-1990s and also moved northwestwards, in conjunction with a similar shift in the Saharan Heat Low. However, these changes were relative to 1979, a year in which rainfall was well below the long-term mean. Redl *et al.* (2016) suggested that the Saharan Heat Low has also weakened.

Numerous authors have examined other aspects of Sahel rainfall and its global teleconnections since the worst drought years of the early 1970s and early 1980s. Mohino *et al.* (2011a) and Losada *et al.* (2012) demonstrated that the recent conditions in the Sahel are associated with a major change in rainfall–sea surface temperature (SST) relationships. They concluded this change was roughly synchronous with the quasi-global climate shift in the late 1970s. Both papers also indicated that the well-known rainfall "dipole," with anomalies of the opposite sign in the Sahel and Guinea, had nearly disappeared. Lebel and Ali (2009) noted a disappearance of the pronounced August peak in the central Sahel (10°W–0°). Nicholson (2013) suggested that inter-annual variability had increased in recent decades.

The first major objective of this article is to examine the temporal variability of Sahel rainfall over an unprecedented 161-year period and to evaluate whether or not the region's rainfall regime has truly "recovered" from the major droughts of the 1970s and 1980s. The second major objective is to examine the possibility of a change in the Sahelian rainfall regime, which our preliminary analysis suggests occurred around 1968. In evaluating this suggestion, a comparison is made with Guinea Coast rainfall and global SSTs and the changing characteristics suggested by other authors, as noted above, are re-evaluated using a longer time series and expanded geographical coverage. Analyses are carried for the Sahel as a whole and for individual longitudinal sectors, to determine geographical variations in recovery and other characteristics, such as the month of peak rainfall.

There are several unique features of this work. One is the unprecedented length of the Sahelian rainfall gauge series used in the research, extending from 1854 to 2014, as well as the longest gauge series for the Guinea Coast ever presented (1886–2014). Spatial coverage is also expanded compared to previous studies, with a total of 742 stations in the Sahel and Guinea Coast, compared to 254 in Sanogo *et al.* (2015), for example. Other unique features are that the analysis considers the various seasonal phases of the West African monsoon, as described below, and various longitudinal sectors. Finally, novel aspects are added to the question of a change in the rainfall regime; we examine changes in the east–west rainfall gradient, monsoon intensity, the latitude of peak rainfall, and the frequency of the rainfall dipole.

2 | BACKGROUND: THE WEST AFRICAN MONSOON

The West African monsoon is the source of rainfall for both the Sahel and the Guinea Coast. Four phases of the monsoon have been delineated based on the latitudinal location of the rainfall peak (Thorncroft *et al.*, 2011): oceanic, coastal, transitional, and Sahelian. During the oceanic phase, between November and mid-April, a broad rainbelt lies just north of the equator. At this time rainfall is slight over the Sahel. During the subsequent coastal phase, which generally prevails to mid-June, peak rainfall lies over the ocean and along the near-coastal region around 7°–4°N. The Guinea Coast generally receives peak rainfall during this phase, while the Sahel rainy season weakly commences (Figure 1). The transition phase, when the monsoonal rainbelt moves northwards, occurs from mid-June to early July. The Sahelian phase, that is, the rainy season in the Sahel, lasts from mid-July to September, with peak rainfall in the Sahel occurring in August. Throughout this phase the zonal

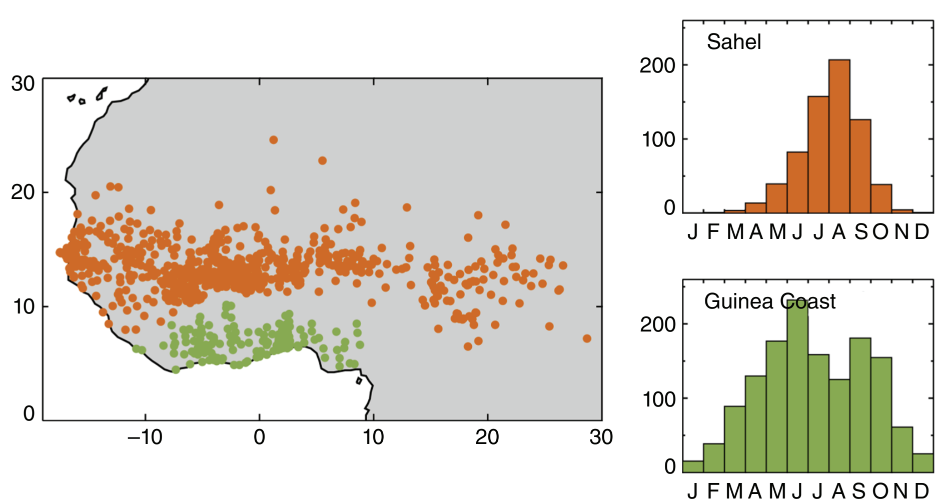

FIGURE 1 Map of the gauge network in the Sahel (orange) and Guinea Coast (green) and the seasonal cycle averaged for stations in the Sahel and the Guinea Coast

band of peak rainfall is more intense and resides in the southernmost Sahel, around 10°–12°N. At this same time a minor dry season occurs along the Guinea Coast. A second rainfall peak occurs in that region in the boreal autumn, late in the monsoon season when the monsoon rains retreat equatorwards.

Inter-annual variability of the monsoon during the Sahelian phase tends to fall within one of two spatial modes: a general decline in rainfall throughout the region or anomalies of the opposite sign between the Sahel and Guinea Coast (Nicholson, 2008). The former is generally associated with a change in the intensity of the monsoon rains while the latter is generally associated with a latitudinal shift in its seasonal evolution.

3 | METHODOLOGY

The methodology consists of deriving precipitation departure series for two regions of West Africa, the Sahel, and Guinea Coast. Both have been shown to be largely homogeneous with respect to inter-annual variability (e.g., Nicholson and Palao, 1993; Sanogo *et al.,* 2015) and their collective evolution provides hints as to the mechanisms underlying rainfall variability in this region.

Time series are calculated at the annual and seasonal scale. The seasonal divisions were chosen to coincide to the extent possible with the four monsoon phases described above. Because the current analysis is based on monthly data, the phases could not be precisely delineated. The analysis considers April–May (coastal phase), June (transition phase), July-to-September (Sahelian phase), and October–November (a second transition phase). The time series are calculated by averaging standardized departures over all stations in each region examined, as has become conventional in the analysis of West African rainfall (e.g.Nicholson, 1986, Ali and Lebel, 2009). The departure is calculated from the entire length of record for each station, as in past work of the first author. This approach gives a more

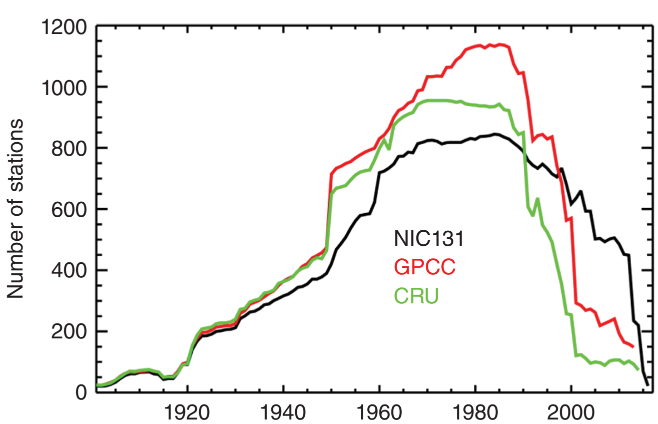

FIGURE 2 Number stations over West Africa (4°–22°N, west coast to 30°E) in the current data set and in the archives of GPCC and CRU

realistic mean than does a constant reference period because of the varying time periods for which individual stations are available and the vast changes of the associated means on multi-decadal timescales. Over half of all station records are at least 50 years in length and few station records are shorter than 30 years.

The gauge data utilized are from an archive that the authors are expanding and updating from that originally produced by the first author (e.g., Nicholson, 1986; Nicholson *et al.,* 2012a). A total of 602 stations are available for the Sahel and 140 for the Guinea Coast (Figure 1), but the actual number of stations available in a given year changes over time.

It should be noted that neither series includes a large number of stations prior to the mid-1880s. For the Sahel, the number available in each year varies between 1 and 7 prior to 1900. However, those lie almost exclusively in the sector west of 10°W prior to the mid 1890s. Although these do correlate well with the time series for the entire Sahel, significant differences occur on occasion because of the strong maritime influence (Nicholson and Palao, 1993). Thus the early years should be interpreted with caution. The trends themselves are supported by hydrologic and documentary data (e.g., Nicholson, 1996), but the magnitudes shown for the very early years might not be representative of the entire Sahel.

In recent decades this data set contains a far greater number of stations than are available in other commonly used archives, such as the Global Historical Climatology Network (GHCN), or available in the networks upon which gridded data sets (e.g., the CRU data set of the University of East Anglia) are based (Figure 2). The station data are being incorporated into a gridded data set as an addition to the CentTrends data set published by Funk *et al.* (2015) and benefit from updates provided by African scientists working with the Famine Early Warning Systems Network.

The number of stations in the gauge data set does not decrease substantially in the 21st century until 2012. Other major archives, such as those of the Global Precipitation Climatology Centre (GPCC) and CRU, and all gauge-calibrated satellite products have far fewer stations and the data are much less complete for the 2000s and 2010s. The more complete data set utilized here allows for a more robust evaluation of rainfall variability and recovery during the last 15 years.

The time series for the Sahel commence in 1854, while those for the Guinea Coast commence in 1886. Time series for both regions continue through 2014. Following Nicholson (1986), a factor is applied to adjust for the changes of variance associated with changes in the number of stations available. This step is necessary only when the number of stations becomes relatively small, for example, fewer than 15 for annual data and on the order of 20 for data for the individual phases. The so-modified years are indicated on the *x*-axes of the annual and seasonal rainfall time series.

