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THE SPATIOTEMPORAL CLIMATE VARIABILITY OVER SENEGAL AND ITS RELATIONSHIP TO GLOBAL CLIMATE

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ABSTRACT

Climate variability over Senegal (West Africa) and its relationship to global climate are examined for the period 1979–1998. Monthly observed rainfall for 20 stations and monthly CPC merged analysis precipitation (CMAP) over Senegal were averaged for the months of June, July, August, and September in order to generate seasonal rainfall totals for the wet season, as well as climate indices averaged over the study period. The spatial distribution patterns are mapped and analyzed using ArcGIS Spatial Analyst. Rainfall distribution over Senegal is dominated by a N–S gradient.

To investigate the climate variability over Senegal, an empirical orthogonal function (EOF) analysis is performed for the 1979–1998 period, using rain-gauge and CMAP rainfall data over Senegal, and CMAP data only for West Africa. The first West African mode agrees strongly with Lamb's rainfall index. One of our major findings is that EOF2 for West Africa is well correlated with EOF1 for rainfall in Senegal. This relationship is supported by the projection of winds on the EOF2 mode by the National Centers for Environmental Prediction (NCEP), as well as the grid-point correlation between the time series of EOF2 over West Africa and the Atlantic sea-surface temperature (SST). The typical circulation associated with positive anomalies over Senegal is a moisture convergence, which takes place over the Guinea Gulf, in conjunction with the warm waters in this area.

The time series for rainfall over Senegal show positive correlations with the South Atlantic SST. Over the Pacific Ocean, the greatest correlation coefficients (up to −0.72) are observed during the April–July period, which provide a modest possibility of predicting Senegal's rainy season.

Given the specificity of coastal West Africa, the traditional indices used by policy makers and end users for the whole Sahel–Sudan region will not work for Senegal.

The CMAP data are robust and suitable for analyses over West Africa. On the basis of its reliability, CMAP data has proven to be a good validation for analyses based on rain-gauge precipitation. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: Senegal; West Africa; EOF; GIS; precipitation; temperature

1. INTRODUCTION

Enclosed between latitudes 12°30′N and 16°30′N and longitudes 11°30′W and 17°30′W, Senegal is the westernmost country in Africa. With the North Atlantic Ocean to the west, it stretches between the moist part of West Africa to the south and the dry Sahara desert to the north. Senegal is generally free of steep terrain, with altitudes mostly under 130 m. The northern part of the country is part of the Sahel zone, and the southern part is situated in the West African climatic zone called the Sudan, a transition zone between the Sahel zone and the very moist Guinean and equatorial climates.

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As all Sahelian countries, Senegal is characterized by highly variable rainfall. During the past three decades, severe droughts have led to socioeconomic hardships for the entire country, including food scarcity and famine due to the deficit in rainfall. Since the rain is mostly confined to the four consecutive months of June, July, August, and September, a deficient rainy season affects the economy of Senegal for the whole year, including public finances, and domestic and foreign trade. In addition, degradation of natural resources and decrease in water supplies often occur owing to these drought conditions. Meanwhile, the population of Senegal is increasing at one of the highest rates in the world (2.54% in 2002 according to the United Nations Population Fund).

The persistence of the last drought epoch in West Africa, which began in 1968 and lasted more than two decades, has drawn increasing interest in (1) the rainfall anomaly regimes over tropical Africa as a consequence of land surface–atmosphere feedbacks, and (2) the study of the connections between sea-surface temperature (SST) anomaly patterns and rainfall variability over the tropical African region. Several studies have investigated the interactions between land-surface boundary conditions and the atmosphere over tropical Africa (e.g. Entekhabi *et al*., 1992; Lare and Nicholson, 1994; Semazzi and Song, 2001; Niyogi *et al*., 2002; Pielke *et al*., 2002). Similarly, a large body of empirical and numerical studies suggests that a strong relationship exists between tropical Atlantic or global SST anomalies and West African climate (Lamb, 1978a, b; Lamb *et al*., 1986; Lough, 1986; Philander, 1986; Bah, 1987; Semazzi *et al*., 1988; Parker *et al*., 1988; Wolter, 1989; Rowell *et al*., 1995; Eltahir and Gong, 1996; Ward, 1998; Janicot *et al*., 1996; Xue and Shukla, 1998; Janicot *et al*., 2001). In most of the empirical studies, investigators usually applied a variety of statistical methods, such as compositing, trend analysis, correlation analysis, and empirical orthogonal function (EOF) analysis to SST fields and/or rainfall anomalies over West Africa. It has been generally observed that the Sahel–Sudan rainfall and South Atlantic SST are negatively correlated (e.g. Lamb, 1978a, b; Lough, 1986; Philander, 1986).

Other studies have investigated the large-scale rainfall variability of the Sahel–Sudan region without linking it to SST fluctuations. Nicholson (1980) derived rainfall departures from the long-term average for the years 1901–1975 and pointed out the strong coherence of rainfall variation in subtropical West Africa, especially in the North–South direction. Janowiak (1988) performed EOF analysis to examine the interannual rainfall variability over the whole continent of Africa for the 1901–1973 period. He also found a high spatial coherence of rainfall anomalies over large areas, including the West African sub-Saharan region. Nicholson and Palao (1993) investigated the characteristics of rainfall variability in West Africa using linear correlations and the EOF method. One of their main conclusions is that homogeneous rainfall variability sectors can be demarcated within West Africa, and that a strong contrast is observable between the climate variability of the West African coast and the rest of the Sahel–Sudan zone.

Several studies based on the application of the EOF method suggest that the leading mode (EOF1) is sufficient for describing the interannual variability of the regional West African climate (e.g. Janowiak, 1988; Nicholson and Palao, 1993). Its time series is found to be in close agreement with the rainfall index of the Sahel region (Nicholson and Palao, 1993). Analysis of the spatial patterns of this first mode for both the JJAS (June, July, August, and September), and the annual total rainfall (Janowiak, 1988) indicates that the EOF1 mode is the dominant mode of variability over the West African region as a whole. Therefore, it is not surprising that for West Africa, EOF1 has been adopted by decision-makers planning for the effects of interannual climate variability. However, it has been recognized that within the Sahel–Sudan zone, different rainfall anomaly regimes exist (Wolter, 1989; Bhatt, 1989; Nicholson and Palao, 1993; Janicot, 1992; Camberlin and Diop, 1999). It is worth mentioning that not all investigators agree on the actual existence of drought in the West African Sahel. For example, Chappel and Agnew (2004) perceive the decline in Sahelian rainfall since the late 1960s as an artifact due to the changes in the climate station networks over the region.

The purpose of this study is to investigate the rainfall variability in Senegal and analyze its relationships with the West African region and the global climate. More specifically, (1) we examine the dominant EOF modes for rainfall and the seasonal number of rainy days, and (2) we also investigate the relationships between the different modes of variability over Senegal, the West African climate variability, and the global climate.

Section 2 gives the background review of the climatology of Senegal with emphasis on the wet season, which is the focus of this study. Section 3 focuses on the description of the data and methods of investigation, and Section 4 presents the statistical analysis and discussion of the results. Summary and conclusions are presented in Section 5.

2. METEOROLOGICAL CONDITIONS

2.1. General conditions

Three factors control the atmospheric circulation of Senegal: (1) the anticyclone over the Azores, (2) the North African anticyclone usually located over Libya in winter, and (3) the anticyclone of Saint Helens. During the northern-hemisphere summer season, the resulting convergence is responsible for development of the convectively active conditions associated with the wet season. The axis of convergence, associated with the intertropical convergence zone (ITCZ), is an extensive region of rising motion due to the confluence of air masses from both the hemispheres – NW and NE trade winds, and the SW monsoon flow.

Over Senegal, the ITCZ is often oriented NE–SW, and appears as a transitional branch linking the continental ITCZ and the maritime ITCZ (Figure 1). This branch, which is often referred to as a liaison zone, has a complex structure depending on the temperature and mixing ratio of the three convergent air masses. It can be very active, especially during August–September, when either the monsoonal flow or the NW trade wind is lifted upward (Garnier, 1976). The migration of the ITCZ determines the onset and duration of the wet season. In Senegal, the latter lasts from early May (June–July in the North) to late October (early October in the North). It begins in the south and spreads north, when the ITCZ migrates northward, so that the monsoon extends over the whole region and brings moisture from the Atlantic Ocean.

