ABSTRACT

FALL, SOULEYMANE. Spatiotemporal Climate Variability over Senegal and its Relationships with Global Climate. (Under the direction of Dr Dev Dutta S. Niyogi and Dr Frederick H. M. Semazzi)

Climate variability over Senegal and its relationships with global climate is examined for the period 1971-1998. Monthly observed rainfall for 20 stations over Senegal, monthly mean temperature for 12 stations and monthly average CMAP data were averaged for the months of June July, August and September, to generate seasonal rainfall totals for the wet season and climate indices averaged over the study period. The monthly SST data is the NOAA Extended Reconstructed SST data (ERSST) provided by the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado.

The monthly, seasonal and annual temperature and precipitation distributions are mapped analyzed using ArcGIS Spatial Analyst. Rainfall distribution over Senegal is dominated by a N-S gradient, and temperature distribution by an E-W gradient.

The mapping of the coefficient of variation for all stations reveals that for both rainfall and the number of rainy days, June is the month that exhibits the greater variability, especially in the West and North of the country. As regard to temperatures, the months from January to April are accountable for most of the variability, especially in the sub-arid areas of the North and Northwest.

Trends in precipitation and temperature are estimated using a linear regression analysis and interpolation maps for the slopes. Areas of positive slopes are limited for rainfall
(Northeast and Southwest of Senegal), but important and statistically significant for temperature throughout the country.

To investigate the climate variability over Senegal two EOF analyses are performed: for 1971-1998 using observations, and for 1979-1998 using additional CMAP data. The first analysis reveals a strong domination of the first EOF mode for rainfall over Senegal. The corresponding time series mostly fluctuates on a high frequency mode. Its correlations with Atlantic and Pacific SST don’t show a strong relationship leading to predictability. However, the second mode for September is well correlated with North Atlantic SST. Despite modest coefficients, the best results are found with Pacific Ocean SST (lag correlation).

The second EOF analysis (1979-1998) includes CMAP data and is conducted over Senegal and 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 Senegal rainfall. This relationship is supported by the projection of NCEP winds on EOF2 mode, and the grid-point correlation between the time series of EOF2 over West Africa and the Atlantic SST. Series for CMAP rainfall over Senegal show good correlation with the South Atlantic SST. Good coefficients are observed during the pre-wet season (January through May) and may offer some predictability for the rainy season. In the Pacific Ocean, the greatest coefficients (up to -0.72) are observed during the April-July period, which can provide hints for the coming rainy season.

The different results obtained in the two analyses suggest an evolution in the relationship between SST fields and Senegal or West African rainfall. The correlations show that the
relationships between the South Atlantic and Senegal or West Africa were stronger in the 1979-1988-period, especially for CMAP rainfall over Senegal and West Africa. The CMAP data is robust and suitable for analyses over West Africa. Based on this liability, it has been possible to use CMAP data in a second EOF analysis, as a validation for the first analysis only based on observed precipitation.

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

The author dedicates this work to his wife Aminatou and their kids; to his parents, sisters, brothers and relatives; to all his friends left in Senegal or found in the United States. He thanks all of them for their support and encouragement as well.

The author dedicates this work to Cheikh Ousmane Mbacke, for his guidance, and to “tonton” Amidou Sene, in memoriam.
BIOGRAPHY

Souleymane Fall was born on November 1, 1950 in Saint-Louis, Senegal. He attended Dakar University and graduated in 1974 with a Bachelor of Arts in Geography. Thereafter he attended Ecole Normale Supérieure de Dakar (teacher training school) and earned a degree in Education. From 1975 to 2001, he worked as a history and Geography teacher in various institutions in Senegal. While teaching, he enrolled in Dakar University and earned a Master’s degree in 1979 and an Advanced Diploma in Geography in 1982. In June 2001, he received a Fulbright grant and enrolled in North Carolina State University for a Master’s degree in Atmospheric Sciences and a minor in Geographic Information Systems (GIS). In May 2003, he earned a Graduate Certificate in GIS. The title of his Master thesis is: SPATIOTEMPORAL CLIMATE VARIABILITY OVER SENEGAL AND ITS RELATIONSHIPS WITH GLOBAL CLIMATE.
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1: INTRODUCTION

Senegal is a country which broadly depends on a rain-fed agriculture. This activity involves about 70% of the active population and provides approximately 40% of external revenues. It also provides raw materials for a large part of industries, and constitutes the alimentary basis for the populace and livestock.

However, as all West African countries entirely or partly lying over the semi-arid region called Sahel, Senegal is characterized by a highly variable rainfall. During the past three decades, severe droughts have led to hardships for the whole socio-economic life, and the country has been often exposed to scarcity in food supplies imposed by rainfall deficit.

Given the occurrence of rains in only four consecutive months (specify the months), a deficient rainy season affects the economic system for a whole year, including public finances, and home and foreign trades. In addition, a degradation of natural resources and a decrease in water supplies are felt. Every year, the ongoing desertification reduces the surface of lands suitable for agriculture and cattle grazing in the northern part of the country called Ferlo. Meanwhile, the population is increasing at one of the highest rates in the world (36.2‰).

It is therefore necessary to come up with a way of predicting seasonal rainfall, so that appropriate measures can be taken ahead of time to minimize drought-related problems. Many investigations related to the tropical climate variability have provided hints that the most important factor modulating seasonal rainfall in West Africa is the tropical Sea Surface Temperatures (SST), both Atlantic and global. Some of these studies have demonstrated that specific SST dynamic patterns, developing before the summer season are associated
with dry or wet epochs in West Africa. Therefore, the intensity of the rainy season may be predictable to a certain degree several months in advance with knowledge of the variations of SST fields.

However, most of these studies focus on large areas on a regional basis (e.g. Sahel, Sudan, West Africa, East Africa, or even the whole continent). Localized investigations involving smaller areas are lacking. A major problem is the lack of consistent observation data, stretching continuously over long periods and originating from well distributed stations.

The purpose of this study is to increase our understanding of rainfall variability and to verify the predictability of seasonal rainfall in Senegal using SST fields.

More specifically, this research has two objectives:

- Provide a descriptive characterization about rainfall patterns in Senegal over 28 years, by compiling surface precipitation data. A well documented description, with Tables, maps and graphs, is a first step to develop an understanding of rainfall distribution and variability.

- Investigate the relationship between the climate variability over Senegal and the global climate using geostatistical approaches. We retain the hypothesis that rainfall over Senegal has a statistical predictability with SST patterns developing prior to the wet season.

The following second chapter is a background study dealing with the geographic and meteorological conditions in Senegal and a literature review about climate variability in West Africa. The third chapter focuses on the description of the data and method. The fourth chapter deals with the climate characterization: it will include a description of the temperature and rainfall distribution from 1971 to 1998, and the climate trends and
variability during this period. The fifth chapter presents the statistical analysis based on the Empirical Orthogonal Function (EOF) analysis performed for the rainfall totals, the number of rainy days and the CMAP (CPC Merged Analysis of Precipitation) rainfall. The results are then correlated with SST fields, the Southern Oscillation Index (SOI), and the Northern Oscillation Index (NAO). A summary and conclusions follow in chapter 6.
2 – BACKGROUND

2.1 – Presentation

Enclosed between the latitudes 12°30 N and 16°30 N, and the longitudes 11°30 W and 17°30 W, Senegal is the westernmost country in Africa, bordering the North Atlantic Ocean (Figure 2.1a). Its total area is 196,700 square kilometers (75,749 square miles). The bounding countries are Mauritania (North), Mali (East), Guinea-Bissau and Guinea (South). Senegal surrounds the Republic of Gambia, which is a little enclave (Figure 2.1b).

2.1.1 - Terrain

The country is a sedimentary basin relatively flat, generally free of steep terrain, with altitudes below 130 meters (Figure 2.2). The dominant features are low plateaus gently sloping westward and covered with sand hills in the northern regions. The most remarkable elevations, which are the southeastern foothills, remain below 600 meters.

2.1.2 - Hydrography

The main rivers of the country are the Senegal (which forms the boundary with Mauritania), its affluent the Falémé (which forms the boundary with Mali), the upper Gambia in the South-East, and the Casamance in the South. All the streams have a tropical regime, based on the rainfall distribution: the rising of the waters corresponds to the core of the wet season (June-July to October), with a short lag, and the fall in water levels take place from late November to May.
Figure 2.1: Position of Senegal: a) position in Africa; b) neighboring countries.
2.1.3 – Soils

Despite a great variety (Figure 2.3), soils are generally very poor in nutrients and exposed to different forms of erosion, especially in the peanut basin where cultural practices have led to the removal of tree parkland and wind erosion. The thickness of soils decreases from south to north, in accordance with the rainfall distribution. In the northern Senegal, soils are composed of thin layers of brown or brown-red sand.

In central regions, sandy ferruginous soils, better known as “Dior” soils, prevail. This zone corresponds to the central Peanut Basin.

In the south-east, soils are mostly covered with pebbles or ferruginous crusts, and the southwestern region is characterized by ferralitic soils.
2.1.4 – Vegetation

Despite a great diversity of species (Figure 2.4), there are three major vegetation domains in accordance with the rainfall decrease from south to north:

- The Sub-Guinean domain in the southwest is covered by a dense mangrove around the mouth of the river Casamance (South), gallery forests along the numerous streams, and secondary forests. Actually, a few patches of forested areas remain because of the deforestation performed in order to provide more area for crops.

- The Sudanian domain lies in most of lower half of the country, between the 500 mm and 1000 mm isohyets. It is the domain of various types of savannahs (herbaceous, shrub
woodlands, and woodlands). This vegetation type has been highly degraded because of bush fires and other human activities.

- The Sahelian domain, where annual rainfall totals are below 500 mm, is a transitional region towards the Saharan desert. The typical vegetation type is a poor steppe (herbaceous and shrub). The onset of the rainy season triggers a rapid growth of the herbaceous cover, but as soon as the rains stop, many vegetal species die back to the ground and highly eroded bare soils prevail for 9 to 10 months, when there is no rain.

Figure 2.4: Vegetation and land use of Senegal (source: USGS/EROS)
2.2 – Meteorological conditions

Two factors play an important role in determining Senegal’s climate:

- The flatness of the terrain: the country is widely open to different air masses.

- The geographical position: the country is bounded by the parallels 12°30 N and 16°30 and therefore lies entirely within the tropical region.

It is the westernmost part of a transitional stripe stretching between moist West Africa to south and the Sahara desert to the north. The northern part of this stripe, called Sahel, is an interplay between continental scale mechanisms and mesoscale mechanisms influencing the rainfall regionally (Dolman et al, 1977). Moreover, it forms the southern border of the widest desert in the world, the major source of sensible heat in the atmosphere, and any extension or reduction of desert conditions via the fluctuation of rainfall, takes place in this area (Prince et al, in press). The southern part of the stripe, called Sudan, is a transition toward the very moist Guinean and equatorial climates.

The location of the country at the western edge of Africa implies another key feature: Senegal undergoes a double influence both oceanic and continental, which is particularly noticeable when examining the temperature and wind fields.

In addition, the geographical setting has three processes that control the atmospheric circulation: two from the northern hemisphere: anticyclone of Azores and North African anticyclone (usually positioned over Libya in winter), one from the southern hemisphere, anticyclone of Saint-Helens. During the northern hemisphere summer, the resulting flows converge and the wet season is a result of their interaction.
2.2.1 - The dry season

The dry season lasts from six months in the south (November to April) to 8-10 months in the north. It occurs when the ITCZ migrates southward, so that the country is out of reach of the moist monsoonal flow (Figure 2.5 a). During this period, the climate is mostly determined by prevailing winds from two directions, separated in the western Senegal by a discontinuity (Figure 2.6).

- The NW marine trade winds originate from the anticyclone of Azores and blow from north or northwest, mainly from November to May. With a marine trajectory, the northwesterly trade winds are relatively moist and cool, and cause a significant drop in temperature, especially in the coastal areas of northern Senegal. However, temperatures increase quickly as one moves inland.

The vertical structure of the NW trade wind is characterized by a low inversion separating the cool and moist marine air mass and a warm and dry one aloft. Consequently, a deep convection cannot develop in this structure, and northwesterly trade winds are not rain-bearing flows.

The east or northeast continental trade winds, better known as “harmattan”, is a very dry, warm and dust-laden wind that originates from the North Saharan anticyclone. The dust is transported from the desert from NE to SW, at an altitude of about 1500 meters. In the western part of Senegal, aerosols transported by the harmattan constitute a warm layer
Figure 2.5: Mean atmospheric circulation: a) in January; b) in August (source: Darchen, 1980). In northern hemisphere winter (January), the anticyclone of Azores extends over North Africa a ridge that sometimes acts as an individual cell. The shaded stripe in a) and b) corresponds to the active band of the ITCZ.
Figure 2.6: Mean trade winds circulation during the northern hemisphere winter.
overlying the NW maritime trade wind (Dulac et al, 2001), and preventing it from generating rainfall. Large dry aerosol depositions are often noticed off the Sahelian regions of West Africa (Bowie et al, 2001), along with an advection of Saharan dust toward the American continent.

Even though the period from November to April is referred to as dry season, precipitation occurring during this period is not unusual, especially from December to April. Off-season rains, which represent about 1% of the annual rainfall, are caused by cloud bands oriented SW-NE and coming from the Atlantic ITCZ (Figure 2.7 a). Many meteorological studies have highlighted the presence of large cloud bands originating from the ITCZ and heading for mid-latitudes in a SW-NE axis (De Felice and Viltard, 1975; Thepenier, 1981; De Brum Ferreira, 1983). One of the zones where these cloud bands repeatedly develop is the area stretching from the tropical Atlantic to Europe and/or Asia. The presence of mid-latitude depressions picking moisture from the ITCZ at the upper level can cause an increase of cloud bands. In that case, Senegal, which lies in their trajectory, can experience off-season rains (Figure 2.7 c). This situation is associated with a southward advection of cold air coming from the mid-latitudes (Figure 2.7 d).

In the whole, this original meteorological situation can be summarized as follows:

- At the upper level (from 700 mb up to 200 mb), a moisture transfer from the ITCZ to mid-latitudes, in a SW-NE axis
- At the surface level, a cold spell coming from mid-latitudes, moving southward and causing a sudden drop in temperature.
a) Meteosat 7, 01/10/2002. 12:00 UTC

b) MM5 simulation of wind direction at 500 mb, January 2002, at 12:00 UTC

c) MM5 simulation of rainfall
January 10, 2002, 18:00 UTC

d) MM5 simulation of temperatures
January 10, 2002, 18:00 UTC

Figure 2.7: Typical situation of an off-season rain. Figure 2.7a shows the presence of a long cloud band oriented SW – NE. Over West Africa, this situation is always associated with a SW – NE subtropical jet: in (b), we simulated this circulation at 500 mb using MM5. Figure 2.7c displays a distribution of rainfall (in mm) with the highest values recorded in the western Senegal. Figure 2.7d shows a cold spell (values are in degrees Celsius), which constitutes the surface level component of North-South exchanges that take place in winter between tropical regions and midlatitudes.
2.2.2 – The wet season

The wet season’s occurrence is controlled by the ITCZ, which is a large scale ascendance zone onto which converge air masses from both hemispheres: NW and NE trade winds, and SW monsoon flow (Figure 2.5 b).

Over Senegal, the ITCZ is often oriented NE-SW, and appears as a transitional branch linking the continental ITCZ and the maritime ITCZ (Figure 2.8). This branch, which is often referred to as a liaison zone, has a complex structure, depending on the temperature and mix ratio of the 3 convergent air masses. It can become very active, especially in August-September, when either the monsoonal flow or the NW trade wind is lifted upward, and overlies the other flow (Garnier, 1976).

Figure 2.8: Mean position of the ITCZ on the extreme West Africa during the northern hemisphere summer (adapted from Garnier, 1976). The continental ITCZ is a “drift”: an anticyclone in one hemisphere faces a trough in the other. The maritime ITCZ is a “duct”: 2 anticyclones face each other, one in each hemisphere.
The structure of the ITCZ presents from North to South different zones (Figure 2.9) described in many studies (Dhonner, 1970; Leroux, 1973c; Darchen, 1980):

- Zone A, located to the North of the ITCZ, is dry and hot, mostly influenced by the continental trade wind.
- Zone B is the northernmost fringe lying to the immediate south of the ITCZ. The shallow monsoonal layer is overlaid by the harmattan, but is thick enough to allow isolated thunderstorm activity.
- Zone C1 is characterized by a thick layer (3500 meters) and a high occurrence of squall lines.
- Zone C2 corresponds to the deepest part of the monsoonal layer (4500 meters) and the heaviest rainfall.
- Zone D, which is closer to the Saint-Helens high, is relatively stable: the flow has just crossed the Equator and is still affected by divergence.

Figure 2.9: North-south cross-section of the monsoon showing the structure of the ITCZ (from Dhonner, 1970).
The ITCZ is a mobile band of cloudiness and rainfall, shifting in a North-South seasonal pattern, in relation with the apparent movement of the sun (with a lag of 6 weeks at least), and the resulting shift of the two major anticyclones of this region: anticyclone of Azores and anticyclone of Saint-Helens. The northernmost position of the ITCZ is reached in August. 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 reaches the whole territory and brings moisture from the Atlantic Ocean. Figure 2.10 shows different positions of the ITCZ in Senegal from May to October.