The factors are calculated by systematically removing an increasing number of stations and determining how the variance changes with station number. It is applied not to individual stations, but to the multi-station average. The only effect on 19th century and early 20th century is to "compress" the departures to some extent. For example, if 14 stations are available instead of 15, standardized annual departure is multiplied by roughly .98. By the time the station number is down to 2 or 3, the factor might be on the order of .6 or .7. This technique works because the regime is fairly homogeneous within the sectors evaluated. Application of the factors will change the magnitude of anomalies in the Sahel or Guinea Coast time series, but neither the sign of the anomaly nor the relationships between seasonal and annual values.

Rainfall in five longitudinal sectors of the Sahel is also investigated. Because fewer long-term stations are available in these sectors than for the region as a whole, this aspect of the study is based only on the period 1926–2014. This serves to illustrate geographical variations in recovery and to examine select characteristics of the monsoon before and after 1968. The value and latitude of the rainfall maximum in each sector in August are evaluated and compared before and after 1968, as is the percent of stations with an August maximum. The prominence of the August peak as a function of latitude is also assessed for the central-most region.

Temporal changes in the relationship between the Sahel and Guinea Coast and in links to SSTs are depicted by sliding 20-year correlations. The SST data utilized are taken from the Extended Reconstruction Sea Surface Temperature version 4 (ERSST.v4) data set (Huang *et al.,* 2015). A comparison between the Sahel and the Atlantic multidecadal oscillation is also made.

An objective regime-shift detector (RSD) method (Rodionov, 2004) is applied to identifying significant regime shifts in all Sahel rainfall series. This is a sequential analysis method (Manatsa *et al.,* 2012). The crux of the method is using the Student's *t* test to determine the difference in mean necessary for a change to be statistically significant at a chosen confidence level. In this study, the 5 and 10% confidence levels are considered. The approach of van Oldenborgh and Burgers (2005), based on Gershunov *et al.* (2001), is used to assess the significance of changes in teleconnections.

4 | RESULTS

4.1 | Inter-annual variability in the Sahel and the question of recovery

Figure 3 shows the standardized annual departure series for the Sahel. The record is continuous for the period 1854–2014. Rainfall was almost continuously above the long-term (1854–2014) mean from the early 1870s to 1967. Three periods of particularly wet conditions were the 1870s and 1880s, the 1920s and 1930s, and the 1950s through early to mid-1960s. Rainfall peaked during the third period and the persistence of anomalies from year-to-year was remarkably strong during that interval.

Regime shifts statistically significant at the 5% level are seen to occur at 1876, 1897, 1927, 1950, 1968, 1982, and 1994 (Table 1). The results showed that the shift at 1968 is by far the largest and the abrupt change in the annual series

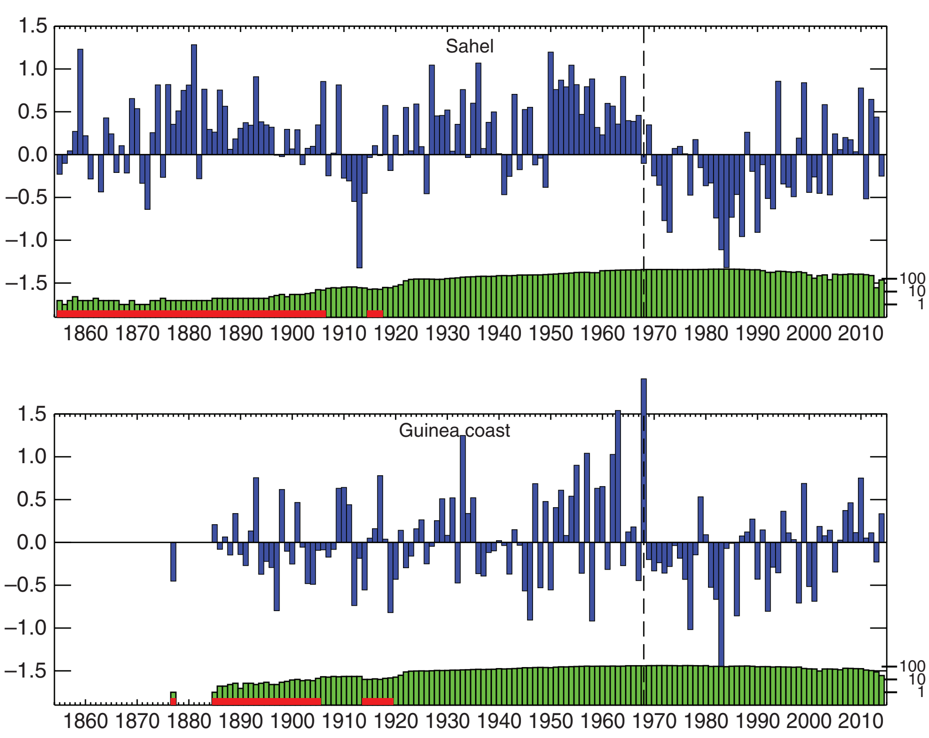

FIGURE 3 Time series of Sahel rainfall from 1854 to 2014 and Guinea Coast rainfall from 1886 to 2014. Rainfall is represented by a regionally averaged standardized departure from the long-term mean (i.e., the total record length for each station). A value of 1 is equivalent to one standard deviation. The years indicated in black along the *x*-axis are those to which a scaling factor was applied. The dashed vertical line indicates the year 1968. The number of stations in the average is indicated at the bottom in green

starting in 1968 is striking. After 1967 there were few years with rainfall above the long-term mean. Rainfall was either below or minimally above the long-term mean from 1968 to 1993. Overall the 1970s and 1980s were the driest period since at least the mid-19th century. However, a comparable period of aridity occurred early in the 19th century (Nicholson *et al.,* 2012a,b), so the lengthy drought is not unprecedented.

From 1994 onwards the inter-annual variability was strong and only a few years were as wet as the 1950s, but these wet conditions did not persist from year to year. The average standardized departure for the years 1993–2014 is −0.08. This suggests that the rainfall regime in the Sahel has not fully recovered to its pre-drought conditions (prior to 1968), when the standardized departure was on the order of 0.5 to 1. The frequent shift between anomalously wet and anomalously dry years since 1994 appears to signal an increase in inter-annual variability. This is quantified in Figure 4, using the standard deviation of values in running 5-year periods. This shows that while inter-annual variability has increased compared to the preceding wet and dry decades, comparable intervals of strong variability occurred in the 1940s and in much of the late 19th century.

Figure 5 presents seasonal anomalies for the period 1854–2014. Not surprisingly, conditions in July-to-September mirror the annual time series. The time series for June shows similar long-term trends since roughly 1910, including the abrupt change in 1968. However, the wet periods are not as long or persistent and June rainfall showed relatively little recovery in recent years. One other contrast is evident prior to roughly 1880; rainfall was generally below average in June and October–November but on the whole above average for the July-to-September season.

Despite the pre-1880 similarity of June and October–November, inter-annual variability in these two transitions seasons (Figure 5) is generally markedly different. For October–November the greatest similarity with annual or July-to September rainfall is the run of predominantly dry

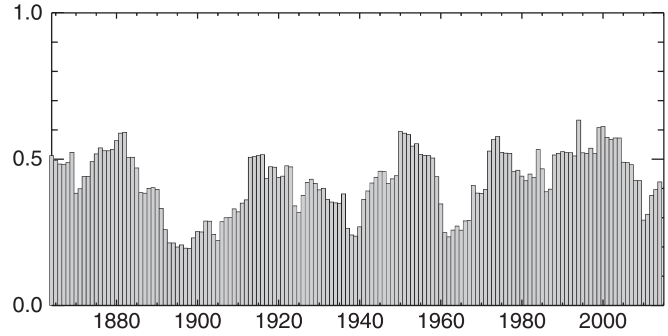

FIGURE 4 Standard deviation of July-to-September rainfall anomalies for sliding 5-year periods. Values are plotted at the end of each 5-year period

years since 1968. However, the wet conditions of the 1940s and 1950s are much less evident and maximum rainfall occurred from the 1870s to roughly 1906, when an abrupt shift to drier conditions occurred. Rainfall was near normal from then until 1951. The time series for the oceanic phase in April–May also shows much less persistent anomalies, an absence of extremely wet conditions in the 1940s or 1950s, and a shift to predominantly dry conditions commencing in 1985, considerably later than during the other seasons. Since that time the trends for April–May and for October–November have been similar to that for the year as a whole and for the July-to-September season: an upwards trend but with few years with rainfall exceeding the long-term mean. Confirmation of this is provided by Sanogo *et al.* (2015) using a somewhat different methodology, who noted a particularly strong recovery in October.

The results of the RSD analysis for the seasons are presented in Table 1. Four of the shifts that are apparent in the annual time series are also apparent in July-to-September, but only 1950 and 1968 are significant at the 5% level. These shifts are not apparent in any other season. The 1876 regime shift in the annual time series appears to be related to increased rainfall in April–May (when a regime shift occurred in 1876) and in October–November (when a regime shift occurred in 18,783). The 1994 shift in the annual time series is not apparent in any of the individual seasons.

