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The relationship of rainfall variability in West Central Africa to sea-surface temperature fluctuations

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Abstract:

This study examines the interannual variability of rainfall in western equatorial Africa and its links to sea-surface temperatures (SSTs). Five geographical regions within the latitudes 10 °N–5 °S are delineated for the analysis. The links to SSTs in the tropical Atlantic, Pacific and Indian Oceans are examined via seasonal composites of wet and dry years and via linear correlations.

The results show that interannual variability is extremely complex in this region and that several factors govern it. The most important include SST anomalies along the Benguela Coast, a general warming or cooling of the tropical oceans, Atlantic SSTs specifically, the contrast between the Atlantic and Indian Oceans, and the Pacific El Niño-Southern Oscillation (ENSO). These factors differ seasonally. In much of the region, rainfall variability is linked to the Pacific El Niño and the western Indian Ocean early in the year, but to the Atlantic during the boreal summer months. The Indian Ocean again becomes important in late summer/early fall.

The role of the Atlantic appears to be the modulation of the north–south excursion of the Intertropical convergence Zone (ITCZ). Hence the polarity of the SST/rainfall association depends on location. The association between SSTs near the coast and rainfall is positive if the influence is direct but can be positive or negative for indirect influences. An opposition between the Indian and Atlantic Oceans appears to displace convection in an east–west direction.

Our results suggest several generic conclusions concerning the link between SSTs and continental rainfall. One is that the influence of the three oceans is seasonally dependent. The impact of a specific SST anomaly is also seasonally dependent. The same SST pattern may enhance rainfall in one season, but reduce it in the following season. Finally, the SST/rainfall associations are generally not symmetric. That is, the factors producing wet conditions are not the reverse of those producing dry conditions. In order to understand these associations, the underlying mechanisms via the general atmospheric circulation must be determined. Copyright © 2007 Royal Meteorological Society

KEY WORDS rainfall; interannual variability; SST; Africa; ITCZ; Atlantic; air-sea interaction

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INTRODUCTION

Africa encompasses the world's largest landmass within the equatorial latitudes. The continent spans nearly 50° of longitude at the equator and includes roughly half of the global land area lying between 10 °N and 10 °S. Comprehensive knowledge of the meteorology of this region is critical to the general understanding of low latitude meteorological phenomena. Eastern equatorial Africa has been well studied, in part because of the long-operative research units of the East African Meteorological Department (now the Meteorological Services of the countries of Kenya, Tanzania and Uganda) and the department of Meteorology at the University of Nairobi. Research has continued in the context of the study of monsoons, the Indian Ocean, and El Niño. Unfortunately, no comparable body of knowledge exists for western equatorial Africa, especially for the region of Zaire, the Congo, Cameroon, Gabon and the Central African Republic. Very little is known about either the synoptic and mesoscale systems that shape the rainy season or about the factors governing the interannual and interdecadal variability.

This region is interesting for a number of reasons. For one, it represents a climatic transition zone between both Northern and Southern Africa and Eastern and Western Africa. Teleconnections have been established between these regions (e.g. Nicholson, 1986a,b), with western equatorial Africa lying at the node of the teleconnection. Also, recent Tropical Rainfall Measuring Mission (TRMM) data have shown that the frequency of lightning here is by far the greatest in the world. Satellite algorithms overestimate rainfall in this region by a factor of two or three (McCollum *et al.*, 1999; Nicholson, 1999), suggesting that the physics of the rain process may be different. Thus, this region (shown in Figure 1 and henceforth termed 'Central Africa') merits much more detailed study.

We have undertaken an investigation of rainfall variability in this region. In particular, our goal is to

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place the region in a continental and global context, to examine its links to other parts of Africa and to the global tropics. Few such links were evident in our prior work (Nicholson and Entekhabi, 1986; Nicholson and Kim, 1997; Nicholson and Selato, 2000). Strong correlations with global-scale phenomenon, such as sea-surface temperatures (SSTs) and el Niño, were not evident. Our work at the continental-scale (e.g. Nicholson, 1986a) suggested that precipitation variability in Central Africa might be remarkably complex. Inter-regional correlations are relatively low and station-region correlations suggest a fairly high degree of local influence on variability. In this respect, the western equatorial region contrasts strongly with the rest of tropical Africa, where interannual variability is coherent over very large sectors.

The complexity relates to the myriad of factors influencing the region. These include the Indian and Atlantic Oceans and the highlands of Cameroon and East Africa. Presumably, the influence of the Atlantic diminishes eastward and the influence of factors governing East African rainfall variability (e.g. the Indian Ocean and the Rift Valley highlands) increases eastward. The influence of the ITCZ changes seasonally as this zone migrates through the region. A mid-level African easterly jet influences the region much of the year (Nicholson and Grist, 2002), while the highlands influence the region all of the year.

Such complexity makes an analysis of the causal factors in the interannual variability of precipitation exceedingly difficult. In view of the above, the approach taken in our current work was to first determine the appropriate spatial and temporal aggregation of data, in order to facilitate identification of the various factors. This analysis is presented in Part I of this three-part study, together with a routine climatological analysis for the so-determined precipitation regions. This article, Part II, presents an analysis of the relationship between SSTs and rainfall. A study of the relationship to Pacific ENSO events and La Niña is presented in Part III (Nicholson, 2005).

The very clear relationships between rainfall and SSTs that have been established for East Africa (Nicholson and Entekhabi, 1987; Ogallo *et al.*, 1988; Camberlin, 1995; Semazzi *et al.*, 1988, 1996; Goddard and Graham, 1999; Mutai and Ward, 2000; Clark *et al.*, 2003; Schreck and Semazzi, 2004) and Sahelian Africa (e.g. Lamb, 1978; Folland *et al.*, 1986; Hastenrath, 1990; Rowell *et al.*, 1992; Fontaine and Janicot, 1996; Camberlin *et al.*, 2001; Giannini *et al.*, 2003) imply that SSTs should be a factor in rainfall variability in the western equatorial region as well. However, no studies have focused on the western equatorial regions. The complexity of the variability there (see, for example, Camberlin *et al.*, 2001) may have masked the SST/rainfall associations in other analyses.

The approach taken here is to utilize wet and dry composites and linear correlation to evaluate the relationship between rainfall variability over western equatorial Africa and SSTs in the tropical and subtropical regions of the Atlantic, Pacific and Indian Oceans. This is done on a seasonal basis, in order to determine if the influence of the various oceans or ocean sectors is seasonally dependent. Results of the wet and dry composites and linear correlations are presented in the Results of Composite Analysis Section and Linear Associations Between SSTS and Rainfall: Seasonality of Ocean Influence Section, respectively. The Discussion Section, summarizes the results and integrates them into more general conclusions concerning SST/rainfall associations.

ANALYSIS

Rainfall data and regions

This study utilizes a precipitation gauge data set consisting of monthly totals for 187 stations (Figure 1) having 45 or more years of record. The records derive from the second author's NIC131 African precipitation data set, with updates post-1984 data from various National Meteorological Services (e.g. Nicholson, 1986a; Nicholson *et al.*, 2000). Station records have been combined to form the five regions shown in Figure 1. These regions were determined to be homogeneous with respect to the interannual variability of rainfall. The seasonal cycle of rainfall in each region is also shown in the figure. The cycles are significantly different, suggesting different mechanisms of variability.

The regional time series were calculated by first transforming station rainfall departures, and then averaging all stations available in the region. For each station the transformed series of rainfall departures are calculated using the following procedure:

$$X_{ij} = \frac{r_{ij} - \overline{r_i}}{\sigma_i} \tag{1}$$

Where:

X_{ij} is the transformed annual rainfall departure,
r_{ij} is the annual total rainfall for station i in the year j,
$\overline{r_i}$ is the long-term mean for station i,
σ_i is the standard deviation of annual totals at station i.

The use of transformed regionally averaged time series reduces two problems inherent in the analysis of rainfall in sub-humid, tropical areas: the highly diverse means and variances and the randomness of the convective process reflected in individual station totals. Similar time series were calculated for the four seasons, with a seasonal mean and a seasonal standard deviation replacing the annual values in (1).