During the rainy season, the most important rain events are caused by West African disturbance lines, also called squall lines or cloud clusters; these tropical convective systems are organized as lines of thunderstorms oriented roughly N–S and propagating westward. Many squall line tracks have been observed throughout West Africa (Burpee, 1974; Reed *et al*., 1977; Peters and Tetzlaff, 1988; Diedhiou *et al*., 1999), but general agreement exists that they tend to merge into a single track located between 15 °N and 20 °N over the Atlantic Ocean (e.g. Reed *et al*., 1988a; Diedhiou *et al*., 1999). Consequently, Senegal, given its latitude, is a point of convergence of the disturbance lines. The number of squall lines over the country during the wet season decreases from SE to the NW – the disturbances weaken as they move westward and most of them

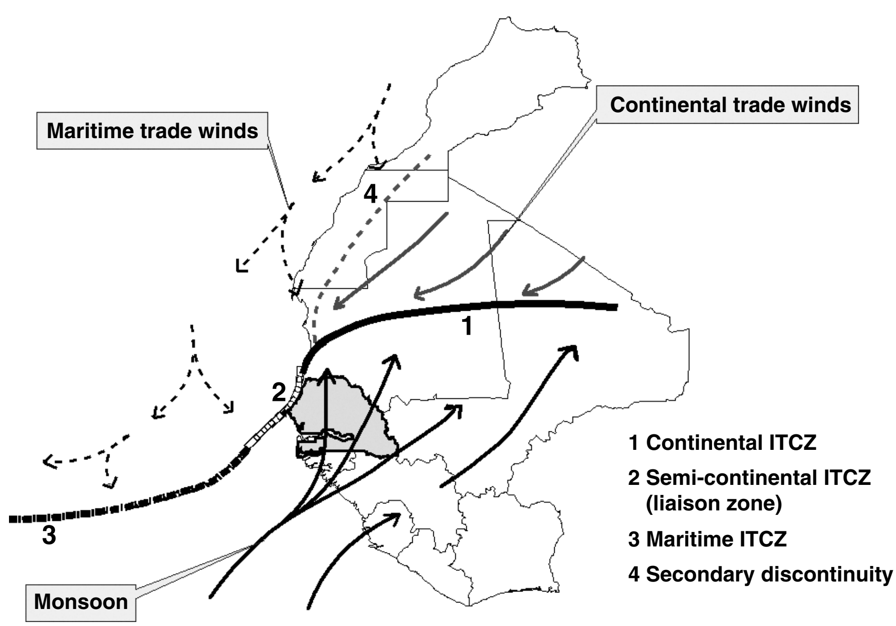

Figure 1. Mean position of the ITCZ in West Africa during the northern-hemisphere summer (adapted from Garnier, 1976)

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decay inland. In addition, in the northwestern Senegal, the proximity of the semicontinental ITCZ liaison zone (Figure 1) reduces convective activities. However, the convective systems that reach the Atlantic Ocean obtain additional moisture and can cause appreciable rainfall in the coastal regions. Some of them may develop into tropical storms or cyclones, as many studies show (Gaucher, 1976; Garnier, 1976; Landsea and Gray, 1992).

2.2. Rainfall distribution (1979–1998)

As discussed in Fall *et al*. (2005a), rainfall distribution in Senegal is characterized by an increase in the amount of precipitation and number of rainy days from N to S, with a high concentration of occurrences in the June–September period (Figure 2). However, the remainder of the year is not completely dry. The rainy season lasts up to October, which may in some instances consist of substantial per annum percentages (e.g. for October 1991: 25.7% in Louga; 25.3% in Velingara; 24.1% in Saint-Louis). The contribution to the seasonal rainfall in October is relatively important in the South as well. In addition, off-season rains may occur from December to March.

The spatial distribution shows the N–S gradient. Rains advance progressively from the southeast to the northwest throughout the wet season, with the largest amounts recorded in August. This SE–NW axis of rainfall precipitation has been noted by a number of studies (e.g. Leroux, 1973a, b) and is due to the westward propagating squall lines.

In August, another precipitation axis develops with a SW–NE orientation, and is associated with a thick monsoon layer and the presence of the meridional section of the ITCZ. This axis is characterized by nonstormy and continuous rains. This precipitation pattern prevails throughout August, particularly in the southwest (Casamance region). More than 60% of this region's seasonal rainfall is recorded during this period.

For most of the regions, August rainfall accounts for more than 35% of the seasonal totals. Rainfall in September, July, and June follow respectively. August and September are especially critical for the northwestern region of Senegal, whereas rainfall in the South is better distributed throughout the season. June's contribution, although generally weak, is relatively significant in the southeast (e.g. more than 15% in Kedougou). On the whole, a strong agreement exists between rainfall and the number of rainy days (Figure 3).

3. DATA AND METHODS

3.1. Data

The meteorological data used in this study spans the period from January 1971 to December 1998. This period was chosen because it is included in the most recent West African drought epoch (which began in 1968), for which we have a complete set of rainfall data for a network of 20 stations in Senegal (Figure 4(a)). The rain-gauge data consists of monthly mean rainfall and the total number of rainy days per month. The data was obtained from Météorologie Nationale, Dakar, Senegal (Office of National Meteorology).

We also used the CPC merged analysis precipitation (CMAP) rainfall data set, which consists of monthly-averaged precipitation rates (mm/day) for the period between January 1979 and December 1998. The algorithm for construction of the gridded CMAP fields of global monthly precipitation on a 2.5 latitude–longitude grid is described by Xie and Arkin (1997). The version used in this study is derived from gauge observations and satellite estimates.

We used the 2° latitude × 2° longitude National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST (ERSST) data provided by the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado. The description of the ERSST data set is provided by Smith and Reynolds (2003). The construction of the ERSST was based on the comprehensive ocean atmosphere data set (COADS) SST, which is an extensive collection of surface marine data available from the world's oceans. Our SST study domain is a latitudinal band lying between 30 °N and 30 °S, for both the Atlantic and the Pacific Oceans.

To investigate the relationships between rainfall and atmospheric circulation, we used a subset (1979–1998) of the National Centers for Environmental Prediction/National Center for Atmospheric Research

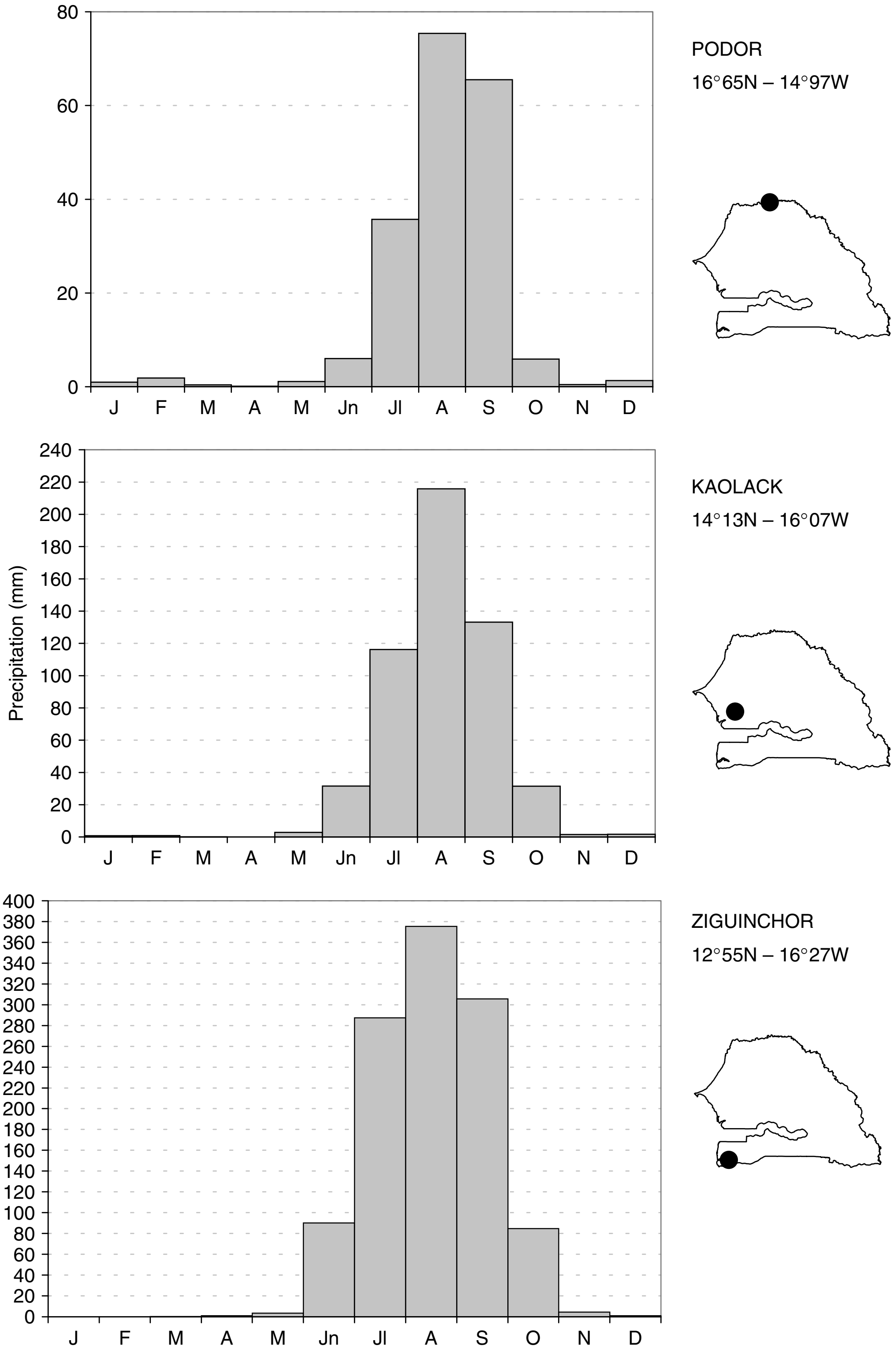

Figure 2. Distribution of mean monthly precipitation for selected stations, from north to south

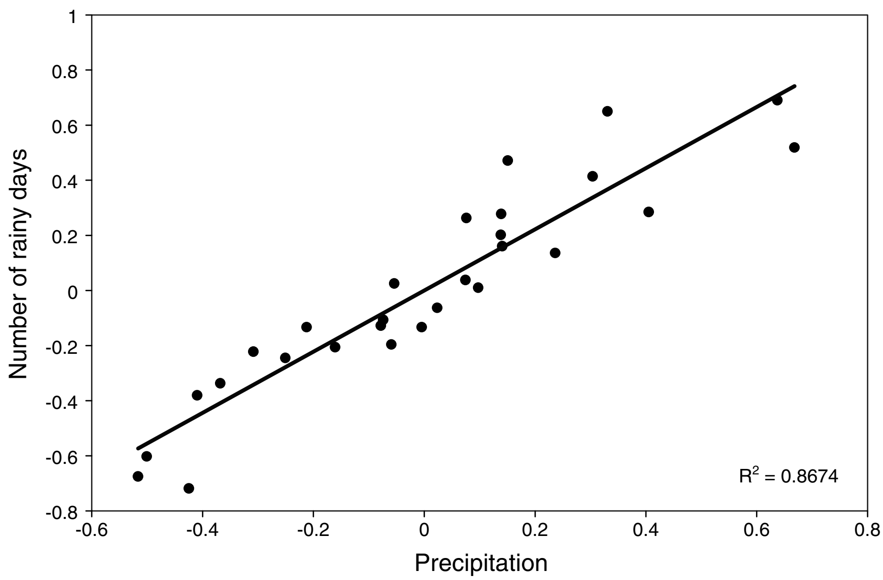

Figure 3. Scatterplot of seasonal precipitation and number of rainy days. Values are averaged for JJAS for the 1971–1998 period

(NCEP/NCAR) 51-year (1948–1998) reanalysis wind data (Kalnay *et al.*, 1996) at the 850 mb level. The horizontal resolution for this data set is T62 (209 km).