It has generally been accepted that inter-annual variability in the Sahel is a function of boreal summer rainfall. Conditions in the 1890s suggest that the contribution of each season to inter-annual variability may change significantly over time. This is tested in Figure 6, which shows running correlations between seasonal and annual rainfall in the Sahel. The correlation between April–May and annual rainfall was relatively high in the 19th and early 20th century, then steadily declined. The correlation with June is lower but significant early in the 20th century. As expected the correlation between the July-to-September season and annual rainfall is steadily strong, but lower at times when the contribution of April–May or June is significant. The correlation between October–November and annual rainfall

TABLE 1 Years in which a significant regime shift occurred for the year and for seasonal periods. Years in bold: significant at the 5%; others at the 10% level

Region	Season	List of years
Sahel	Year	**1876**, **1897**, **1927**, **1950**, **1968**, **1982**, **1994**
	Apr, May	**1876**, 1904, 1927, **1985**
	Jun	**1970**
	Jul, Aug, Sep	1879, 1897, **1950**, **1968**, 1982, 1998
	Oct, Nov	**1873**, 1983
Guinea Coast	Year	1951, 1964, 2007
	Apr, May	1986, 2001
	Jun	**1960**, **1969**, 1996
	Jul, Aug, Sep	
	Oct, Nov	1951, 1964, **1981**, 2002, **2010**

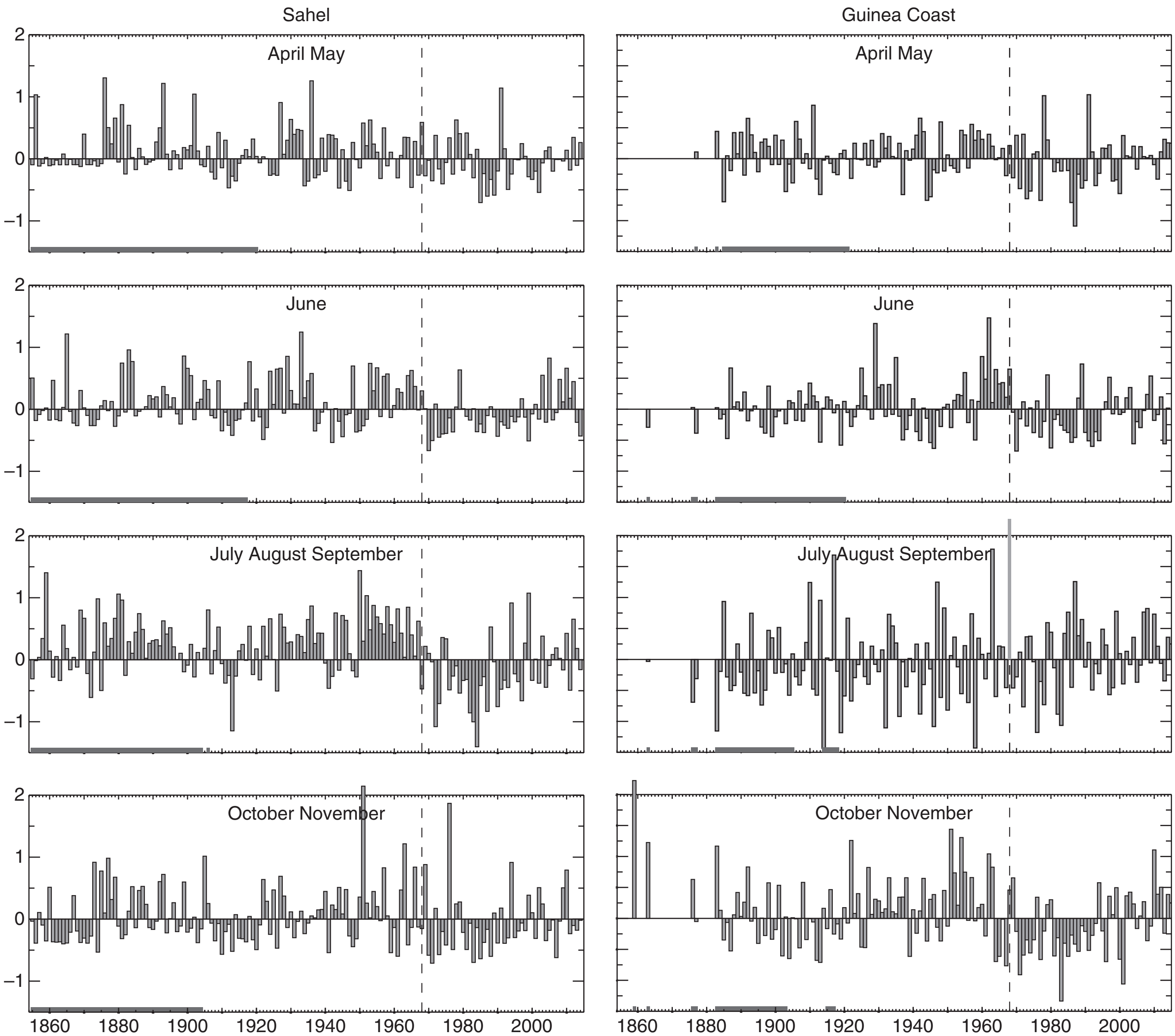

FIGURE 5 Rainfall in four phases of the West African monsoon, expressed in units of standardized departures (as in Figure 3). (left) Rainfall in the Sahel for the periods April–May, June, July-to-September, and October–November. (right) Rainfall in the Guinea Coast for the periods April–May, June, July-to-September, and October–November. The years indicated in black along the *x*-axis are those to which a scaling factor was applied. The dashed vertical line indicates the year 1968

is occasionally significant but not really strong until the 1980s and 1990s. This result is consistent with the finding of Sanogo *et al.* (2015) that recovery was particularly strong in October. Statistically speaking, the results do not indicate a significant shift in the teleconnections, according to the criteria of van Oldenborgh and Burgers (2005). However, collectively, the analyses for the three seasons do suggest periods in which the JAS contribution is reduced and the contribution of other months to annual rainfall is increased.

4.2 | Zonal contrasts in recovery

Across the Sahel the rainfall isohyets run roughly east-to-west, but with somewhat wetter conditions in the west than in the east. Inter-annual variability is also noted to be generally coherent across the east–west extent of the region (e.g., Nicholson, 1980). However, several studies (e.g., Nicholson, 2005; Lebel and Ali, 2009) documented zonal contrasts in the degree of recovery, resulting in reduced east–west contrast across the region. This conclusion is further examined with the updated series by considering variability in five longitudinal sectors. Year-to-year rainfall anomalies in each sector are presented and the question of the dominance of the August maximum is also addressed for each sector.

Figure 7 shows inter-annual variability in five longitudinal sectors of the Sahel. These include 10°W to the Atlantic coast, 0°–10°W, 0°–10°E, 10°–20°E, and 20°–26°E. In

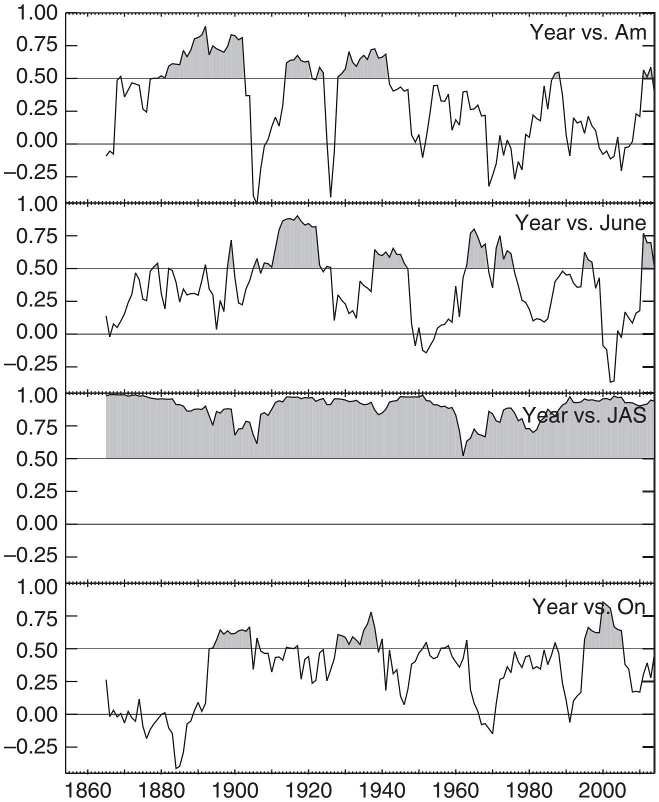

FIGURE 6 Sliding correlations between seasonal and annual anomalies in Sahel rainfall, averaged over a 11-year window. Values are plotted at the end of each interval. Shaded values exceed the 10% significance level

consideration of the paucity of stations in the far northern Sahel (Figure 1), the analysis is confined to stations within the latitudinal limits of 11°–17°N. The departure of rainfall anomalies from that of the entire region is also shown (Figure 7, right).

The variability of rainfall is markedly similar in all sections (Figure 7, left). Rainfall is generally above the long-term mean prior to 1968 in all sectors but the easternmost, then an abrupt shift to dry conditions occurs in all sectors. The contrast between conditions before and after 1968 is striking. As for recovery, post-1968 rainfall remained very low in the western Sahel. Rainfall increased notably in the central sectors since the 1990s, still, however, remaining below the long-term mean. This indicates notable geographical variations in the recovery, with the strongest recovery taking place in the east. This is in agreement with previous findings of Nicholson (2005), Lebel and Ali (2009), and Dieppois *et al*. (2013), based on a considerably shorter period of record.

An interesting contrast among the sectors occurs at 1968. Prior to that time, rainfall anomalies in the west/east were generally wetter/drier than the average for the Sahel as a whole. The pattern reversed after that time in each of the five sectors. This suggests that the post-1968 dry period was associated with a reduction of the east–west climatological rainfall gradient. Table 2 quantifies the gradient between the western and eastern Sahel. The east–west gradient is clearly stronger pre-1968 during August and September, when the monsoon is further north, but not in July, the end of the transition phase and the early part of the Sahelian phase.

The question of the disappearance of the pronounced August peak, as raised by Lebel and Ali (2009), is examined by looking at the north–south gradients in the July to September in the five longitudinal sectors and by calculating the percent of stations with an August rainfall maximum. Figure 8 shows the latitudinal gradients for each month and sector during the periods 1926 to 1967 and 1969 to 2014. For all five sectors August is the wettest month at all latitudes in both periods. However, the contrast between August and the other 2 months is clearly greater in the earlier period, indicating that the change in the rainfall regime was greatest in August.