The station departures calculated from (1) are combined into 5 regional averages. Then for a particular region, the area-averaged rainfall departure for the year j is represented by:

$$\mathrm{R_j} = \frac{\sum_{i'} X_{ij}}{I_j} \tag{2}$$

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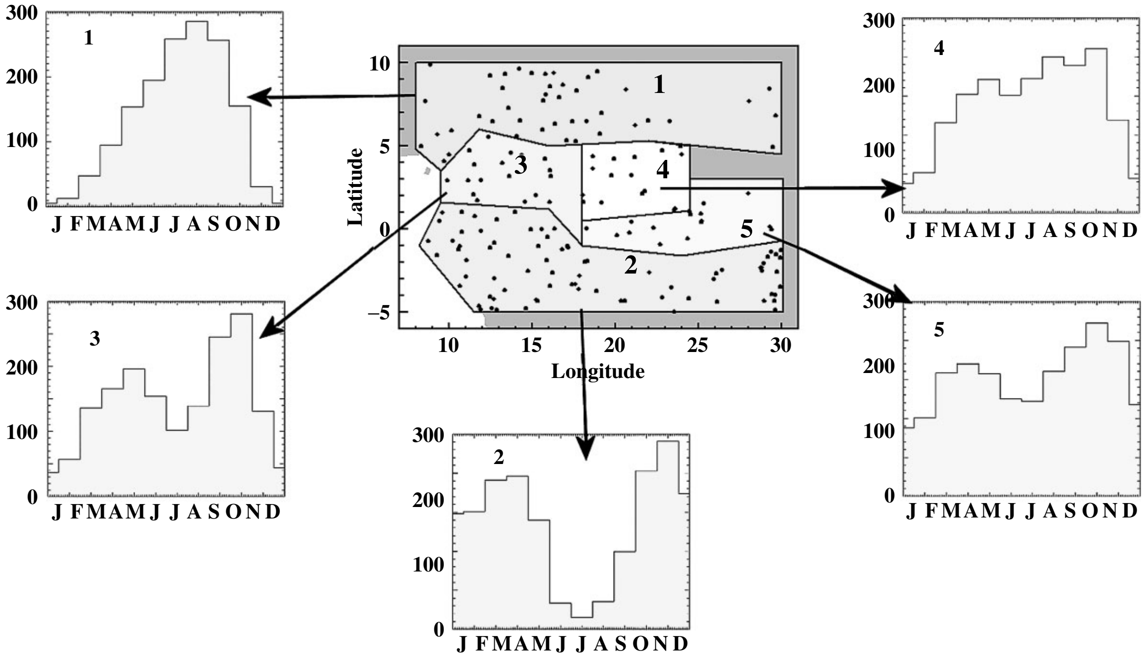

Figure 1. Rainfall regions and stations. The mean seasonal cycle is indicated in the bar graphs (rainfall in mm).

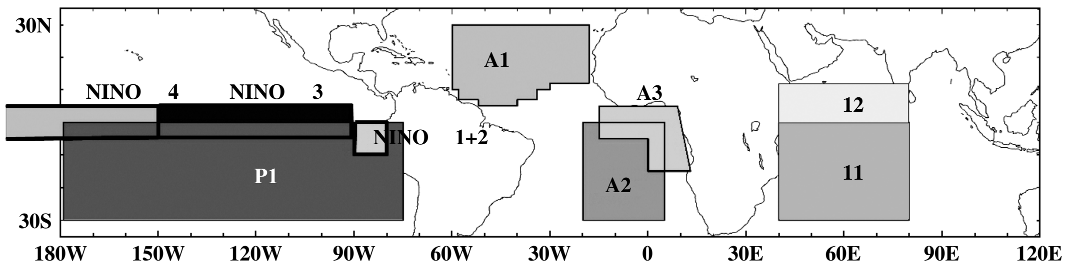

Figure 2. Location of SST sectors used in the analysis.

where the summation is taken over the network i' of all I_j stations available in the year j for the region in question.

Sea-surface temperature data and regions

The SST dataset utilized in this study is the 'enhanced' Comprehensive Ocean–Atmosphere Data Set (COADS) (Worley *et al.*, 2005). SSTs time series for several sectors of the Pacific (Niño-1 + 2, Niño-3, Niño-4) have been obtained from the National Oceanic and Atmospheric Administration (NOAA) web site: ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices. The COADS data cover the period from 1950 to 1998 and consist of 'trimmed' monthly averages for 2-degree latitude and 2-degree longitude squares. These 'enhanced' data have been edited to better represent extreme climate events, adding observations from ships and *in situ* marine platform types (e.g. drifting and moored buoys).

SSTs are expressed as a 'normalized' anomaly, that is, at each grid point, a departure from the long-term mean (1950 to 1998) at the grid point, divided by the standard deviation of SSTs at the grid point during this same period. Here the data have been aggregated to produce spatially averaged time series for three sectors in the Atlantic Ocean, two sectors in the Indian Ocean and one sector in the Pacific Ocean (Figure 2). The sectors are defined on the basis of previous studies (e.g. Nicholson and Nyenzi, 1990; Nicholson, 1997), a rich background of literature concerning spatial modes of variability in the Atlantic and the Pacific Oceans, and the sectors suggested by our wet/dry composites be linked to rainfall.

The COADS data set has been used in many studies of marine surface variables and has proven to provide reliable estimates of temperature, wind and surface pressure (Allan *et al.*, 1995; Deser and Wallace, 1990). The dataset contains two biases produced by changes in observational practices. The first involves SST estimates based on 'bucket', or engine-cooling, water intake data and the second involves the use of anemometer readings *versus* Beaufort force estimates of wind speed. The number of ships utilizing the 'intake' water to measure SSTs increased markedly in the 1940s. For this reason, and because the number of reports increases dramatically following World War II, our analysis begins in 1950 and runs through 1997.

Methodology

The hypothesis for this work is that: (1) many of the factors affecting rainfall variability elsewhere in Africa operate here (e.g. SST, ENSO) and (2) that the influence of the Atlantic Ocean diminishes eastward and the influence of factors governing East African rainfall variability (e.g. the Indian Ocean and the Rift Valley highlands) increases eastward. These ideas are tested in this thesis.

The first step was to determine, for each season and region, the five wettest and five driest years during the analysis. These are listed in Table I. Composites of the SST anomalies corresponding to the wettest and driest years were constructed and examined. Then, the rainfall variability in each season and region was correlated with SSTs in the sectors shown in Figure 2 in order to examine the relative importance of ENSO signal in the Pacific and SST anomalies in the Atlantic and Indian Oceans.

The ocean sectors defined for the analysis include three in the Atlantic Ocean (North Atlantic, South Atlantic and the upwelling area along the Benguela Coast), two sectors in the Indian Ocean covering areas from 0–30S, 40–80E and 0–12N, 40–70E and four sectors in the Pacific: Niño 1 + 2 (0–10S, 80–90W), Niño3 (5N–5S, 90–150W), Niño4 (5N–5S, 150W–160E) and the South Pacific (0–30S, 80–180W). These sectors are relatively homogeneous with respect to the interannual SST variability and figure prominently in studies on interannual variability. For example, the two most common modes of Atlantic variability, the Interhemispheric and the Atlantic Niño modes, involve the sectors shown. The former mode is an SST dipole with opposite signs of SST anomalies in the north and south tropical Atlantic regions A1 and A2 (Carton *et al*., 1996; Ruiz-Barradas *et al*., 2000; Sutton *et al*., 2000). The latter is a mode of warming in the equatorial Atlantic (A3) (Zebiak, 1993; Carton and Huang, 1994; Latif and Grötzner, 2000; Grodsky and Carton, 2003).

Table IA. Five wettest and five driest years in regions 1 through 5 during December-to-February.

Region	Wet years					Dry years				
1	53	56	57	61	76	83	87	92	93	95
2	60	61	70	77	91	72	78	92	94	97
3	52	56	60	63	73	84	87	89	92	95
4	54	57	60	80	90	51	62	89	92	95
5	55	60	63	69	94	50	62	67	71	89

Table IB. Five wettest and five driest years in regions 1 through 5 during March-to-May.

Region	Wet years					Dry years				
1	62	66	69	91	96	71	77	83	86	87
2	55	57	63	70	91	58	72	78	83	84
3	56	62	66	69	85	61	77	83	90	97
4	50	55	64	66	73	67	68	71	82	90
5	62	66	81	92	95	65	67	70	73	83

Table IC. Five wettest and five driest years in regions 1 through 5 during July-to-August.

Region	Wet years					Dry years				
1	63	65	68	69	78	53	72	73	84	87
2	62	70	77	84	88	51	56	58	61	73
3	52	66	84	90	93	54	56	58	64	83
4	50	61	70	90	93	84	91	92	94	95
5	61	71	74	84	93	54	64	73	75	86

Table ID. Five wettest and five driest years in regions 1 through 5 during September-to-November.

Region	Wet years					Dry years				
1	51	54	57	62	64	71	77	83	84	87
2	61	75	82	89	94	57	58	63	79	93
3	51	57	62	64	75	63	73	79	91	96
4	56	61	62	69	76	73	78	94	95	96
5	61	65	73	77	92	57	58	84	85	96

RESULTS OF COMPOSITE ANALYSIS

Region 1

Region 1 is the southern extension of the Sahel/Soudan zone, in which rainfall has a maximum in the boreal summer and a pronounced dry season in the boreal winter. The seasons, from wettest to driest, are June–July–August (JJA), September–October–November (SON), March–April–May (MAM), and December–January–February (DJF). Nearly 50% of the rainfall occurs in JJA, but less than 3% occurs in DJF.