During the rainy season, the most important rain events are caused by West African disturbance lines, also called squall lines or cloud clusters, which are tropical convective systems organized as lines of thunderstorms oriented roughly north-south and propagating westward. Over Senegal, the number of squall lines during the wet season decreases from SE to NW: the disturbances weaken as they move westward and most of them decay inland. In addition, the aerologic conditions in the Northwest are less favorable because of the proximity of the semi-continental ITCZ that reduces convective activities (see Figure 2.8). However, the convective systems that reach the Atlantic Ocean get additional moisture and can cause appreciable rainfall amounts in the costal regions. Some of them may develop into tropical storms or cyclones, as shown in many studies (Gaucher, 1976, Garnier, 1976, Landsea & Gray, 1992).
Figure 2.9: Mean positions of the ITCZ and its related zones in Senegal from May to October (adapted from Leroux, 1983).
2.3 Literature review

Since 1968, West Africa, especially the Sahelo-Sudanian zone, has experienced a severe drought disrupted only by short wet sequences. The steady decline in rainfall totals has caused a continuous degradation of the environment and led to dramatic consequences for the economy of the region. The persistence of the phenomenon has drawn a growing interest in the study of rainfall mechanisms over the region and prompted numerous investigations.

These studies can be classified into several groups, but the largest bodies of literature focus on coupled ocean-atmosphere features and their relation with West African rainfall, land surface-atmosphere interaction, circulation mechanisms, African Easterly Waves (AEW) and associated disturbances, and the predictability of West African rainfall, which is usually the ultimate objective of investigators.

2.3.1 Coupled ocean-atmosphere features and their relation with West African rainfall

A great body of studies suggest that tropical Atlantic or global Sea Surface Temperatures (SST) and associated anomalies are strongly linked with West African rainfall anomalies. Evidences that West African rainfall variability may be predicted from SSTs anomaly patterns have been provided. Two groups can be distinguished: (i) studies linking West African rainfall anomaly with tropical Atlantic SST; (ii) studies that establish a relationship between West African rainfall and global (worldwide) SSTs.
2.3.1.1 Relations between tropical Atlantic SST and West African rainfall

Early empirical studies linking tropical Atlantic SST anomalies with rainfall fluctuations in West Africa are from Lamb (1978a and 1978b), who investigated composite sets of wet and dry years. Lamb (1978b) found that during the dry July-September, the zone of maximum Atlantic SST was displaced 200-300 km south of its mean location, while during the wet July-September, an expansion of the zone of maximum SST toward the north and south was observed (Figure 2.10a). In a Principal Component Analysis (PCA), Lough (1986) examined SST patterns associated with recent dry and wet periods in the Sahel: the second eigenvector of monthly normalized SST is found to be significantly correlated with the Sahel rainfall (Figure 2.10b), and warm SSTs in the southeastern tropical Atlantic are associated with reduced rainfall in the Sahel, while cold SSTs correspond to high rainfall seasons. Such patterns, already identified by Lamb (1978a and 1978b), were confirmed by Philander (1986), Lamb et al (1986), Lamb and Peppler (1991), Janowiak (1988), Bah (1987), Eltahir and Gong (1996) and Ward (1998). Bah (1987) focused on more localized SST patterns and acknowledged the coincidence of warm waters in the Gulf of Guinea with the reduction of rainfall in the Sahel, but he didn’t find similar relationship during wet periods. Ward (1998) studied separately the West African decadal variability (Low Frequency) and the variability within the decadal regime (High Frequency). One of his main findings is that as regard to the decadal rainfall variability, warmer SST and lower sea level pressure (SLP) in the Equatorial zone and the southern tropical Atlantic are associated with reduced rainfall in the Sahel. A GCM study of Druyan (1991) offers support to the aforementioned association between Atlantic SSTs and the
Figure 2.10: a) seasonal sea surface temperature fields for 1968 (dry) expressed as departures from the 1911-1970 average patterns. Solid lines are departure isotherms (tenths of 1°C). Dotted lines enclose area of maximum SST east of 40°W for 1967 (wet) and 1968 (dry); dashed lines do likewise for the 1911-1970 mean (from Lamb, 1978b); b) second eigenvector of monthly normalized SST departures, 1948 to 1972. Loadings are multiplied by 10 (from Lough, 1986).
West African rainfall. But overall, most of the studies dealing with this theory are empirical investigations.

A second group of statistical or numerical studies have examined these relationships using worldwide SSTs.

### 2.3.1.2 Relations between worldwide SSTs and West African rainfall

The first investigation, combining statistical and numerical methods, was conducted by Folland et al (1986) who showed a global SST anomaly pattern for July to September, obtained from the difference between the July driest and the July wettest rainfall season in the Sahel since 1945 (Figure 2.11). In these anomaly patterns, the south-east Pacific, the south Atlantic and the whole Indian Ocean are warm. Thus, the Atlantic SST patterns found by Lamb (1978 a; 1978b) are included in this global SST patterns. Folland et al (1986) attributed the teleconnections between the Pacific Ocean and West Africa to the anomalous upper tropospheric westerlies generated by the Pacific Ocean anomalies, and suggested that “worldwide SST anomalies may have more fundamental influence on Sahel rainfall”. This theory was supported by subsequent statistical analyses performed by Parker et al (1988), Semazzi et al (1988) and Rowell et al (1995). The July-September global SST anomaly pattern during the 1968-1986 Sahel drought epoch found by Parker et al (1988) is very close to that from Folland et al (1986) shown in Figure 2.11. Semazzi et al (1988) performed an EOF (Empirical Orthogonal Function) analysis and identified tropical Pacific and Atlantic anomaly patterns to be significantly correlated with sub-Saharan rainfall anomalies. Their results suggested “a three-way connection among sub-Saharan rainfall, ENSO and the interannual variability of Atlantic SST”. The Atlantic EOF2 is similar to the
Figure 2.11: SST, July to September: average of 1972, 1973, 1982, 1983, and 1984 (Sahel dry) minus average of 1950, 1952, 1953, 1954, 1958 (Sahel wet). Contour interval: 0.5°C. Shaded areas are different from 0 at the 90% level; of significance according to a t-test (from Folland et al, 1986).
Sahel drought departure pattern already identified by Lamb (1978a; 1978b). Rowell et al (1995) combined an empirical analysis and GCM experiments to confirm the above-mentioned correlation and the north-south interhemispheric contrast of SST anomalies found by Folland et al (1986). Several modeling studies have brought support to the theory that links global SST with West African rainfall: e.g. Palmer (1986), Rowell et al (1992), Palmer et al (1992), Semazzi et al (1996), Xue and Shukla (1998). All of them agree that worldwide SST anomalies are the primary factor influencing the variability of seasonal rainfall. However, for Palmer et al (1992), the tropical Pacific SST anomalies are much more related to African rainfall variations.

This raises the problem of the relationship between ENSO (El Niño Southern Oscillation), which is an important component of Pacific SSTs, and precipitation patterns over West Africa. With respect to ENSO, the geographical position of the African continent is unique: “The broader Atlantic Ocean-Africa-Indian Ocean can be viewed as the meeting point of ENSO effects propagating eastward and westward, mainly through the upper atmosphere, from the tropical Pacific” (CLIVAR, 1999). Most of the relationships between ENSO events and the African continent are established via circulation mechanisms (Kidson, 1975). However, while there is an agreement in the influence of ENSO warm events on East and South Africa, there is considerable disagreement concerning ENSO signal in West Africa and the Atlantic basin.

Various statistical analyses have concluded that evidences of an association between ENSO and West African climate variability are weak. Statistical methods used include: (i) correlation of spatially averaged anomalies (Stockenius, 1981); (ii) harmonic analysis
(Ropelewski and Halpert, 1987; Nicholson and Kim, 1997; Nicholson and Selato, 2000); (iii) EOF analysis (Parker et al, 1988; Tourre and White, 1995). Ropelewski and Halpert (1987) did not find any “any large coherent areas of ENSO-related precipitation in the Sahel region”, as shown in Figure 2.12, and suggested instead the possible preponderance of Atlantic SST relationship with Sahel rainfall.

Figure 2.12: “Core regions” of consistent ENSO-related precipitation for Africa (subjectively determined). 24-month precipitation composites are plotted in form of a vector for each station (from Ropelewski and Halpert, 1987).
Nicholson and Kim (1997), and Nicholson and Selato (2000) showed the lack of ENSO signals for both El Niño and La Niña events, respectively. Parker et al (1988) found that only a strong El Niño can influence West African rainfall. The EOF analysis of SST and heat storage of the upper 400 meters of the ocean performed by Tourre and White (1995) led to the conclusion that the ENSO signal in the Atlantic Ocean is weaker than in the other oceans (it represents only 12% of the total interannual variance).

On the other hand, the potential for ENSO events to influence West African rainfall and tropical Atlantic climate has been demonstrated by many investigators using GCM. The ENSO signal is associated with rainfall variability in the western Sahel (Palmer, 1986); anomalous patterns (such as wind signal) in the tropical Atlantic (Delecluse et al. 1994); a weakened convection in West Africa (Janicot, 1997); and a weaker moisture advection consistent with a weaker monsoon strength (Janicot et al, 2001). Statistical studies supporting the role of ENSO have been reported by Semazzi et al (1988), Wolter (1989), Bhatt (1989), Hastenrath (1990b), Palmer et al (1992), Rowell et al (1995) and Janicot et al (1996). Wolter (1989) performed a Principal Component Analysis of ship data (SST, SLP, surface wind and cloudiness) to investigate the large-scale climate variability in the tropics, and found that the Southern Oscillation (SO) is the most important circulation mode. His third Principal Component, called Sahel mode, expresses an increased rainfall correlated with ENSO. Bhatt (1989) showed that the Southern Oscillation is strongly associated with the eastern Sahel (Nile basin), while the western part (Senegal basin) “shows strongest associations with circulation departures in the tropical Atlantic”. Hastenrath (1990) used satellite-derived highly reflective clouds and found that increased rainfall in the Sahel is
associated with the high SO phase (which is defined by anomalously high/low pressure at Tahiti/Darwin). Janicot et al (1996) noticed that most of ENSO events after 1970 were associated with West African rainfall deficits, and one of the causes might be an atmospheric circulation anomaly, which consists of a zonal wind convergence in the upper atmosphere and subsiding motions over West Africa. Ward (1998) limited the connection between ENSO and West African rainfall to the years with the same rainfall anomaly sign in the Sahel and Guinea Coast region, at an interannual time scale (High Frequency).

This anomaly pattern observed by Ward (1998) is referred to as “no dipole” pattern and is associated to the warm ENSO phase. The concepts of dipole and no dipole regions over West Africa have been mentioned in a number of studies not exclusively devoted to SSTs-rainfall investigations. Janowiak (1988) defined dipole regions as adjacent regions that tend to experience rainfall anomalies of opposite sign. An example of dipole pattern is shown in Figure 2.13. Janowiak’s study revealed an association between above normal SST in the south Atlantic and positive rainfall anomalies in the Guinea Coast region and negative anomalies in the Sahel-Sudan. His findings were later confirmed by Mo et al (2001) who found that cold Atlantic SST anomalies contribute to a north-south dipole pattern over West Africa, with an increase of moisture in the Sahel and a decrease in the Guinea Coast region. Other studies not focusing in SST forcing but confirming this pattern include Nicholson (1980), Nicholson and Palao (1993), Fontaine et al (1995) and Rowell et al (1995). The dipole pattern usually operates at the interannual time scale (Fontaine et al, 1995; Rowell et al, 1995; Ward, 1998).
2.3.2 Land surface-atmosphere interaction

The African continent is the largest tropical land in the world. Its northern part is particularly massive, with a great diversity of features, including the largest desert in the world. The Sahelian stripe south of the Sahara desert is experiencing a persistent drought in conjunction with a rapid population growth, thus severely impacting and modifying the land cover (Xue and Fennessy, 2002). Hence there has been a growing interest in the study of land surface-atmosphere feedbacks in this region, which are believed to enhance and further maintain climate anomalies (Entekhabi et al, 1992; Nicholson, 1983; Lare and Nicholson, 1994), thus playing an important role in the modeling and characterization of climate variability in West Africa. Several studies, mostly GCM experiments, have investigated the interactions between land surface boundary conditions and the atmosphere over West Africa. Extensive reviews of those investigations have been performed by Mintz (1984), Rowntree (1985) and Nicholson (1988). The main processes involved are
vegetation and soil moisture, which are associated with land surface albedo, surface roughness and evaporation. The Orography is another factor included in this section.

2.3.2.1 Vegetation, albedo and surface roughness

Charney (1975) suggested a feedback mechanism in which the reduction of vegetation causes an increase in albedo, which in turn induces a sinking motion leading to a decrease of relative humidity and rainfall. Such a mechanism taking place in the Sahel could cause a shift of the ITCZ southward and reduce rainfall. Other numerical experiments in which the land surface albedo has been changed confirmed Charney’s results (Walker and Rowntree, 1977; Sud and Fennessy, 1982): they found an inverse correlation between land surface albedo and sensible heat flux. Cunnington and Rowntree (1986) also confirmed Charney’s hypothesis, using an atmospheric GCM in which land surface albedo and other parameters such as atmospheric water content and radiation scheme were taken into account. Further support to these results was reported by Lofgren (1995a) and Semazzi and Song (2001). Lofgren (1975a) found that increased surface albedo forces thermally sinking motion and a decrease in rainfall which in turn causes sparser vegetation and a further increase in surface albedo. Semazzi and Song (2001) conducted a modeling study in which a simulated total deforestation caused reduced evapotranspiration, increased surface ground temperature and reduced rainfall in West Africa. Zheng et al (1999), using a model with interactive vegetation and soil moisture, concluded that allowing vegetation feedback to the atmosphere not only impacts rainfall amounts, but also enhances the decadal rainfall variability.
Increased land surface albedo not only lowers precipitation and evaporation rate, but also induces changes in the atmospheric circulation. Laval and Picon (1986), simulating the circulation over Africa with respect to an increased albedo, found strong low level easterlies and a weak Tropical Easterly Jet (TEJ). Lofgren (1995b) found that perturbations in surface albedo can affect the large-scale zonal overturning circulation between land and ocean. The change in land surface roughness associated with vegetation cover alters the boundary layer water vapor convergence, thus affecting large-scale atmospheric circulation and rainfall (Sud et al. 1988). It can also delay the onset of the rainy season by almost half a month; cause a southward shift of the maximum rainfall; a weaker TEJ and monsoon flow; a stronger than normal African Easterly Jet (AEJ); a reduced intensity of African Easterly Waves (AEW) disturbances (Xue and Shukla, 1993). Zheng and Eltahir (1998), investigating the sensitivity of West African monsoon to perturbations in the vegetation cover, found minor impacts when the changes take place in the Sahel, and a dramatic drop of the monsoonal circulation when deforestation occurs along the Guinea Coast region. The results of numerical simulations conducted by Xue and Fennessy (2002) support these findings and in addition, show that the simulated climate anomaly is not limited to the specified period test (northern summer), but also extends in autumn. In addition, it is not limited to the area test (Sahel), but extends in East Africa.

On the whole, the change in land surface albedo associated with vegetation plays a central role in land-atmosphere interactions. However, a caveat of all sensitivity studies is that a large perturbation of the land surface properties is assumed, and its magnitude is often unjustified (Zheng and Eltahir, 1998). Xue and Shukla (1993) point out conflicting
opinions on the magnitude of changes in albedo in West Africa in the 60s and 70s and add that the area associated with land surface changes is arbitrary. Nicholson (1988) recommends the use of realistic values of perturbation of surface parameters, and the simulation of ensemble effects of various types of surface change, instead of simulating changes of individual surface parameters. Another controversial point is the increasing degradation of land cover which leads to the widely recognized desertification. Nicholson et al (1998) demonstrates that during the 1980-1995 period, there has been no progressive change in either the desert boundary or vegetation cover in the Sahel.

2.3.2.2 Soil moisture

Another parameter which is positively correlated with both land surface albedo and vegetation is soil moisture. Its key-role in land surface processes has been increasingly recognized and is well documented. Walker and Rowntree (1977) described a classic feedback mechanism: in arid regions with low moisture level, there is less evaporation, less precipitation, higher temperature and more sensible heat flux, so that the initial soil moisture level is maintained. This mechanism is confirmed by Cook and Ganadeskian (1991) who showed that a soil moisture anomaly causes the precipitation to evolve so that the initial soil condition is enhanced. Soil moisture is considered as a good indicator of the balance between supply and demand of moisture (Lofgren, 1995b). Basically, changes in vegetation and surface albedo cause changes in interception (and subsequent evaporation), which in turn affect soil moisture availability (Rowntree, 1985; Cunnington and Rowntree, 1986; Lofgren, 1995b).
Soil moisture can also play a role on the large-scale atmospheric circulation. Its persistence and variability can partly modulate the variability of the lower troposphere (Delworth and Manabe, 1993), and also influence rainfall variability: Rowell et al (1995), combining empirical and modeling approaches for the Sahel, Sudan and Guinea Coast region, examined the relationships rainfall/SST patterns, and then rainfall/soil moisture. The results suggest that even though SST forcings are stronger, the feedback of soil moisture evaporated from the land surface play a key-role in some years. In a numerical study, Bounoua and Krishnamurti (1993) introduced a soil moisture parameter and performed seasonal simulations covering the onset and active phase of the West African monsoon: the northernmost position of the monsoon coincided with a decrease of net solar radiation reaching the ground, a subsequent increase of soil wetness and an increase in the PBL moisture, causing heavy rainfall.