3.2. Methodology

As stated in the previous section, rainfall in West Africa is highly concentrated during the summer months. Most of the studies dealing with climate variability in the region focus on July, August and September (JAS). This choice is generally justified by the fact that most of the investigations concern the Sahel zone, which has experienced severe droughts in recent decades. However, the Sahel only covers the northern part of the country and this study involves the entire geographic domain of Senegal, which also includes the Sudanian zone to south. In order to determine the months to be considered in this study, precipitation amounts of the six wet months of the rainy season (May through October) were combined. Then the contribution of each month was computed. The two lowest contributions (May and October) were eliminated. This procedure was then repeated, considering only June, July, August, and September (JJAS). Although June was found to have the lowest contribution, it was retained for its significance to the southern stations in the Sudanian zone. Consequently, this study defines the wet season as lasting from June to September (JJAS).

All the rainfall maps displayed in this study are generated using the Spline interpolation method with ArcGIS Spatial Analyst. Various methods were first tested with ArcGIS Geostatistical Analyst. The choice of the Spline method from a wide range of possible options available in the software package was based on the following criteria: (1) the quality of the interpolated data that was tested using a built-in cross-validation procedure, (2) the quality of visual display of the interpolated fields, (3) the physical interpretation of the data in relationship to the climatic phenomenon of interest based on the knowledge of the study area.

Rainfall variability in Senegal with respect to the whole Sahel–Sudan and its relationship with SST were examined on the basis of several methods. For each station, the seasonal rainfall and number of rainy days were computed on the basis of monthly observations in order to generate distribution maps. Then the monthly and seasonal indices were computed by performing EOF analysis. This method decomposes the data into spatial variability patterns consisting of their corresponding time variations, and it also gives a measure of the 'importance' of each pattern (Bjornsson and Venegas, 1997). EOF eigenvector loadings were then plotted using ArcGIS Spatial Analyst software to display the spatial patterns of variability. The corresponding time series were examined to determine their temporal variability.

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Figure 4. (a) Meteorological stations used in the study; (b) grid-points used to perform CMAP EOF analysis over Senegal

The analysis was performed over Senegal using rain-gauge and CMAP data for the 1979–1998 period. Since comprehensive rain-gauge data coverage was not readily available to us for the other countries, the CMAP rainfall data set was used to extend the analysis to the entire West African region. The relationships between Senegal and West African variability modes were examined by analyzing the spatial patterns of the different modes and then correlating the time series. To further investigate the relationships between Senegal rainfall and the global climate, monthly EOF modes for rainfall over Senegal and West Africa were correlated with tropical Atlantic and Pacific SSTs for the 1979–1998-period (with a lag correlation of up to 6 months). In addition, circulation patterns associated with the different EOF modes were obtained by

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weighting the NCEP/NCAR 51-year (1948–1998) reanalysis wind data with the corresponding EOF mode and time series – for each year the u and v components were multiplied by the corresponding EOF amplitude, and the resulting values were averaged over the study period.

4. DISCUSSION OF RESULTS

Prior to the EOF analysis, a comparison between the observed precipitation and the CMAP climatology was performed to test the suitability of the CMAP data for this investigation of Senegal's climatology. Figure 4(b) shows the grid-points that have been used for the CMAP EOF analysis over Senegal. Figure 5 displays the change in precipitation climatology between the onset of the rainy season in June and the end of the season in September. As expected, in part because of its coarse resolution, we can see that the CMAP is not able to resolve some of the details of the spatial gradient of the rainfall patterns. However, the comparison also confirms that the CMAP accurately reproduces the primary evolution of the rainfall pattern during the wet season, thus giving us increased confidence to use it as a proxy for *in situ* observations.

4.1. The EOF analysis

4.1.1. Senegal. A histogram representation of all the EOF modes is shown in Figure 6. Neighboring eigenvalues are statistically significant when they are distinctly separated. Kendall (1980) proposed a test based on the following equation:

$$\delta\lambda = \lambda\ (2/N)^{1/2} \qquad (1)$$

where $\delta\lambda$ is the sampling error, λ is a given eigenvalue, and N is the sample size. An eigenvalue is significant when its associated sampling error is smaller than its spacing from the neighboring value. Histograms of the EOF modes are displayed in Figure 6. According to Kendall's test, over Senegal, only the first EOF mode (EOF1) is significant for the seasonal rainfall (rain gauge), number of rainy days (JJAS), and the CMAP rainfall.

The spatial patterns for the CMAP EOF1 mode, displayed in Figure 7, are in general agreement with the observed rainfall EOF map (Figure 7(a)), showing a decrease of values toward the southeast. However, differences between the two patterns are observed in northern Senegal, where the EOF1 for the observed rainfall has relatively much lower loadings than the EOF1 for the CMAP. The corresponding EOF1 time series (Figure 8) suggests interannual fluctuations with a periodicity of approximately 6–7 years, on the basis

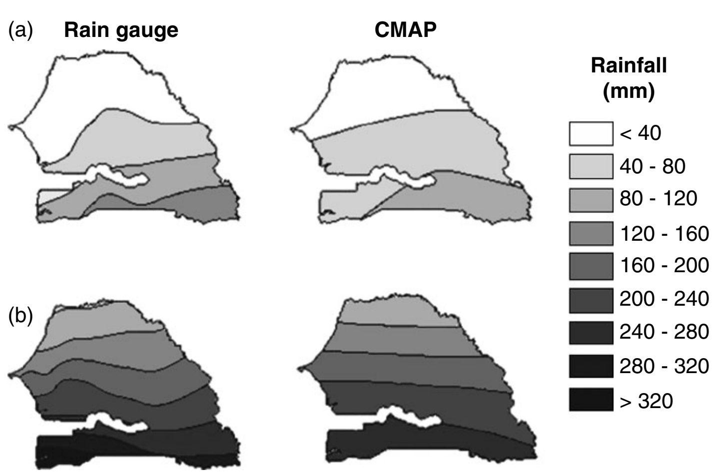

Figure 5. Mean monthly precipitation (1979–1998): (a) June; (b) September

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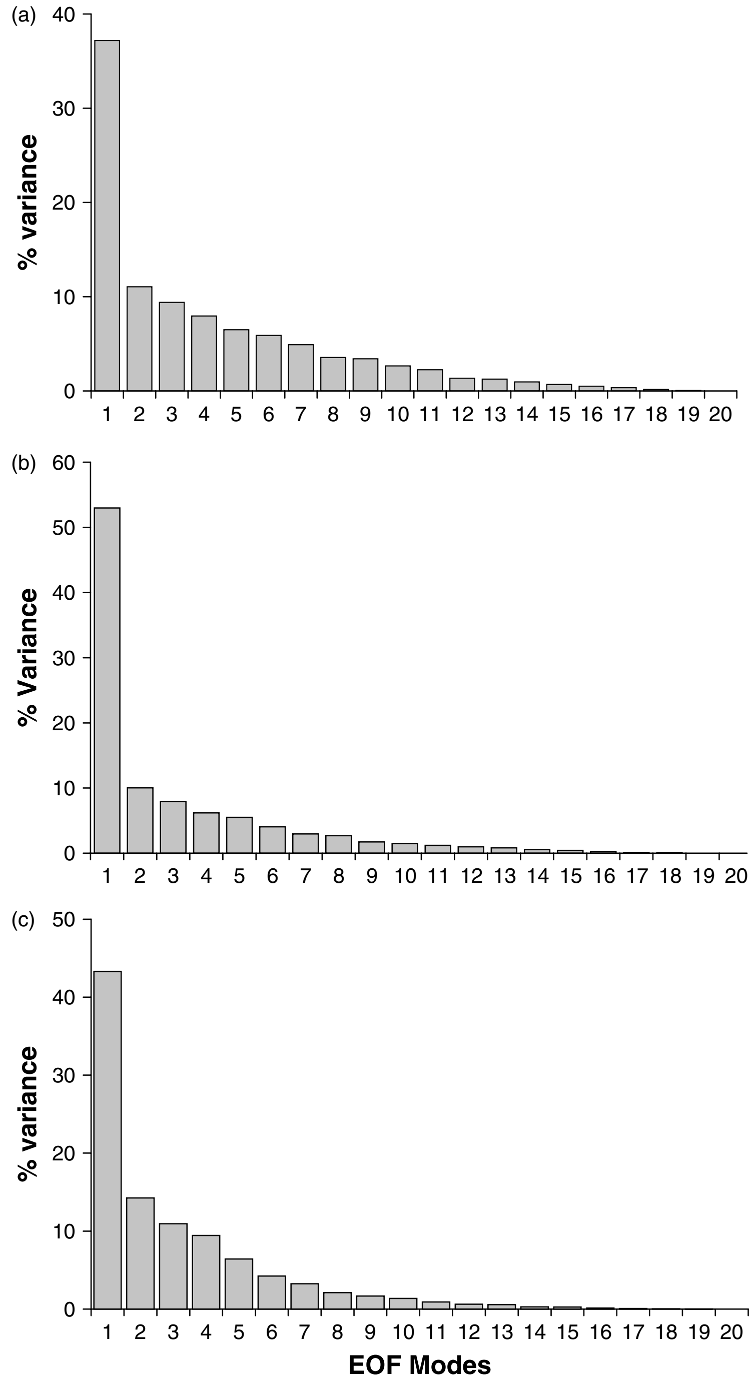

Figure 6. Histograms of EOF modes over Senegal (1979–1998): (a) rain-gauge precipitation; (b) number of rainy days; (c) CMAP rainfall

of visual inspection. A good agreement exists between the two time series between 1979 and 1998, where only one mismatch is observed, and the series are well correlated, as shown by the correlation coefficients in Figure 8.