Figure 3 shows the SSTs corresponding to the five wettest years and five driest years, respectively for each season. The most striking result is that in the dry composites the SSTs tend to be positive throughout all three oceans in all seasons. The strongest anomalies are in the equatorial Pacific. The anomalies are weaker in SON than in the other seasons.

In the wet composites, the sign of SST anomalies is reversed in three of the four seasons, so that the oceans tend to be anomalously cold when Region 1 is anomalously wet. The SST anomalies tend to be strong in the eastern equatorial regions of the Atlantic and the Pacific. In MAM the oceans tend to be anomalously warm in both the dry and wet composites, except in the eastern Pacific. There, a strong reversal occurs, and the typical El Niño pattern of warm anomalies is strongly evident in the dry composite. This suggests that the eastern Pacific is a prevailing influence in Region 1 during MAM.

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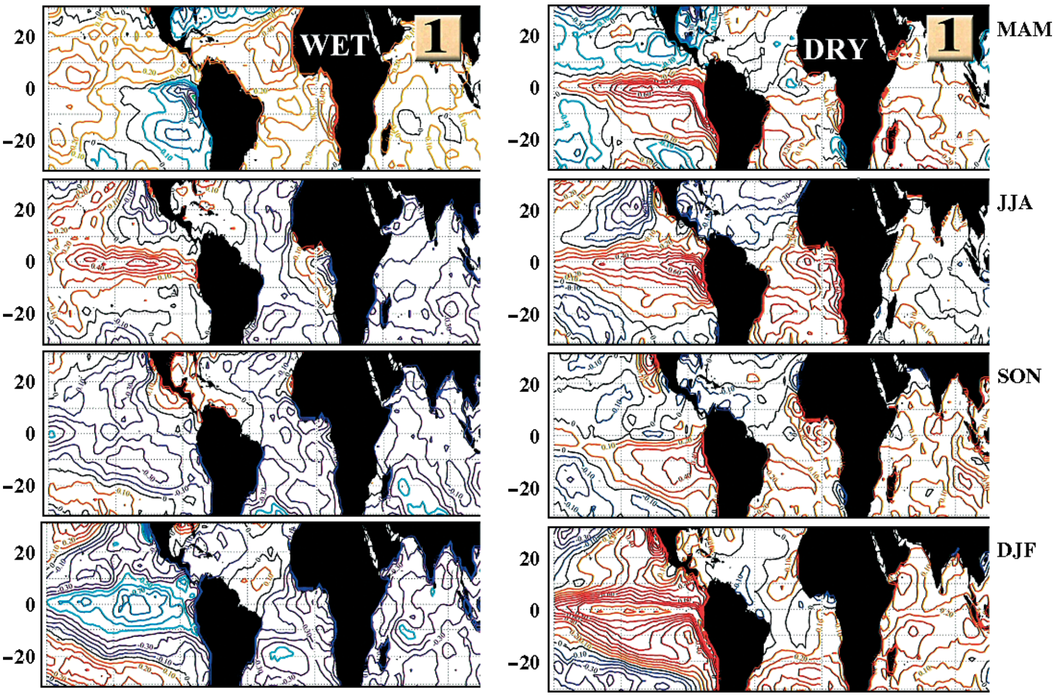

Figure 3. SST anomalies corresponding to the five driest and five wettest years for each season in Region 1. Positive anomalies are red, negative anomalies are blue, contour interval is 0.1 °C.

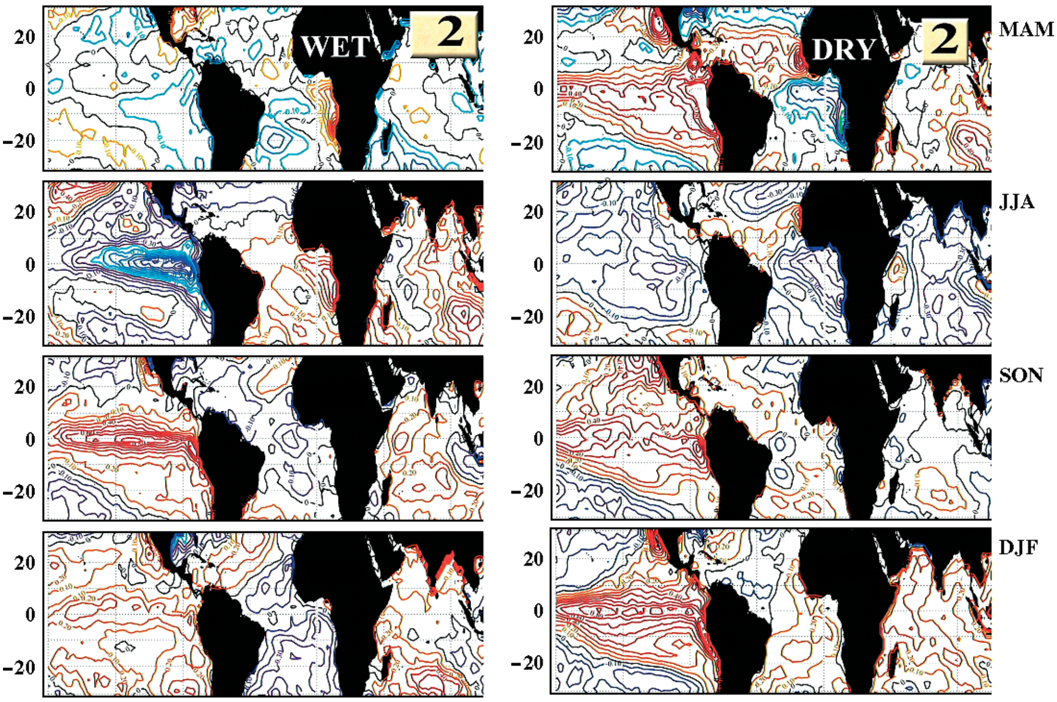

Figure 4. As in 3, but for Region 2.

During JJA the strongest SST contrast between wet and dry is in the equatorial and South Atlantic. A cold tongue appears in the wet case, while coastal and equatorial warming occurs prominently in the dry case. The sign of the SST anomalies reverses in the southwestern Atlantic as well, with cold conditions corresponding to the wettest years. A dipole pattern is evident in the tropical Atlantic in the dry case. The equatorial Pacific is warm during JJA in both the wet and dry composites. However, in the wet case the warming is further west and there is minimal warming along the South American coast.

In SON and DJF a reversal from warm SSTs in the dry composite to cold SSTs in the wet composite is seen in all

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three oceans. In DJF the reversal is nearly ubiquitous and the El Niño/La Niña SST patterns are strongly developed. Thus, in Region 1 the driest DJF seasons clearly occur in conjunction with the Pacific El Niño and the wettest DJF seasons correspond to La Niña.

Region 2

Region 2 lies just south of the equator and its dry season occurs in the boreal winter (JJA), coincident with the summer rainy season on Region 1. Only about 3% of the rain occurs then. Rainfall occurs during the rest of the year but is concentrated in the two transition seasons. The wettest months are March–April in the first rainy season and October–November in the second. Although DJF is a secondary dry season, roughly 25% of the annual rainfall occurs in these months.

Seasonal rainfall/SST associations. Region 2 shows some of same tendencies as Region 1 for warm SSTs, particularly in the Atlantic, to occur during the driest years (Figure 4). However, cold SSTs do not characterize the wet composites. This suggests that the large-scale patterns of the global oceans are not a major factor in rainfall variability in this region. The Atlantic appears to exert the strongest influence.

This is illustrated by SST anomalies during the MAM and the SON rainy seasons. During MAM, positive SST anomalies are apparent in the dry composite throughout the tropical oceans except in the equatorial Atlantic. A strong El Niño warming pattern is evident in the Pacific and extends across the North Tropical Atlantic, creating a strong dipole. The positive anomalies become negative in the wet composite, but only weakly so. The strongest wet/dry contrast is seen in the anomalies along the Benguela Coast. These are positive in the wet case and negative in the dry case, contrary to the global pattern. Nicholson and Entekhabi (1987) showed a similar SST/rainfall association during these months. Most likely, the effect is a direct, local one that influences the thermodynamic state of the atmosphere (Hirst and Hastenrath, 1983a,b).