The ability of the soil to supply moisture to the atmosphere and to trigger convection can be used in short-range rainfall forecasting, as demonstrated by Rowell and Blondin (1990), who showed that an improved moisture analysis has significant impact on 3 to 4 days forecasts in the Sahel. In addition, they pointed out that surface moisture is one of the factors that may trigger the release of instability, which is necessary for the generation and propagation of West African Squall Lines (SL).

2.3.2.3 Orography

So far, the role of large-scale orographic forcing in the modulation of West African climate is less documented than that of other parameters (vegetation, albedo, moisture level). West Africa has a less complex topography structure than the rest of the continent. Low plateaus
and basins are the predominant features, while high terrains are isolated. Consequently, the relative flatness of the terrain doesn’t suggest a major influence on rainfall. However, numerical modeling evidences that the high landmasses along the Guinea Coast, the Atlas Mountains and Ahaggar Plateau may play an important role in determining West African rainfall anomalies have been provided by Semazzi and Sun (1997). Their main findings are that the crossing of mountainous ranges by flows generates two features: (i) along the coastal Guinea region, an orographic ridge created by the monsoonal flow over high terrains; (ii) at the northwest region of the Sahel, a trough generated by the low-level easterly flow over the Atlas-Ahaggar Mountains (Figure 2.14). The associated cyclonic circulation may transport moisture from the Atlantic Ocean into the western part of the Sahel. Also, the simulations show that the amount of rainfall in the Sahelian region may depend on the strength of the flow originating from the trough.

Figure 2.14: Circulation features associated with the interaction among West African orographic forcing, the prevailing low-level easterly flow, and the south-westerly monsoon flow (from Semazzi and Sun, 1997).
On the whole, it is clear that both ocean and land surface processes interact with the boundary layer and modulate atmospheric variables such as temperature, moisture, atmospheric pressure and winds, thus influencing the moisture advection, which greatly determines rainfall. In addition, both land surface and sea surface anomalies have associated atmospheric circulation anomalies (Diedhiou and Mahfouf, 1997). That is why the tropical belt circulation, which establishes teleconnections linking anomalies, has been the subject of many investigations.

2.3.3 Tropical atmospheric circulation

Most of the studies dealing with tropical atmospheric circulation over West Africa focus on contrasting patterns during wet and dry periods. Particular attention is given to the monsoon circulation, the ITCZ location and intensity, the West African jets and the pressure and wind patterns over the neighboring Atlantic Ocean.

The southwest monsoonal flow is a prominent feature of the West African atmospheric circulation during the northern summer (Hastenrath and Lamb, 1997). Following the northward shift of the ITCZ, this flow brings moisture to the continent and allows the development of West African disturbances (Squall Lines), which are the major sources of rainfall in the region. The West African jets play a key-role in the transport of moisture (Cadet and Nnoli, 1987) and the vigor of squall lines.

The characteristics of the monsoon during dry periods have been documented in empirical and numerical studies. Empirical studies point out a reduced monsoonal flow (Newell and Kidson, 1984; Fontaine and Janicot, 1992; Fontaine et al, 1995), with lower water content of the monsoonal flux north of the 10°N (Janicot, 1992). Fontaine et al (1995) noticed a
reduction of the zonal velocity in upper levels of the monsoon flow during years when opposite rainfall anomalies were observed between the Sahel (negative sign) and Guinea Coast region (positive sign). These results are supported by modeling studies. Druyan (1987), Druyan and Koster (1989), Semazzi et al (1993), Druyan and Hastenrath (1991), Cook (1994), Cook (1997) and Janicot et al (2001) found a weak moisture advection related to a weak and shallow cross-equatorial monsoon flow during dry years.

The shallowness of the monsoon layer is associated with a southward shift of not only the ITCZ, but also all major circulation patterns over the Atlantic Ocean (Lamb, 1978a and 1978b; Hastenrath, 1990; Janicot, 1997) and West Africa (Kanamitsu and Krishnamurti, 1978; Janicot, 1992; Fontaine and Janicot, 1992). Kraus (1997) explains the latitude reached by the ITCZ over the continent during the latest drought period (which peaks in 1972) by a reduced demand of energy transport from the tropics and a resulting weak tropical circulation. Not all investigators agree on the influence of the ITCZ position in West Africa: for example Nicholson (1981) reports that the Subsaharan drought is probably caused by a weakened intensity of the rainy season, which does not depend on the ITCZ position.

Other circulation patterns shifting southward include the center of the North Atlantic subtropical high (Lamb, 1978a and 1978b) and the Hadley cells (Janicot, 1992).

Over the tropical Atlantic, it has been found that Sahel droughts are also associated with a pressure rise (Hastenrath, 1990; Janicot, 1992) and enhanced NE trade winds (Bhatt, 1989; Hastenrath, 1990; Janicot, 1992; Janicot et al, 2001).
The upper level circulation is also well documented. During the northern summer over West Africa, strong easterly winds aloft are observed: the TEJ and the AEJ (Figure 2.15a). The TEJ, originating from Asian landmasses, is located at approximately 200 mb, and south to 10°N (Rowell, 1988). It is generated by the meridional thermal gradient established during the northern summer Asian monsoon between the Tibetan Highlands and the Indian Ocean (Koteswaram, 1958). Dhonneur (1981) considers the TEJ as the most determining feature in investigating teleconnections linking Asian and African monsoons and explaining planetary-scale droughts throughout the northern hemisphere tropical belt. The AEJ is a midtropospheric flow that originates from the region west of Ethiopian highlands (Rowell, 1988; Lare and Nicholson, 1994). It results from the low level gradient between the hot Sahara desert and the cool and moist Guinea Coast and Atlantic regions (Rowell, 1988; Lare and Nicholson, 1994). The AEJ is generally located at about 650 mb, and 15°N, but its position changes with respect to underlying conditions: the jet is influenced by changes of the meridional gradient of surface moisture and heating (rainfall, evapotranspiration, latent heat) as shown in numerical simulations by Lare and Nicholson (1994) and Rowell et al (1992). The AEJ plays a key-role in rainfall production and distribution over West Africa and is referred to as a major artery for the transport of moisture from the Gulf of Guinea (Cadet and Nnoli, 1987; Peters and Tetzlaff, 1988). It is also known for providing energy for the maintenance of West African disturbances (Peters and Tetzlaff, 1988; Druyan, 1988; Lare and Nicholson, 1994). As noticed by many authors, dry summers over West Africa are associated with a weak TEJ and a stronger and
more southward extending AEJ (e.g. Kanamitsu and Krishnamurti, 1978; Dhonneur, 1981; Druyan, 1988; Fontaine and Janicot, 1992; Fontaine et al, 1995).

Figure 2.15: Vertical cross-section of the zonal wind at 5°E, for August monthly means. Units are in ms⁻¹ (from Burpee (1976)).

2.3.4 African Easterly waves and associated disturbances

AEW constitute a major feature of the northern summer in the Sahel/Sudan region, because they are associated with westward propagating squall lines, which are the most important convective systems (Peters and Tetzlaff, 1987). About 80 to 90% of West African rainfall is provided by SLs. A better understanding of AEW and SL mechanisms is therefore crucial to investigate the problem of rainfall variability over the Sahel/Sudan region (Druyan, 1988, Thorncroft and Hodges, 2001), and to provide a better forecast of rainfall (Rowell and Blondin, 1990).

AEW are synoptic scale disturbances which are related to the AEJ (Diedhiou et al, 1999), at the midtropospheric level, during the northern summer. Generation may be related to
barotropic/baroclinic instability of the AEJ (Burpee, 1972; Reed et al, 1988a; Peters and Tetzlaff, 1988). AEWs are usually generated over West Africa. Reed et al (1988b) indicate two main source regions: “one in the desert region of northern Mali …another in the rain belt to the south, stretching from Lake Chad across Nigeria to southern Ghana”.

The waves propagate westward with an average speed of 8 ms\(^{-1}\) (Reed et al, 1988a; Peters and Tetzlaff, 1988). Diedhiou et al distinguish two speeds, south of the jet (12 ms\(^{-1}\)) and north of the jet (8 ms\(^{-1}\)). The wavelength and wave period are variable according to the case studies. On an average, waves have approximately 2500 km wavelength (Burpee, 1976; Reed et al, 1977, Reed et al, 1988a, 1988b), and a 3-5 days wave period. However, Diedhiou et al (1999) found a 5000 km wavelength south of the jet and a 3000 km wavelength north of the jet. They also observed a 6-9 days regime which has a 5000 km wavelength.

Many tracks are proposed by different investigators: the latitudinal belts of 10-15°N (Peters and Tetzlaff, 1988), 16-17°N (Reed et al, 1977) and 5-30°N (Burpee, 1974). Diedhiou et al (1999) proposed two tracks, at 5°N and 15°N. There is a general agreement that the tracks merge into a single one located between 15°N and 20°N over the Atlantic Ocean (e.g. Reed et al, 1988a; Diedhiou et al, 1999).

Most of the studies show the AEW to be active at 600-650 mb and at 850 mb. Thorncroft and Hodges (2001), using an automatic tracking of vorticity centers in ECMWF (European Center for Medium Range Weather Forecasts) analyses, found that the 850 mb activity is
characterized by a marked interannual variability, especially at the West African coast, between 10°N and 15°N.

Over the Sahel/Sudan region, AEW modulate the daily rainfall as well as the thunderstorm activities associated with squall lines (Burpee, 1974; Reed et al, 1977). Squall lines are disturbance lines which travel westward at an average speed of 40-60 km/h (Leroux, 1998). Figure 2.16a shows the possible SL tracks over West Africa. Squall lines are organized as convective cells forming a curve oriented north-south, which may be up to 1000 km long (Rowell, 1988; Leroux, 1998).

The atmospheric conditions favorable for the formation of SLs are: (i) a vertical moisture profile characterized by low-level moist air overlaid by very dry air; (ii) conditional instability; and (iii) presence of wind shear below the AEJ (Aspliden et al, 1976; Rowell and Blondin, 1990; Lister and Palutikof, 2001). Surface heating, topography, large-scale moisture convergence and sensible heat flux from the ground are also important factors that may trigger the formation of squall lines (Aspliden et al, 1976; Peters and Tetzlaff, 1988; Rowell and Blondin, 1990). Leroux (1998) has attributed the formation of squall lines to “the penetration of a powerful trade wind pulse into the Atlantic monsoon blowing in the opposite direction”.

Aspliden e al (1976) found that during the three phases of the GATE experiment, the frequency for SL generation was high in two West African areas: in the 5°E-10°E belt and in the 0°-5°W belt. These locations agree with AEW source regions proposed by Reed et al
(1988b). The maximum decay frequency was found in the 0°-5°W belt and in the 5°E-10°E belt (Figure 2.16b). Consequently, many SLs decay before they reach Senegal.

Figure 2.16 - a) Most observed tracks for cloud clusters: (1) southwestward; (2) westward; (3) northwestward. (From Dhonneur, 1981); b) generation and decay distribution of disturbance lines with longitude during all GATE phases (from Aspliden et al, 1976).
The convective processes leading to the formation of cloud clusters is characterized by a strong diurnal cycle (Aspliden et al, 1976; Desbois et al, 1988), with the highest frequency of generation observed from 3:00 to 6:00 PM, and the lowest frequency from 3:00 to 6:00 AM (Aspliden et al, 1976).

Even though West African SLs have been the focus of many studies, much work remains to be done as regard to the related rainfall distribution and the role the disturbances play in rainfall variability over the region. Thiao et al (1990) showed the existence, in each cloud cluster, of multiple convective cells, each of them producing different rainfall amounts. Some studies point out different properties shown by AEWs and SLs in wet and dry years, and suggest that rather than the number of events in a season, the location of their sources, their trajectories, propagation speed or intensities are the most determinant factors (Desbois et al, 1988; Grist et al, 2002). Other studies in which SLs are not the primary focus support this point of view: e.g. Ba et al (1995) who used Meteosat data to examine rainfall variability over West Africa in wet and dry years, and concluded that rainfall variability in the Sahel may be mostly modulated by “factors governing the vigor of the convection, such as those determining the number and intensity of squall lines or the efficiency of water vapor convergence within the region”.

AEWs and their associated disturbances are not limited to West Africa. Several studies have shown that summer rainfall in the region is associated with hurricane activity in the Caribbean and U.S. Related investigations include Garnier (1976), Darchen (1980), Read et al (1988b), Landsea et al (1992), Landsea and Gray (1992) and Mo et al (2001). This topic is not covered in the present study.
2.3.5: The predictability of West African rainfall

Attempts to predict the quality of West African rainfall rely on various evidences that (i) specific Atlantic and global SST patterns are associated with West African rainfall anomalies; (ii) the wet season patterns may be predicted from prior developments (Lamb 1978a and 1978b); and (iii) SST patterns can themselves be predicted a few months in advance.

West African rainfall may be predicted using knowledge of Atlantic SST patterns. Lamb (1978a) enumerated atmospheric SST anomalies that evolved prior the rainfall season: they include positive SST anomalies south of 10°N; positive trade wind speed departures and a northward displacement of the North Atlantic High centre during the preceding January-June and a southward displacement of the kinematic axis during the preceding April-June. Lamb therefore suggests the possibility that “Subsaharan drought may be predictable three to six months in advance”. However, he did not notice the predictability of increased West African rainfall from prior developments. These conclusions were confirmed by Lough (1986) who performed a PCA of Atlantic SST and SLP and found a high correlation with April-June second SST eigenvector series with the Sahel rainfall index. Statistical analyses from Bah (1987) also lead to the conclusion that summer Sahel rainfall can be predicted one to two months earlier using the SST of the Gulf of Guinea (equatorial upwelling zone and intermediate warm waters area). The aforementioned predictability was confirmed with numerical experiments from Druyan (1987): his GCM simulations showed that anomalously warm SSTs are often observed in the southeast Atlantic several months’ prior to dry summers in the Sahel. The mechanism suggested by Druyan’s simulations is that
warm SST and the resulting weakening of south Atlantic high pressure system cause a weak southwesterly flow and less moisture transport toward West Africa. Another GCM simulation from Druyan (1991) confirmed the predictability of Sahel summer rainfall from spring SST patterns or spring atmospheric circulation patterns (e.g. the reduction in speed of the southerly winds over the Atlantic near the prime meridian).

Evidences that worldwide SST patterns may be used as predictors were presented earlier in this chapter. Parker et al (1988) used two statistical methods (linear regression method and multivariate linear discriminant prediction), both depending on relationships between Sahel rainfall and SST anomalies several months in advance. Wolter (1989) used a PCA method to examine the importance of ENSO with respect to interannual climate variations. His second and third PCs are well correlated with Subsaharan rainfall, and also with precursors in boreal winter (SO and NAO). He therefore considers that “a favorable prospect is opened of predicting some Sahel rainfall variance a semester ahead of time”.

GCM simulations from Rowell et al (1992) support these results: in seven experiments, SST anomalies were forced for April, May or June. Six of them indicated that skilful prediction may be done using the persistence of June SST anomalies.

On the whole, as regard to the predictability of West African rainfall, much work has been done, but there is still a lot to do, in order to better understand the teleconnections between West Africa and remote oceans, the relationship between Pacific ENSO events and other oceans (Nicholson and Kim, 1997) and the effects of SST forcings on West African wave disturbance regimes.
3 DATA AND METHODS

3.1 Data

The meteorological data used in this study covers the period from January 1971 to December 1998. This period was chosen because it is includes in the last West African drought epoch (beginning in 1968) and presents a completeness of rainfall data set for a network of 20 stations in Senegal (Figure 3.1). The data consists of:

- monthly rainfall (from rain gauges)
- number of rainy days per month
- monthly mean temperature \( \frac{[t_{\text{max}} + t_{\text{min}}]}{2} \) for 12 stations (Figure 3.1).

The data originate from Météorologie Nationale, Dakar, Senegal (Office of National Meteorology).

We use additional rainfall data is based on CMAP (CPC Merged Analysis of Precipitation). The construction of gridded fields of global monthly precipitation on 2.5 latitude-longitude grid is described by Xie and Arkin (1997). The version of CMAP data used in this study is derived from gauge observations and satellite data.

The monthly SST data is the NOAA Extended Reconstructed SST data (ERSST) provided by the NOAA-CIRES\(^1\) Climate Diagnostics Center in Boulder, Colorado. The data is available from their website at [http://www.cdc.noaa.gov](http://www.cdc.noaa.gov). The original source is from Smith, T.M. and Reynolds, R.W (Smith and Reynolds, 2003). The monthly SST for 2°latitude x 2°longitude boxes were constructed using the Comprehensive Ocean

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\(^1\) Cooperative Institute for Research in Environmental Sciences
Atmosphere Data Set (COADS) SST, which is an extensive collection of surface marine data available from the world ocean. Our SST study domain is a latitudinal band comprised between 30°N and 30°S for both Atlantic and Pacific Oceans.

![Map of Senegalese meteorological stations](image)

**Figure 3.1:** Senegalese meteorological stations used in this study.
Many indices are used in this study:

- The West African seasonal rainfall index from Lamb has a normalization period from 1941 to 2000, for April through October. This updated index has been kindly provided by Dr Lamb.

- Nicholson’s Sahel and Sudan rainfall indices are averages of standardized annual rainfall amounts for stations in the indicated regions (Nicholson, 1979). They cover the period from 1901 to 1994.

- The SOI (Southern Oscillation Index) was obtained from the Australian Bureau of Meteorology. The method used by this Bureau is the standardized anomaly of the Mean SLP difference between Tahiti and Darwin. It is calculated as follows:

\[
SOI = \frac{[P_{diff} - P_{diffav}]}{SD(P_{diff})} \times 10
\]

where

\( P_{diff} = \) (average Tahiti MSLP for the month) - (average Darwin MSLP for the month).