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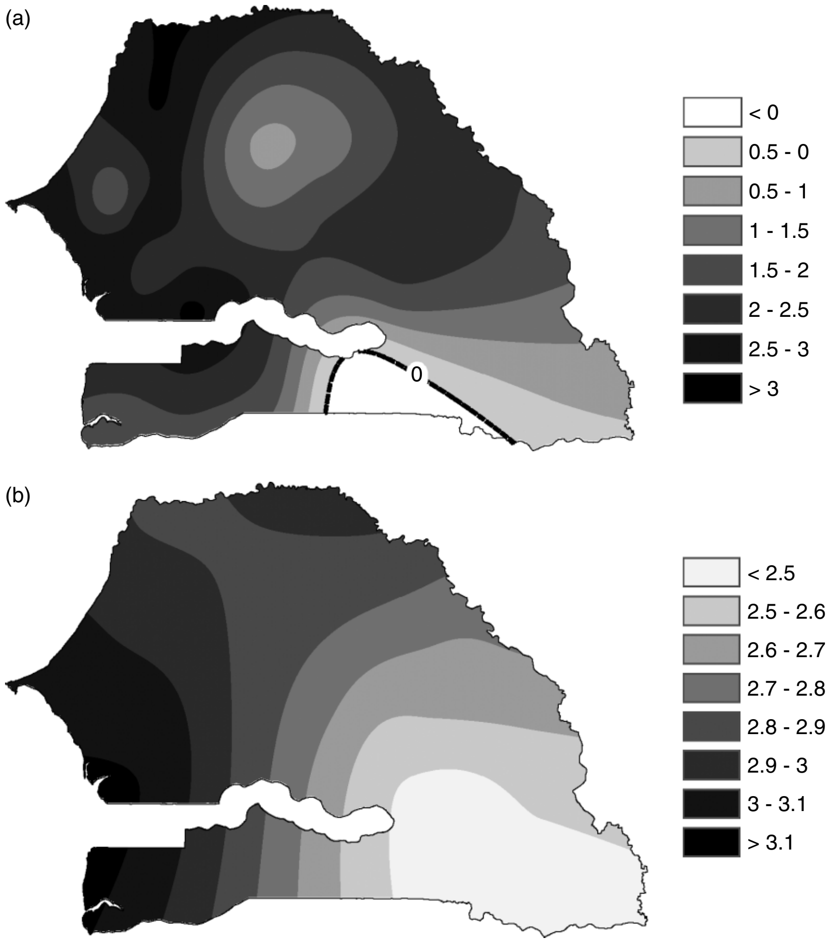

Figure 7. Spatial patterns of EOF1 for JJAS: (a) observed precipitation (1979–1998); (b) CMAP rainfall (1979–1998). Loadings are multiplied by 10

4.1.2. West Africa. To examine how the climate variability in Senegal relates with the rest of West Africa, an EOF analysis of the CMAP rainfall was performed over the region. The five leading modes are significant according to Kendall's criterion. However, in this study we only examined the first three EOF modes because the other two explain a relatively low variance and are only marginally significant. The EOF1, which explains 49.87% of the variance, exhibits a dipole pattern over West Africa, with positive loadings in the Sahel–Sudan zone and negative loadings further south (Figure 9(a)). The two zones are separated around 10 °N. The band of positive loadings extends all across West Africa, but can be divided into two domains with high loadings east of 6 °W, and low loadings west of 6 °W. This pattern is consistent with the first eigenvector pattern for August and September analyzed by Nicholson and Palao (1993). Their results show positive anomalies throughout the Sahel–Sudan region and negative anomalies in the Guinea Coast. The EOF1 for West Africa also agrees with the spatial patterns resulting from the principal component analysis (PCA) performed by Moron (1994) and shown by Camberlin and Diop (1999) who point out a distinct variability in the western and continental parts of the Sahel. The time series associated with the EOF1 (Figure 9(b)) exhibits interannual fluctuations and marked negative amplitudes during the 1982–1984 period, which corresponds to a strong El Niño event (1982–1983). The decadal-like variability associated with this mode stands out. Prior to early 1980s a steady and rapid decrease in rainfall over the Sahel–Sudan region occurred, petering out in the early 1980s, and then showing a general increase in the background trend of rainfall time series for this mode for the remainder of the analysis period. Similar temporal behavior was also found recently by Schreck and Semazzi (2004),

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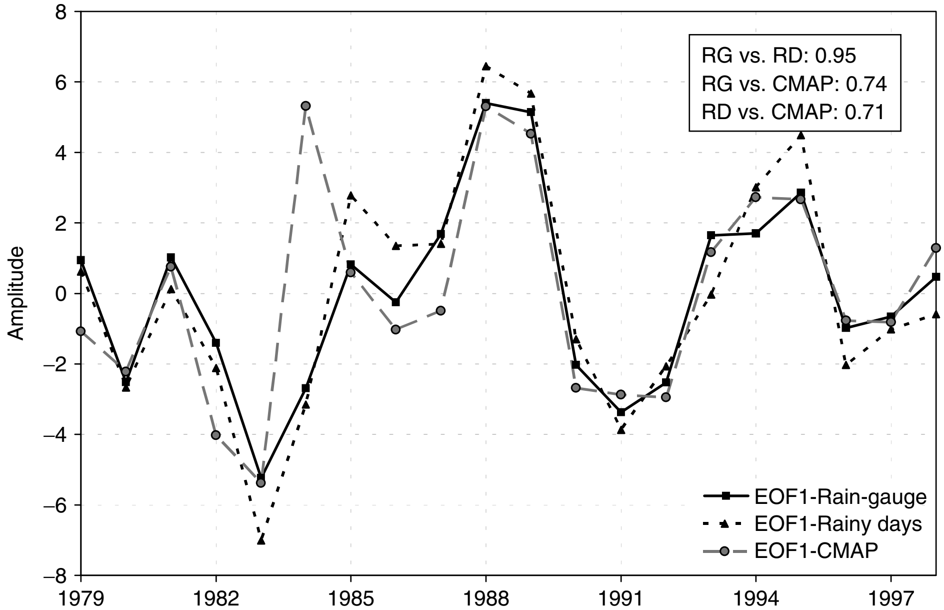

Figure 8. EOF1 time series of observed rainfall, number of rainy days, and CMAP rainfall over Senegal for the 1979–1998 period. The correlation coefficients of the time series are added (RG: rain-gauge index; RD: number of rainy days index)

which raises the possibility of a spatially much more extensive anomaly pattern that may even be present on a continental scale (see also Hoerling *et al*., 2005). Of course, these results are inherently limited by the short period of our analysis, and do not lead to firm inferences about the low frequency variability component of the West African climate.

EOF2 (15.66%) is characterized by a band of positive loadings across the Sahel–Sudan region and along the Atlantic coast (Figure 10(a)). This band is surrounded by two zones of negative values in the north and south.

A dipole pattern is clearly evident, and the negative loadings over southern West Africa are opposed to two positive centers, in the eastern part of the region (10–11 °N; around 8E), and in the northwestern Sahel (18–20 °N; 12–14 °W). Again, this pattern is similar to Nicholson and Palao's (1993) 'mode 2' that shows uniform anomalies throughout the Sahel but opposite values between the Sahel and Guinea Coast. The corresponding time series shows relatively low frequency variability with timescales of about 7 years (Figure 10(b)). The negative or near zero amplitudes appear to correspond to El Niño years (e.g. 1982–1983, 1986, 1992–1993, 1997–1998). The 1982–1983 warm El Niño event corresponds to the lowest amplitude throughout the region, while the largest amplitude occurred in 1988–1989, which was a La Niña phase.

The third EOF represents 11.92% of the variance. Figure 11(a) shows its spatial eigenvector pattern. Negative or weakly positive loadings are observed throughout the West African domain. The lowest loadings are found south of 13 °N. The EOF3 time series is dominated by a decadal-like variability, with the exception of the period from 1987 to 1994, which is characterized by high frequency fluctuations (Figure 11(b)).