In the main dry season, JJA, the wettest years are associated with positive anomalies in the Indian and Atlantic Oceans, particularly along the Benguela Coast, but a cold La Niña pattern is evident in the eastern Pacific. A comparison with the anomalies of the MAM season suggests that, in Region 2, the primary factor in both seasons is the anomaly pattern in the eastern equatorial Atlantic and along the Benguela Coast. However, cold SSTs in this region appear to be linked to ENSO, with the warm anomalies linked to Pacific La Niña. In either case, the Pacific may be forcing the Atlantic anomalies.

The SST anomaly patterns for SON and DJF are quite similar. Positive anomalies are prominently developed in the Pacific in the dry composites. Anomalies are generally positive in the Atlantic and the Indian Ocean as well. Only the Atlantic SST anomalies switch to negative in the wet composite. In the Pacific, however, the positive anomalies are markedly weaker in the wet composite during DJF, but markedly stronger in the wet composite for the SON season.

We interpret these results collectively to indicate that variability in the MAM rainy season is locally forced by SST anomalies along the Benguela Coast. However, the coastal anomalies appear to be remotely forced by the Pacific. During the SON rainy season and the somewhat drier season of DJF, the critical factor in rainfall variability appears to be the overall pattern of SSTs in the Atlantic. The Pacific probably plays some role in these seasons. The effect of El Niño, for example, appears to be a modification of the seasonal cycle, enhancing both the SON rainy season and the DJF dry season. An El Niño pattern is also associated with reduced rainfall during the MAM rainy season.

Region 1 versus Region 2: subequatorial regions of the northern and southern hemisphere. A second interesting aspect of the SST/rainfall associations in Region 2 is that the SST patterns associated with high rainfall are opposite in sign to those linked to high rainfall in Region 1. This is particularly true for JJA. Then, wet conditions in Region 1/Region 2 are associated not with a cold/warm eastern Pacific but with a warm/cold eastern Atlantic. During this season opposite patterns also prevail in the two regions in the dry composites. One interpretation is that the temperatures affect the northward excursion of the ITCZ between MAM and JJA, with warm Atlantic SSTs limiting the extent of its northward displacement. This would increase rainfall in Region 2, which lies further south, but reduce it in Region 1.

The SST patterns associated with dry conditions in the two regions are much more similar, especially in SON and DJF. In both seasons and regions, the dry conditions are associated with generally positive SST anomalies. These anomalies are strongest, however, in the Pacific, where an ENSO–like pattern of SSTs is evident. An anomalous excursion of the ITCZ would not be consistent with this. Overall, these results suggest a lack of symmetry in the factors producing wet and dry conditions.

Region 3

Region 3 lies just north of the equator, in close proximity to the Atlantic Ocean. The pattern of rainfall is similar to that in Region 2, but the two dry seasons are reversed in intensity. The main dry season is DJF. The secondary dry season, JJA, contributes some 20% of the mean rainfall.

The most striking aspect of the SST/rainfall associations for Region 3 is the presence of strong anomalies along the Benguela Coast (Figure 5). However, the SST patterns associated with dry and wet conditions in this sector are quite different in the various seasons. The most dramatic examples are the cold equatorial Atlantic during the JJA dry composite and the cold Benguela Coast during the MAM dry composite. The association between cold SST anomalies and low rainfall again suggests a

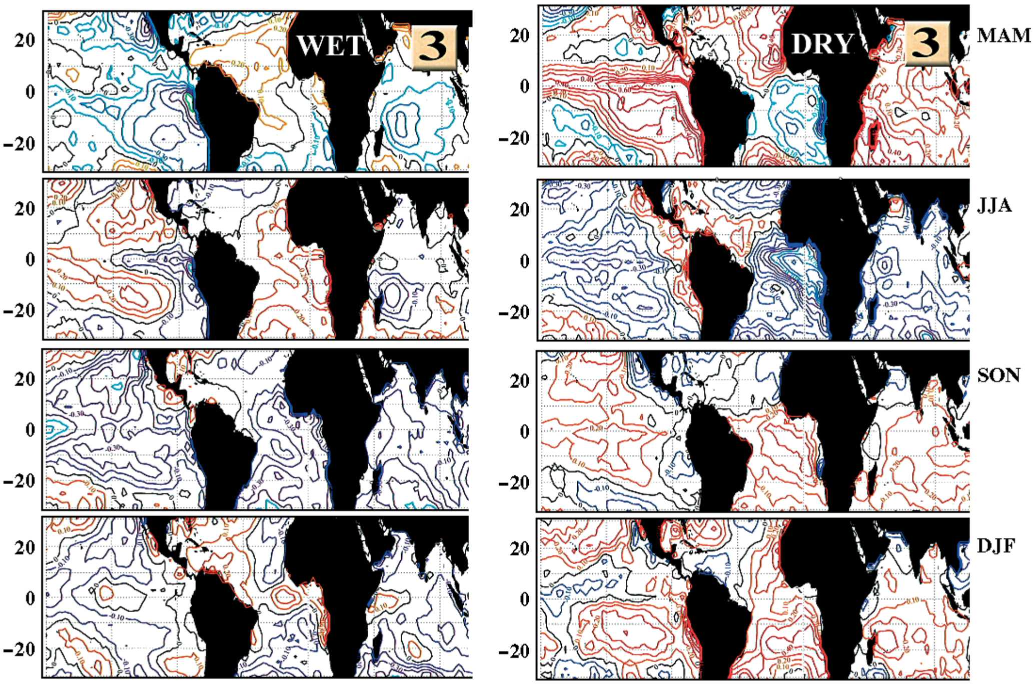

Figure 5. As in 3, but for Region 3.

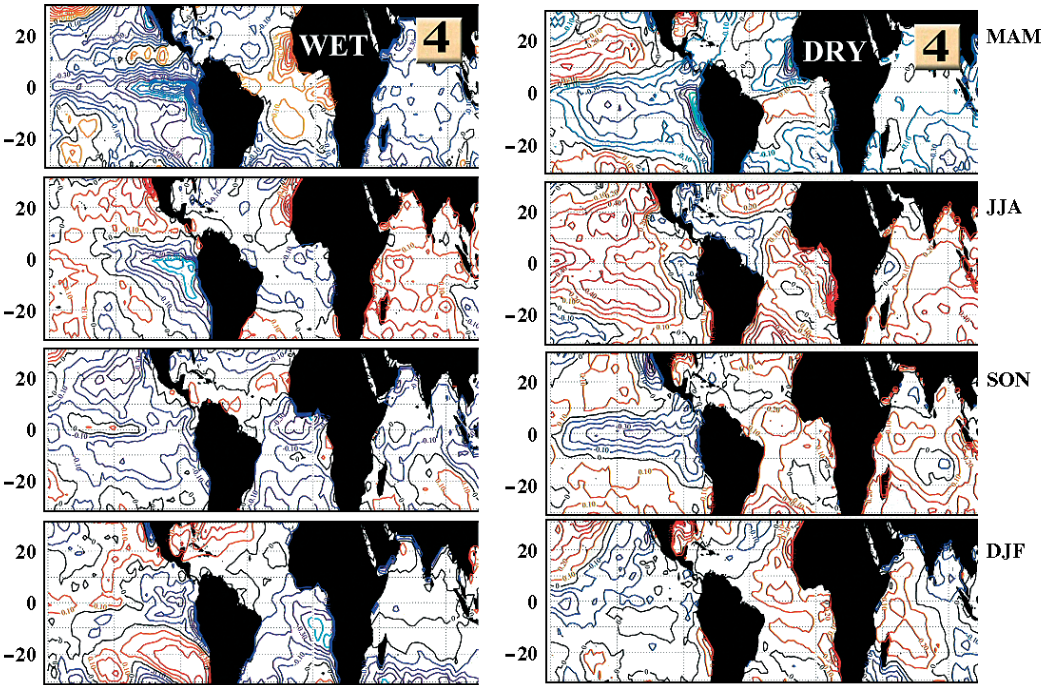

Figure 6. As in 3, but for Region 4.

local and direct influence of SSTs in this sector. These are replaced by warm anomalies in the dry composites for SON and DJF. Hence the impact of a particular SST pattern is seasonally dependent.

It is further interesting that, as in Region 1, there is an ocean-wide tendency for positive SST anomalies to be associated with dry conditions and for negative SST anomalies to be associated with wet conditions. This is true for all seasons except JJA, when dry/wet conditions are associated with negative/positive SST anomalies. Quite unlike Regions 1 and 2, the wettest and driest conditions here do not appear to show a strong link to the Pacific El Niño. The El Niño SST pattern is apparent only in the MAM dry composite.

