The Relationship of Rainfall Variability in Western Equatorial Africa to the Tropical Oceans and Atmospheric Circulation. Part II: The Boreal Autumn

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ABSTRACT

This paper examines the mechanisms controlling the year-to-year variability of rainfall over western equatorial Africa during the rainy season of October–December. Five regions with distinct behavior are analyzed separately. Only two show strong associations with the ocean and atmospheric features in the global tropics. These two regions, in the east (the eastern Zaire basin) and west (Angolan coast) of the study area, respectively, demonstrate strikingly opposite relationships with the anomalies of sea surface temperatures (SSTs), sea level pressure (SLP), and east–west atmospheric circulation. The wet (dry) conditions in the eastern Zaire basin are associated with El Niño (La Niña)–like phases. The inverse pattern is apparent for the Angolan coast. The other three regions, lying between these two poles of variability, represent a transition zone with a weak linear relationship to the circulation features.

The vital impact of the east–west circulation cells on rainfall variability results in a stronger association with zonal wind than with SSTs or SLP. In addition to the zonal shift, changes in intensity of the zonal cells also play a crucial role. Variability in both magnitude and location of the circulation cells appear to be modulated by the remote forcing from the Pacific via an atmospheric bridge. However, the eastern sector is impacted mainly when synchronous changes occur in the Indian Ocean, and the western sector is impacted mainly when synchronous changes occur in the Atlantic Ocean.

1. Introduction

Western equatorial Africa has long been neglected, meteorologically speaking. Even the seasonal cycle of rainfall is not well understood. In contrast to most other equatorial regions, a pronounced dry season occurs during the boreal summer. The rainy season is bimodal, with maximum rainfall in the transition seasons. This pattern of seasonality has traditionally been explained by the twice-annual passage of the intertropical convergence zone (ITCZ). However, this explanation breaks down when the patterns of surface convergence and wind flow are examined (S. E. Nicholson and A. K. Dezfuli 2012, unpublished manuscript). Moreover, the character of the two rainy seasons is quite different, a fact that is inconsistent with rainfall being linked to ITCZ.

In Nicholson and Dezfuli (2013, hereafter Part I), we examined the rainy season of the boreal spring, the months of April–June (AMJ). In the current paper, we examine the rainy season of the boreal autumn, the months of October–December. The article commences with a description of select features of the mean climatology of the October–December season. Then rainfall variability is examined for the five regions shown in Fig. 1. Rainfall is correlated with sea surface temperatures (SSTs) and sea level pressure (SLP) in the global tropics and two cases with strong links to these large-scale factors are considered in greater detail, in order to examine atmospheric factors prevailing during anomalous wet or dry October–December seasons.

2. The equatorial rainy season of boreal autumn

The rainy season of boreal autumn, October–December (OND), is the primary one in most of western equatorial
Africa. The exceptions are the far north, where rainfall peaks in the boreal summer, and the extreme east, where the boreal spring season becomes progressively more important. The pattern of rainfall in OND (Fig. 1) is markedly different than it is in the AMJ season (Jackson et al. 2009). In AMJ rainfall, the rain belt is a zonally oriented band stretching over nearly all the equatorial region. In OND the band is broader and markedly farther south, but the bulk of rains fall west of the Rift Valley highlands and East Africa is relatively dry.

Balas et al. (2007) examined the relationship between rainfall in the September–November (SON) season and tropical SSTs for five regions of western equatorial Africa and found strong links for only two regions. For both regions, the correlations were strongly negative with SSTs in the tropical Atlantic and Indian Oceans, but correlations with the equatorial Pacific were weak. Okumura and Xie (2006) also found a strong correlation between equatorial Atlantic SSTs and SON rainfall, specifically along the Angolan coast.

Nicholson and Grist (2003) evaluated the seasonal cycle in western equatorial Africa, focusing on the sector 10°–30°E. They showed that the rain belt was much stronger in the OND season than in the AMJ season and that in both seasons the maximum rainfall occurred some 10°–15° of latitude south of the surface ITCZ. They also documented the existence of a strong mid-level easterly jet in the Southern Hemisphere during the OND season. Termed the Southern Hemispheric African easterly jet (AEJ-S), this feature appears to modulate the spatial distribution of rainfall, limiting the eastward extension of the rain belt during OND.