Recently, Hoerling *et al.* (2005) analyzed a number of global climate models and concluded that the Sahel region will be 20 to 30% wetter by 2049 compared to the 1950–1999 average. The study notes that when SSTs are warmer in the South Atlantic than in the North Atlantic, the Sahelian monsoon system is drawn southward as well, and this situation deprives the region of its usual rains. The study observes that this was the situation during much of the latter half of the twentieth century. However, Hoerling *et al.* (2005) assert that the North Atlantic Ocean cooling was natural and masked an expected greenhouse-gas warming effect. Moreover, since 1990, the SST gradient has reversed, warming more rapidly in the North Atlantic than in the South. This has resulted in a reversal of the rainfall anomaly pattern over the region, thus explaining why their models project that the Sahel will become much wetter in the future decades compared to the present

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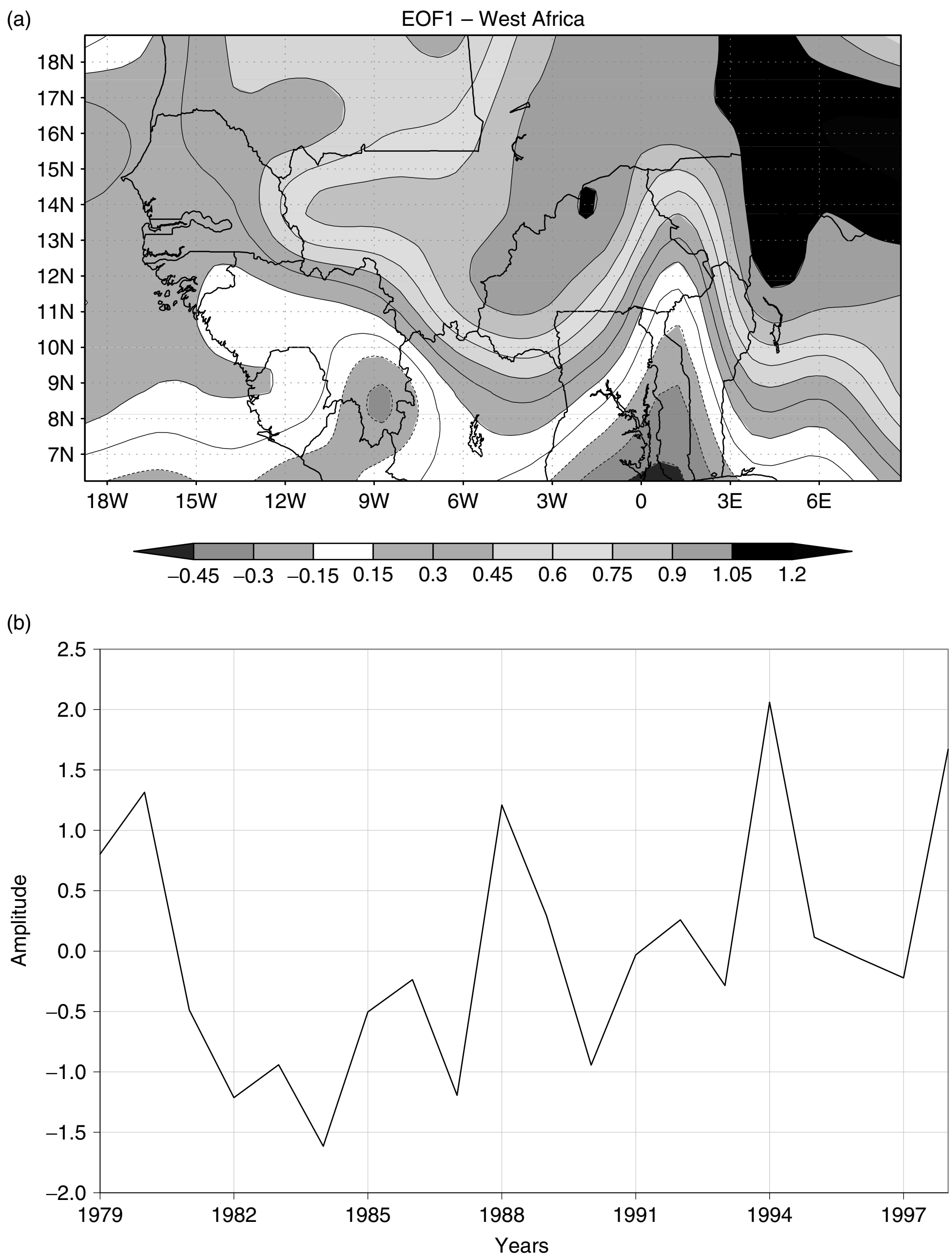

Figure 9. EOF1 for CMAP rainfall over West Africa: (a) spatial patterns (b) corresponding time series

and previous decades. It is unclear and premature for the present study to infer that our EOF1 and EOF3 over West Africa are the two competing modes associated with the natural and anthropogenic components identified in the Hoerling *et al*. (2005) study. In the future it would be constructive to examine General Circulation Model (GCM) hindcasts and climate projections to see how EOF1 and EOF3 feature in the GCM simulations. In particular, since these two observational modes exhibit opposite trends, it would be critical that GCMs accurately reproduce the relative contribution of these modes to the regional West African climate variability.

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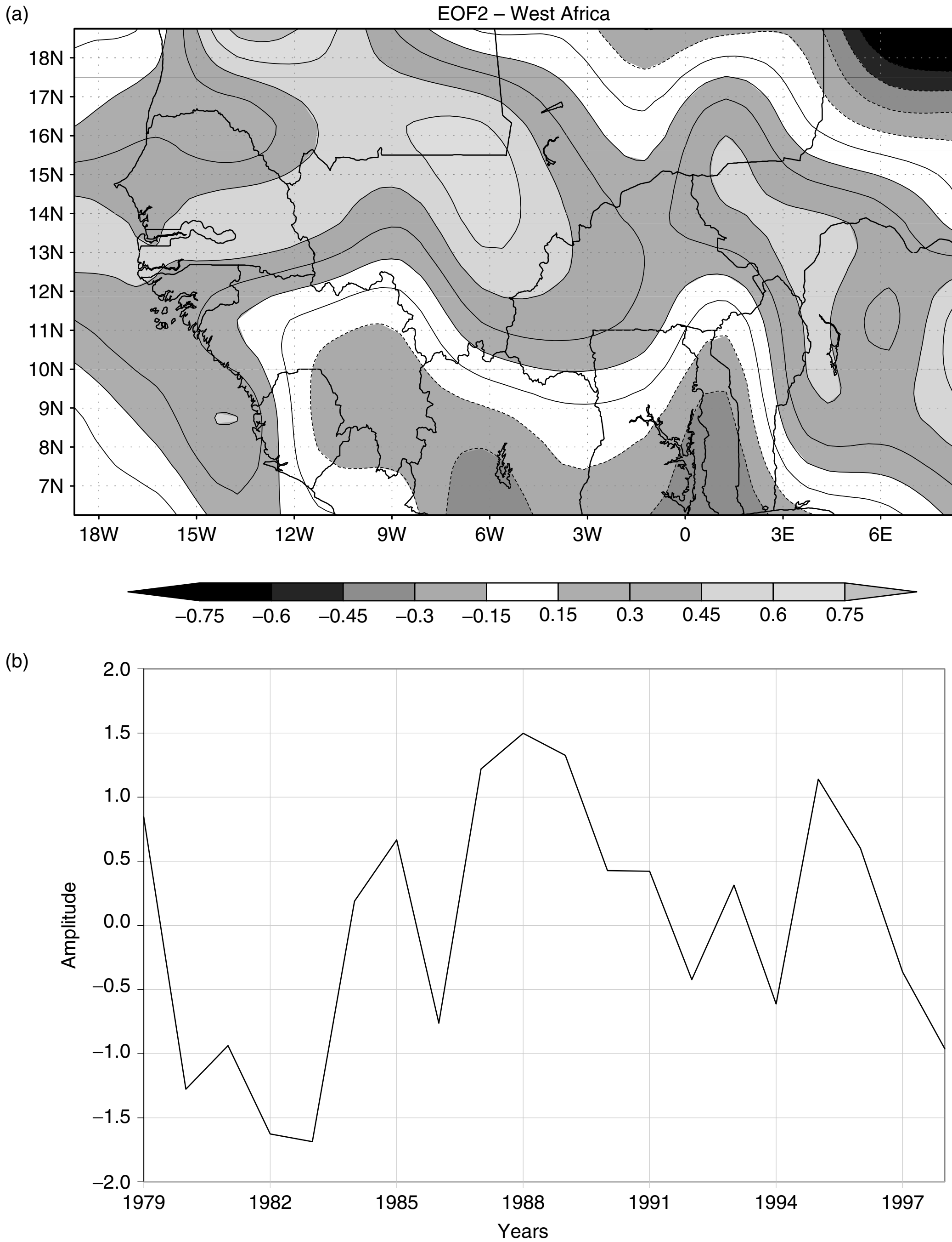

Figure 10. Same as Figure 9, except for EOF2

4.2. The relationship between Senegal and the rest of West Africa

The leading modes of the CMAP rainfall for West Africa are first compared to Lamb's rainfall index, which is widely used to monitor the variability for the climate of the Sahel–Sudan region. The EOF1 for the West African rainfall is strongly correlated with Lamb's index (Table I). This agreement confirms that the EOF1 for West Africa is the representative mode of rainfall variability over the region.