Region 4

Region 4 lies just north of the equator and just to the east of Region 3. Both regions experience a pronounced

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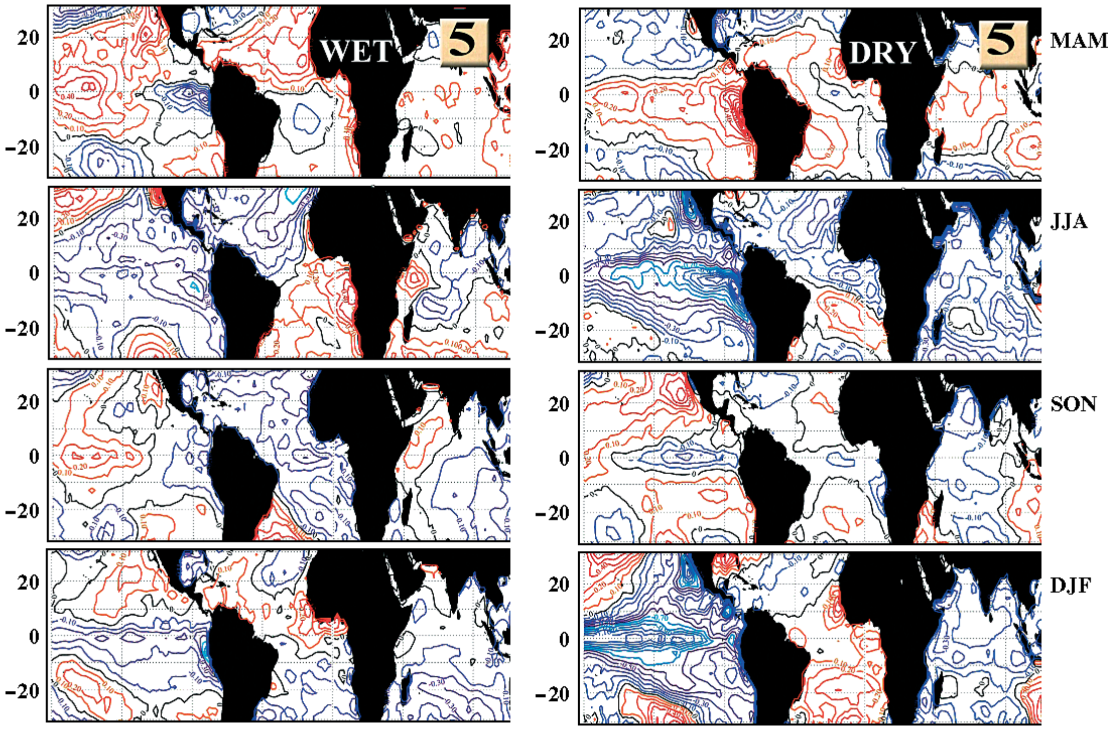

Figure 7. As in 3, but for Region 5.

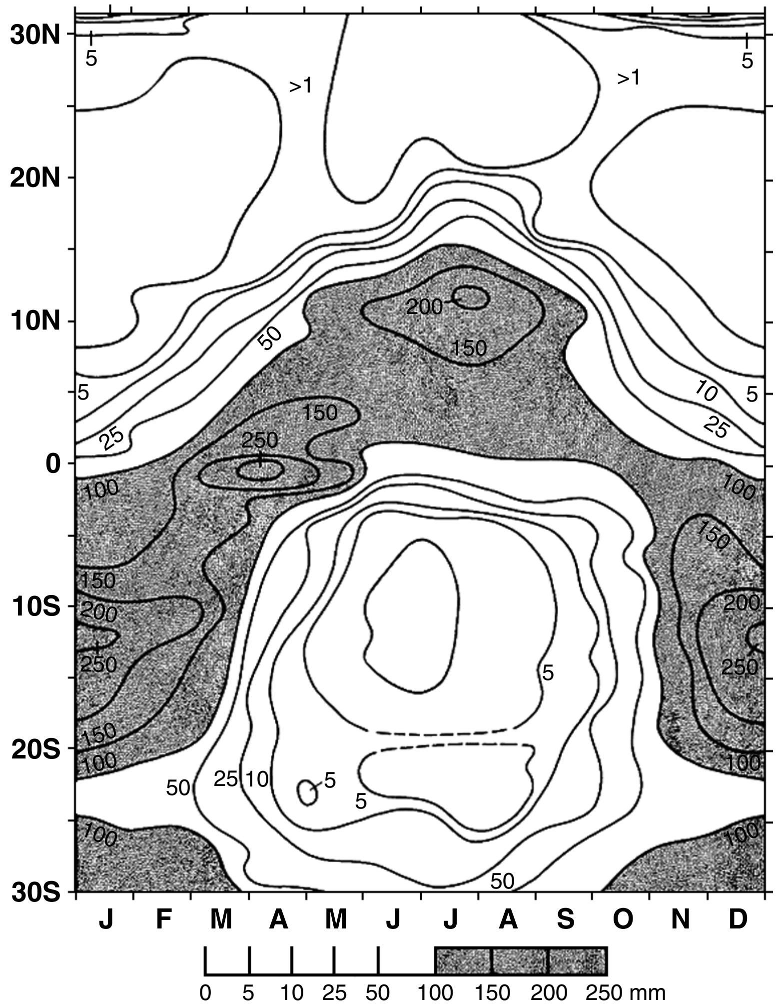

Figure 8. Location of maximum convective activity over Africa during each month of the year, as assessed from rainfall maxima.

dry season in DJF, but there is no pronounced rainy season or dry season during the remaining months of the year. However, in Region 4 three peaks are apparent in the annual cycle: May, August and October. This region thus combines the characteristics of Region 1 and the equatorial Regions 3 and 5; hence it appears to be a transition zone between the equatorial and tropical climates. It is most likely that rainfall in Region 4 is linked to equatorial variability in some years and to variability in the northern tropics in other years.

The most consistent contrast between wet and dry conditions in Region 4 is seen in the Atlantic (Figure 6). The SST anomalies tend to reverse signs between the wet and dry composite in each season. Coastal upwelling appears to play a prominent role in MAM and JJA. In contrast to other regions, the change in the upwelling is apparent not only along the Benguela Coast, but also it is even more marked off the coast of West Africa. In no case is a Pacific El Niño warming signal apparent, but La Niña-like cooling is evident in both the wet and dry composites for MAM, in the JJA wet composite, and in the SON dry composite.

Integrating the various associations, a reasonable conclusion is that the SST anomalies along the Benguela Coast are most important in Region 4. This was also the case for Region 3. This is illustrated using the MAM composites. Strong cooling in the Pacific is evident in both the dry and wet case, as is upwelling along the Benguela Coast. The sign of the rainfall anomaly in Region 4 appears to depend on how far northward the upwelling reaches. When SST anomalies are positive near the equator, MAM in Region 4 is anomalously wet.

Region 5

Region 5 lies to the south of Region 4 and straddles the equator. Its rainfall seasonality has the typical equatorial signature of two wet seasons, occurring during the transition seasons, and two dry seasons occurring in the extreme seasons. The SON rainy season is the dominant one. The seasonal cycle is less pronounced in Region 5 than in Region 3, to the west of it.

In contrast to other regions, there is not a strong reversal in the signs of the SST anomalies between the wettest and driest years (Figure 7). Also, the anomalies are overall weak, especially in the wet composites. An examination of the patterns season by season suggests an interpretation based on shifts in the areas of strongest convection, with different factors prevailing in the dry and rainy seasons.

The most striking feature of the anomalies is La Niña-like cold anomalies in the Pacific during the wettest years for the JJA and DJF dry seasons. However, cold anomalies cover the tropical Pacific in the wet years as well, although they are less pronounced. Thus, the Pacific is probably not the controlling influence.

The most pronounced wet/dry contrast is in the equatorial Atlantic but the SST/rainfall association is quite different in JJA and DJF. In JJA/DJF the equatorial and South Atlantic is anomalously warm/cold during wet years and anomalously cold/warm during the dry years. Our interpretation is based on the seasonal positions of the ITCZ (Figure 8). During both seasons rainfall in Region 5 would be enhanced by an SST pattern that reduces the ITCZ's poleward excursion, promoting a more equatorial location. The Atlantic dipole in the wet JJA composite, with positive anomalies in the equatorial and eastern Atlantic, does just that (Lamb, 1978). However, the warmer/cooler temperatures along the Benguela Coast in the wet/dry composite probably also play a role. During DJF the inverse dipole, with negative anomalies south of the equator, would likewise serve to keep the ITCZ near the equator.

The SST/rainfall association in the two rainy seasons is quite different. Our interpretation involves an east–west shift in the region of maximum convection. To see this, consider the seasonal cycle of rainfall in the western equatorial regions. In all of those with two rainy seasons and two dry seasons, the main rainy season is around SON and the secondary rainy season occurs around MAM. Exactly the opposite is true in eastern equatorial Africa: the main rains occur in MAM and ON is the 'short rains'. This suggests an east/west shift in the convective maximum between the two seasons. We suggest that the balance shifts in the opposite direction when MAM is abnormally wet in Region 5 or OND is abnormally dry.