Mohr and Zipser (1996) showed that this region is the site of some of the world’s most intense convective activity. Jackson et al. (2009) evaluated the mesoscale convective systems in the region and provided evidence that the very intense convection is linked to the presence of the AEJ-S. Easterly waves with periods of 3–5 days are common features in SON, but the origin appears to be near the coast, possibly triggered by the coastal highlands of the thermal discontinuity at the coast (J. D. Baum 2012, personal communication). It is not known whether there is a link between the waves and convection, although such a link has been demonstrated for the AMJ season (Nguyen and Duvel 2008).

Figure 2 shows the mean sea surface temperatures for the OND season. Notable features of the Atlantic near Africa include an area of strong upwelling along the Benguela coast of the southeastern Atlantic, an equatorial cold tongue in the Atlantic, and an area of upwelling off the northwest coast of Africa. Notable in the Indian Ocean is the strong zonal temperature gradient in its western sector from roughly 15°N to 15°S, with anomalously cold temperatures along the coast of East Africa.

The dominant features of the mean sea level pressure field (Fig. 2) are subtropical high pressure cells; three of which are in proximity to the African continent. High pressure prevails over most of North Africa, while a smaller low pressure cell is evident over southern Africa.

Figure 3 shows the mean vector winds at five levels for the 3-month season. Throughout the lower troposphere (1000, 925, and 850 hPa) easterlies prevail east of the Rift Valley highlands. West of the highlands, the flow is primarily easterly or northeasterly north of the equator (to 20°N) and very weak in the low latitudes. At 850 hPa, easterlies prevail in the equatorial Atlantic. At 925 and

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**Fig. 1.** (middle) Homogeneous rainfall regions for the October–December season, superimposed upon a map of topographic relief. Asterisks indicate stations utilized. (left) The typical seasonal cycle for each region is also indicated. (right) Mean rainfall (mm) during the October–December season for the period 1948–88.
1000 hPa, southeasterlies prevail over the south and equatorial Atlantic. These winds take on a westerly component as they cross the equator, converging with the northeasterly Harmattan flow off the Sahara at \( \sim 10^\circ \text{N} \), marking the location of the ITCZ. At 600 hPa, easterlies prevail throughout equatorial Africa, to be replaced by westerlies at 200 hPa poleward of roughly \( 10^\circ \) of latitude in either hemisphere.

3. Data and methodology

Figure 1 shows the western equatorial sector considered in this study. It includes the Zaire basin and the highlands surrounding it on all sides. The western extension stretches along the Atlantic coast; the eastern extreme includes the western part of the Rift Valley highlands. The heterogeneity of the region with respect to rainfall variability and the difficulties in producing an appropriate regionalization were recognized in previous works (Nicholson 1986; Balas et al. 2007). Part of the difficulty is the sparse and irregular station network (Dezfuli 2011).

The approach used here was to delineate regions based on Tropical Rainfall Measuring Mission (TRMM) rainfall estimates and use gauge data to produce time series for these regions. This compromise allows for the continuous spatial coverage afforded by TRMM and the longer temporal coverage of the gauge data. TRMM 3B42 precipitation estimates, which have a \( 0.25^\circ \times 0.25^\circ \) spatial resolution, were utilized for the period 1998–2008.

These are available from the National Aeronautics and Space Administration (NASA) website (http://mirador.gsfc.nasa.gov). The gauge dataset assembled by the second author (Nicholson 1986) includes 141 stations in the study area, but those with more than 10% missing data were eliminated from the analysis. This left 107 stations. Although the gauge dataset extends from early in the twentieth century to 1998, analyses were based on the period 1948–88 because most stations were available throughout this period.