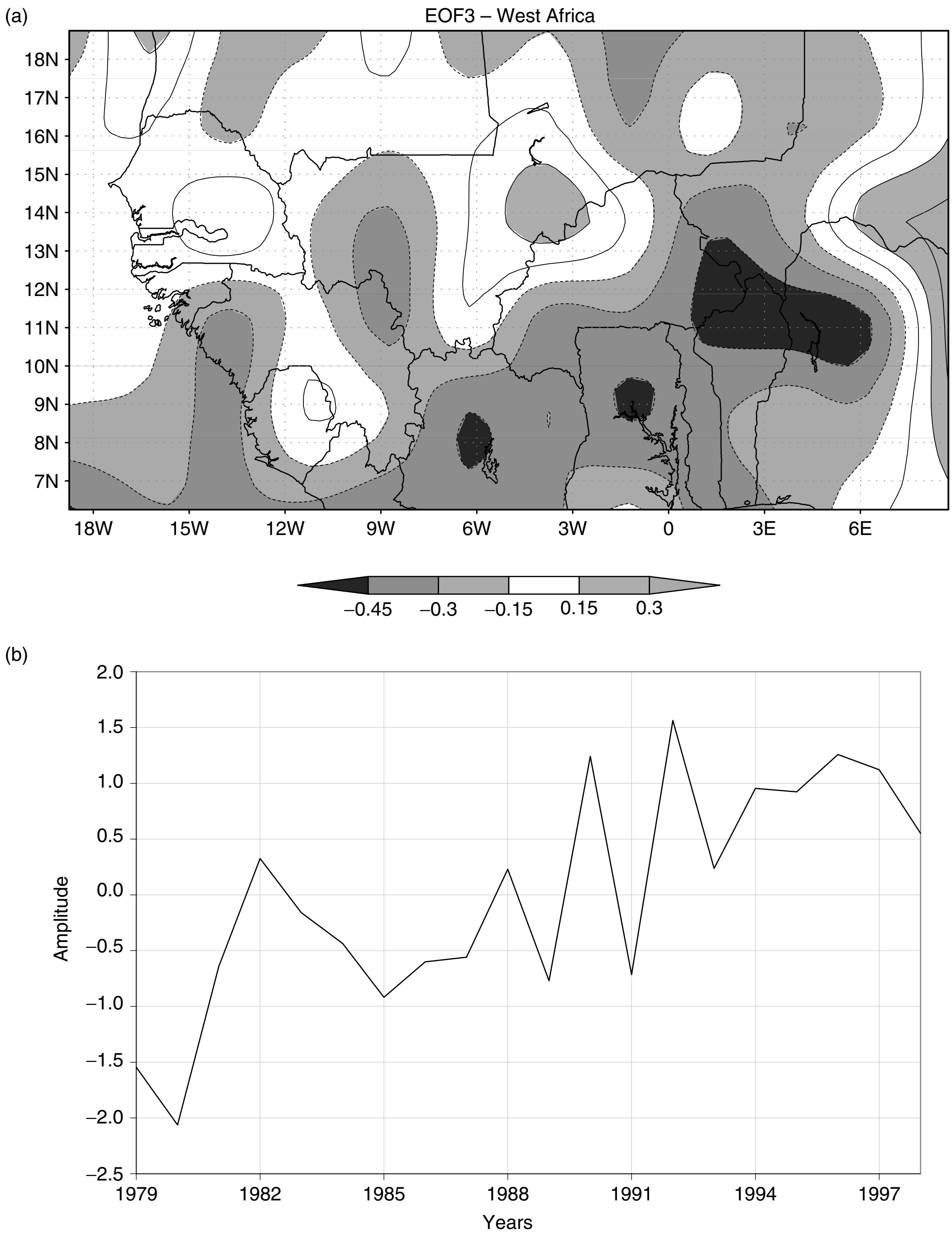

Figure 11. Same as Figure 9, except for EOF3

Table II shows the cross-correlation between the three leading modes of CMAP rainfall over West Africa and first EOF modes over Senegal. The EOF1 over Senegal (precipitation, number of rainy days and CMAP) is not correlated with the EOF1 over West Africa, but shows a good relationship with the EOF2. In the previous section, we pointed out that EOF2 for West Africa is characterized by a homogeneous band extending throughout the Sahel–Sudan zone and includes Senegal (Figure 10(a)). A further confirmation is provided

Table I. Correlation between the leading EOF modes for West Africa and Lamb's rainfall index. The shaded value is significant at the 95% confidence level, according to the *t*-test

	EOF1-WA	EOF2-WA	EOF3-WA
Lamb's Index	0.91	0.19	0.09

Table II. Cross-correlation between the three EOF leading modes for CMAP over West Africa and EOF1 over Senegal (cmapsen: CMAP rainfall; obsppsen: observed precipitation (rain gauge); obsrdsen: observed number of rainy days). Shaded values are significant at the 95% confidence level, according to the *t*-test

	EOF1_WA	EOF2_WA	EOF3_WA
Cmapsen1	0.27	**0.55**	−0.01
Obsppsen1	0.37	**0.62**	−0.01
Obsrdsen1	0.38	**0.63**	0.00

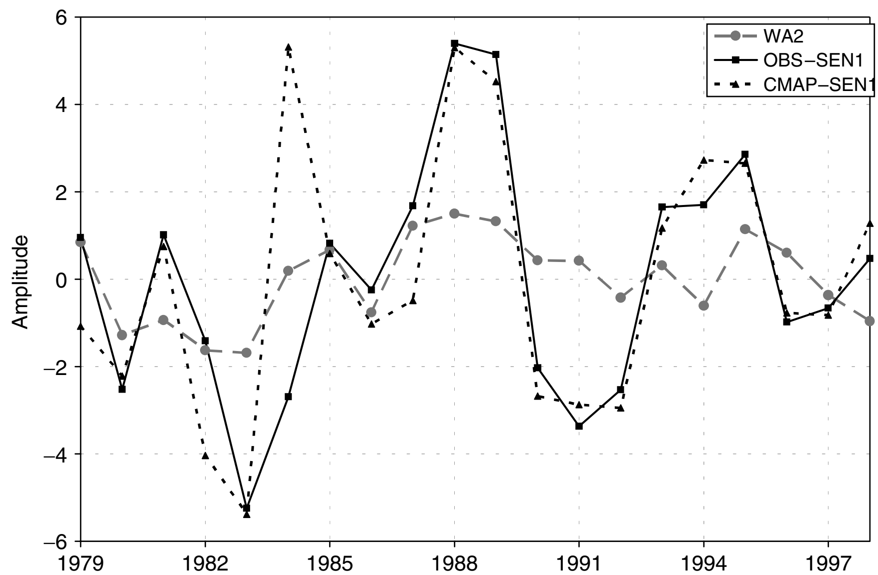

Figure 12. Time series of EOF2 for West Africa (WA2), EOF1 for observed rainfall, and CMAP rainfall Senegal (respectively, SEN1 and CMAP.SEN1). Loadings for WA2 (EOF2 for CMAP West Africa) are multiplied by 2

by the comparison between the corresponding time series (Figure 12), which shows very few mismatches. Therefore, we can see that the second mode for West Africa, traditionally neglected in the studies of variability over the region, is important for explaining the variability of rainfall over Senegal.

The intercomparison of the EOF1 and EOF2 temporal variations is supported by wind anomaly patterns. More specifically, we find that the wind circulation component associated with the EOF1 for West Africa (Figure 13) does not show any significant circulation in the vicinity of Senegal, but appears to be more consistent with the West African monsoon regime (southwesterly flow over Senegal and convergence related to the ITCZ north of the country). In contrast, the EOF2 for West Africa, which is poorly correlated with Lamb's index but important for Senegal, is more consistent with the wind atmospheric circulation over the

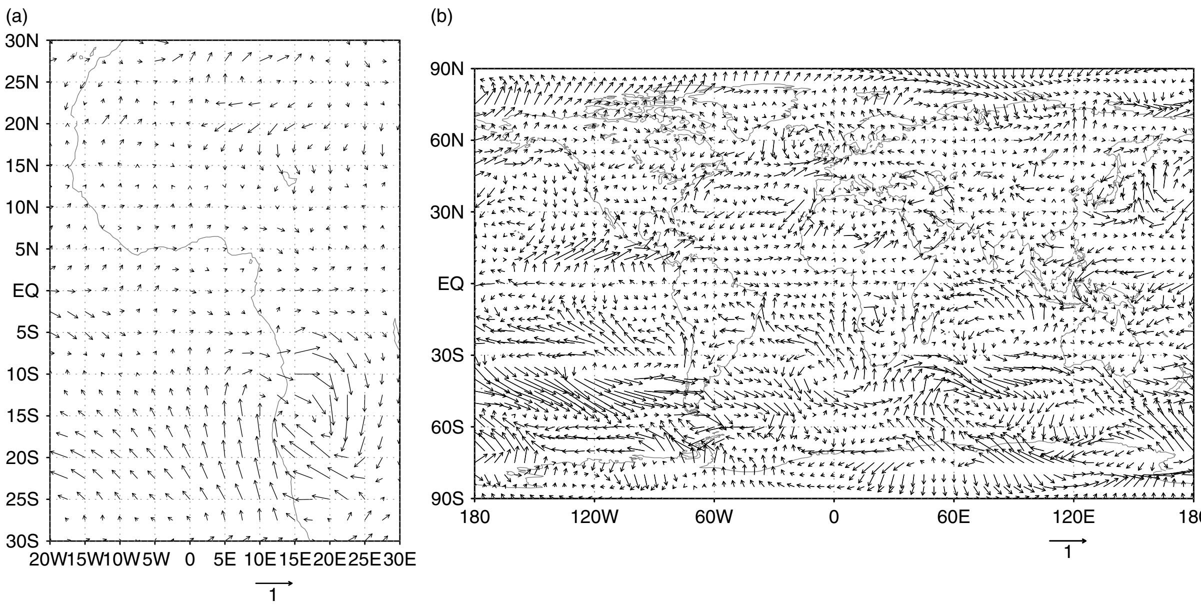

Figure 13. Projection of NCEP 850 mb winds onto CMAP EOF1 for West Africa: (a) West African region; (b) global