Two observations support this hypothesis. In MAM wet and dry years appear to be distinguished primarily by the sign of SST anomalies along the Benguela Coast, with wet conditions corresponding to positive anomalies. This suggests a local SST influence, as was noted earlier for this season in all regions except Region 1. During the SON season, the strongest contrast appears to be in the Atlantic, with more positive anomalies in the dry composite than in the wet composite. However, the Atlantic anomalies are weak in both cases. We suggest that the important contrast in this case is the temperature gradient between the Indian and Atlantic Oceans during the wet seasons. The SST anomaly configurations in MAM dry and SON wet would enhance it, the result being an eastward shift of convection in both cases.

The study by Camberlin *et al*. (2001) also gives credence to our interpretation, at least for the SON season. They show that the seasonal response to ENSO systematically shifts from the western to the eastern equatorial regions. Specifically in SON, the eastern and western extremes show correlations of the opposite sign with Pacific SSTs in the Niño3 sector.

Associations among equatorial Regions 3, 4 and 5

The factors producing variability appear to be particularly complex in the three equatorial regions. In all three (Regions 3, 4 and 5) two rainy seasons occur during the year and the major dry season occurs during DJF. A number of interesting similarities and contrasts are apparent in the SST/rainfall relationships in these regions, particularly in MAM and JJA.

The first feature to note is that the SST anomalies linked to dry conditions during MAM in Regions 3 and 5 are quite similar, but the pattern is reversed for Region 4. The patterns for a dry MAM in Regions 1 and 2 resemble those for 5 and 3, respectively. In those four regions dry conditions are associated with generally warm SSTs, but in Region 4 dry conditions are associated with cold SSTs. No explanation for the contrasting controls in Region 4 is readily apparent. Region 4 lies at the same latitude as Region 3 and at about the same distance from the coast as Region 5.

The only geographical difference between Region 4 and the others is that it is encompasses a low-lying basin surrounded by higher terrain. The other regions encompass the higher terrain. Thus, one possibility is compensatory subsidence when rainfall is anomalously high in the surrounding regions. Consistent with this idea, the large-scale SST patterns associated with a dry MAM in Region 4 are similar to those associated with a wet MAM in Region 3. However, they are also similar to those associated with wet conditions in Region 4.

Thus, the link to rainfall is probably more localized. The contrast between the wet and dry MAM composites for Region 4 is the extent of the coastal upwelling. When it extends to the equator, Region 4 is dry; if coastal SSTs are warm near the equator, Region 4 is wet. The key to understanding the SST patterns affecting Region 4 appears to be La Niña. The cold pattern corresponding to the wet MAM seasons is strongly reminiscent of that occurring in the Atlantic and Indian Oceans during AMJ of the La Niña year; that of the dry composite resembles that of the post-La Niña year (Nicholson and Selato, 2000). An examination of the time series of rainfall during MAM (not shown) indicates this to be the case. Hence, both the wet and dry extremes of the MAM season in Region 4 appear to be linked to La Niña. In the other regions the SST patterns corresponding to dry conditions in MAM appear to be those occurring in the post-ENSO year (Nicholson, 1997). Thus during MAM, dryness in Region 4 is associated with La Niña while the dry conditions in the other regions are linked to ENSO. This suggests that El Niño and la Niño shift the position of convection during MAM over western equatorial Africa.

Another interesting feature is that the SST patterns linked to dry conditions in JJA are essentially the reversal of those linked to dry conditions in MAM. The only exception is Region 1. A determination of the meteorological factors explaining this situation is beyond the scope of this article. However, it should be noted that the SST conditions of the dry JJA for Regions 2 to 5 are similar to those occurring in the summer prior to El Niño years. The relevant point is that the pattern of SSTs linked to dry conditions is the opposite in the two seasons. Hence, the rainfall variability is not directly forced by the ocean, but rather by coupled ocean–atmosphere dynamics.

The situation is quite different for the wet composites and for JJA. The SST patterns associated with wet years in JJA bear little relationship to those associated with wet conditions in MAM. However, they are opposite in sign to those prevailing in the dry composite for JJA, especially in the tropical Atlantic and Indian Oceans. This suggests that the rainfall in JJA is more closely coupled to the ocean, especially to the tropical Atlantic. The SST patterns of JJA for the wet composites suggest a possible mechanism. For Regions 1 and 4, with generally high rainfall in JJA, cold SSTs are linked with the wet composites. For the other regions, where a pronounced dry season prevails during JJA, wet conditions are linked to warm SSTs. This suggests a local displacement of the convection and ITCZ southward by the warm waters during JJA. This mechanism has been identified as a factor in rainfall variability in West Africa in those seasons (e.g. Lamb, 1978).

LINEAR ASSOCIATIONS BETWEEN SSTS AND RAINFALL: SEASONALITY OF OCEAN INFLUENCE

The composites suggest that several factors govern the interannual variability of rainfall and that these differ seasonally. The ones that seem to be most important include SST anomalies along the Benguela Coast, a general warming or cooling of the tropical ocean regions, Atlantic SSTs specifically, the contrast between the Atlantic and Indian Oceans, and the Pacific ENSO or La Niña. The influence of the coastal anomalies may be local, in which case SSTs and rainfall are positively correlated, or remote, in which case the correlation is more likely to be negative. The composites suggest that, in general, the Pacific plays the greatest role in MAM in all regions except 4. SSTs along the Benguela Coast also seem to be important in that season. These may, in fact, be closely linked to events in the Pacific (Nicholson and Entekhabi, 1987). Atlantic SSTs individually appear to be most important in Regions 2 and 5.

To test the generality of the above conclusions, seasonal rainfall totals for each region are correlated with SSTs in each of the ocean sectors shown in Figure 2. A correlation is also made with the mean anomaly in a sector including the South Tropical Atlantic and Indian Ocean sectors (A2 + I1) and in a sector including those regions plus the South Pacific (P1). The results are presented in Table II.

These confirm that in four of the five regions the highest correlation in MAM is with the Niño 1 + 2 in the Pacific. In all cases the correlation is negative. Correlations are also high with Niño3, but considerably lower with Niño4. The correlation also tends to be high and negative with the South Tropical Indian Ocean during this season, particularly for Regions 1 and 3. Rainfall in Region 4 and SSTs are uncorrelated for MAM.

The impact of the Pacific on rainfall in MAM is illustrated in Figure 9. An ENSO warming signature is evident during the driest MAM seasons for all regions except 4. A La Niña cooling pattern is evident in Region 4, but the same pattern is also evident in the

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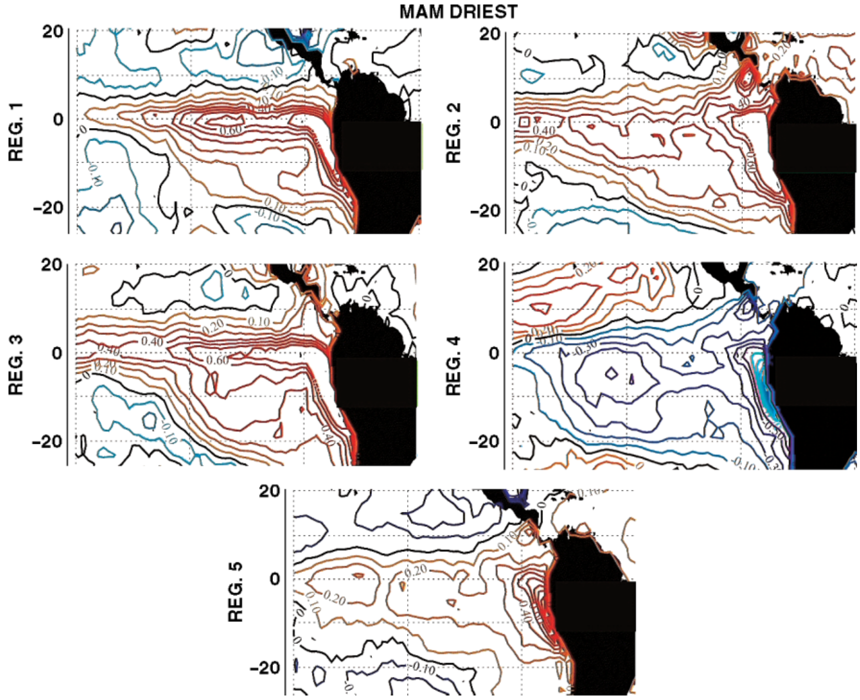

Figure 9. Tropical Pacific SST anomalies corresponding to the five driest MAM seasons in all regions.