\( P_{diffav} = \) long term average of \( P_{diff} \) for the month in question, and

\( SD(P_{diff}) = \) long term standard deviation of \( P_{diff} \) for the month in question.

The multiplication by 10 is a convention. Using this convention, the SOI ranges from about –35 to about +35.

- The monthly index of the NAO (North Atlantic Oscillation) is based on the difference of the normalized SLP between Ponta Delgada (Azores) and Stikkisholmur/Reykjavik
(Iceland), for the period 1865-2000. The data was obtained from Hurrel’s website (Dr Hurrel, J., Climate Analysis section, NCAR).2

### 3.2 Methods

As stated in the previous section, rainfall in West Africa is highly concentrated in 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 focus on the Sahel zone, which has experienced severe droughts in the past decades. In this zone, most of the rain is indeed concentrated in the JAS period. However, with reference to Senegal, Sahel lies only in the northern part for the country. The lower half of the country belongs to the Sudanian zone. In order to determine which month would be considered in this study, the first step was to sum up all the wet months of the rainy season, and to compute the contribution of each (Table 3.1). The two lowest contributions (May and October) were eliminated. This procedure was repeated, this time considering only June, July, August and September (JJAS), to verify the consistency of the month of June. It stood out that in Senegal, the contribution of June is appreciable, especially for the southern stations lying in the Sudanian zone (Table 3.2). Consequently, in this study, it is assumed that the wet season lasts from June to September (JJAS).

To show the monthly, seasonal and annual temperature and rainfall distributions in Senegal, ArcGIS Spatial Analyst and Geostatistical Analyst were used to create surface interpolation maps. Several interpolation methods are available in Geostatistical Analyst (Hoef, 2003):

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2 National Center for Atmospheric Research, Boulder, Colorado.
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**Table 3.1** – Contribution of each month to the seasonal rainfall, from May to October (as percentage of rainfall recorded).

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<td>Tambacounda</td>
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<td>28.1</td>
<td>32.5</td>
<td>25.5</td>
</tr>
<tr>
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<td>17.8</td>
<td>42.9</td>
<td>34.0</td>
</tr>
<tr>
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<td>25.5</td>
<td>34.1</td>
<td>26.4</td>
</tr>
<tr>
<td>Ziguinchor</td>
<td>8.5</td>
<td>27.2</td>
<td>35.5</td>
<td>28.9</td>
</tr>
</tbody>
</table>

**Table 3.2**: Same as Table 3.1, except for June to September.
- Inverse Distance Weighted (IDW) uses the known values surrounding the prediction location, taking into account the weight of the sample points and the distance separating them from the prediction location. However, IDW cannot make predictions above the maximum and below the minimum sample values.

- Global Polynomial creates a surface interpolation by fitting one single smooth plane to the sampled data points.

- Local Polynomial uses many planes fitted to different neighborhoods to create a surface.

- Radial Basis functions fit a flexible plane to each of the sample points. They are exact interpolators (the plane must pass through each sampled point).

- Kriging predicts unknown values using a best-fit model based on the distance and direction of all possible pairs of sample points.

Each of these interpolation methods has several options and settings. All are examined in this study. The choice of a method for this study was based on two criteria:

- The quality of the models tested is the primary criterion: this is assessed by a cross-validation procedure\(^3\): the difference between known and predicted values is expressed by the Root Mean Square (RMS). The smaller the RMS, the better the model. Figure 3.2 summarizes the quality of the models tested.

\(^3\) The procedure where one datum is removed and the rest of the data are used to predict the removed datum. To produce a cross-validation graph in Geostatistical Analyst, each data point is systematically removed and the model is used to get a predicted value for that location. The process is repeated for all points and the predicted and actual values are plotted (Hoef, 2002).
a) Inverse Distance Weighted  
RMS: 1.835
b) Global Polynomial  
RMS: 2.013
c) Local Polynomial  
RMS: 1.96
d) Radial Basis (Spline with tension)  
RMS: 1.516
e) Ordinary Kriging  
RMS: 1.514
f) Universal Kriging  
RMS: 1.995

Figure 3.2 – Different interpolation methods tested for this study, and the corresponding Root Mean Squares. Spline (a Radial Basis function) combines a low RMS and smooth surface contours.
The visual display of the models, which is based on the way the features are modeled.

Figure 3.2 shows the different surfaces created using the aforementioned interpolation methods for the same dataset. It appears that Ordinary Kriging and Spline with tension (which is a Radial Basis function) are the best models in this case (lower RMS) and produce surfaces which are very close each other. However, Radial Basis presents smoother surface contours. Hence all the interpolation maps in this study were produced using this method available in ArcGIS Spatial Analyst, which has a great flexibility with respect to the symbology.

To analyze trends in the different time series (precipitation, number of rainy days and temperature), a simple linear regression was used. In this method used by many investigators (e.g. Hastenrath, 1990a; Boyles and Raman, 2003), the series of values is related to time by the least-squares fit equation:

\[ y = a + b(t) \quad (2) \]

Where \( y \) is the variable; \( t \) is time; \( a \) is the intercept coefficient and \( b \) is the slope coefficient, which indicates the average rate of change. This method is applied to all stations of the study area, and the slope values are used to plot maps of the spatial distribution of the trends, using ArcGIS Spatial Analyst. Additionally, for each station, the nonparametric Pettitt test is used to detect change point in the series (Pettit, 1979). In this test, the series is divided into two sub-samples of size \( m \) and \( n \) respectively. The values of these two sub-samples are sorted in ascending order. The ranks of elements of each sub-
sample within the total sample are summed. The Pettit test defines a statistical method which verifies whether the two sub-samples belong to the same population (null hypothesis). If they don’t belong to the same population, a change point (statistical break) is detected.

Rainfall variability in Senegal with respect to the whole Sahel and Sudan and its predictability based on SST were examined in several steps. For each station, the seasonal rainfall and number of rainy days were computed, based on monthly observations. Then the monthly and seasonal indices were computed by normalizing the time series of the 20 stations with the 1971-1998 mean and its standard deviation, using the following equation:

$$x_{ij} = \frac{(r_{ij} - \bar{r}_i)}{s_i}$$  \hspace{1cm} (3)

where $x_{ij}$ is the monthly or seasonal rainfall departure for station $i$ and year $j$; $r_{ij}$ is the monthly or seasonal value for station $i$ and year $j$; $\bar{r}_i$ is the mean value at station $i$ averaged over the period of observation (here, 1971-1998); $s_i$ is the standard deviation of the monthly or seasonal value at station $i$ (Nicholson, 1979). The resulting departures for all stations are then averaged to yield a monthly or seasonal index for the country.

This index was then compared to other rainfall indices: Nicholson’s Sahel and Sudan indices, Lamb’s West African index) using linear correlation, scatterplots and other graphs.

A first estimate of climate variability is given by the contribution of each month in the seasonal variability, by computing the coefficient of variation during this month for each station as follows:
The coefficient of variation, which measures the variability relative to the magnitude of the data, is expressed as percentage and allows good comparison of variations. The results are expressed as bar graphs and maps.

Then, an EOF analysis is performed for monthly and seasonal rainfall data. This method, which has been used in a number of statistical analyses (see previous section), “finds the spatial patterns of variability; their time variation, and gives a measure of the “importance” of each pattern” (Björnsson and Venegas, 1997). The computation was performed in five steps:

- Arrange the raw data into a matrix and reduce data size by standardization

\[
( \frac{x_i - \bar{x}}{\sigma} ) \quad (3)
\]

- Compute covariance/correlation matrix \( R \): this is the first step to see how the stations correlate to each other.

- Generate eigenvalues from characteristic equation-determinant:

\[
(R - \lambda I) = 0 \quad (4)
\]

- Get eigenvectors associated with each eigenvalue in step 3 (use row reduction method).

- Plot time series of the eigenmodes (Principal Components).
EOF eigenvector loadings are then plotted in GIS to express the spatial patterns of variability, and the corresponding time series are examined to determine the temporal variability.

The predictability of rainfall in Senegal using SST is investigated by correlating EOF modes for rainfall with tropical Atlantic and Pacific SSTs, for the 1971-1998-period (month-to-month and lag correlation up to 6 months). Grid-point maps are used to identify the Atlantic and Pacific zones which are likely to provide predictability for rainfall. In this step, the correlation of Senegal index with SOI and NAO is emphasized.
4. ANALYSIS OF MEAN CLIMATE CONDITIONS

In this chapter, ArcGIS and statistical tools are used to analyze rainfall and temperature distribution, variability and trends. The statistics used are monthly, seasonal (JJAS) and annual averages relative to the study period (1971-1998).

4.1: Rainfall and number of rainy days

4.1.1: Distribution

The precipitation regime is characterized by an increase in amount of precipitation and number of rainy days from north to south and a high concentration of occurrences in the June-September period (Figure 4.1 and 4.4). However, the remainder of the year is not completely dry: the rainy lasts up to October, which may, in some instances, record substantial amounts (e.g. October 1991: 25.7% of the annual rainfall in Louga; 25.3% in Velingara; 24.1% in Saint-Louis). Besides, the contribution of October in the seasonal rainfall is relatively important in the South (Figure 4.1b). In addition, off-season rains may occur from December to March (under conditions explained in chapter 2) as shown in Figure 4.2.

The spatial distribution confirms the north-south gradient: Figure 4.3 shows the progressive occurrence of rains from southeast to northwest throughout the wet season, with the highest values recorded on August. This SE-NW axis of penetration of rainfall activities, mentioned in a number of studies (e.g. Leroux, 1973a and b), is due to the westward propagating squall lines.
Figure 4.1: Seasonal rainfall distribution (JJAS) for the period 1971-1998. Rainfall in mm (colors) and number of rainy days (isolines); b) monthly distribution for the rainy months. The north-south gradient is evident. The southern Senegal is the first and the last region which records rainfall, in accordance with the seasonal shift of the monsoon.
Figure 4.2: Mean monthly rainfall distribution (in mm) for the period 1971-1998. March (which recorded traces of rainfall) and April are omitted. Off-season rains are mostly observed in the North and West. The wet season picks up in May, when the first disturbances reach the South-East, while most of the country remains relatively dry (too shallow monsoon layer in central Senegal or no monsoon at all further north).
Figure 4.3: Mean monthly rainfall and number of rainy days for the period 1971-1998. There is a strong agreement between rainfall amounts and the number of rainy days (see also Figure 4.6) and both spatial patterns reveal the N-S gradient of distribution.
Figure 4.4: Annual rainfall cycle for Diourbel (14.65N – 16.23W); a) mean monthly distribution for the period 1971-1998; b) annual cycle of the seasonal rainfall for the same period, expressed as box plots for 12 running 3-months periods. The median is indicated by the black line inside the boxes; the upper and lower limits of each box show the 75%ile and 25%ile amounts (respectively upper and lower quartiles). The vertical lines extending from the top and bottom of boxes indicate the maximum and minimum records of the data set. Extremely high (or low) records which are outside of this range are outliers (indicated by circles in the graph). All stations in the study area exhibit the same profile as Diourbel.
Figure 4.5: Contribution of each month in the seasonal totals (expressed as percentage). Values are averaged over the study period.
Figure 4.6: Scatterplot of seasonal precipitation and number of rainy days. Values are averaged over the JJAS 1971-1998 period.
In August, appears another axis oriented SW-NE, which is associated with a thick monsoon layer and the presence of the C2 zone (non-stormy and continuous rains) in the South-West (Casamance). More than 60% of the seasonal amount of rainfall is recorded in this region during this period.

The contribution of each month in the seasonal rainfall and number of rainy days is shown in Figure 4.5. For most of the stations, August rainfall accounts for more than 35% of the seasonal totals. September, July and June follow respectively. The maps show that August and September are especially critical for the northwestern Senegal, while rainfall in the South is better distributed throughout the season. June’s contribution, although generally weak, is relatively significant in the South-East (e.g. more than 15% in Kedougou).

In the whole, there is a strong agreement between rainfall amounts and the number of rainy days (Figure 4.6).

**4.1.2: Variability**

Average seasonal precipitation maps don’t show the year-to-year fluctuations. Mapping the coefficient of variation for all stations provides a measure of the relative variability of the data according to the mean of the data sets.

For both rainfall and the number of rainy days, June is the month that exhibits the greater variability, especially in the West and North of the country (Figure 4.7). In this sector, from one wet season to another, meteorological conditions can be totally different, depending on the position of the ITCZ and the strength of the Azores high. The latter can block the rain-bearing systems or impose a more meridional trajectory, especially at the beginning of the wet season. However, in some rare years, when favorable conditions
exist, substantial amounts of rainfall can be recorded in June. In other words, June is a relatively dry month in which unusual heavy rainfall may sometimes occur, especially in sub-arid areas such as the northern Senegal. This high interannual variability observed in periods and areas with low mean precipitation is consistent with findings from Conrad (1941) who pointed out an inverse relationship between the mean precipitation and the coefficient of variation: as the mean precipitation increases, the relative variability decreases. August and September, with the highest mean precipitation, exhibit a lower interannual variability. The N-S gradient is omnipresent, particularly with rainfall. When considering the number of rainy days, an E-W component seems to be added to the main gradient.

The seasonal variability map (Figure 4.8) confirms the aforementioned monthly patterns: high rainfall coefficients extend over the North, in contrast with low values in the South: the coefficient of variation increase from less than 10% in the South-East to more than 40% in the North, which exhibits a high variability. The spatial patterns for the number of rainy days are globally similar, with a smaller range.

The higher variability of the drier northern areas is also evident when considering the year-to-year rainfall (Figure 4.9). High frequency fluctuations are observed in the northern stations (e.g. Saint-Louis). In contrast, southern stations (e.g. Kedougou) show less contrasting rainfall amounts from one year to another and a relatively smooth profile.
Figure 4.7: Spatial patterns of variability for rainfall and number of rainy days. Values are coefficients of variation, expressed as percentage, for all stations in the study area. Higher values indicate a greater interannual variability.
Figure 4.8: Seasonal variability (JJAS): a) precipitation; b) number of rainy days. Values are same as in Figure 4.7.
Figure 4.9: Seasonal rainfall distribution for the period from 1971 through 1998: a) Saint-Louis (16.05N – 16.45W); b) Kedougou (12.57N – 12.22W). The addition of a 3-years moving average trend line (red line) highlights the high frequency variability of the northern stations (e.g. Saint-Louis), in contrast with lower frequency fluctuations for the southern stations (e.g. Kedougou).
4.1.3 Trends

As mentioned in the previous chapter, trends of precipitation and number of rainy days are estimated by applying for each station a linear regression analysis and estimating the slope of the regression line, for a 28-years period. Then, interpolation maps are generated from the slope values of all stations in the study area. In addition, the Pettit test is applied for each station to detect the occurrence of change points (statistical breaks) in the series.

The interpolation map of linear slopes for seasonal rainfall (Figure 4.10a) shows a wide SE-NW corridor of negative or weakly positive values. Positive slopes can be found in only two small portions in the North and the Southwest. Figure 4.11 shows two stations representative of the above-mentioned areas, exhibiting opposite trends.

The seasonal trends for the number of rainy days (Figure 4.10b) present more areas with positive slopes, in the coastal zone, the central country and along the river Senegal, but the magnitude is weak. The map presents some similarities with the precipitation map in that negative trends are observed in both the Southeast and Northwest.

Another aspect of the trend analysis is to check whether a change point can be detected in the sequence of observations for each station, thus dividing the time series into two periods. The Pettit test suggests that 18 stations out of 20 experienced a step change in mean precipitation (Figure 4.12 and Table 4.1) in 1989 (4 stations), 1975 (3), 1976 (3) and 1979 (3). The records are split into two periods with different mean precipitation (Table 4.1). The decreasing trend is observed for all stations that experience a change point: the mean of the recent period is lower than that of the first period. Kolda (-173.3 mm) and Tambacounda (-167.7 mm) exhibit greater differences.
Figure 4.10: Spatial patterns of the seasonal rainfall trends (JJAS 1971-1998): a) precipitation; b) number of rainy days. Areas with negative trends are encompassed by a solid yellow line.
Table 4.1: Change point (or statistical break) for meteorological stations according to the Pettit test. For all the stations where the series are segmented into two periods, the mean precipitation decreases from the first to the recent period. For two stations, no shift was detected.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Year of shift</th>
<th>Mean precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before</td>
</tr>
<tr>
<td>Bakel</td>
<td>1975</td>
<td>437.7</td>
</tr>
<tr>
<td>Bambey</td>
<td>1979</td>
<td>448.2</td>
</tr>
<tr>
<td>Dakar</td>
<td>1989</td>
<td>326.9</td>
</tr>
<tr>
<td>Diourbel</td>
<td>1979</td>
<td>479.8</td>
</tr>
<tr>
<td>Fatick</td>
<td>1976</td>
<td>485.7</td>
</tr>
<tr>
<td>Kaolack</td>
<td>1989</td>
<td>516.5</td>
</tr>
<tr>
<td>Kedougou</td>
<td>1970</td>
<td>1067.5</td>
</tr>
<tr>
<td>Kolda</td>
<td>1975</td>
<td>1042.5</td>
</tr>
<tr>
<td>Kougheul</td>
<td>1979</td>
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</tr>
<tr>
<td>Linguere</td>
<td>1976</td>
<td>279.8</td>
</tr>
<tr>
<td>Louga</td>
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<tr>
<td>Matam</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Mbour</td>
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</tr>
<tr>
<td>Nioro</td>
<td>1990</td>
<td>625.1</td>
</tr>
<tr>
<td>Podor</td>
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<tr>
<td>St Louis</td>
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<tr>
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<td>Velingara</td>
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<tr>
<td>Ziguinchor</td>
<td>1976</td>
<td>1132.2</td>
</tr>
</tbody>
</table>

Figure 4.12: Year of shift for each station (if applicable) according to the Pettit test. Most of the shifts occurred in the years 1975 (3 stations), 1976 (3), 1979 (3) and 1989 (4).
The lowest differences are observed in Saint-Louis (-10.9 mm) and Fatick (-12.4 mm). No shift is observed for Podor and Matam which are already known for experiencing positive (but not statistically significant) rainfall trends (Figure 4.10a). In summary, the precipitation patterns are dominated by the omnipresence of a N-S gradient.