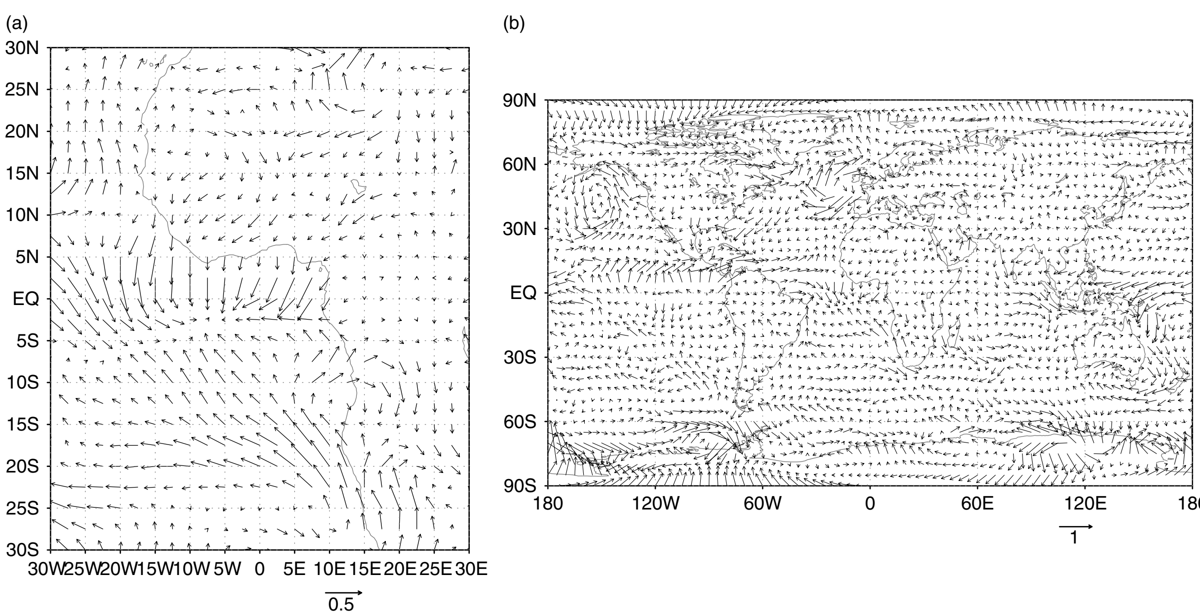

Figure 14. Same as Figure 13, except for CMAP EOF2

tropical Atlantic and eastern tropical Pacific (Figure 14). This circulation pattern is associated with positive anomalies over Senegal. In contrast, this pattern is characterized by outflow motion along the Guinea Coast region. A qualitative explanation for this counter-intuitive result can be inferred from Semazzi *et al.* (1993). They contend that counter-monsoonal southerly anomalous circulation, such as the one we observe in this study (Figure 14), tends to weaken – but not reverse – the low-level southwesterly prevailing flow, which is the primary source of moisture transportation from the Atlantic Ocean. Consequently, the moisture that

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Table III. Cross-correlation between South Atlantic monthly mean SST (0°–20 °S; 30 °W–10 °E) and EOF leading time series over Senegal (period: 1979–1998); PP, RD, and CM are, respectively, precipitation, number of rainy days and CMAP rainfall over Senegal. Shaded values are significant at the 95% confidence level, according to the *t*-test

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EOF1-PP	0.34	0.21	0.32	0.37	0.46	0.22	0.47	0.40	0.32	0.42	0.29	0.05
EOF1-RD	−0.39	−0.36	−0.24	−0.17	−0.25	0.20	−0.34	−0.20	−0.08	−0.17	−0.27	−0.21
EOF1-CM	0.55	0.45	0.55	0.54	0.57	0.35	0.60	0.70	0.60	0.55	0.35	0.14

would have penetrated further inland and caused rain over sub-Sahara is instead deposited over the near-coastal regions of West Africa, including Senegal. Our results are in agreement with previous studies, which indicate that deficient sub-Saharan rainy seasons tend to coincide with the southwesterly surface monsoon flow that does not extend as far north along the West African coast as during wetter years (Lamb and Peppler, 1991; Druyan and Hastenrath, 1991, 1992; Owen *et al*., 1988).

4.3. Relationships with sea-surface temperatures

Our exploration of the possible association between the EOF modes for the seasonal rainfall and the SST over the North Atlantic yields no significant correlations (not displayed). However, the correlation with the South Atlantic SSTs (Table III) yields more significant results – the EOF1 time series for the CMAP rainfall over Senegal is well correlated with the South Atlantic SST. The highest coefficients are observed during the wet season, up to 0.70 in August. Moderately high coefficients are also observed during the prewet season, up to 0.57 in May. These correlations indicate that a positive correlation exists between South Atlantic SSTs and rainfall anomalies over Senegal. This relationship contrasts strongly with observations usually made in other studies. The warm waters over the South Atlantic Ocean are traditionally thought to correspond to negative anomalies in the Sahel (e.g. Lamb, 1978a, b; Lough, 1986; Philander, 1986; Lamb and Peppler, 1991; Janowiak, 1988; Bah, 1987; Eltahir and Gong, 1996; Ward, 1998), and cold South Atlantic SST anomalies correspond to an increase of moisture in the Sahel (Mo *et al*., 2001). This result further confirms the difference between the Atlantic Sahel and the continental Sahel, even though one can argue that Senegal does not lie entirely in the Sahel zone. Correlations with the Pacific SST (not displayed) also provide interesting results. The greatest coefficients (up to −0.72) are observed during the April–July period and may indicate a high predictive value potential for the rainy season.

To further investigate the association between the EOF1 for Senegal (gauge) and the EOF2 for West Africa (CMAP), we performed a grid-point correlation between the Atlantic SST and the time series of the EOF2 for West Africa. The lag-correlations are weak and insignificant, yet a strong relationship exists between them from June to September. High values (up to 0.80) occur between 5 °N and 10 °S in June and July (Figure 15), and extend northward up to 20 °N in August (not shown). The EOF2 (CMAP) for West Africa is strongly driven by the Atlantic SST.

These results confirm the strong relationship already noted between the EOF1 time series over Senegal and the South Atlantic SST. They are also consistent with the wind circulation observed in the Atlantic Ocean, south of West Africa. Results suggest that the warm waters contribute to an increased moisture supply, which in turn results in increased rainfall along the West African coast.

5. CONCLUSIONS

Climate variability over Senegal and its relationships with the global climate have been examined for the period 1979–1998. The observational rainfall data analyzed in this study consists of rainfall and number of rainy days occurring at 20 rain-gauge stations throughout Senegal, and the CMAP rainfall for the months of June, July, August, and September. These values were averaged to generate seasonal rainfall totals for the wet season, and climate indices for the study period were obtained using the EOF method.

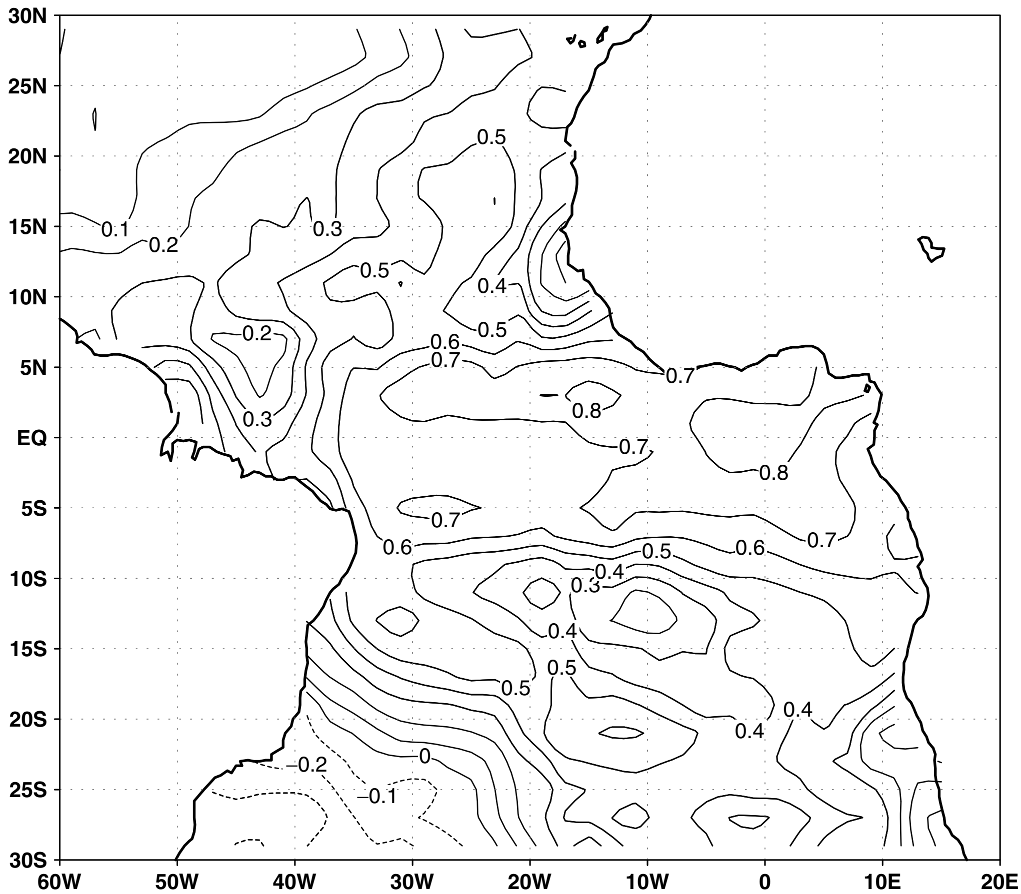

Figure 15. Grid-point correlation between time series of EOF2 for CMAP rainfall over West Africa (JJAS 1979–1998) and mean Atlantic SST (July 1979–1998)

The main conclusions can be summarized as follows:

- A strong agreement exists between the EOFs rainfall total amounts and the number of rainy days for Senegal.
- The EOF1 for West Africa is strongly correlated with Lamb's rainfall index, and is traditionally believed to be representative of the whole Sahel–Sudan region. However, in this analysis, we find a weak correlation between Senegal rainfall and the EOF1 for West Africa. In contrast, a good relationship exists with the West African EOF2.
- Positive anomalies over Senegal are associated with warm waters and a strong moisture convergence over the Guinea Gulf, as revealed by projection of the NCEP winds onto the CMAP EOF modes. We envisage that this circulation pattern causes the outflow from the Guinea Coast region and subsequent negative rainfall anomalies.
- The comparative analysis of the EOF (CMAP) over West Africa and the EOFs over Senegal has helped improve our understanding of the relationship between the climate variability over the two domains. The EOF1 spatial patterns for West Africa reveal three distinct domains: the Guinea Coast region (negative loadings), the eastern or continental domain (strongly positive loadings), and the western or Atlantic domain (weakly positive loadings). The difference in climate behavior between the 'Atlantic Sahel' and the rest of the West African Sahel region has been stressed in a number of studies, e.g. Bhatt (1989); Wolter (1989); Nicholson and Palao (1993); Janicot (1992); Camberlin and Diop (1999). Our analysis has further confirmed

this distinction. Consequently, relying on rainfall indices averaged over the whole of the Sahel–Sudan region may mislead socioeconomic decisions related to weather conditions in Senegal.