The August maximum is further examined in Figure 9, showing for each year and longitudinal sector the percent of stations with an August maximum. In all sectors there is a downwards trend over the period 1926–2014. The trends suggest that the decreasing dominance of the August maximum is generally more pronounced in the east than the west. Table 3, comparing the periods before and after 1968, confirms this. The percent in the westernmost sector is 66 versus 57% before and after 1968, compared to 75 versus 60% and 72 versus 60% in two easternmost sectors. The change in the west is marginally significant (at the 6% level), while those in the east are significant, respectively, at the 2% level and .2% level. Analysis of July and September (not shown) indicates that in the westernmost sector the shift was towards a September maximum, while the other regions have shifted towards a July maximum.

4.3 | Relationship between rainfall in the Sahel and in the Guinea Coast

Annual rainfall along the Guinea Coast (Figure 3) displays many of the characteristics of the Sahel series: relatively dry conditions in the 1940s, peak rainfall in the 1950s and 1960s, and very dry conditions since 1969. Notably, this was 1 year after the onset of dry conditions in the Sahel. Strong contrasts between the Sahel and Guinea Coast are evident, however, in the degree of inter-annual persistence of anomalies and the degree of recovery the last decade. The recovery in the Sahel is stronger and the persistence of year-to-year anomalies somewhat greater. Nevertheless, despite an upwards trend since the early 1980s, few recent years have been as wet as many years earlier in the century.

While trends in annual rainfall clearly tend to run parallel in the Guinea Coast and Sahel, contrast is evident on a seasonal basis (Figure 5). Inter-annual variability in the two regions is similar in June, October–November, and to a lesser extent April–May. However, the time series for the two regions contrast sharply during the Sahelian phase of July-to-September, with recent rainfall being generally

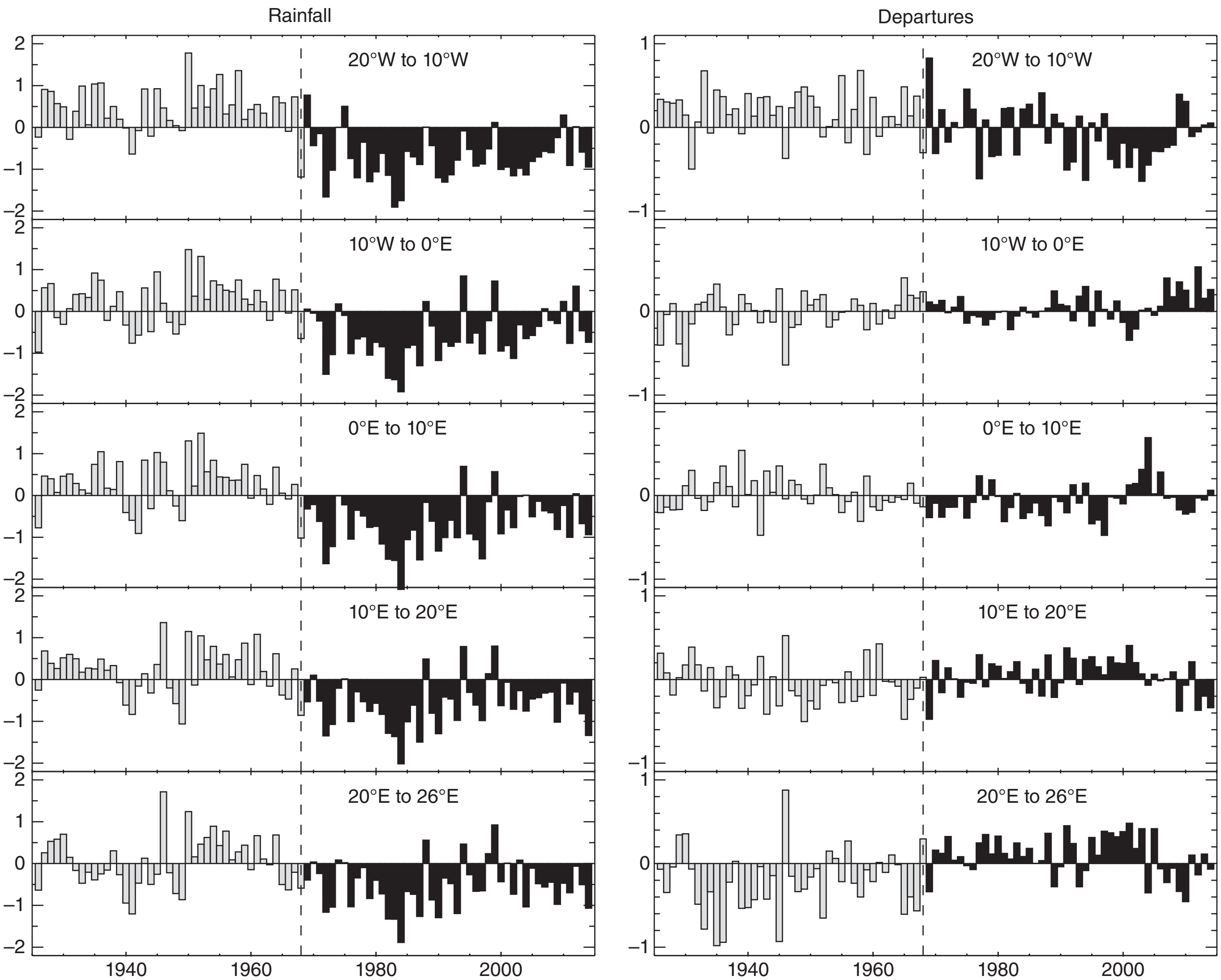

FIGURE 7 Rainfall in five longitudinal sectors of the Sahel, between latitudes 11°N and 17°N. (left) Standardized departure, as in Figure 3. (right) Departure of sector rainfall from rainfall in the Sahel as a whole, between 11°N and 17°N. The values indicated represented the difference between the Jul–Aug–Sep anomaly for the indicated sector and the Jul–Aug–Sep anomaly for the region as a whole, as seen in Figure 5. The dashed vertical line represents 1968

above average in the Guinea Coast but below average in the Sahel. These generalizations are confirmed via linear correlation: $r = .46$, .42, −.16, and .50 for April–May, June, July-to-September, and October–November, respectively, for the period 1886–2013.

The relationship during July-to-September is further explored in Figure 10, which shows the sliding 20-year correlations between rainfall in the Sahel and the Guinea Coast. The correlations were generally negative but insignificant at the 5% level and became increasingly negative until 1968 (i.e., the 20-year interval from 1948 to 1968). After 1968 the correlation rose sharply and steadily, eventually becoming positive (but near zero). This further supports the hypothesis of a regime change in 1968. The change in the teleconnection is significant at the 94% confidence level.

The negative correlation prior to 1968 reflects the well-known (e.g., Nicholson, 1980; 2008; Janicot, 1992) mode of opposition between the Sahel and Guinea Coast (the

TABLE 2 Mean contrast in rainfall (in mm/month) between western and eastern Sahel in July, August, and September at five Sahelian latitudes during the periods 1926–1967 and 1969–2014. Western Sahel extends from 8 to 14; eastern Sahel extends from 24°E to 26°E

	July		August		September	
	1926–1967	1969–2014	1926–1967	1969–2014	1926–1967	1969–2014
11 N	174	150	245	201	220	150
13 N	133	130	205	150	215	130
15 N	79	86	111	89	105	86
17 N	28	19	40	32	50	19

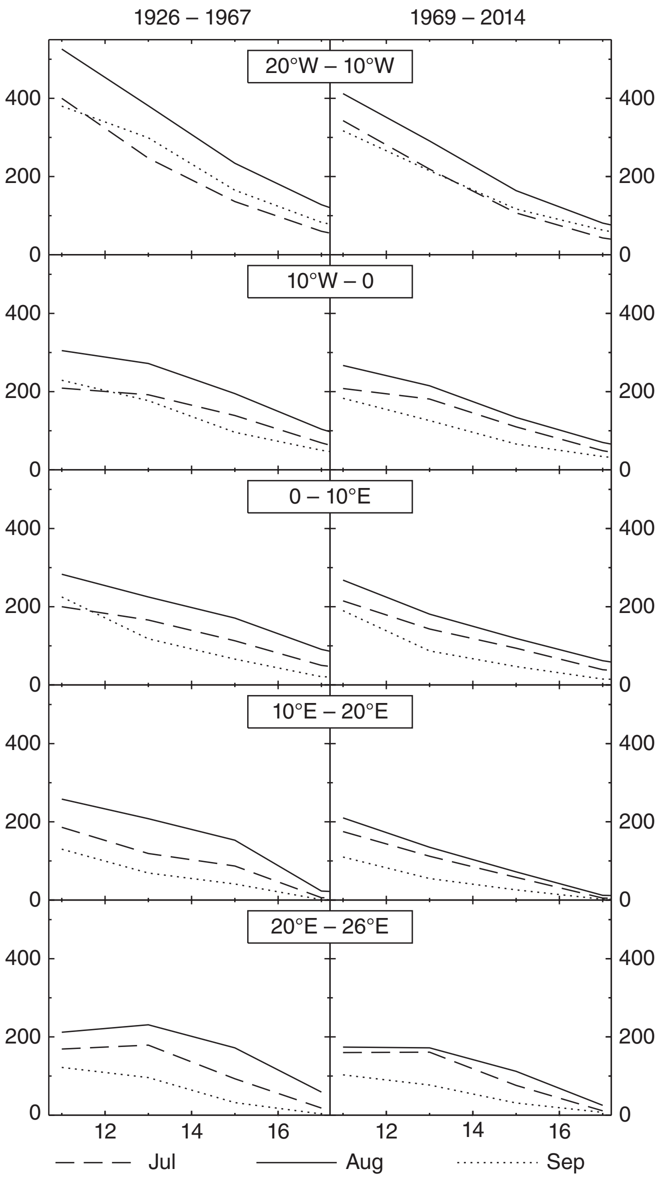

FIGURE 8 July, August, and September rainfall (mm/month) as a function of latitude in five longitudinal sectors of the Sahel. Rainfall is compared for 1926–1967 and 1969–2014