### 4.2: Temperatures

#### 4.2.1 Temporal and spatial distribution

The temporal variation of temperatures is related to the seasonal shift. Most of the stations present a profile with two maxima (one in May or June and another in September or October), and two minima (in December or January and in August or September). The secondary minimum in August or September is related to the increased moisture and cloud cover. At the end of the rainy season, the decrease of moisture and the consequent disappearance of cloud cover cause a secondary maximum (Figure 4.13b). However, a few stations along the northern coast (Saint-Louis and Dakar) have a profile characterized by only one maximum in September or October, and one minimum in January or February (Figure 4.13b). The evolution of mean monthly temperatures throughout the year is spatially expressed in Figure 4.15a and b.

The spatial distribution of mean annual temperatures, shown in Figure 4.14, is driven by an opposition between two influences:

- oceanic: temperatures are much lower along the coast than inland because of the cool trade winds and the effects of the cold current of Canaries. An E-W gradient appears clearly in Figure 4.14.
- continental: the highest temperatures are recorded in the Northeast where the NE trade winds (harmattan) blow during 9 months at least. A NE-SW gradient expresses this influence (fig 4.14).

However, during the wet season, another factor becomes determinant in the distribution of temperatures, namely the moisture: in the August – September period, a N-S gradient related to the distribution of humidity is observed, and the coolest values are recorded in the South.
Figure 4.13: Monthly mean temperature profile for the period 1971-1998: a) Dakar (14.73 N, 17.50 W); b) Matam (16.65 N, 13.25W). Units are in °C. The lower panel shows a typical temperature profile in Senegal, with a primary minimum in January and a secondary minimum in August-September; a primary maximum in May-June and a secondary maximum in October, the latter corresponding to the end of the rainy season.
Figure 4.14: Spatial distribution of the mean annual temperature. Units are in °C. The E-W gradient denotes a double influence: (i) maritime (cool NW trade winds and cold maritime current); (ii) continental (dry and warm trade winds called harmattan).
Figure 4.15a: Spatial distribution of mean monthly temperatures. Units are in °C. During the dry season, a decreasing trend is observed with the lowest values recorded in January; the coolest temperatures are observed in the northern coastal areas and the Northwest. Then, from March to May (see Figure 4.15b), contrasts in temperature between the West and East increase, while a heating trend is observed. The highest values are recorded in the East.
4.2.2: Variability

From the mean annual and monthly temperatures for the 1971-1998 period, coefficients of variation for each station were computed and spatially expressed using ArcGIS. The greatest annual variability occurs in the West and North of the country, and the values decrease from NW to SE (Figure 4.16a). Coefficients below 1.6% are observed in the Southeast.

According to Figures 4.16b and 4.17a, the months from January to April are accountable for most of the variability. This is confirmed by Figure 4.13 which shows that the greater ranges between extreme maximum and minimum values for a given station (given by the vertical lines extending in both sides of the boxes) are noticed during this period. During the dry season, takes place the aforementioned opposition between the relatively cool NW trade winds and the dry and warm continental trade winds. From one year to another, the predominance of either flow can vary widely, allowing a great fluctuation around the mean.

For the rest of the year (wet season), a weaker magnitude of variation is observed (Figure 4.17a and b): the predominance of the monsoon flow over the country brings more homogeneity and reduces the amplitude between extreme records.

On the whole, the greatest fluctuations of temperature occur during the dry season, especially in the sub-arid areas of the North and Northwest.
Figure 4.15b: Same as 4.15a, except for May through October. From July to October, the previously observed E-W gradient is replaced by a N-S gradient. The core of rainy season (August-September) corresponds to a relative decrease of temperatures, particularly in the South, which is more humid.
Figure 4.16: Coefficient of variation for the mean temperature: a) spatial patterns for the mean annual temperature (expressed as percentage); b) mean monthly variation for selected stations. Most of the variability is observed in a stripe stretching along the coastal areas and the North. As shown in (b), the northern stations exhibit greater fluctuations; a greater variability is observed during the dry months, especially the January-April period.
Figure 4.17a: Spatial patterns of variability for mean temperatures. Values are coefficients of variation, expressed as percentage, for all stations in the study area.
Figure 4.17b: same as Figure 4.17a, except for July through December.
4.2.3: Trends

As in section 4.1, spatial and temporal trend patterns are analyzed with interpolated linear slopes for all stations. In addition, an index based on the 1971 – 1998 period is computed and an EOF analysis is performed. The resulting spatial patterns and corresponding time series are compared with the linear trend patterns. The analysis is based on monthly and annual mean temperatures. A study based on maximum and minimum temperatures could have allowed a more precise and detailed analysis, but the choice of mean values was imposed by the late availability of data.

During the period 1971-1998, most of the warming trend took place from November to May (Figure 4.18a and b). The warmest temperatures occur in February and, to a lesser extent, May: during these two months, statistically significant trends are observed for most of the stations. The Southeast is the only region that experiences negative slopes throughout the year.

Annual temperature trends are shown in Figure 4.19a. All slopes are positive, with the exception of the Southeast. The highest values are recorded in a region extending from the central North to the Southwest, all across the country. According to the t-test, most of the trends are statistically significant (Figure 4.19a). The annual mean temperature for Kaolack (Figure 4.19b) shows the increasing trend. All stations in the study area, in the exception of Kedougou, exhibit a similar profile.

A comparison of the trends map (Figure 4.18a) with the spatial patterns of the first EOF mode (Figure 4.20a) reveals a striking similarity between the two patterns and confirms the robustness of the linear trend method.
Figure 4.18a: mean monthly temperature trends (1971-1998). Slopes are multiplied by 100. Black dots represent the stations whose trends are significant at the 95% confidence level, using the t-test. Black triangles represent stations with trends that are not significant.
Figure 4.18b: same as in Figure 4.19a, except for July through December.
Figure 4.19: a): mean annual temperature trends relative to the period 1971-1998. Negative values (in the Southeast) are delimited by the white solid line. Yellow dots represent the stations whose trends are significant at the 95% level, using the t-test. Black triangles represent stations with trends that are not significant; b) mean annual temperature for Kaolack (14.13N, -16.07W). A linear regression line is fitted. The warming trend, which is observed in most of the stations in the study area, is obvious.
Figure 4.20: EOF analysis of temperatures for the period 1971-1998: a) EOF1 eigenvector patterns (loadings are multiplied by 10); b) corresponding time series fitted with a linear trend line. The highest values occur in 1998 and 1983, which are also known for being El Niño years.
The time series for the first EOF mode (Figure 4.20b) clearly depicts a warming trend. This tendency appears also in Figure 4.21, which shows a comparison between the normalized temperature anomalies in Senegal (Figure 4.21a) and the global (worldwide) mean temperature relative to the period 1951-1980 (Figure 4.21b). This comparison allows to replace the evolution of temperatures in Senegal in the more global context of the warming trend observed worldwide in the past 30 years, despite high frequency fluctuations. The moving average curve in Figure 4.20a shows two main warming phases over the country for the study period: 1978-1983 and 1995-1998. As demonstrated in a great body of literature, the warming trend is mainly caused by the increase of greenhouse gases in the atmosphere. The largest annual increase of CO$_2$ occurred in 1998 (Hansen et al, 2000), which turned out to be the warmest year (Figure 4.21a and b). Hansen et al (2002) also linked the record warmth of 1998, which was observed throughout the world, with “a strong El Niño that raised global temperature 0.2°C above the trend line”.

Correlations (i) between EOF1 for temperature over Senegal and Pacific SST in the El Niño zones and (ii) between the normalized temperature index for Senegal and the Southern Oscillation Index (SOI) are shown in Table 4.2. There is a significant correlation between EOF1 for Senegal and Pacific SST during the January to April period: the highest values (up to 0.70) are observed in the Niño3 zone (Table 4.2b). For the remainder of the year, values are modest or weak. The normalized temperature index is inversely correlated with SOI during the first months (-0.79 in March) as shown in Table 4.2e.
Figure 4.21: a) Normalized temperature anomalies relative to the period 1971-1998 (Senegal). A 5-years moving average curve is fitted; b) Global mean temperature in degrees Celsius relative to the mean temperature for the period 1951-1980 based on measurements at meteorological stations (the mean for 1951-80 is about 14°C). The vertical lines at several dates indicate the estimated uncertainty in the annual-mean temperature due to the incomplete coverage of stations. The Figure was obtained from the Goddard Institute for Space Studies: (http://www.giss.nasa.gov/research/observe/surftemp/1998.html).
Table 4.2: Correlations between temperature indices over Senegal and Pacific Ocean features: a) between EOF1 (Temp_EOF1) and monthly SST in the Niño1-2 zone (0°-10°S and 90°W-80°W); b) EOF1 and monthly SST in the Niño3 zone (5°N-5°S and 150°W-90°W); c) EOF1 and monthly SST in the Niño4 zone (5°N-5°S and 160°E-150°W); d) EOF1 and monthly SST in the Niño3-4 zone (5°N-5°S and 170°W-120°W); and e) Normalized temperature anomaly for the period 1971-1998 (T_Index) and the Southern Oscillation Index (SOI). SST data were obtained from the Climate Prediction Center (http://www.cpc.noaa.gov/data/indices/). Shaded values are significant at the 95% confidence level, according to the t-test.
In summary, there is an E-W gradient in the distribution of mean temperatures over the country, explained by the opposition between oceanic and continental influences. The Northwest experiences the greatest variability and the coefficient of variation decreases toward the Southeast. Most of the variation takes place from January to April. There is a significant warming trend, in the exception of the Southeast.
5: CLIMATE VARIABILITY OVER SENEGAL

In chapter 2, we reviewed a number of studies assessing the modulation of West African rainfall by Atlantic and global SST. Atmosphere-ocean coupled models and empirical statistical methods were used to analyze SST patterns associated with West African rainfall anomalies, to detect SST signals developing prior to the rainy season, and to find ways of predicting West African rainfall a few months in advance.

The main objective of this chapter is to investigate the relationship between Senegal rainfall and sea surface patterns, in order to better understand how it relates with the global climate and to test its predictability.


In a first step, an EOF analysis is performed with monthly observed precipitation and the number of rainy days covering Senegal and spanning the period 1971-1998. The resulting time series are correlated with reliable indices over West Africa. This step allows to replace Senegal in the wider context of the West African region, and to analyze its behavior with respect to the Sahel-Sudan region. Then the rainfall and number of rainy days time series are correlated with sea surface patterns to investigate the connections with the global climate.

5.1.1 Results of the first EOF analysis (1971 – 1998).

A graphic representation of all EOF modes for precipitation over Senegal is shown in Figure 5.1. Tables 5.1 and 5.2 show the percentage of variance represented by the three leading modes for precipitation and the number of rainy days.
Table 5.1: Variance represented by the three EOF leading modes of observed rainfall over Senegal (1971-1998). Statistically significant EOF modes (according to Kendall’s criterion for distinctly separated EOFs) are in bold.

<table>
<thead>
<tr>
<th>MODE</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>JJAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOF1</td>
<td>47.96</td>
<td>41.02</td>
<td>35.51</td>
<td>36.91</td>
<td>43.3</td>
</tr>
<tr>
<td>EOF2</td>
<td>11.36</td>
<td>11.38</td>
<td>11.79</td>
<td>15.36</td>
<td>8.6</td>
</tr>
<tr>
<td>EOF3</td>
<td>9.27</td>
<td>8.12</td>
<td>8.13</td>
<td>7.94</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Table 5.2: Same as Table 5.1, except for the number of rainy days.

<table>
<thead>
<tr>
<th>MODE</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>JJAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOF1</td>
<td>61.26</td>
<td>57.44</td>
<td>62.61</td>
<td>56.92</td>
<td>64.7</td>
</tr>
<tr>
<td>EOF2</td>
<td>8.23</td>
<td>8.31</td>
<td>7.05</td>
<td>9.94</td>
<td>8.6</td>
</tr>
<tr>
<td>EOF3</td>
<td>6.79</td>
<td>7.27</td>
<td>6.13</td>
<td>6.01</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Figure 5.1: Histogram of EOF modes (eigenvalues) for observed rainfall over Senegal (JJAS 1971-1998).
Neighboring eigenvalues are statistically significant when they are distinctly separated. Kendall (1980) proposed a test based on the following equation:

\[ d^2 = \frac{?}{(2/N)^{1/2}} \]  

where \( d^2 \) is the sampling error, \( ? \) 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. According to Kendall’s test, only the first EOF mode (EOF1) is significant for seasonal rainfall or the number of rainy days (JJAS). However, EOF2 for rainfall in September is significant.

EOF1 loadings are positive over the entire study area (Figure 5.2). Camberlin and Diop (2003) also performed an EOF analysis over Senegal and found this EOF1 monopole pattern, which demonstrates “a relatively uniform behavior of the rains all over Senegal”. Figure 5.2a shows the spatial patterns of EOF1 for precipitation. The regions of largest amplitude are found in the western Senegal, in a coastal stripe extending from the Dakar region to the central Gambia. The lowest magnitudes of EOF1 (less than \( 1^4 \)) are found in two regions separated by a belt of higher loadings: the central South (called Haute Casamance) and the central North (called Ferlo).

The eigenvector patterns found by Camberlin and Diop (2003) present some similitude: largest magnitudes in the West and decreasing values toward the Southeast.

The map of EOF1 eigenvector patterns for the number of rainy days (Figure 5.2b) also shows positive loadings extending over the entire domain.

---

\(^4\) Actually 0.1 (instead of 1): loadings in the map are multiplied by 10.
Figure 5.2: EOF analysis of rainfall and the number of rainy days over Senegal (June, July, August and September 1971-1998): a) spatial patterns of EOF1 for observed rainfall; b) spatial patterns of EOF1 for the number of rainy days; c) corresponding EOF1 time series. For (a) and (b), loadings have been multiplied by 10.
Figure 5.3: EOF2 of observed rainfall over Senegal (1971-1998): a) spatial patterns; b) time series for EOF2. A 5-years-moving average shows the decadal oscillation of this mode (two peaks, in 1978 and 1988).
The highest values are observed in a crescent-like belt running along the coast (in the exception of the Southwest) and the northern River Senegal. The lowest loadings are found in the Southeast. The corresponding time series for rainfall and the number of rainy days (Figure 5.2c) are strongly correlated and both exhibit high frequency fluctuations (1 to 5 years). Most of the negative weakly positive values correspond to El Niño years (e.g. 1972, 1977, 1983, 1991 and 1998).

An EOF analysis has also been performed for individual months of the wet season (June to September). As mentioned earlier, only September rainfall has two significant leading modes. The second EOF mode explains 15.36% of the variance. The EOF2 eigenvector map for this month (Figure 5.3a) reveals a dipole-like pattern, with positive loadings in the South and negative ones in the North. This pattern reflects the north-south gradient, which is a prominent feature of rainfall in Senegal, as seen in chapter 4. The time series associated with this mode oscillates on mainly decadal time scale, as shown by the 5-years moving average trend line, and is dominated by negative anomalies (Figure 5.3b).

5.1.2: Connection of Senegal’s climate with regional and global climate

In this section, the connection of Senegal’s climate with regional and global climate is investigated. EOF1 loadings are compared with other West African indices, and their relationship with sea surfaces features is examined.

5.1.2.1: Correlation between Senegal rainfall and West African rainfall

Tables 5.3 and 5.4 show the coefficients of correlation between EOF1 for Senegal, West African rainfall indices, and the normalized rainfall index for Senegal (JJAS standardized
anomalies for the period 1971-1998). As expected, there is a strong agreement between EOF1 and the normalized index for Senegal (Table 5.3). With respect to Lamb’s rainfall index, there is a good, but not very strong correlation between Senegal and the rest of West Africa, as shown in Figure 5.4. The monthly indices (Table 5.4) show that August and September, which are the two rainiest months, are more correlated with West African rainfall. These results conciliate the homogeneity of rainfall anomalies throughout the Sahel (e.g. Nicholson, 1979) with the differential behavior of the West African Atlantic sector with respect to the continental sector (e.g. Nicholson and Palao, 1993).

<table>
<thead>
<tr>
<th></th>
<th>Ind.pp-Lamb</th>
<th>Ind.pp_Sen</th>
<th>EOF1-pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ind.pp_Sen</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EOF1-pp</td>
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<td>0.98</td>
<td></td>
</tr>
<tr>
<td>EOF1-rd</td>
<td>0.66</td>
<td>0.93</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 5.3: Correlation between Lamb rainfall index and different Senegal indices: EOF1 for precipitation (EOF1-pp), EOF1 for the number of rainy days (EOF1-rd) and Senegal rainfall index (Ind.pp_Sen: normalization period: 1971-1998). All values are significant at the 95% confidence level according to the $t$ test.