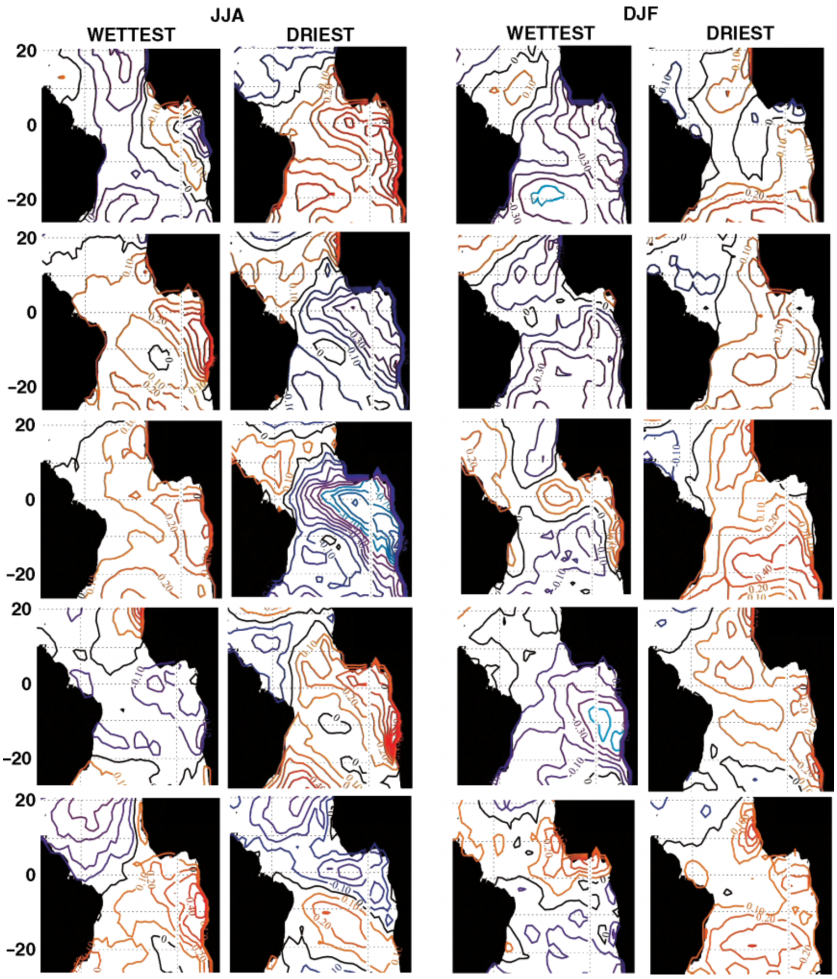

Figure 10. Tropical Atlantic SST anomalies corresponding to the five wettest and five driest JJA seasons in all regions. Regions 1 to 5 are arranged from top to bottom.

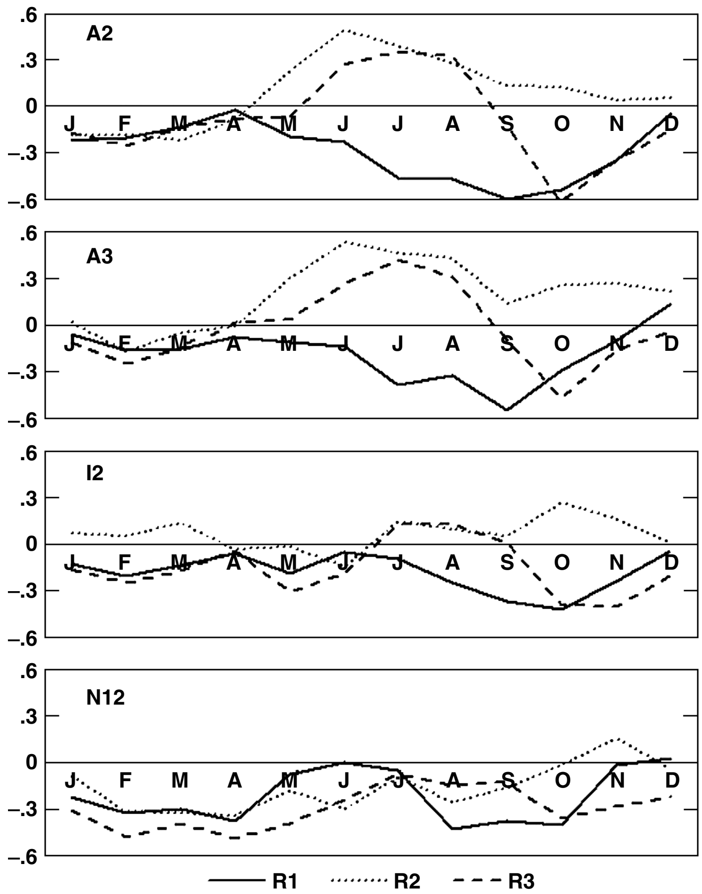

Figure 11. Correlation between monthly rainfall and monthly SSTs for select regions and sectors. Rainfall is represented by a 3-month running mean. With 49 correlation pairs in each case, the 1% significance level is 0.36 and the 5% significance level is 0.28.

wettest MAM seasons of Region 4 (see Figure 6). This accounts for the low correlations. The critical factor there appears to be the extent to which the Benguela coastal sector is affected.

During the JJA season the best correlations are with the Atlantic for all regions except Region 5, where the best correlation is with the South Tropical Indian Ocean. The correlation with A3 reaches 0.5 for Region 3 and 0.6 for Region 2. Since each correlation consists of 49 correlation pairs, these values are highly significant. In most cases, the highest correlation is with A3. During this season, correlations are also high with the global South Tropical Oceans, but these are generally much lower than the correlations with the Atlantic alone. It is important to note that in JJA, the Atlantic is positively correlated with rainfall in Regions 2 and 3, but negatively correlated with rainfall in Region 1.

In SON the situation is quite different and the SST sector best correlated with rainfall varies considerably from region to region. For Regions 1 and 3 it is with the South Tropical Atlantic or with that sector plus the South Tropical Indian Ocean. Correlations are as large as −0.58 for Region 3. Correlations are negative with rainfall in Regions 1 and 3, and positive with rainfall in Regions 2 and 4.

In DJF the best correlation tends to be with the Atlantic, and it is negative. For Regions 1, 2, and 3 the best SST/rainfall correlation is with Atlantic 3. For Region 5 it is with Atlantic 2. For Region 1, correlations are equally large with Pacific sectors Niño 1 + 2 and Niño3, with the South Tropical Indian Ocean and with the global South Tropical Oceans.

The importance of the Atlantic in JJA and DJF is illustrated in Figure 10, which shows SSTs in the driest and wettest years for each region in these two seasons. Two features are immediately apparent. One is that there is a reversal of the sign of the anomalies between the wettest and driest years. The second is that a warm Atlantic is associated with high rainfall in JJA, but with low rainfall in DJF. Hence the impact of the Atlantic anomalies reverses between the boreal summer and the austral summer. Also interesting is that an exception is evident for Regions 1 and 4. There a warm/cold Atlantic is instead associated with low/high rainfall in JJA.

DISCUSSION

One of the most interesting results of this study is the apparent seasonal shift in controls on rainfall variability. The foregoing analyses suggest that in much of western equatorial Africa, rainfall variability is linked to the Pacific El Niño and the western Indian Ocean early in the year, but to the Atlantic during the boreal summer

Table II. Linear correlation between SST sectors and seasonal rainfall in the five analysis regions. Location of the SST sectors is shown in Figure 2.