The five regions shown in Fig. 1 were delineated (Dezfuli 2011; A. K. Dezfuli and S. E. Nicholson 2012, unpublished manuscript) using a combination of rotated principal component analysis and Ward’s clustering technique (e.g., Gong and Richman 1995; Unal et al. 2003; Rao and Srinivas 2006). Each was determined to be homogeneous with respect to the interannual variability of rainfall. The regions bear some relationship to topography. Region 1 includes mainly the southern areas of the Zaire basin and the northern slopes of the central African plateau. Region 2, the easternmost region, lies over the western highlands of the Rift Valley. Region 3 includes mainly the southern areas of the Zaire basin and the northern slopes of the central African plateau. Region 4 includes mainly the northern portion of the Zaire basin. Region 5, the westernmost region, includes the Atlantic coast and the highlands of Cameroon.

For each region, a standardized rainfall anomaly series for the three-month season was calculated, following Nicholson (1986). Each time series was correlated
with SSTs and sea level pressure in the global tropics. The National Oceanic and Atmospheric Administration (NOAA) extended reconstructed sea surface temperature V3 product, which is available at a 2° × 2° resolution, was utilized (Smith et al. 2008). Surface pressure and other atmospheric variables were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996; Kistler et al. 2001). These are monthly data available on a 2.5° × 2.5° grid. For both datasets, anomalies were calculated with respect to the 1948–88 mean.

Fig. 3. Mean wind vectors from (top to bottom) five levels during October–December for the period 1948–88.
Two regions that show particularly strong links to SSTs were further examined, using composites of the four wettest years and the four driest years. Composites of SST anomalies and anomalies of various atmospheric parameters, such as winds, divergence, and vertical motion, are derived and compared with the mean climatology, described in section 2.

4. Rainfall variability

Figure 4 shows the time series for the five regions from 1948 to 1988. In regions 3, 4, and 5, there is some tendency for lower rainfall starting in the mid- to late 1960s. This same tendency was evident in most regions of western equatorial Africa in the April–June season as well (Part I). This shift to drier conditions is roughly commensurate with the onset of drought conditions in the West African Sahel. Region 2 has a tendency for wetter conditions commencing in the 1960s, but the 1970s were relatively dry. The interannual variability is notably stronger in regions 2 and 5 than in the remaining regions. Year-to-year changes are particularly small in region 1. Correlations are positive and significant among regions 3, 4, and 5 (Table 1). Regions 1 and 2 are also highly correlated.

These facts suggest a scenario in which regions 2 and 5 (eastern Zaire basin and Angolan coast, respectively) comprise two poles of variability, with regions 1, 3, and 4 (collectively termed the central Zaire basin) representing transition zones lying between them. The term “dipole” would not apply, as the anticorrelation between the poles is weak. Rather, this represents one of several modes of variability in equatorial Africa, one in which a clear east–west opposition is evident (S. E. Nicholson and A. K. Dezfuli 2012, unpublished manuscript).

Table 2 lists the wettest and driest OND seasons for each region. There is some tendency for the wettest seasons to occur in the 1950s and 1960s, and the driest years tend to occur at any time. The wettest and driest years appear to be markedly different in the five regions, confirming the independence of these regions.

5. Links to sea surface temperatures and sea level pressure

The relationship between rainfall and SST and pressure patterns is examined by way of linear correlation (Figs. 5, 6) and composites of wet and dry years (Fig. 7). From the correlation maps in Figs. 5 and 6, regions of particularly high correlation are identified. The SST and SLP data for these sectors are averaged and the resultant spatial averages are correlated with rainfall, with the results summarized in Table 3.

Only regions 2 and 5 show strong associations with SSTs. Notably, the spatial patterns of correlation are roughly the opposite for the two regions. This is consistent with the hypothesis that regions 2 and 5 represent opposing poles of variability and that the remaining regions are transition zones. The correlations shown in Table 3 reinforce this opposition. Rainfall in region 2 is positively correlated with SSTs in the equatorial Pacific \( (r = 0.43) \) and western Indian Oceans \( (r = 0.60) \), but correlation with the Atlantic is weak. Rainfall in region 5 is negatively correlated with SSTs in the tropical Pacific Ocean \( (r = -0.53) \), the equatorial Indian Ocean \( (r = -0.46) \), and the equatorial
South Atlantic ($r = -0.48$). A strong positive correlation ($r = 0.53$) appears with local SSTs along the Benguela coast. Notably, rainfall in region 5 is much more highly correlated ($r = 0.74$) with the difference between SSTs in the eastern equatorial Atlantic and western equatorial Indian Oceans ($10^\circ$E–coast, $2^\circ$–$16^\circ$S, coast–$56^\circ$E, and $2^\circ$–$14^\circ$S). This indicates a simultaneous control of both oceans on rainfall in this region.