<table>
<thead>
<tr>
<th></th>
<th>EOF1-Jun</th>
<th>EOF1-Jul</th>
<th>EOF1_Aug</th>
<th>EOF1_Sep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun J</td>
<td>0.47</td>
<td>-0.14</td>
<td>-0.20</td>
<td>-0.32</td>
</tr>
<tr>
<td>Jul J</td>
<td>-0.16</td>
<td>0.44</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>Aug J</td>
<td>-0.29</td>
<td>0.26</td>
<td>0.66</td>
<td>0.18</td>
</tr>
<tr>
<td>Sep J</td>
<td>-0.12</td>
<td>-0.13</td>
<td>0.22</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 5.4: Correlation between monthly rainfall EOF1 (Senegal) and Sahel rainfall indices based on the rotated principal component analysis of average June through September African rainfall in Janowiak (1988) (obtained from Mitchell (http://tao.atmos.washington.edu/data_sets/sahel/). Shaded values are significant at the 95% confidence level, according to the $t$-test.
5.1.2.2: Correlation between Senegal rainfall and tropical Atlantic SST

Figure 5.4 shows the grid-point correlation between EOF1 for JJAS rainfall in Senegal and Atlantic SST for the same period. The lag 0 correlation doesn’t show significant relationship between the two data sets: in the June-September period, the highest positive correlation occurs in the North Atlantic between 5°N and 11°N (Figure 5.5a), and doesn’t exceed 0.40 (16% of the variance). Correlation coefficients for July and August range from 0.35 along the northern coast of America to -0.45 along the southern coast (Figure 5.5b and c). The most significant feature is the negative correlation (up to -0.55) observed off the Senegal and Mauritania coasts in September (Figure 5.5d).
To investigate the possibility of a predictability of Senegal rainfall based on Atlantic SST, a lag correlation is performed between EOF1 of the seasonal rainfall over Senegal (JJAS) and tropical Atlantic SST for the 6 months which precede the summer rainfall season. From January to April (Figure 5.6 a-d)), correlation coefficients range from 0.30 (along the South American coast in March) to -0.40 (off the South American coast, between latitudes 25°S and 30°S). The values slightly increase in the aforementioned area in May (Figure 5.6 e), ranging from 0.40 to -0.50. The highest values occur in June (Figure 5.6f): a dipole-like pattern exists along the South American coast, opposing the northern sector between 10°N and 5°S (up to 0.50 representing 25% of the variance) and the southern sector between 20S and 30S (up to -0.55). As regard to the northern sector of the South American coast, similar patterns were found by Camberlin and Diop (1999). Based on the grid-point correlation results, the probability of predicting Senegal rainfall from the tropical Atlantic SST is not strong. The best possibilities are found along the South American coast in June (0.50 to -0.55) and, to a lesser extent, in May. These results are relatively close to the values obtained by Lough (1986) who performed a correlation between the Sahel rainfall index (from Nicholson, 1979) and his Atlantic SST EOF2 mode: his highest correlation coefficient (0.58) occurred in the AMJ (April, May and June) period.

To further investigate the relationship between Atlantic SST and Senegal rainfall, the leading EOF modes of rainfall and the number of rainy days are correlated with another SST data set in which the Atlantic Ocean is split into two parts: the North Atlantic (5°N-20°N; 60°W-30°W) and the South Atlantic (0°-20°S; 30°W-10°E).
Figure 5.5a: Grid-point correlation map between Atlantic SST (30°N-30°S) and EOF1 of June rainfall over Senegal (1971-1998).
Figure 5.5: Grid-point correlation map between Atlantic SST (30°N-30°S) and EOF1 of rainfall over Senegal (1971-1998): b) July; c) August.
Figure 5.5d: Grid-point correlation map between Atlantic SST (30°N-30°S) and EOF1 of September rainfall over Senegal (1971-1998). Absolute values equal to or greater than 0.36 are significant at the 95% confidence level, according to the t-test.
Figure 5.6: Lag-correlation map between Atlantic SST and EOF1 of seasonal rainfall (JJAS) over Senegal (1971-1998): a) January; b) February
Figure 5.6: Same as figure 5.6a and b, except for c) March; d) April.
Figure 5.6e: Same as figure 5.6a and b, except for e) May.
Figure 5.6f: Same as figure 5.6a and b, except for f) June.
The results, shown in Tables 5.5 and 5.6, don’t suggest any significant correlation, but reveal that despite the weak coefficients, May and June present the highest values, as observed with the grid-point correlation. In addition, there is an inverse relationship of the two SST fields with Senegal rainfall: negative coefficients for the North Atlantic, positive coefficients for the South Atlantic. The latter (positive correlation) means that an increase of South Atlantic SST corresponds to positive anomalies for Senegal rainfall. This relationship is the opposite of what is usually observed in many studies: warm SST in the southeastern tropical Atlantic are associated with reduced rainfall in the Sahel (e.g. Lamb, 1978a and 1978b; Lough, 1986; Philander (1986). This further confirms the difference between the Atlantic Sahel and the continental Sahel.

<table>
<thead>
<tr>
<th></th>
<th>SST_jan</th>
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<th>SST_mar</th>
<th>SST_apr</th>
<th>SST_may</th>
<th>SST_jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jjaspp1</td>
<td>-0.03</td>
<td>-0.15</td>
<td>-0.17</td>
<td>-0.19</td>
<td>-0.26</td>
<td>-0.22</td>
</tr>
<tr>
<td>Jjasrd1</td>
<td>-0.07</td>
<td>-0.16</td>
<td>-0.19</td>
<td>-0.20</td>
<td>-0.23</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

Table 5.5: Correlation between the tropical North Atlantic SST (5°N-20°N; 60°W-30°W) and EOF1 (seasonal rainfall: Jjaspp1; number of rainy days: Jjasrd1) over Senegal. The correlation is lagged to detect a possible predictability, but the variables are not correlated.

<table>
<thead>
<tr>
<th></th>
<th>SST_jan</th>
<th>SST_feb</th>
<th>SST_mar</th>
<th>SST_apr</th>
<th>SST_may</th>
<th>SST_jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jjaspp1</td>
<td>0.15</td>
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<td>0.27</td>
</tr>
<tr>
<td>Jjasrd1</td>
<td>0.22</td>
<td>0.10</td>
<td>0.25</td>
<td>0.20</td>
<td>0.33</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 5.6: Same as Table 5.5, except for the tropical South Atlantic (0°-20°S; 30°W-10°E).

We also correlate EOF1 and EOF2 for September rainfall with North Atlantic and South Atlantic SST. Let’s recall that the second EOF mode for September is significant according to Kendall’s criterion. The results, displayed in Tables 5.7 and 5.8, show that (i)
there is no relationship between EOF1 and either North or South Atlantic SST; (ii) EOF2 is not correlated with the South Atlantic SST; (iii) there is a good correlation between EOF2 and the North Atlantic SST, especially during the months which precede the rainy season. Consequently, North Atlantic SST may provide useful hints for the prediction of rainfall over Senegal in September.

<table>
<thead>
<tr>
<th></th>
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<th>feb</th>
<th>mar</th>
<th>apr</th>
<th>may</th>
<th>jun</th>
<th>jul</th>
<th>aug</th>
<th>sep</th>
<th>oct</th>
<th>nov</th>
<th>dec</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SEP 1</strong></td>
<td>-0.03</td>
<td>-0.07</td>
<td>-0.06</td>
<td>-0.09</td>
<td>-0.13</td>
<td>-0.14</td>
<td>-0.11</td>
<td>0.00</td>
<td>0.05</td>
<td>0.12</td>
<td>0.08</td>
<td>-0.11</td>
</tr>
<tr>
<td><strong>SEP 2</strong></td>
<td>-0.36</td>
<td>-0.54</td>
<td>-0.59</td>
<td>-0.66</td>
<td>-0.64</td>
<td>-0.61</td>
<td>-0.52</td>
<td>-0.48</td>
<td>-0.54</td>
<td>-0.47</td>
<td>-0.50</td>
<td>-0.36</td>
</tr>
</tbody>
</table>

Table 5.7: Correlation between EOF1, EOF2 for September rainfall (respectively SEP_1 and SEP_2) and North Atlantic SST (5°N-20°N; 60°W-30°W). Shaded values are significant at the 95% confidence level, according to the \( t \)-test.

<table>
<thead>
<tr>
<th></th>
<th>jan</th>
<th>feb</th>
<th>mar</th>
<th>apr</th>
<th>may</th>
<th>jun</th>
<th>jul</th>
<th>aug</th>
<th>sep</th>
<th>oct</th>
<th>nov</th>
<th>dec</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SEP 1</strong></td>
<td>-0.10</td>
<td>-0.01</td>
<td>0.09</td>
<td>0.02</td>
<td>0.17</td>
<td>0.18</td>
<td>0.07</td>
<td>0.10</td>
<td>-0.11</td>
<td>-0.13</td>
<td>-0.12</td>
<td>-0.19</td>
</tr>
<tr>
<td><strong>SEP 2</strong></td>
<td>-0.05</td>
<td>-0.12</td>
<td>-0.14</td>
<td>-0.12</td>
<td>-0.08</td>
<td>-0.15</td>
<td>-0.29</td>
<td>-0.10</td>
<td>-0.19</td>
<td>-0.26</td>
<td>-0.26</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

Table 5.8: Correlation between EOF1, EOF2 for September rainfall (respectively SEP_1 and SEP_2) and South Atlantic SST (0°-20°S; 30°W-10°E). Shaded values are significant at the 95% confidence level, according to the \( t \)-test.

5.1.2.3: Lag correlation between Senegal rainfall and tropical Pacific SST

As demonstrated in the literature review, many investigators privilege the relationship between global (worldwide) SST and West African rainfall, but for some of them, the latter is much more related to tropical Pacific SST (e.g. Palmer et al, 0992).

A lag correlation between the first EOF mode of precipitation over Senegal and the tropical Pacific SST shows that during the months which precede the Senegal wet season (January through June), correlation coefficients range from 0.55 to -0.60 (Figure 5.7a). From January to March, the area of significant positive correlation (more than 0.50) is located in the
central North Pacific (23°N-30°N; 170°E-180°E). During the April-June period, it extends southward (up to latitude 14°N). Positive correlations are also found in the South pacific (20°S-30°S). Significant negative correlation (up to 0.60) can be found east of the 120°W, between 15°S and 25°S during the January-February period. Then this area of negative values shifts northward and extends in the central Pacific around the Equator, from April to June (Figure 5.7b).

From January to August, a wide zone of negative correlations has persisted in the eastern Pacific Ocean all along the American coast, and the central pacific around the Equator.

To have a closer look at this correlation, an EOF analysis is performed on SST in an El Niño zone along the Equator (5°N-5°S; 160°E-150°W), and its EOF1 time series is compared with that of EOF1 JJAS rainfall for Senegal. The result (Figure 5.8) confirms the negative correlation: high SST in the El Niño zone tends to correspond with negative rainfall anomalies in Senegal. Departures from the mean rainfall (1971-1998) for some El Niño years are shown in figure 5.9. For the three examples, negative departures extend throughout the country. The southwestern Senegal, which records the heaviest deficits, is most affected during El Niño years.

On the whole, tropical Pacific SSTs are more significantly correlated with Senegal rainfall and offer a greater probability of prediction than the tropical Atlantic SST.
Figure 5.7a: Grid-point correlation (lag) between Pacific SST (January) and EOF1 of seasonal rainfall (JJAS) over Senegal (1971-1998). Absolute values equal to or greater than 0.37 are significant at the 95% confidence level, according to the $t$-test.
Figure 5.7b: Grid-point correlation (lag) between Pacific SST (May) and EOF1 of seasonal rainfall (JJAS) over Senegal (1971-1998).
Figure 5.8: Time series of SST EOF1 for El Niño zone 4 (5°N-5°S; 160°E-150°W) and EOF1 for rainfall in Senegal (JJAS).
Figure 5.9: Deviation from the mean rainfall (1971-1998): a) 1972; b) 1977; c) 1982.
However, the very limited areas of significant correlation and the absence of very strong coefficients prompted additional analyses. The relationships of the leading EOF modes for rainfall in Senegal with SOI and NAO are examined.

The lag 0 correlation for the rainy season months (Tables 5.9a and 5.10a) shows that July is better correlated with SOI and NAO, but there is no strong relationship. A lag correlation with the months prior to the wet season (Tables 5.9b and 5.10b) also yields relatively weak values.

So far, even though some interesting results have been obtained, the significant values are modest and locally limited, compared to the coefficient obtained in some studies: Semazzi et al (1988) found strong coefficients by correlating the global SST leading EOF modes with the Nicholson Sahel and Sudan rainfall index (more than 0.80 over the central equatorial Pacific). To verify the robustness of our results and further investigate the climate variability and predictability in Senegal, a second analysis is performed with additional CMAP rainfall data.
### Table 5.9: Correlation between SOI (the Southern Oscillation Index) and rainfall EOF leading modes for Senegal: a) lag 0 correlation; b) lag-correlation. Shaded values are significant at the 95% confidence level, according to the \( t \)-test.

<table>
<thead>
<tr>
<th></th>
<th>Jun_EOF1</th>
<th>Jul_EOF1</th>
<th>Aug_EOF1</th>
<th>Sep_EOF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun_SOI</td>
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<tr>
<td>Jul_SOI</td>
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<td>Aug_SOI</td>
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</tr>
<tr>
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<td>0.46</td>
<td>0.13</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>soi-jan</th>
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</thead>
<tbody>
<tr>
<td>Sen_eof1_pp</td>
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<td>0.39</td>
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<td>0.38</td>
</tr>
<tr>
<td>Sen_eof1_rd</td>
<td>0.23</td>
<td>0.14</td>
<td>0.40</td>
<td>0.34</td>
<td>0.39</td>
<td>0.31</td>
</tr>
</tbody>
</table>

### Table 5.10: Correlation between NAO (North Atlantic Oscillation) and rainfall EOF leading modes for Senegal: a) lag 0 correlation; b) lag-correlation (EOF1_JJAS-p: EOF1 of seasonal precipitation in Senegal; EOF1_JJAS-rd: EOF1 of the seasonal number of rainy days). Shaded values are significant at the 95% confidence level, according to the \( t \)-test.

<table>
<thead>
<tr>
<th></th>
<th>NAO_Jun</th>
<th>NAO_Jul</th>
<th>NAO_Aug</th>
<th>NAO_Sep</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOF1_Jun</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOF1_Jul</td>
<td>-0.15</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOF1_Aug</td>
<td>-0.09</td>
<td>0.06</td>
<td>-0.06</td>
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<tr>
<td>EOF1_Sep</td>
<td>-0.31</td>
<td>-0.34</td>
<td>-0.24</td>
<td>-0.21</td>
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</tbody>
</table>

<table>
<thead>
<tr>
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<th>NAO-Jan</th>
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<th>NAO-Mar</th>
<th>NAO-Apr</th>
<th>NAO-May</th>
<th>NAO-Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOF1_JJAS-p</td>
<td>0.20</td>
<td>-0.10</td>
<td>0.03</td>
<td>-0.16</td>
<td>-0.05</td>
<td>-0.20</td>
</tr>
<tr>
<td>EOF1_JJAS-rd</td>
<td>0.25</td>
<td>-0.03</td>
<td>0.17</td>
<td>-0.14</td>
<td>-0.04</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

For the second analysis, CMAP data is used in addition to the observed precipitation and the number of rainy days, and the analysis is extended to West Africa. The study period (1979-1998) is determined based on the data availability (the CMAP rainfall starts in 1979 and the rain-gauge data ends in 1998).

5.2.1: CMAP rainfall climatology over Senegal

Prior to the EOF analysis, the comparison between the observed precipitation and the CMAP climatology constitutes a first test to assess the suitability of the CMAP data for investigating Senegal’s climatology. The CMAP climatology over Senegal for the rainy season (JJAS) is displayed in Figure 5.10b. There is a good agreement with the rain-gauge climatology shown in Figure 5.10a.

The north-south gradient of rainfall distribution is well picked by CMAP. Some minor differences are observed: the CMAP rainfall generates slightly wetter conditions in the northern Senegal and in some parts in the South, while the extreme Southwest is wetter according to the rain-gauge climatology. But in the whole, there is a good agreement with respect to the amounts.

5.2.2: Results of the second EOF analysis (1979 – 1998).

As for the previous analysis, only the first EOF modes are significant according to Kendall’s criterion for distinctly separated EOFs (Table 5.11). Figure 5.12 displays the spatial patterns for the leading EOFs.
Figure 5.10: Mean seasonal precipitation (1979-1998): a) observed; b) CMAP
Table 5.11: Variance represented by the three EOF leading modes of observed and CMAP rainfall over Senegal and West Africa (1979-1998). Statistically significant EOF modes (according to Kendall's criterion for distinctly separated EOFs) are in bold. CMAP-Sen = CMAP rainfall over Senegal; CMAP-WA = CMAP rainfall over West Africa.