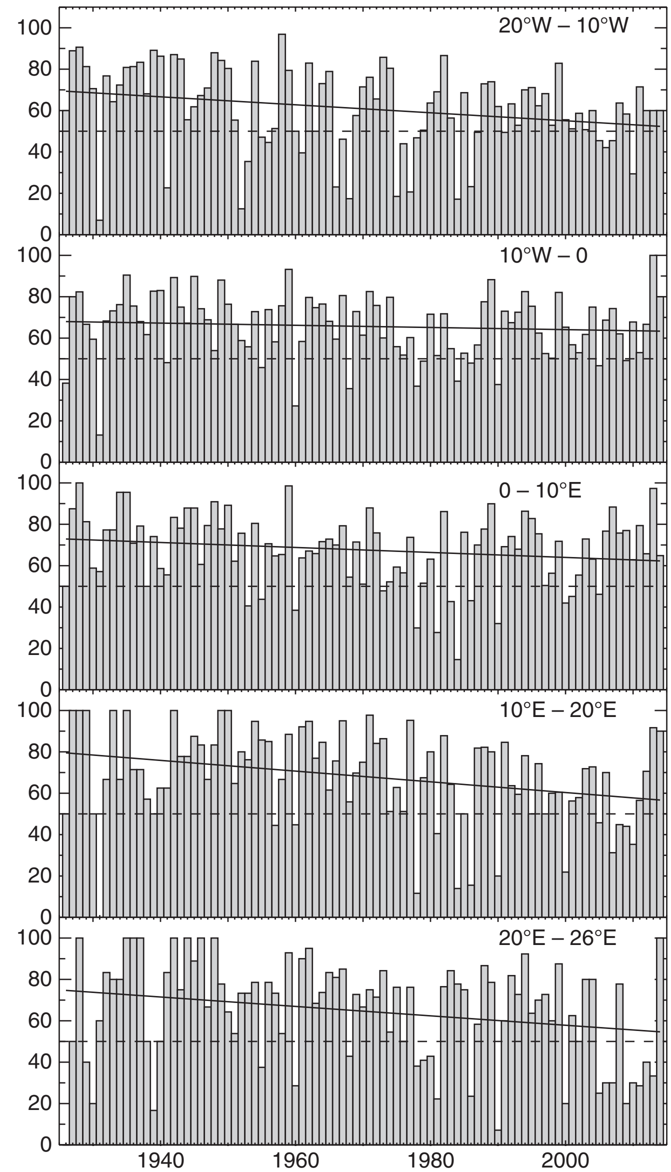

FIGURE 9 Percent of stations with an August maximum in five longitudinal sectors of the Sahel, between latitudes of 11°N and 17°N. The dashed lines indicate 50% and the solid line is the trend line (least squares regression)

rainfall dipole) but this mode was apparently best developed in the 1940s through 1960s. Post-1968 there was little opposition between the two regions during July-to-September. Losada *et al.* (2012) even suggested that the dipole had disappeared in recent years.

That suggestion is tested by directly comparing individual years in the Sahel and Guinea Coast. To do so, only those years in which a dipole is evident are plotted in Figure 11. These are simply defined as years in which the rainfall anomaly is of opposite sign in the two regions (regardless of magnitude of the anomalies). Annual rainfall exhibited a dipole in 32% of all years and in most cases anomalies were positive in the Sahel and negative along the Guinea Coast. Post-1968 a dipole prevailed slightly less frequently (28% of all years) and the contrast between the two regions was generally small. The frequency of occurrence of the dipole changed little during July or September, but decreased dramatically in August, from 58% of years prior to 1968 to 34% of years post-1968. In addition, the sign of the dipole shifted in 1968 in July and August, with positive/negative anomalies occurring in the Sahel/Guinea coast in earlier years, and negative/positive anomalies prevailing in the Sahel/Guinea Coast during most dipole years in 1968 and later.

After 1968 drier conditions in all seasons and less frequent occurrence of the dipole, suggest that the drier

TABLE 3 Percent of stations with an August maximum in five longitudinal sectors and two time periods. Analysis extends from 11 N to 17 N

	20–10 W	10 W–0°	0°–10°E	10°–20°E	20°–26°E
1926–1967	66%	68%	72%	76%	72%
1969–2014	57%	63%	64%	61%	59%

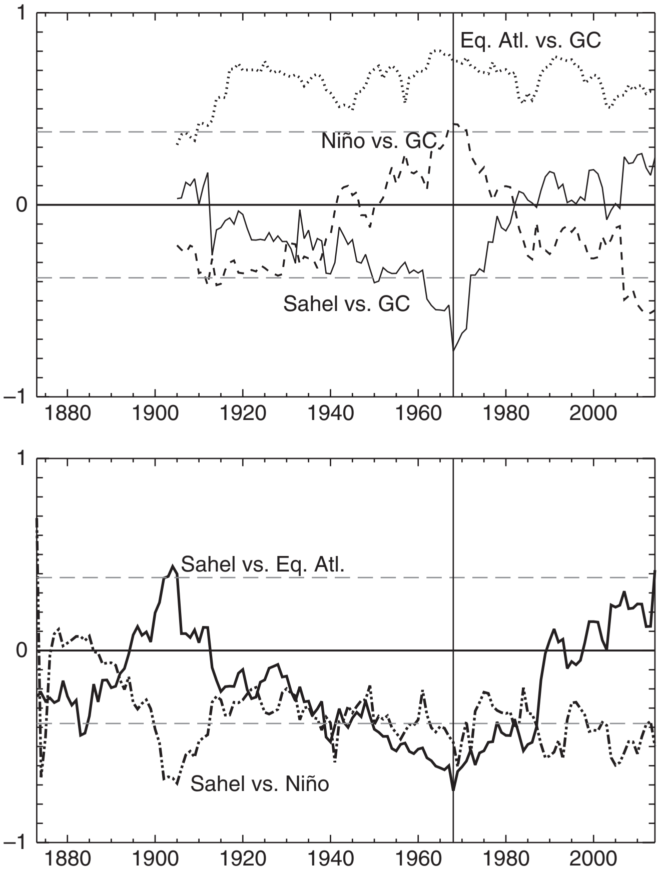

FIGURE 10 Sliding 20-year correlations for the July-to-September season. (top) Correlation of Guinea Coast rainfall with Sahel rainfall, Niño3.4 SSTs, and SSTs in the equatorial Atlantic (4°S–4°N, 22°–6°W). (bottom) Correlation of Sahel rainfall with Niño3.4 SSTs, and SSTs in the equatorial Atlantic (4°S–4°N, 22°–6°W). Dashed lines at ±.38 indicate the 5% significance level. Data are plotted at the end of the 20-year interval. The solid vertical line indicates 1968

conditions are generally associated with a change in the intensity of monsoon (i.e., the amount of rainfall associated with the monsoon), as opposed to a meridional shift in rainfall. The trends in July-to-September are not totally consistent with this, since conditions were notably wetter along the Guinea Coast than in the Sahel. That observation suggests a southwards displacement of the monsoon rains post-1968. Both hypotheses were tested for the months of July, August and September. Results were similar so only the results for August are presented here. The maximum monthly rainfall is used to indicate monsoon intensity and the latitude of this maximum is used as an indicator of monsoon displacement.

Figure 12 shows this for five longitudinal sectors of West Africa in the core of the monsoon region. Each spans two degrees of longitude and these are centred on 8°W, 4°W, 0°W, 4°E, and 8°E. This particular analysis is limited to this longitudinal sector in order to reduce the topographic influences further east and further west. In each sector the average latitude of the rainfall maximum (Figure 12, left) is lower post-1968 than pre-1968. Except at 0°W, the difference is significant at the 1 or 2% level. This agrees with the finding of Dieppois *et al.* (2013) for the 1970s and 1980s. Except at 8°E, the rainfall maxima (Figure 12, right) were significantly further south (one-half to one degree of latitude) post-1968 than pre-1968. These results suggest both that the monsoon was weaker and that the associated rain belt was further equatorwards post-1968. Notably, rainfall in July-to-September has been increasing steadily in both regions since the early 1980s. If a comparison were made with the period 1968–1984 instead of 1969–2010, the contrasts would have been much more dramatic.