- The correlations our study observed between sea-surface fields and rainfall anomalies over Senegal reveal (1) the positive correlation between Senegal rainfall and the South Atlantic SST, strongly contrasting with the traditional correlation of negative anomalies in the Sahel with warm waters in the South Atlantic Ocean, (2) the strong correlation between the EOF1 time series for CMAP rainfall over Senegal and the South Atlantic SST, and (3) the relationship between the Pacific SST along the equatorial zone and the EOF1 time series for Senegal. The SSTs of the Pacific region may be a good predictor for the rainy season over Senegal.

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REFERENCES

Bah A. 1987. Towards the prediction of Sahelian rainfall from sea surface temperatures in the Gulf of Guinea. *Tellus* **39A**: 39–48.
Bhatt US. 1989. Circulation regimes of rainfall anomalies in the African–South Asian monsoon belt. *Journal of Climate* **2**: 1133–1144.
Bjornsson H, Venegas SA. 1997. A manual for EOF and SVD analyses of climatic data. Centre for Climate and Global Change Research (CCGCR) Report 97-1. Montréal: Québec; 52.
Burpee RW. 1974. Characteristics of North African easterly waves during the summers of 1968 and 1969. *Journal of Atmospheric Science* **31**: 1556–1570.
Camberlin P, Diop M. 1999. Inter-relationships between groundnut yield in Senegal, interannual rainfall variability and sea-surface temperatures. *Theoretical and Applied Climatology* **63**: 163–181.
Chappel A, Agnew C. 2004. Modelling climate change in West African Sahel rainfall (1931–1990) as an artifact of changing station locations. *International Journal of Climatology* **24**: 547–554.
Diedhiou A, Janicot S, Viltard A, De Felice P, Laurent H. 1999. Easterly waves regimes and associated convection over West Africa and the tropical Atlantic. Results from the NCEP/NCAR and ECMWF reanalyses. *Climate Dynamics* **15**: 795–822.
Druyan L, Hastenrath S. 1991. Modeling the differential impact of 1984 and 1950 sea surface temperatures on Sahel rainfall. *International Journal of Climatology* **11**: 367–380.
Druyan L, Hastenrath S. 1992. GCM simulation of the 1984 Sahel drought with alternative specifications of observed SST. *International Journal of Climatology* **12**: 521–526.
Eltahir EAB, Gong C. 1996. Dynamics of wet and dry years in West Africa. *Journal of Climate* **9**: 1030–1042.
Entekhabi D, Rodriguez-Iturbe I, Bras RL. 1992. Variability in Large-Scale Water Balance with Land Surface-Atmosphere Interaction. *J. Climate* **5**: 798–813.
Fall S, Niyogi D, Semazzi F. 2005. Analysis of mean climate conditions in Senegal (1971–1998). *Earth Interactions* **10**: 1–40.
Garnier R. 1976. L'Equateur météorologique. *La Météo, VI série* **6**: 113–136.
Gaucher LR. 1976. Origine africaine du cyclone Fifi. *La Météo, VI série* **6**: 159–166.
Hoerling MP, Hurrell JW, Eischeid J. 2005. Detection and Attribution of 20th century Northern and Southern African monsoon change. *Journal of Climate* in press.
Janicot S. 1992. Spatiotemporal variability of West African rainfall. Part II: Associated surface and airmass characteristics. *Journal of Climate* **5**: 499–511.
Janicot S, Moron V, Fontaine B. 1996. Sahel droughts and ENSO dynamics. *Geophysical Research Letters* **23**: 515–518.
Janicot S, Trzaska S, Poccard I. 2001. Summer Sahel-ENSO teleconnection and decadal time scale SST variations. *Climate Dynamics* **18**: 303–320.
Janowiak JE. 1988. An investigation of interannual rainfall variability in Africa. *Journal of Climate* **1**: 240–255.
Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds B, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne Roy, Joseph Dennis. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**(3): 437–472.
Kendall M. 1980. *Multivariate Analysis*, 2nd edition. Charles Griffin and Company Ltd.: London.
Lamb PJ. 1978a. Large-scale tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. *Tellus* **A30**: 240–251.
Lamb PJ. 1978b. Case studies of tropical Atlantic surface circulation patterns during recent sub-Saharan weather anomalies: 1967 and 1968. *Monthly Weather Review* **106**: 282–291.

Lamb PJ, Peppler RA. 1991. West Africa. In *Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*. Glantz MH, Katz RW, Nicholls N. (eds). Cambridge University Press: London; 121–189, Chapt. 5.

Lamb PJ, Peppler RA, Hastenrath S. 1986. Interannual variability in the tropical Atlantic. *Nature* **322**: 238–240.

Landsea CW, Gray WM. 1992. The strong association between western Sahelian monsoon rainfall and intense Atlantic hurricanes. *Journal of Climate* **5**: 435–453.

Lare AR, Nicholson SE. 1994. Contrasting conditions of surface water balance in wet and dry years as a possible land surface – atmosphere feed back. *J. Climate* **7**: 653–668.

Leroux M. 1973a. La dynamique des précipitations au Sénégal. *Notes Africaines* **140**: 105–108.

Leroux M. 1973b. La saison des pluies 1973 au Sénégal. **32**: Agence pour la Securité de la Navigation Aérienne ASECNA-Dakar.

Lough JM. 1986. Tropical Atlantic sea surface temperatures and rainfall variations in Subsaharan Africa. *Monthly Weather Review* **114**: 561–570.

Mo K, Bell GD, Thiaw WM. 2001. Impact of sea surface temperature anomalies on the Atlantic tropical storm activity and West African rainfall. *Journal of Atmospheric Science* **58**(22): 3477–3496.

Moron V. 1994. Guinean and Sahelian rainfall anomaly indices at annual and monthly time scales (1933–s1990). *International Journal of Climatology* **14**: 325–341.

Nicholson SE. 1980. The nature of rainfall fluctuations in subtropical West Africa. *Monthly Weather Review* **108**: 473–487.

Nicholson SE, Palao IM. 1993. A re-evaluation of rainfall variability in the Sahel. Part I. Characteristics of rainfall fluctuations. *International Journal of Climatology* **4**: 371–389.

Niyogi D, Xue Y-K, Raman S. 2002. hydrological land surface response in a tropical regime and a midlatitudinal regime. *Journal of hydrometeorology* **3**: 39–56.

Owen J, Folland C. 1988. Modeling the influence of SST on rainfall. In *Recent Climate Change*, Gregory S (ed). Belhaven Press: London; 141–153.

Parker DE, Folland CK, Ward MN. 1988. Sea-surface temperature anomaly patterns and prediction of seasonal rainfall in the Sahel region of Africa. In *Recent Climatic Change*, Gregory S (ed). Belhaven Press: London; 166–178.

Peters M, Tetzlaff G. 1988. The structure of West African squall lines and their environmental moisture budget. *Meteorology and Atmospheric Physics* **39**: 74–84.

Pielke RA Sr., Marland G, Betts RA, Chase TN, Eastman JL, Niles JO, Niyogi D, Running S. 2002. The influence of land-use change and landscape dynamics on the climate system-relevance to climate change policy beyond the radiative effect of greenhouse gases. *Philosophical Transactions* A Special Theme Issue **360**: 1705–1719.

Philander SGH. 1986. Unusual conditions in the tropical Atlantic Ocean in 1984. *Nature* **322**: 236–238.

Reed RJ, Klinker E, Hollingsworth A. 1988a. The structure and characteristics of African easterly wave disturbances as determined from the ECMWF operational Analysis/forecast system. *Meteorology and Atmospheric Physics* **38**: 22–23.

Reed RJ, Norquist DC, Recker EE. 1977. The structure and properties of African wave disturbances as observed during Phase III of GATE. *Monthly Weather Review* **105**: 317–333.

Rowell DP, Folland CK, Maskell K, Ward MN. 1995. Variability of summer rainfall over tropical North Africa (1906–92): Observations and modelling. *Quarterly Journal of the Royal Meteorological Society* **121**: 669–704.

Schreck CJ III, Semazzi FHM. 2004. Variability of the recent climate of eastern Africa. *International Journal of Climatology* **24**: 681–701.

Semazzi HFM, Lin N-H, Lin Y-L, Giorgi F. 1993. A CCM1-MM4 nested model study of the influence of sea-surface temperature anomalies on the Sahelian Climate. *Geophys Res Lett* **20**: 2897–2900.

Semazzi FHH, Mehta M, Sud YC. 1988. An investigation of the relationship between Sub-Saharan rainfall and global sea surface temperatures. *Atmosphere-Ocean* **27**: 601–609.

Semazzi FHM, Song Y. 2001. A GCM study of climate change induced by deforestation in Africa. *Climate Research* **17**: 169–182.

Smith TM, Reynolds RW. 2003. Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). *Journal of Climate* **16**: 1495–1510.

Ward MN. 1998. Diagnosis and short-lead time prediction of summer rainfall in tropical North Africa and interannual and multidecadal timescales. *Journal of Climate* **11**: 3167–3191.

Wolter K. 1989. Modes of tropical circulation, Southern Oscillation, and Sahel rainfall anomalies. *Journal of Climate* **2**: 149–172.

Xie P, Arkin P. 1997. Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society* **78**: 2539–2558.

Xue Y, Shukla J. 1998. Model simulation of the influence of global SST anomalies on the Sahel rainfall. *Monthly Weather Review* **126**: 2782–2792.