Reg 1	Niño1 + 2	Niño3	Niño4	A1	A2	A3	I1	I2	A2 + I1	P1 + A2 + I1
DJF	−0.33	−0.31	−0.19	0.01	−0.23	−0.31	−0.36	−0.36	−0.02	−0.35
MAM	−0.35	−0.20	0.04	0.05	−0.04	−0.02	−0.29	−0.12	−0.2	−0.22
JJA	−0.01	−0.01	−0.11	0.19	−0.36	−0.34	−0.15	−0.10	−0.34	−0.28
SON	−0.10	−0.10	−0.22	0.28	−0.4	−0.24	−0.22	−0.37	−0.46	−0.38
Reg 2	**Niño1 + 2**	**Niño3**	**Niño4**	**A1**	**A2**	**A3**	**I1**	**I2**	**A2 + I1**	**P1 + A2 + I1**
DJF	−0.17	−0.13	−0.03	−0.31	−0.17	−0.40	0.03	0.10	−0.10	−0.13
MAM	−0.31	−0.22	−0.16	−0.04	0.04	0.14	−0.22	−0.02	−0.10	−0.2
JJA	−0.13	−0.22	−0.16	−0.09	0.49	0.60	0.15	0.14	0.41	0.26
SON	−0.10	−0.12	−0.09	−0.13	0.07	0.34	0.13	0.25	0.16	0.03
Reg 3	**Niño1 + 2**	**Niño3**	**Niño4**	**A1**	**A2**	**A3**	**I1**	**I2**	**A2 + I1**	**P1 + A2 + I1**
DJF	−0.1	0.02	−0.12	−0.02	−0.25	−0.44	−0.42	−0.37	−0.2	−0.29
MAM	−0.41	−0.35	−0.2	0.05	−0.10	−0.07	−0.38	−0.24	−0.27	−0.37
JJA	−0.1	−0.05	0.13	−0.07	0.41	0.51	0.10	0.07	0.31	0.25
SON	−0.23	−0.22	−0.28	0.03	−0.54	−0.35	−0.27	−0.39	−0.58	−0.53
Reg 4	**Niño1 + 2**	**Niño3**	**Niño4**	**A1**	**A2**	**A3**	**I1**	**I2**	**A2 + I1**	**P1 + A2 + I1**
DJF	0.14	0.18	0.19	0.01	0.15	0.06	0.03	0.12	0.09	0.27
MAM	−0.03	0.15	−0.06	0.14	−0.11	0.13	−0.01	−0.04	−0.08	−0.09
JJA	−0.30	−0.29	−0.17	0.13	−0.16	−0.14	−0.10	0.12	−0.06	−0.19
SON	0.33	0.29	0.27	0.12	−0.08	−0.07	0.02	0.16	−0.05	0.21
Reg 5	**Niño1 + 2**	**Niño3**	**Niño4**	**A1**	**A2**	**A3**	**I1**	**I2**	**A2 + I1**	**P1 + A2 + I1**
DJF	−0.08	0.10	0.10	0.15	−0.24	0.12	−0.02	0.21	0.12	−0.09
MAM	−0.40	−0.31	−0.20	−0.17	−0.04	0.17	−0.14	0.05	−0.06	−0.21
JJA	0.03	0.05	0.01	−0.21	−0.10	0.21	0.31	0.24	0.21	0.17
SON	−0.07	−0.02	−0.09	−0.01	−0.03	0.17	0.01	0.15	−0.02	−0.02

months. The western Indian Ocean again becomes important in late summer/early fall. To further test these conclusions and simplify the relationships shown in Table II, SST/rainfall correlations are calculated on a monthly basis for the SST and rainfall regions showing the strongest associations. Figure 11 presents a plot of the results.

The results shown in Figure 11 also underscore the complex relationships between Regions 1, 2, and 3. The correlations between rainfall and Atlantic 3 SSTs are significant only during the months of May through November. Throughout the boreal summer the rainfall/SST correlation is negative for Region 1 but positive for Regions 2 and 3. Presumably, the underlying physical link is the ITCZ, with warm SSTs in the equatorial Atlantic stabilizing its equatorial position (i.e., near Region 2 and 3) and retarding its advance into the northern hemisphere, toward Region 1. In October and November the situation changes markedly. A3 is inversely correlated with Regions 1 and 3 but positively correlated with Region 2. The seasonal displacement of the ITCZ could again explain this result, with the warm SSTs promoting its southward retreat during boreal fall. A similar pattern is seen with A2; however, correlations are somewhat higher with A3 early in the boreal summer and with A2 in late summer and early fall.

In boreal fall correlations with I2 are similar to those for the two Atlantic regions in both sign and magnitude (Figure 11). The correlation is negative for Region 1 and positive (but insignificant) for Region 2. For Region 3 the correlation shifts from positive in the boreal summer to negative in fall, being close to zero during September as the shift occurs.

The seasonal variation of apparent controls on rainfall variability is interesting in view of what is known about the variability of the tropical Atlantic. The two major spatial modes are the Atlantic Niño (Covey and Hastenrath, 1978; Philander, 1986; Zebiak, 1993; Carton and Huang, 1994; Latif and Grötzner, 2000), an equatorial warming that resembles the pattern in the wet composite for Region 2 in JJA, and the Interhemispheric mode (Sutton *et al*., 2000; Covey and Hastenrath, 1978; Philander, 1986; Carton and Huang, 1994; Chang *et al*., 2000; Wang and Carton, 2003), a dipole with a node near or north of the equator and opposite anomalies to the north and south.

During the Atlantic Niño positive SST anomalies develop in the eastern equatorial basin, displacing convection southeastward (Ruiz-Barradas *et al*., 2000). This mode has its strongest expression in boreal summer and fall (Chang *et al*., 2000; Sutton *et al*., 2000; Wang and Carton, 2003). The rainfall/Atlantic SST correlation is also strong in these two seasons. Either the Atlantic Niño warming pattern or its inverse is apparent in all of the wet and dry composites for JJA, shown in Figure 10. The southeastward displacement of convection would account for the correspondence between the Atlantic Niño and dry conditions in Region 1 and 4, wet conditions in Regions 2, 3 and 5. Likewise, when the upwelling is strong and equatorial Atlantic anomalies negative, dry conditions

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prevail in Regions 2, 3 and 5, while Regions 1 and 4 are wet. Thus, the Atlantic Niño appears to be a major factor in rainfall variability in western equatorial Africa during boreal summer and fall.

The Pacific influences Atlantic variability in at least two ways. The Interhemispheric mode is forced largely by ENSO, especially on the interannual times scales evaluated in this study (Czaja *et al*., 2002). ENSO's influence is strongest in the boreal spring, and is associated with anomalies in the Walker circulation, but some teleconnections exist in the boreal winter as well (Saravanan and Chang, 2000). Also, during ENSO events, a wave train sometimes emanates from the central Pacific across South America to the South Atlantic. This occurs most frequently in the austral spring, September to December (Mo, 2000; Mo and Häkkinen, 2001). The area of the South Atlantic that is affected strongly influences variability in the tropical Atlantic (Venegas *et al*., 1997; Rajagopalan *et al*., 1998; Tourre *et al*., 1999; Hickey and Weaver, 2003). This region also shows up prominently in our reconstruction of links between tropical Atlantic SSTs and Pacific ENSO (Nicholson, 1997; Nicholson and Kim, 1997) and in our contrast between wet and dry years in West Africa (Nicholson and Webster, 2005) and Southern Africa (Nicholson, 1989).

SUMMARY AND CONCLUSIONS

The factors governing interannual variability in western equatorial Africa differ among the five regions evaluated. The most pervasive influences are those of the equatorial Pacific and the Benguela Coast of the Atlantic. The coastal SSTs are probably a response to the Pacific ENSO and they can modulate rainfall directly or indirectly. The influence of both factors is limited mainly to the period MAM. This is the secondary rainy season in four of the five regions.

During the remaining seasons, the prime influence varies among the regions. In Region 1 the dominant factor appears to be a general warming or cooling of the tropical oceans; warm/cold SSTs correspond to anomalously low/high rainfall. This is the case in Region 3, as well, during SON and DJF; but the Atlantic is the primary factor during JJA. Region 2 appears to be governed mainly by Atlantic SSTs. However, in JJA, high/low rainfall is linked to a warm/cold Atlantic, and in SON/DJF, the sign of the SST anomalies reverses. The situation is more complex in Region 4 and 5. During JJA there appears to be a link between the Pacific and Region 4, but the Atlantic appears to be most important in Region 5 in that season and in DJF. The sign of anomalies in the tropical Atlantic and Indian Oceans appears to be most important in SON and DJF in Region 4 and in SON in Region 5.

The role of the Atlantic, especially the coastal Atlantic, appears to be a modulation of the north–south excursion of the ITCZ. Hence the polarity of the SST/rainfall association depends on location. The association between SSTs near the coast and rainfall depends on whether the influence is direct, in which case the correlation is positive, or indirect, in which case the correlation can be positive or negative. An opposition between the Indian and Atlantic Oceans appears to displace convection in an east–west direction. Anomalies along the Benguela Coast can influence the east–west displacement of the convection. The combination of the various influences accounts for the complexity within the western equatorial regions.

The mechanisms of the associations with the Pacific and with the global South Tropical Oceans are more difficult to determine from this limited analysis. We do, however, suggest that the Pacific's role is indirect and is manifested via its influence on the Atlantic and that the global influence is mainly thermodynamic, with warm SSTs promoting convection over the oceans with a compensating reduction over land.

Our results also suggest several generic conclusions concerning the relationships between SSTs and continental rainfall. The first is that the influence of the three oceans is seasonally dependent. In this case, the Pacific is important mainly in MAM and the prime influence in JJA is the Atlantic. Secondly, the impact of an SST anomaly is seasonally dependent. It may enhance rainfall in one season, but reduce it in the following season. Finally, the SST/rainfall associations are generally not symmetric. That is, the factors producing wet conditions are not the reverse of those producing dry conditions. In order to understand these associations, the underlying mechanisms via the general atmospheric circulation must be determined.

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