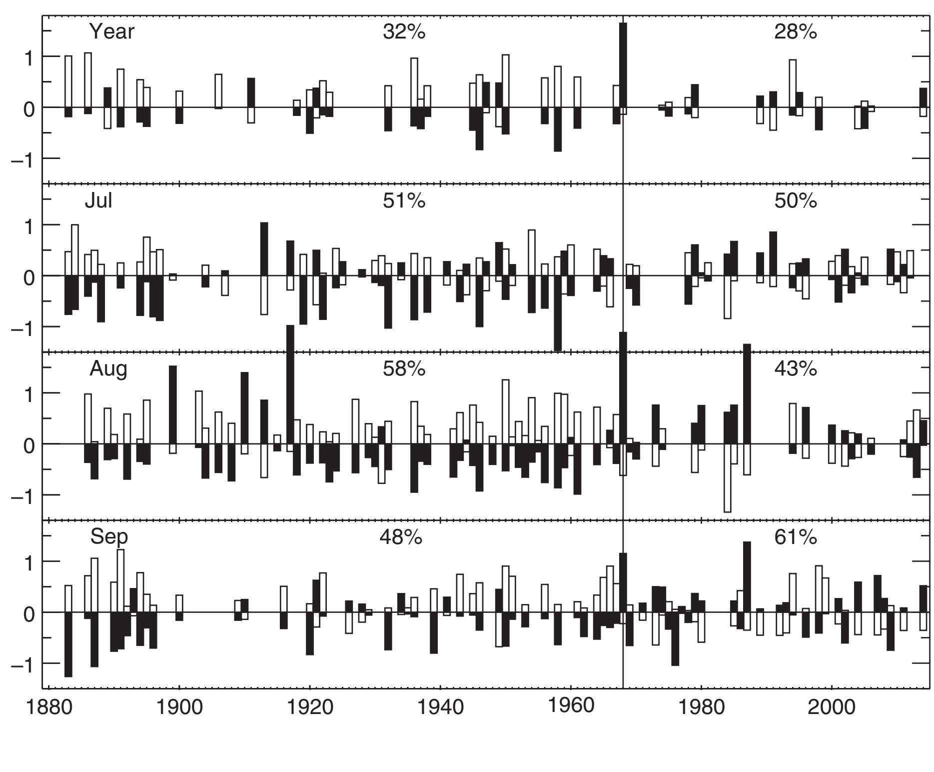

FIGURE 11 Years in which the dipole occurred in the months of July, August, and September. Open bars indicate Sahel rainfall; shaded bars indicate Guinea Coast rainfall. Rainfall is expressed in standardized departures as in Figure 3. The solid vertical line indicates 1968. Also indicated is the percent of years with a dipole before and after 1968

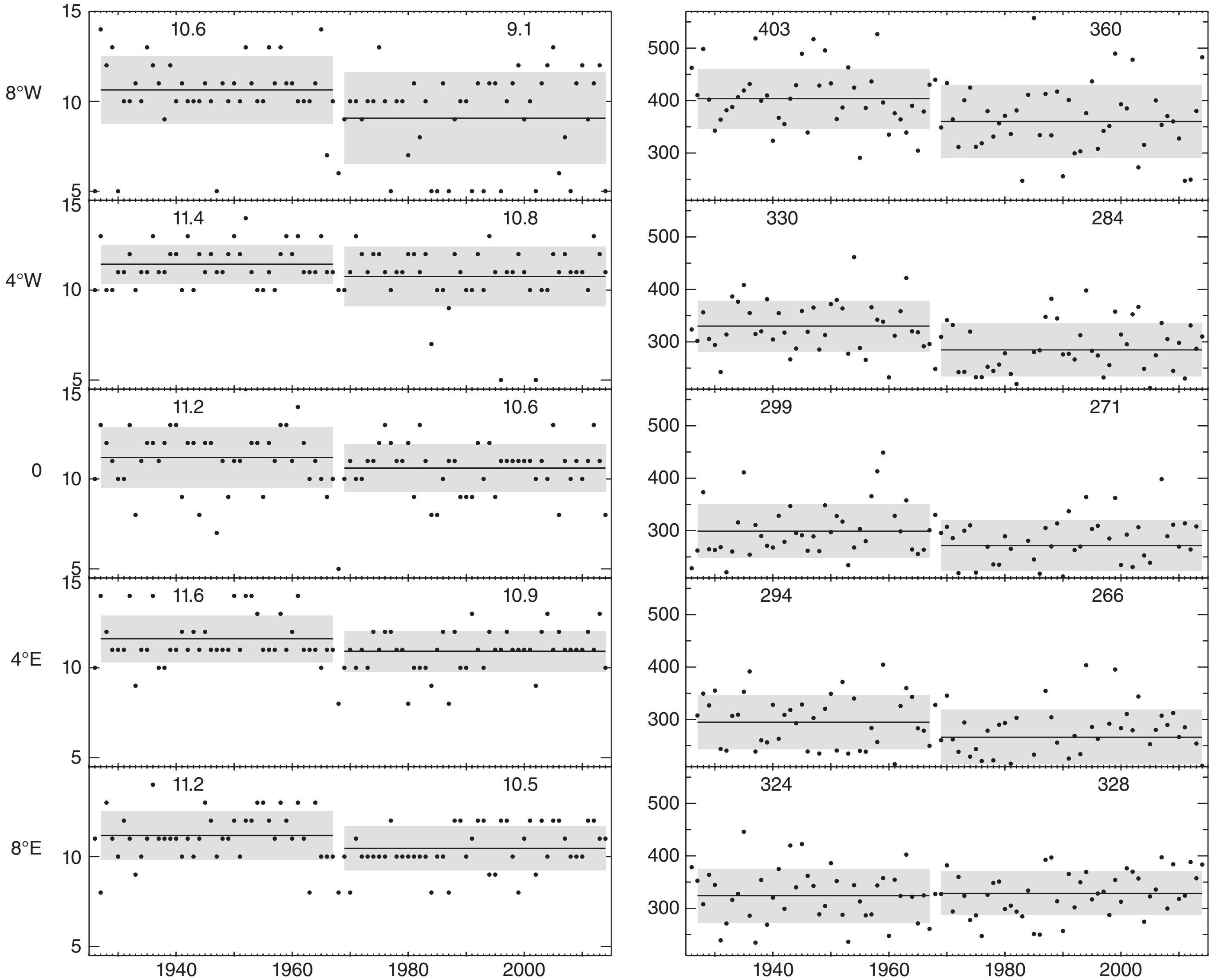

FIGURE 12 Indicators related to monsoon latitude and intensity in August in five longitudinal sectors. (left) Latitude of maximum rainfall in each sector. (right) Maximum rainfall (mm/month) in each sector. Mean values for the periods 1926–1967 and 1969–2014 are indicated numerically and by the horizontal solid lines. Shading indicates values within one standard deviation of the mean

Collectively these results suggest that a major change in the rainfall regime occurred in both the Sahel and Guinea Coast around 1968/1969. Relatively dry conditions have prevailed in both regions since that time. The change is most strongly evident for annual rainfall, but is evident in almost all seasonal time series as well. The exception is July-to-September in the Guinea Coast. Some recovery is evident since the mid-1990s, but more so in the Sahel than in the Guinea Coast. Notably, inter-annual variability in the Sahel has increased since that time, especially during July-to-September.

4.4 | Relationship to sea surface temperatures

It has long been accepted that SSTs play a major role in the inter-annual variability of rainfall in both the Sahel and the Guinea Coast regions (e.g., Folland *et al.,* 1986; Joly and Voldoire, 2009; Losada *et al.,* 2010; Mohino *et al.,* 2011a,b; Diatta and Finkc, 2014; Rodríguez-Fonseca *et al.,* 2015). Losada *et al.* (2012) documented a change in the relationship between the Sahel and tropical SSTs after the 1970s. Our results, though markedly similar to theirs, suggest the change actually took place around 1968. The SST–rainfall teleconnections provide a physical explanation for the changing relationship between the two regions in July-to-September and for the more similar patterns of inter-annual variability in the other seasons.

Figures 13 and 14 show the correlations between rainfall and global SSTs for all four phases of the monsoon. Correlations are calculated and presented separately for the period 1886–1967 and 1969–2014. This analysis commences in 1886, because that is the first period for which a continuous series of Guinea Coast data is available.

For the earlier period (Figure 13) the spatial patterns of correlation show many similarities for the two regions during April–May and June and to a lesser extent in October–November. In April–May the strongest correlations are with the Atlantic, particularly for the equatorial and tropical