<table>
<thead>
<tr>
<th>MODE</th>
<th>Obs. Precip</th>
<th>Obs. RD</th>
<th>CMAP-Sen</th>
<th>CMAP-WA</th>
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</thead>
<tbody>
<tr>
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<td>37.2</td>
<td>52.98</td>
<td>43.30</td>
<td>49.87</td>
</tr>
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<td>EOF3</td>
<td>9.4</td>
<td>7.93</td>
<td>10.95</td>
<td>11.92</td>
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</table>

Figure 5.11: EOF analysis of rainfall over Senegal. Histograms of EOF modes (eigenvalues): a) observed precipitation; b) observed number of rainy days; c) CMAP rainfall; d) grid-points used to perform CMAP EOF analysis over Senegal.
Figure 5.12: Spatial patterns of EOF1 for JJAS (1979 – 1998): a) Observed precipitations; b) Observed number of rainy days; c) CMAP rainfall. In a, negative values are encompassed by a solid white line. Loadings are multiplied by 10.
EOF1 maps for observed rainfall and the number of rainy days are very similar to those of the 28-years analysis: the largest magnitudes are found in the western country and the loadings decrease toward the Southeast (Figure 5.12a and b). However, the range of values of the 20-years analysis is greater, and negative loadings are observed in the Southern Senegal (Figure 5.12a).

Figure 5.11c shows the grid-points that have been used for the CMAP EOF analysis over Senegal. The spatial patterns for CMAP EOF1 mode, displayed in Figure 5.12c, generally agree with the observed rainfall EOF map, with largest loadings in the West and a decrease of values toward the Southwest. However, differences between the two patterns are observed in the northern Senegal, where EOF1 for the observed rainfall has much lower loadings than EOF1 for CMAP. High loadings for both observed and CMAP rainfall are shown in a combination of EOF1 maps using Map Algebra in ArcGIS Spatial Analyst to overlay the maps (Figure 5.13). High loadings extend along the coast and the River Senegal, in a crescent-like pattern. The striking similitude of the two maps (observed rainfall/number of rainy days and observed rainfall/CMAP rainfall) shows a good agreement between the datasets. The corresponding EOF1 time series (Figure 5.14) suggest interannual fluctuations combined with a background time scale of 6 to 7 years. As for the previous EOF analysis, most of the negative values correspond to El Niño years (e.g. 1983, 1991, 1997-1998).

The time series show the agreement between observed rainfall and CMAP rainfall: from 1979 to 1998, only one mismatch is observed, and the series are well correlated, as shown in Table 5.12. Scatterplots in Figure 5.15 confirm this agreement.
Figure 5.13: Higher loadings: a) areas where loadings are greater than 2 for both observed rainfall and the number of rainy days; b) areas where loadings are greater than 2 for both observed rainfall and CMAP rainfall. The similitude of the two maps shows the good agreement between observed and CMAP rainfall.
<table>
<thead>
<tr>
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<th>Obs_pp</th>
<th>Obs_rd</th>
<th>CMAP-Sen</th>
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</thead>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>Obs_rd</td>
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<td>1</td>
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<tr>
<td>CMAP-Sen</td>
<td>0.74</td>
<td>0.71</td>
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</table>

Table 5.12: Cross-correlation of the different EOF1 modes: Obs – pp: observed precipitation; Obs_rd: observed number of rainy days; CMAP-Sen: CMAP rainfall over Senegal. All values are significant at the 95% confidence level according to the t test.

Figure 5.14: Time series: pp1obs: EOF1 for observed precipitation; rd1: EOF1 for the number of rainy days; pp1cm: EOF1 for CMAP rainfall.
Figure 5.15: Scatterplots of the first EOF mode over Senegal: a) observed precipitation and CMAP rainfall; b) Number of rainy days and CMAP rainfall.
To examine how Senegal relates with the rest of West Africa, an EOF analysis of CMAP rainfall is performed over the region. The five leading modes are significant according to Kendall’s criterion. However, in this study, we only examine the first three EOF modes because the two others express relatively low variance. 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 5.16a). The two zones are separated around the 10°N by a winding limit. The band of positive loadings extends all across West Africa, but can be divided into two domains with high loadings east of the 6°W, and low loadings west of the 6°W. This pattern is consistent with the first eigenvector pattern for August and September produced by Nicholson and Palao (1993): their results show positive anomalies throughout the Sahel-Sudan and negative anomalies in the Guinea Coast. EOF1 for West Africa also agrees with the spatial patterns produced by the Principal Component Analysis adapted by Camberlin and Diop (1999) from Moron (1994): the authors show “the evidence of a slightly distinct variability in the “western” and “continental” parts of the Sahel”. The time series associated with EOF1 (Figure 5.16b) exhibits a relatively low-frequency variability (about 8 years), an increasing trend and marked negative amplitudes during the 1982-1984 period (1982-1983 was a strong El Niño event). The time series of Nicholson and Palao (1993) also exhibits a low-frequency variability (time-scales longer than 7 years).

EOF2 (15.66% of the total variance) exhibits a band of positive loadings across the Sahel-Sudan and along the Atlantic coast (Figure 5.17a). This band is surrounded by two zones of negative values in the north and south.
Figure 5.16: EOF1 for CMAP rainfall over West Africa: a) spatial patterns; b) corresponding time series.
Figure 5.17: Same as figure 5.13, except for EOF2.
Figure 5.18: Same as figure 5.13, except for EOF3.
The dipole pattern is effective, and the negative loadings in the southern West Africa are opposed to two positive centers, in the eastern part of the region (10°N-11°N; around 8E), and in the northwestern Sahel (18°N-20°N; 12°W-14°W). Again, this pattern is similar to the “Mode 2” of Nicholson and Palao (1993), “which shows uniform anomalies throughout the Sahel but an opposition between the Sahel and Guinea Coast”. In our EOF2 spatial scheme, Senegal is well integrated to rest of the Sahel-Sudan zone. The corresponding time series shows relatively low frequency variability, with time-scales of about 7 years (Figure 5.17b). The negative or near 0 amplitudes 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 entire region, while the largest amplitude occurred in 1988-1989, which are referred to as La Niña years. In the late 1990s, there is decreasing tendency of the amplitudes.

The third EOF represents 11.92% of the variance. Figure 5.18a shows its spatial eigenvector pattern. Negative or weakly positive amplitudes are observed throughout the entire West African domain. The lowest amplitudes are found south of the 13°N. EOF3 time series is dominated by low-frequency variability, in the exception of the period from 1987 to 1994, which is characterized by high frequency fluctuations (Figure 5.18b). Amplitudes are negative or near 0 from 1979 to 1989, and the lowest value occurred in 1980. Then the amplitudes increase sharply despite interannual variability and peak in 1992. The increasing trend of this time series is very strong, but the last two years (1997-1998) suggest the beginning of a decreasing trend.
5.2.3: Relationships between Senegal, West Africa and sea surface features

Relationships are assessed by using correlations between the different modes of the second analysis (1979-1998), Lamb rainfall index, NCEP wind analysis, and sea surface data. The objective is to further investigate the mechanisms that drive the climate of Senegal, with respect to the global climate.

5.2.3.1: Relationship between Senegal and the rest of West Africa.

The leading modes of CMAP rainfall for West Africa are first compared to Lamb’s rainfall index, which constitutes a well-known reference and describes the variability for the Sahel-Sudan region. EOF1 for West African rainfall is strongly correlated with Lamb’s index (table 5.13). This agreement confirms well known results of the first EOF of West Africa: this mode is representative of the average variability rainfall over the region. The good agreement between the two time series (Figure 5.19a and b) constitutes another proof of the robustness of CMAP data over West Africa.

Table 5.14 shows the cross-correlation between the three leading modes of CMAP rainfall over West Africa and first EOF modes over Senegal. EOF1 over Senegal (precipitation, number of rainy days and CMAP) is not correlated with EOF1 over West Africa, but shows a good relationship with EOF2. In the previous section, we pointed out that with EOF2 for West Africa, Senegal is well integrated in the Sahel-Sudan spatial patterns (Figure 5.16a). A further confirmation is provided by the comparison between corresponding time series (Figure 5.20), which shows very few mismatches. The second mode for West Africa, which is traditionally neglected in the studies of variability over the region, is the one that is important in explaining the variability of rainfall over Senegal.
Table 5.13: correlation between leading EOF modes for West Africa and Lamb rainfall index.

<table>
<thead>
<tr>
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<th>EOF1-WA</th>
<th>EOF2-WA</th>
<th>EOF3-WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMB-Index</td>
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<td>0.19</td>
<td>0.09</td>
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</table>

Figure 5.19: Comparison between EOF1 for CMAP rainfall over West Africa (JJAS 1979-1998) and Lamb’s West African rainfall index (normalization period: April-October 1941-2000): a) time series; b) scatterplot of time series;
Table 5.14: Cross-correlation between the three EOF leading modes for CMAP over West Africa and EOF1 over Senegal (cmapsen: CMAP rainfall; obsppsen: observed precipitation; obsrdsen: observed number of rainy days). Shaded values are significant at the 95% confidence level, according to the *t*-test.

<table>
<thead>
<tr>
<th></th>
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<th>EOF2 WA</th>
<th>EOF3 WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>cmapsen1</td>
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<td>0.62</td>
<td>-0.01</td>
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<tr>
<td>obsrdsen1</td>
<td>0.38</td>
<td>0.63</td>
<td>0.00</td>
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</table>

Figure 5.20: 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.
These observations about EOF1 and EOF2 are supported by the wind anomaly patterns. More specifically, we find that the component of the wind circulation that is associated with EOF1 for West Africa (Figure 5.21a) doesn’t show any significant circulation in the vicinity of Senegal, but rather appears to be more related to the nature of the West African monsoon regime (southwesterly flow over Senegal and convergence related to the ITCZ north of the country). In contrast, EOF2 for West Africa, which is poorly correlated with Lamb index but important for Senegal, is associated with a strong coupling between the circulation over the tropical Atlantic and eastern tropical Pacific (Figure 5.22b). This pattern is consistent with La Niña conditions (negative phase of ENSO): convergence over the eastern Pacific Ocean and convergence over the maritime continent (Indonesia). The circulation pattern shown in Figure 5.22a is associated with positive anomalies over Senegal (Figure 5.17a). In addition, in time series for EOF1 over Senegal and EOF2 over West Africa (Figure 5.20), the peaks generally correspond to La Niña years (e.g. 1988). In contrast, this circulation is characterized by an outflow along the Guinea Coast region. We hypothesize that this situation causes a reduction in the monsoonal flow, which explains the negative anomalies observed in the region (Figure 5.17a).

5.2.3.2: Relationships with sea surface temperatures

The leading EOF modes for Senegal and the West African region are correlated with sea surface temperatures.

Tables 5.15 and 5.16 show the correlation between leading EOF modes and SST over the North Atlantic (5°N-20°N; 60°W-30°W) and the South Atlantic (0°-20°S; 30°W-10°E).
Figure 5.21: Projection of NCEP 850 mb winds on to CMAP EOFI for West Africa: a) West African region; b) Global.
Figure 5.22: Same as figure 5.21, except for CMAP EOF2.
<table>
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<tr>
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<th>mar</th>
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<td>-0.15</td>
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<tr>
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<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
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<td>-0.31</td>
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<td>-0.33</td>
<td>-0.16</td>
<td>0.06</td>
<td>0.12</td>
<td>0.01</td>
<td>0.09</td>
<td>0.05</td>
<td>0.00</td>
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<tr>
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<td>0.09</td>
<td>0.11</td>
<td>0.09</td>
<td>0.23</td>
<td>0.27</td>
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<td>0.25</td>
<td>0.24</td>
<td>0.12</td>
</tr>
<tr>
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<td>-0.26</td>
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<td>0.19</td>
<td>0.28</td>
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<td>0.26</td>
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<tr>
<td><strong>WA3</strong></td>
<td>0.16</td>
<td>0.08</td>
<td>0.02</td>
<td>0.09</td>
<td>0.07</td>
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<td>0.10</td>
<td>0.08</td>
<td>0.19</td>
<td>0.30</td>
<td>0.16</td>
<td>0.07</td>
</tr>
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</table>

Table 5.15: Cross correlation between North Atlantic monthly mean SST (5°N-20°N; 60°W-30°W) and EOF leading time series over Senegal and West Africa (period: 1979-1998); *pp*, *rd* and *cm* are respectively precipitation, number of rainy days and CMAP rainfall over Senegal. *WA1*, *WA2* and *WA3* are the three leading EOF modes for CMAP rainfall over West Africa. Shaded values are significant at the 95% confidence level, according to the *t*-test.

<table>
<thead>
<tr>
<th></th>
<th>jan</th>
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<tr>
<td><strong>EOF1-pp</strong></td>
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<td>0.32</td>
<td>0.37</td>
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<td>-0.36</td>
<td>-0.24</td>
<td>-0.17</td>
<td>-0.25</td>
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<td>-0.34</td>
<td>-0.20</td>
<td>-0.08</td>
<td>-0.17</td>
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<td>0.57</td>
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<td>0.55</td>
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</tr>
<tr>
<td><strong>WA1</strong></td>
<td>0.27</td>
<td>0.02</td>
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<td>0.25</td>
<td>-0.08</td>
<td>0.06</td>
<td>0.04</td>
<td>-0.14</td>
<td>-0.26</td>
<td>-0.17</td>
<td>-0.36</td>
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<tr>
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<td>0.43</td>
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<td>0.57</td>
<td>0.56</td>
<td>0.39</td>
<td>0.36</td>
<td>0.16</td>
<td>0.08</td>
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<tr>
<td><strong>WA3</strong></td>
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<td>0.16</td>
<td>0.03</td>
<td>-0.07</td>
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<td>-0.29</td>
<td>-0.15</td>
<td>0.00</td>
<td>0.22</td>
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</table>

Table 5.16: Same as Table 5.15, except for South Atlantic SST (0°-20°S; 30°W-10°E).
As for the first analysis (1971-1998), there is no relationship between the EOF modes and SST over the North Atlantic (Table 5.15). But the correlation of the same EOF modes with the South Atlantic yields more significant results: EOF1 time series for 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) and don’t consequently allow any predictability. However, significant coefficients are also observed during the pre-wet season (January through May). CMAP rainfall over Senegal may offer some predictability for the rainy season. These results are different from those obtained in the previous analysis, which didn’t show any significative relationship between the two datasets.

Correlations with the Pacific SST also provide interesting results. In Figure 5.23, we show the monthly stratified correlations between the leading EOF time series for Senegal and Pacific SST in a portion of the El Niño zone 5°N-5°S; 150°W-90°W). The greatest coefficients (up to -0.72) are observed during the April-July period, which can provide hints for the coming rainy season. Other sectors of the El Niño zone (0-10°S; 90°W-80°W and 5°N-5°S; 170°-120°W) not shown here also present good possibilities for predicting Senegal rainfall from the Pacific Ocean from the April-June period (values ranging from 0.55 to 0.65).

The different results obtained in the two analyses suggest an evolution in the relationship between SST fields and Senegal or West African rainfall. Janicot et al (1996) suggested periods of weak and strong associations.
Figure 5.23: Monthly stratified correlations of Pacific SST over the El Niño zone (5°N-5°S; 150°W-90°W) and EOF1 time series over Senegal, for the period 1979-1998: pp1obs: observed precipitation; rd1: number of rainy days; pp1cm: CMAP precipitation. Values are in reverse order. Above the dashed green line, values are significant at the 95% confidence level.
To investigate this possibility, we split the datasets into two decades (1979-1988 and 1989-1998), and we perform correlations for each period. The results are displayed in Tables 5.17 and 5.18 and in Figure 5.24. The relationships between the South Atlantic and Senegal or West Africa were stronger in the 1979-1988-period, especially for CMAP rainfall over Senegal and West Africa (correlation coefficient up to 0.88). The same trend exists in the Pacific Ocean (El Niño zone), as shown in Figure 5.24: the monthly correlations between SST in this zone and EOF1 time series for the observed precipitation over Senegal were stronger during the first period, in the exception of the October-December period. Understanding the mechanisms that generate this variation would be an important step in understanding the teleconnections between remote oceans fields and West African rainfall. Janicot et al (1996) suggest subsiding motions over West Africa related to circulation anomalies.

However, even though these results seem interesting and the highest correlation coefficients passed the \( t \) test, one should keep in mind that the 10-years period is too short to draw valid conclusions.