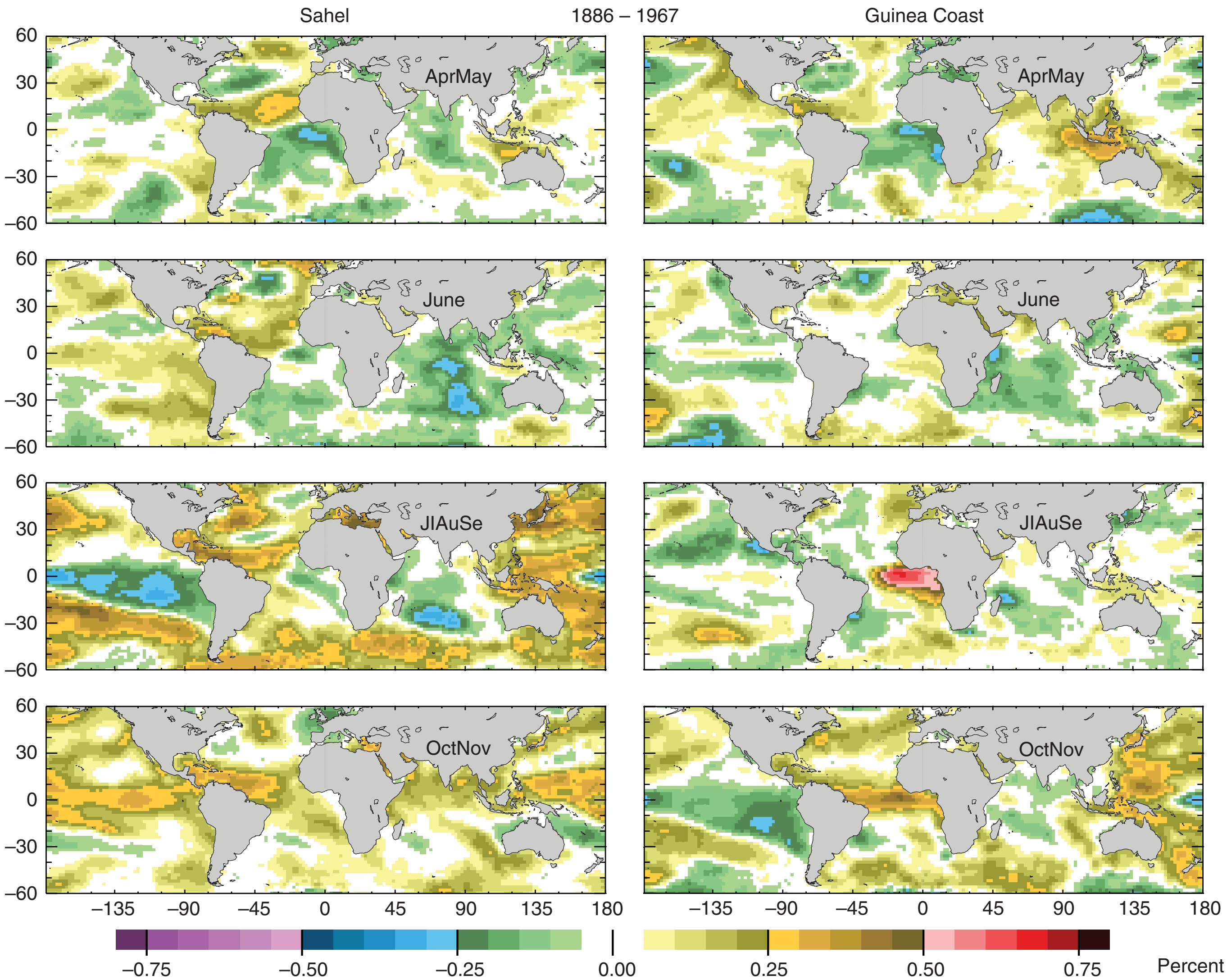

FIGURE 13 Correlation between rainfall and SSTs in the four seasons, 1886–1967. (left) Sahel. (right) Guinea Coast. The 1 and 5% significance levels are ±.28 and ±.22, respectively

South Atlantic. Over a vast area, correlations range from −.20 to −.25 or greater for the Sahel (−.30 for the Guinea Coast), being significant at roughly the 1% significance level. Those for the Sahel are nearly as large in the subtropical North Atlantic. The Atlantic SST dipole described by Lamb (1978a, 1978b) is only weakly evident. For June, the correlation with SSTs is generally weaker for both regions, although the negative correlations over the Indian Ocean may be meaningful. For October–November Sahel rainfall is strongly and positively correlated with SSTs throughout the equatorial oceans. The pattern for Guinea Coast rainfall is relatively similar except in the central and eastern Pacific, where the correlation is weakly negative and suggestive of a negative link to El Niño.

During the Sahelian phase of July-to-September (Figure 13), the association with SSTs is strikingly different for the two regions. During the period 1886–1967, Sahel rainfall is strongly correlated with SSTs throughout most of the area from 60°S to 60°N. The correlations tend to be negative in the low-latitudes, especially the central and eastern Pacific, and positive in the higher latitudes and western Pacific, resulting in a pattern associating El Niño-like SST anomalies with dry conditions in the Sahel. Correlation with Guinea Coast rainfall tends to be weak, except in the equatorial Atlantic/Gulf of Guinea, where correlations exceed .65 over the 82-year period. In most areas the correlation is of the opposite sign as that for Sahel rainfall. Of particular importance is the contrasting sign in the equatorial Atlantic/Gulf of Guinea. Hence, the association with SSTs can explain the prevalence of the rainfall dipole during the July-to-September season (Mohino *et al.,* 2011a; Rodríguez-Fonseca *et al.,* 2015).

Correlations with rainfall during the period 1969–2014 are shown in Figure 14. One striking contrast is the magnitude of the correlations, especially for the Sahel. Although a higher magnitude would be anticipated merely as a result of the shorter analysis period, the level of significance also tends to be notably higher in the 1969–2013 period than in the 1886–1967 period. For the Sahel, the increased magnitude of the correlations is particularly marked in June,

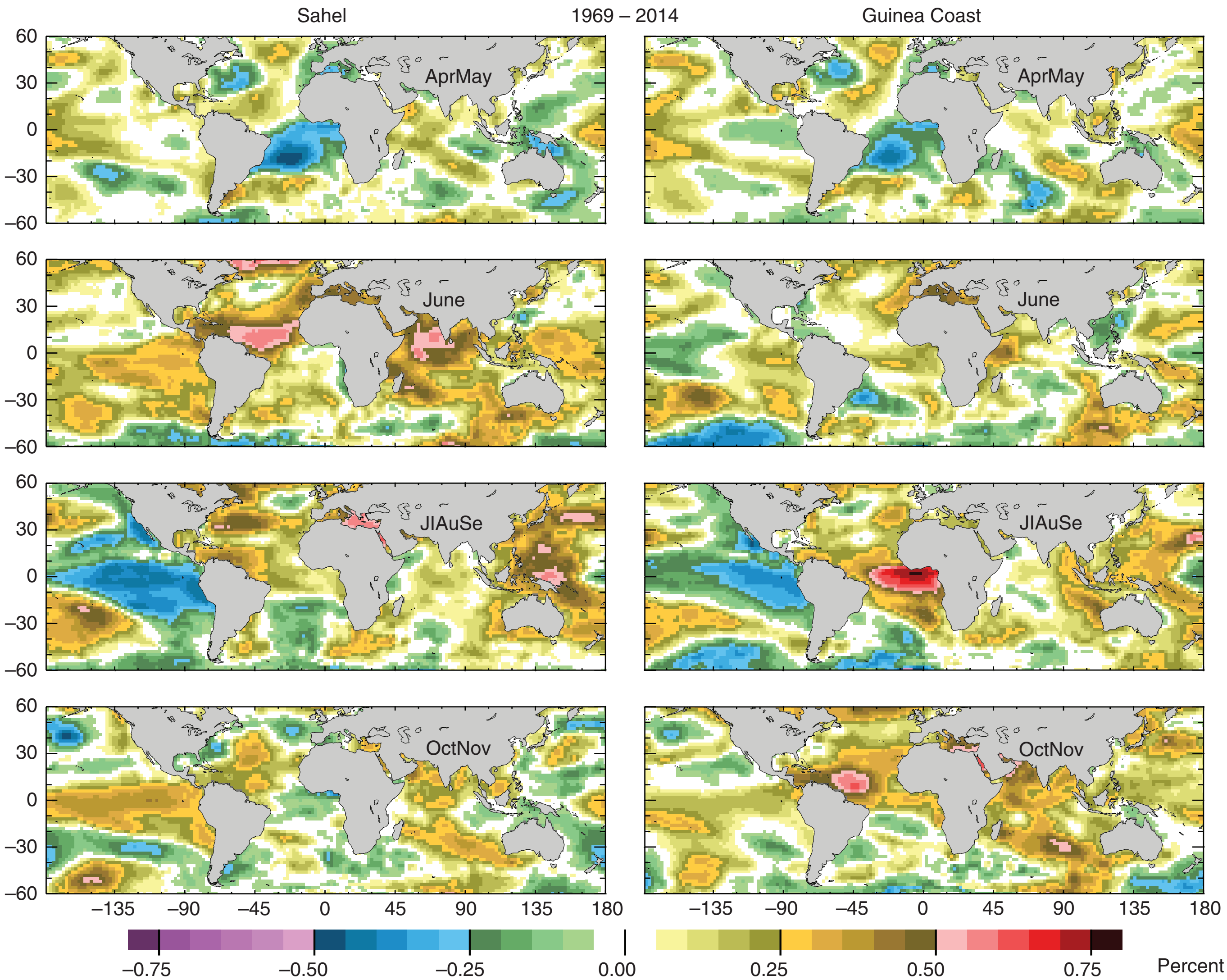

FIGURE 14 Correlation between rainfall and SSTs in the four seasons, 1969–2014. (left) Sahel. (right) Guinea Coast. The 1 and 5% significance levels are ±.38 and ±.29, respectively

where the links to the eastern Pacific (La Niña) and the North Atlantic become strong. This may indicate opportunities for predicting the onset of rains. Such forecasts may be particularly useful in the Sahel, where photoperiod sensitive crops like millet and sorghum have a fixed temporal window for germination and grain filling. The correlation with Indian Ocean SSTs switches from negative to strongly positive in June and to weakly positive in July-to-September. It becomes strongly positive in both June and October–November. During July-to-September the link to the Pacific and North Atlantic is virtually unchanged. However, in the equatorial Atlantic/Gulf of Guinea the correlation, though weak, changes from negative to positive. Comparatively little change in the correlations is apparent in either April–May or October–November.

For Guinea Coast rainfall striking changes in the correlation with SSTs are seen in July-to-September and October–November. Post-1968, strong correlations develop with the Pacific in July-to-September, in agreement with the results of Mohino *et al*. (2011a). This reduces the anti-correlation between the Sahel and Guinea Coast and correlations between the two regions during this season become insignificant (Figure 10). Post-1968 the correlation between Guinea Coast rainfall and October–November SSTs becomes strongly positive in the Indian and Atlantic Oceans, thus enhancing the correlation between the Sahel and Guinea Coast in this season, as seen in Figure 5.

Thus, these analyses provide two reasons for the post-1968 change in the teleconnections between the Sahel and Guinea Coast during the Sahelian phase. One has to do with a change in the sign of the relationship between Sahel rainfall and SSTs in the Gulf of Guinea/equatorial Atlantic. It was negative prior to 1968, while Guinea Coast rainfall was positively correlated with SSTs in that region. After 1968, rainfall in both regions is positively correlated with Gulf of Guinea/equatorial Atlantic SSTs. The second factor is that the links between El Niño-Southern Oscillation (ENSO) and Guinea Coast rainfall became much stronger. Notably, Baines and Folland (2007) identified a global climate shift around this time as well. The strengthening of the Guinea

Coast ENSO teleconnection may have helped synchronize rainfall in this region with variations in the Sahel.

Figure 10, showing sliding 20-year correlations, strikingly depicts the changing rainfall–SST relationships in these two sectors during July-to-September. The relationship between the Sahel rainfall and equatorial Atlantic SSTs is highly non-stationary. The change is significant at the 96.5 confidence level. There is a steady decrease from significantly positive towards the end of the 19th century to strongly negative in the period ending in 1968, when a strong trend towards positive values occurs. Diatta and Finkc (2014) found a similar trend in the correlation between equatorial Atlantic/Gulf of Guinea SSTs and rainfall in the far western Sahel. In contrast, the relationship with Niño3.4 is relatively stable and generally negative except late in the 19th century.

The link between Sahel rainfall and SSTs in the equatorial Atlantic/Gulf of Guinea and the link between Sahel and Guinea Coast rainfall show remarkably similar trends. Correlations are negative during most of the 20th century and become continually more negative from the beginning of the series to 1968, when an abrupt shift towards less negative/more positive values occurs. The trend in the correlation between Guinea Coast rainfall and SSTs in Niño3.4 is very much the opposite. The shift towards more negative values similarly commences in 1968. These observations further support the hypothesis of a regime shift in 1968.

The ultimate cause of this regime shift is beyond the scope of this article. Rodríguez-Fonseca *et al.* (2009) suggested that changes in the relationship between Pacific and Atlantic Niños might be responsible, noting that 1968 was the time of the change. This is consistent with our results. Zhang and Delworth (2006) argue that the inter-decadal fluctuations are governed mainly by the Atlantic multi-decadal oscillation (AMO). Figure 15 shows the AMO over the time period of our analysis, with times of regime shift in the annual Sahel rainfall indicated. While the correlation is not perfect, most regime shifts roughly correspond to a major change in the AMO, particularly those marking a change between wet and dry conditions in the Sahel: 1927, 1950, 1968, and 1994. The others occur at times when a large but short-lived change in the AMO occurs. On a decadal scale negative values of the AMO tend to be associated with reduced rainfall in the Sahel. This is true even for the major period of aridity early in the 19th century (Nicholson, 2013). However, despite very positive values of the AMO, Sahel rainfall has not returned to the very high values of the 1950s.

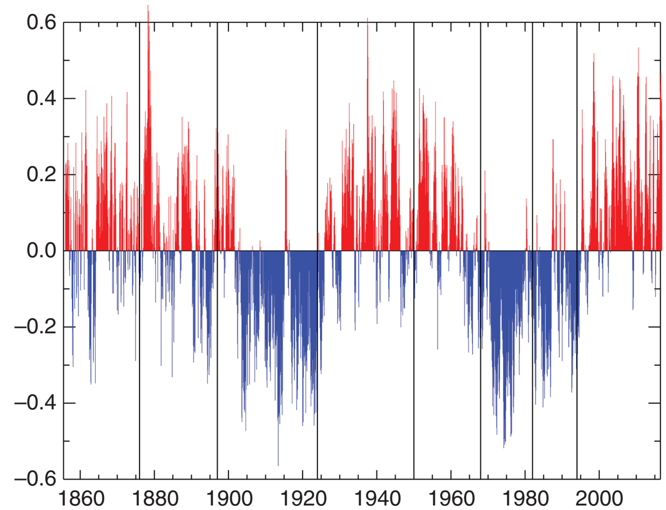

FIGURE 15 Monthly values of the Atlantic multi-decadal oscillation (data from Kaplan SST V2 – esrl.noaa.gov). Vertical bars indicate years of statistically significant regime shifts in Sahel rainfall

5 | SUMMARY AND CONCLUSIONS

The availability of a 161-year time series for the Sahel allows us to put the recent dry conditions in the Sahel into a longer time frame. The contrasting behaviour of the four monsoon "phases" (i.e., the four seasons evaluated) is clearly apparent, as are changes in the contribution of each phase to inter-annual variability. The teleconnections to global SSTs are likewise dissimilar for each of the four phases. This strongly suggests June should not be combined with July, August, and September in evaluating factors in inter-annual or inter-decadal variability. Our results also indicate that June teleconnections might support prediction of the onset of the rains.

The dry conditions commencing in the Sahel in 1968 have no prior analogue during the 161-year period. Notably, the rainfall decline at this time was evident not only in July-to-September, but also in June and October–November. It did not occur in April–May until roughly one decade later. In the Guinea Coast a major decline in rainfall also occurred in 1968. As in the Sahel, the drier conditions that have prevailed since then are unprecedented within the period of gauge coverage. In the Sahel a very wet interval prevailed in the 1950s and early 1960s. The wet conditions were apparent in June and July-to-September. Previous analyses suggested it was unique (e.g., Nicholson, 1993). The longer time series presented here shows that a comparable wet interval occurred in the late 19th century. In contrast to the 1950s, the early and late phases of the monsoon (April–May and October–November) played a role in creating the wet conditions.

In the Sahelian phase of July-to-September 1968 marked a statistically significant regime change. This was the year when drought first became evident (Lamb, 1978a). In addition to the increased aridity, teleconnections between the Sahel and Guinea Coast and teleconnections between those regions and the large-scale SST patterns changed dramatically. While the association between the Guinea Coast and SSTs in the equatorial Atlantic/Gulf of Guinea remained robust over time, the link between SSTs in that region and

Sahel rainfall changed from negative to mildly positive after 1968. This is consistent with the results of Losada *et al.* (2012), who found that after the 1970s the impact of the Pacific on Sahel rainfall counteracts the impact of the Atlantic. At the same time the link between Guinea Coast rainfall and El Niño became steadily stronger and out-of-phase. Those changes led to a dramatic change in the Sahel-Guinea Coast teleconnections, with a weakening and reduced frequency of the rainfall dipole that previously typified July-to-September. The change in the dipole was most evident in August. Several other changes in the rainfall regime occurred after 1968. The August Sahel rainfall maximum became less pronounced; the east–west rainfall gradient in the Sahel became weaker; the latitude of the rainfall maximum shifted southwards; and the intensity of the monsoon became weaker.

Other regime shifts identified in the Sahel occurred in 1876, 1897, 1927, 1950, 1982, and 1994 (Table 1). This first of these, a shift to wetter conditions, was strongly linked to changes in April–May. However, increased rainfall in October–November and in July-to-September (Figure 5) also contributed to the wetter conditions. The shifts at 1950, 1982, and 1998 were associated mainly with northwards displacement of the rainfall maximum, with little change in intensity of the monsoon.

Overall, there has been some recovery of the "good" rains, following the intense droughts of the 1970s and 1980s, the persistently good conditions that prevailed prior to 1968 have not been achieved in either the Sahel or the Guinea Coast. Since the 1990s, annual rainfall in the Sahel occasionally reached the levels of the very wet years of the 1950s. However, it remained overall predominantly below average. In the Guinea Coast, where the droughts were never as extreme as in the Sahel, recovery has been even less complete. In both regions the recovery was most pronounced during the Sahelian phase and, to a lesser extent, the second transition season of October–November.

Farmers in the Sahel depend primarily on photoperiod sensitive crops, such as millet and sorghum. This sensitivity means a limited window for plant growth within the seasonal cycle of rainfall. Hence, Sahelian farmers are strongly impacted by the onset date of the rains, in late May and June, and there has been little recovery in these seasons. Maximum temperature increases related to decreases in actual evapotranspiration (Marshall *et al.,* 2012) and increases in potential evapotranspiration (Cook and Vizy, 2012) may also be acting to shorten and degrade the quality of the growing season.

The Sahelian phase is critical because it determines annual rainfall in both the Sahel and the Guinea Coast, although July-to-September is generally a drier season in the latter. During that season, Guinea Coast rainfall is clearly determined by SSTs in the equatorial Atlantic and in the Gulf of Guinea and this relationship has been robust since the early 20th century. This is consistent with the findings in Losada *et al*. (2012) and Diatta and Finkc (2014), who noted a strong and stationary correlation between Guinea Coast rainfall and the eastern equatorial Atlantic. For the Sahel as a whole the most robust SST associations are in the western Pacific, central and eastern equatorial Pacific, North Atlantic, and Mediterranean. The correlation is positive except in the central and eastern equatorial Pacific. However, these associations are to some extent geographically dependent (Diatta and Finkc, 2014). For example, correlation with the Mediterranean is particularly strong in the central Sahel while the strongest SST association with the far western Sahel in their analysis appears to be with the tropical Indian Ocean.

A major open question is the cause of the regime change in 1968. The issue is extremely complex and beyond the scope of this article. However, a few papers may shed some light on this. The reduced intensity of the monsoon in the Sahelian phase suggests a reduction in the intensity of the tropical easterly jet (Nicholson, 2009). The southwards displacement of the rainfall maximum suggests a reduction in the cross-equatorial pressure gradient over the region (Nicholson and Webster, 2007). Losada *et al*. (2012), who also noted changes in the rainfall/SST teleconnections, suggested that development of a pronounced anti-correlation between Pacific and Atlantic Niños (Rodríguez-Fonseca *et al.,* 2009) was responsible. This is certainly consistent with our results. On the other hand, the regime change we noted is part and parcel of the inter-decadal variability in the region. The inter-decadal scale is clearly evident in the time series in Figures 4 and 7, for example. Some studies have linked this to the Atlantic multi-decadal oscillation (e.g., Zhang and Delworth, 2006). Yet when the AMO returned to the strong positive values of the 1950s, rainfall in the Sahel did not. Moreover, the timescale of the rainfall variability appears to be on the order of 40–50 years, in contrast to the roughly 30-year scale of the AMO.

Clearly, then the large-scale drivers of Sahel rainfall are not fully understood. Quite possibly the drivers are different on inter-annual versus inter-decadal scales. The resultant regime reflects the superimposition of the two timescales. This complexity has strong implications for projections of the region's future climate (Biasutti, 2013), as well as for seasonal forecasting.

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