To investigate further the association between EOF1 for Senegal and EOF2 for West Africa, we performed a grid-point correlation between Atlantic SST and the time series of EOF2 West Africa. The lag-correlation doesn’t show strong relationship. The best possibilities occur in January and March (not shown), but are relatively limited. In contrast there is a strong relationship from June to September: high values (up to 0.80) occur between 5°N and 10°S in June-July, and extend northward up to 20°N in August (Figure 5.25). EOF2 for West Africa is strongly driven by Atlantic SST.
<table>
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<td>0.20</td>
<td>0.39</td>
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<td>0.51</td>
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<td>0.76*</td>
<td>0.86</td>
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<td>0.39</td>
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<td>-0.07</td>
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<td>-0.58</td>
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<td>0.48</td>
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<td>-0.14</td>
<td>0.07</td>
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</tbody>
</table>

Table 5.17: Cross correlation between South Atlantic monthly mean SST (0°-20°S; 30°W-10°E) and EOF leading modes over Senegal and West Africa (period: 1979-1988); pp, rd and cm are respectively precipitation, number of rainy days and CMAP rainfall over Senegal. WA1, WA2 and WA3 are the three leading EOF modes for CMAP rainfall over West Africa. Shaded values are significant at the 95% confidence level, according to the t-test.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EOF1-pp</strong></td>
<td>0.47</td>
<td>0.38</td>
<td>0.43</td>
<td>0.37</td>
<td>0.31</td>
<td>0.59</td>
<td>0.34</td>
<td>0.54</td>
<td>0.52</td>
<td>0.39</td>
<td>0.31</td>
<td>-0.04</td>
</tr>
<tr>
<td><strong>EOF1-rd</strong></td>
<td>-0.45</td>
<td>-0.30</td>
<td>-0.22</td>
<td>-0.13</td>
<td>-0.17</td>
<td>0.26</td>
<td>-0.35</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.12</td>
<td>-0.28</td>
<td>-0.20</td>
</tr>
<tr>
<td><strong>EOF1-cm</strong></td>
<td>0.58</td>
<td>0.45</td>
<td>0.50</td>
<td>0.44</td>
<td>0.41</td>
<td>0.50</td>
<td>0.38</td>
<td>0.57</td>
<td>0.48</td>
<td>0.34</td>
<td>0.30</td>
<td>-0.06</td>
</tr>
<tr>
<td><strong>WA1</strong></td>
<td>0.69</td>
<td>0.36</td>
<td>0.28</td>
<td>0.20</td>
<td>0.26</td>
<td>-0.14</td>
<td>0.08</td>
<td>0.15</td>
<td>-0.12</td>
<td>-0.28</td>
<td>-0.06</td>
<td>-0.26</td>
</tr>
<tr>
<td><strong>WA2</strong></td>
<td>-0.01</td>
<td>0.28</td>
<td>0.41</td>
<td>0.44</td>
<td>0.41</td>
<td>0.45</td>
<td>0.36</td>
<td>0.43</td>
<td>0.27</td>
<td>0.16</td>
<td>-0.17</td>
<td>-0.22</td>
</tr>
<tr>
<td><strong>WA3</strong></td>
<td>-0.38</td>
<td>-0.17</td>
<td>-0.24</td>
<td>-0.28</td>
<td>-0.42</td>
<td>-0.25</td>
<td>-0.30</td>
<td>-0.46</td>
<td>-0.29</td>
<td>-0.19</td>
<td>0.05</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 5.18: Same as Table 5.17, except for period: 1989-1998
Figure 5.24: Monthly stratified correlations of Pacific SST over the El Niño zone (5°N-5°S; 150°W-90°W) and EOF1 time series over Senegal, for the periods 1979-1988 and 1989-1998: pp1obs: observed precipitation; rd1: number of rainy days; pp1cm: CMAP precipitation. Values are in reverse order.
Figure 5.25: Grid point correlation between time series of EOF2 for CMAP West Africa (JJAS 1979-1998) and Atlantic SST: a) June SST; b) July SST.
Figure 5.25: c) August SST; d) September SST.
These results confirm the good correlation already observed between the time series for EOF1 over Senegal and the South Atlantic SST (Table 5.16). They are also consistent with the wind circulation observed in the Atlantic Ocean south of West Africa (Figure 5.22): the warm waters cause a convergence of moisture related to the evaporation, and this increased moisture in the monsoonal flow causes increased rainfall in the West African coast. It is traditionally admitted that warm waters in the South Pacific Ocean correspond to negative anomalies in the Sahel (e.g. Lamb, 1978a and 1978b; Lough, 1986; Philander, 1986; Lamb and Peppler, 1991; Janowiak, 1988; Bah, 1987; Eltahir and Gong, 1996; Ward, 1998). That is not the case for Senegal, which is positively correlated with South Atlantic SST.

Figure 5.26 summarizes the relationships between Senegal and the global climate. It shows the teleconnections linking Senegal and West Africa with the Pacific and Atlantic Oceans, as suggested by the global wind patterns shown in Figure 5.22b. It also emphasizes the role played by the tropical Atlantic SSTs (i) in Senegal and Sahelo-Sudan positive rainfall anomalies; (ii) in the negative anomalies observed in the Guinea Coast region. Figure 5.17a (positive anomalies in the Sahel-Sudan region and negative anomalies in the Guinea Coast region), Figures 5.22a and 5.25 (wind convergence over warm waters in the Atlantic Ocean) bring support to this theory. All these features are related to EOF2 mode over West Africa, which is the most correlated with Senegal rainfall.
Climate variability over Senegal (1979-1998): relationships with global climate

Figure 5.26: Relationships between Senegal rainfall and the global climate. The second EOF mode for West Africa is the one that is important in explaining the variability of rainfall over Senegal.
6: SUMMARY AND CONCLUSIONS

Climate variability over Senegal and its relationships with global climate have been examined for the period 1971-1998. Monthly observed rainfall for 20 stations over Senegal, monthly mean temperature for 12 stations and monthly average CMAP data were averaged for the months of June July, August and September, to generate seasonal rainfall totals for the wet season and climate indices averaged over the study period.

The monthly, seasonal and annual temperature and distributions are mapped analyzed using ArcGIS Spatial Analyst. Rainfall over Senegal is highly concentrated in 3 to 4 months (JJAS), especially in August and September, and its distribution is dominated by a N-S gradient, with decreasing amounts from south to north. June exhibits the greatest coefficient of variation. Spatially, there is an increase of variability from south to north.

Trends in precipitation are estimated using a linear regression analysis and interpolation maps for the slopes. According to the $t$-test, there is no statistically significant trend for both rainfall and the number of rainy days. Areas of positive slopes are limited (Northeast and Southwest for the rainfall map). The Pettitt test, used for a change point detection, shows that 18 stations out of 20 experienced a step change; the mean of the recent period is lower than that of the first period.

The spatial distribution of mean annual temperatures is driven by an opposition between oceanic and continental influences. Temperatures generally decrease eastward, but during the wet season, a N-S gradient is observed. Based on the coefficient of variation, the greatest variability occurs in the western and northern country, and the months from
January to April are accountable for most of the variability. The greatest fluctuations of temperature occur during the dry season, especially in the sub-arid areas of the North and Northwest. To examine the trends, spatial and temporal patterns are analyzed with interpolated linear slopes for all stations, an index based on the 1971 – 1998 period is computed and an EOF analysis is performed. During the period 1971-1998, most of the warming trend took place from November to May. For the annual temperature trends, all slopes are positive, with the exception of the Southeast. According to the t-test, most of the trends are statistically significant. There is a striking similarity between the trends map and the spatial patterns of the first EOF mode. The time series for the first EOF mode clearly depicts a warming trend. There is a significant correlation between EOF1 time series for Senegal and Pacific SST (El Niño zone) during the January-April period.

Two statistical analyses, mainly based on EOF analysis and correlations, are performed.

In the first analysis, the data analyzed are observed precipitation and the number of rainy days over Senegal, for 1971-1998. The rainfall and number of rainy days time series are correlated with Atlantic and Pacific sea surface patterns to investigate the connections with the global climate. According to Kendall’s test, only the first EOF mode (EOF1) is significant for seasonal rainfall or the number of rainy days (JJAS). However, EOF2 for rainfall in September is significant. EOF1 loadings are positive over the entire study area. The regions of largest amplitude are found in the western Senegal, in a coastal stripe extending from the Dakar region to the central Gambia, and the lowest magnitudes of EOF1 are found in the central South and the central North. These patterns present some similitude with the results of Camberlin and Diop (2003). The corresponding time series
for rainfall and the number of rainy day are strongly correlated and both exhibit high frequency fluctuations (1 to 5 years). Most of the negative or weakly positive values correspond to El Niño years (e.g. 1972, 1977, 1983, 1991 and 1998). September rainfall has two significant leading modes. The second EOF mode explains 15.36% of the variance. The EOF2 eigenvector map for this month (Figure 5.3a) reveals a dipole-like pattern, with positive loadings in the South and negative ones in the North. This pattern is consistent with the north-south gradient, which is a major characteristic of rainfall in Senegal.

To investigate the connection of Senegal’s climate with regional and global climate, EOF1 loadings are compared with other West African indices, and their relationship with sea surfaces features is examined. There is a strong relationship between EOF1 time series for rainfall and the normalized index for Senegal, and a good, but not very strong correlation with Lamb’s rainfall index for West Africa.

A grid-point correlation between EOF1 for JJAS rainfall in Senegal and Atlantic SST for the same period (lag 0) reveals the lack of relationship. A lag correlation between EOF1 of the seasonal rainfall over Senegal (JJAS) and tropical Atlantic SST for the 6 months which precede the summer rainfall season gives modest coefficients. The best possibilities are found along the South American coast in June (0.50 to -0.55), but the probability of predicting Senegal rainfall from the tropical Atlantic SST is not strong. Another correlation with a dataset in which the Atlantic Ocean is split into two domains (North and South) doesn’t suggest any strong relationship, but reveals that despite the weak coefficients, May and June present the highest coefficients and the best chances of predictability. However,
there is an appreciable negative correlation between EOF2 time series of September rainfall and the North Atlantic SST, especially during the months which precede the rainy season. The tropical Pacific SST are more significantly correlated with Senegal rainfall and offer a greater probability of prediction than the tropical Atlantic SST: the correlation coefficients range from 0.55 to -0.60, but in limited areas.

To further investigate the climate variability and predictability for Senegal, a second analysis is performed for 1979-1998, with additional CMAP rainfall data.

A comparison between the observed precipitation and the CMAP climatology shows a good agreement between the two datasets. This is further confirmed by the EOF analysis: the spatial patterns for CMAP EOF1 mode, generally agree with the observed rainfall EOF map. However, differences between the two patterns are observed in the northern Senegal, where EOF1 for the observed rainfall has much lower loadings than EOF1 for CMAP. The corresponding time series suggest interannual fluctuations and combined with a background time scale of 6 to 7 years.

An EOF analysis of CMAP rainfall is also performed over West Africa. The spatial patterns of EOF1 and EOF2 for West Africa exhibit a dipole pattern, with positive loadings in the Sahel-Sudan zone and negative loadings further south. The EOF2 eigenvector pattern is similar to the “Mode 2” of Nicholson and Palao (1993). EOF3 is characterized by negative or weakly positive amplitudes throughout the entire West African domain.

EOF1 time series for West Africa is strongly correlated with lamb rainfall index. One of the main findings is that there is a good relationship between EOF2 time series for West Africa and EOF1 time series for Rainfall over Senegal.
The correlations with SST in this second analysis yield more interesting results: EOF1 time series for CMAP rainfall over Senegal is well correlated with the South Atlantic SST. Good coefficients are observed during the pre-wet season (January through May) and may offer some predictability for the rainy season. In the Pacific Ocean, the greatest coefficients (up to -0.72) are observed during the April-July period, which can provide hints for the coming rainy season.

The different results obtained in the two analyses suggest an evolution in the relationship between SST fields and Senegal or West African rainfall. When the datasets are split into two decades (1979-1988 and 1989-1998), the correlations show that the relationships between the South Atlantic and Senegal or West Africa were stronger in the 1979-1988 period, especially for CMAP rainfall over Senegal and West Africa (correlation coefficient up to 0.88). The same trend exists in the Pacific Ocean (El Niño zone).

Some main conclusions can be drawn from this study.

The CMAP data is robust and suitable for analyses over West Africa: good relationships have been observed between (i) CMAP rainfall distribution and observed precipitation over Senegal; (ii) EOF1 time series and eigenvector patterns for the two datasets; (iii) EOF1 time series for CMAP West African rainfall and Lamb’s rainfall index for West Africa. Based on this liability, it has been possible to use CMAP data in a second EOF analysis, as a validation for the first analysis, which was based on observed precipitation only.

The EOF analysis performed over West Africa has helped in better relating Senegal to the West African region:
The spatial patterns of EOF1 for West Africa reveal three distinct domains: the Guinea Coast region (negative loadings); the eastern or continental domain (strongly positive loadings); the western or Atlantic domain (weakly positive loadings). The specificity of the “Atlantic Sahel” 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 specificity. Consequently, relying on rainfall indices averaged over the whole Sahel-Sudan may lead to mistakes: attempts to predict the rainy season by correlating those indices with SST anomalies may not work for the entire region. For example, the Lamb rainfall index, which is a reference for West Africa, will not work for Senegal.

EOF1 for West Africa is traditionally believed to be representative of the whole Sahel-Sudan region. However, in this analysis, this traditional wisdom is not correct: the second mode (EOF2) is the one which is important for Senegal. Finding the signification of EOF2 for West Africa will help better understand the mechanisms of climate variability over Senegal.

Despite an overall modest performance of correlations between sea surface fields and rainfall anomalies over Senegal, some interesting results have been found: the good correlation between EOF2 time series for September rainfall and North Atlantic SST; the positive correlation between Senegal rainfall and South Atlantic SST, which is uncommon based on the knowledge from previous studies; the good correlation between EOF1 time series for CMAP rainfall over Senegal and South Atlantic SST; the good relationship between the Pacific SST along the El Niño zone and EOF1 time series for Senegal. This
region offers the best chances for predicting rainfall over Senegal prior to the rainy season. However, this area is spatially limited.

Areas of future work include:

- A further investigation of the second EOF mode for West Africa, which may obviously provide a better understanding of climate variability over Senegal.

- An investigation of the dynamic that drives this EOF2 wind patterns.

- An inclusion of other oceanic and atmospheric fields, such as winds and pressure fields, in the investigation of climate variability over Senegal.

- The use of the spatial analysis capabilities of GIS, in addition to the mapping capabilities.

- The integration of crop data, which will allow an investigation of crop predictability.
REFERENCES


Lister, D. H., and J. P. Palutikof, 2001: Seasonal climate forecasting for West Africa: a review. A report produced for the *CLIMAG West Africa project*, Deliverable n.4


Rowell, D. P. 1988: Short range rainfall forecasting in the West African Sahel, *thesis submitted for the degree of Doctor of Philosophy*, University of Reading, USA.


a) 

Figure A.1: Mean monthly rainfall (1971 – 1998): a) January; b) February.
Figure A.2: Mean monthly rainfall (1971 – 1998): March: less than 1 mm.
Figure A.3: Mean monthly rainfall (1971 – 1998): a) April; b) May.
Figure A.4: Same as Figure A.3, except for d) October; f) November. Units are in mm.

BAKEL (14°90N – 12°47W)

Figure B1: Temporal distribution of observed rainfall for Bakel (1971–1998): a) mean monthly rainfall; b) annual rainfall.
Figure B2: Same as Figure B1, except for Bambey.
Figure B3: Same as Figure B1, except for Dakar.
Figure B4: Same as Figure B1, except for Diourbel.
FATICK (14°33N – 16°40W)

Figure B5: Same as Figure B1, except for Fatick.
KAOLACK (14°13'N – 16°07'W)

Figure B6: Same as Figure B1, except for Kaolack.
Figure B7: Same as Figure B1, except for Kedougou.
Figure B8: Same as Figure B1, except for Kolda.
Figure B9: Same as Figure B1, except for Kounghoul.
Figure B10: Same as Figure B1, except for Linguere.
LOUGA (15°62N – 16°22W)

Figure B11: Same as Figure B1, except for Louga.
Figure B12: Same as Figure B1, except for Matam.
Figure B13: Same as Figure B1, except for Mbour.
Figure B14: Same as Figure B1, except for Nioro.
Figure B15: Same as Figure B1, except for Podor.
Figure B16: Same as Figure B1, except for Saint-Louis.
Figure B17: Same as Figure B1, except for Tambacounda.
THIES (14°80N – 16°95W)

Figure B18: Same as Figure B1, except for Thies.
VELINGARA (13°15N – 14°10W)

Figure B19: Same as Figure B1, except for Velingara.
Figure B20: Same as Figure B1, except for Ziguinchor.

DAKAR (12°55N – 16°27W)

Figure C1: Temporal distribution of mean temperature for Dakar (1971 – 1998): a) mean monthly temperature; b) mean annual temperature. A linear regression line is fitted. A red regression line indicates a trend which is significant at the 95% level according to the $t$-test. A black line indicates that the trend is not significant.
Figure C2: Same as Figure C1, except for Diourbel.
KAOLACK (14°13N – 16°07W)

Figure C3: Same as Figure C1, except for Kaolack.
Figure C4: Same as Figure C1, except for Kedougou.
Figure C5: Same as Figure C1, except for Kolda.
Figure C6: Same as Figure C1, except for Linguere.
Figure C7: Same as Figure C1, except for Louga.
MATAM (15°65N – 13°25W)

Figure C8: Same as Figure C1, except for Matam.
Figure C9: Same as Figure C1, except for Podor.
SAINT-LOUIS (16°05N – 14°45W)

Figure C10: Same as Figure C1, except for Saint-Louis.
Figure C11: Same as Figure C1, except for Tambacounda.
Figure C12: Same as Figure C1, except for Ziguinchor.

Figure D1: Spatial eigenvector patterns of EOF1 for June over Senegal (1971 – 1998): a) observed precipitation; b) number of rainy days. Loadings are multiplied by 10.
Figure D2: EOF 1 time series of observed precipitation and the number of rainy days for June (1971 – 1998)
Figure D3: Spatial eigenvector patterns of EOF1 for July over Senegal (1971 – 1998): a) observed precipitation; b) number of rainy days. Loadings are multiplied by 10.
Figure D4: EOF 1 time series of observed precipitation and the number of rainy days for July (1971 – 1998)
Figure D5: Spatial eigenvector patterns of EOF1 for August (1971 – 1998): a) observed precipitation; b) number of rainy days. Loadings are multiplied by 10.
Figure D6: EOF 1 time series of observed precipitation and the number of rainy days for August (1971 – 1998).
Figure D7: Spatial eigenvector patterns of EOF1 for September (1971 – 1998): a) observed precipitation; b) number of rainy days. Loadings are multiplied by 10.
Figure D8: EOF 1 time series of observed precipitation and the number of rainy days for September (1971 – 1998).