Regions 2 and 5 both show a strong correlation with sea level pressure (Fig. 6). High rainfall in region 5 is associated with anomalously low pressure throughout most of the tropical portions of the Atlantic, Indian Ocean, and western Pacific and throughout the African continent. The correlation reaches $-0.63$ for the eastern equatorial Atlantic (Table 3). The correlation pattern indicates a weakening (intensification) of both the South Atlantic high and the Azores high in wet/dry years.

For region 2, the spatial pattern of correlation is roughly a mirror image of that for region 5, with positive correlations indicating that high rainfall is associated with anomalously high pressure over the Atlantic, western Pacific, and eastern Indian Ocean. The highest correlation ($r = 0.51$; Table 3) is over the western equatorial Atlantic. The typical ENSO pressure pattern, with wet years being associated with anomalously low (high) pressure in the eastern (western) Pacific is also evident, as is a pressure dipole in the Indian Ocean. This dipole has been linked by several studies to interannual variability of the OND ‘short rains’ of East Africa (Clark et al. 2003; Ashok et al. 2004; Behera et al. 2005).

The SST anomalies associated with anomalously wet and dry conditions also suggest that both ENSO and the Indian Ocean dipole mode play a role in both regions. Figure 7 shows the SST anomalies associated with the four wettest and four driest OND seasons, as indicated in Table 2. In region 2 (eastern Zaire basin), the wet composite is associated with abnormally high SSTs in the eastern equatorial Pacific and the typical La Niña SST pattern is apparent in the dry composite. However, a positive Indian Ocean dipole pattern [positive (negative) SST anomalies in the west (east)] is likewise apparent in the wet years. Both the dipole and the link to ENSO are consistent with the rainfall–pressure associations shown in Fig. 6. SST anomalies for region 5 are very much the opposite. El Niño (La Niña) SST patterns in the Pacific are associated with the dry (wet) composite. Indian Ocean SST patterns indicative of the negative (positive) phase of the dipole are apparent in the wet (dry) composite. A link to the Atlantic is also evident, with strong positive (negative) SST anomalies in the eastern equatorial Atlantic associated with wet (dry) conditions in this region.

### 6. Links to atmospheric circulation

The associations with SSTs suggest that remote forcing is strong only in regions 2 and 5. These two regions, in the east and west of the study area, respectively, show strikingly opposite patterns of correlations with both SSTs and SLP. Those correlations cannot, however, identify the mechanisms responsible for the opposition. In this section, potential mechanisms are evaluated by examining various atmospheric circulation parameters in the most extreme years. For both regions, composites are constructed for the four wettest and four driest OND seasons (see Table 2).

#### a. Zonal winds and vertical motion over and near the African continent

1) **Region 2: Eastern Zaire Basin**

The wet and dry composites for region 2 (Figs. 8, 9) show strong contrasts in the vertical motion field and zonal winds. The zone of ascent is markedly stronger and broader in the wet composite, particularly in October, thus favoring higher rainfall over the region. A weakening (acceleration) of the tropical easterlies in the upper troposphere (midtroposphere) is clearly evident in the dry composite. These changes result in weak vertical shear throughout the troposphere in the wet composite but strong negative (positive) shear in the lower (upper) troposphere in the dry composite. The contrast is particularly strong in November, when westerlies appear in the equatorial latitudes above 300 hPa in the dry composite. The correlation between rainfall and 200-hPa zonal winds ($r = -0.56$) confirms the link between higher rainfall and stronger upper-level easterlies over the...
continent (Fig. 10). However, a much higher but positive correlation \( (r = 0.67) \) is apparent with zonal wind at 200 hPa over the eastern Indian Ocean. Zonal wind in the lower troposphere similarly shows an opposition between anomalies over continent and Indian Ocean, as well as an opposition between the lower and upper troposphere.

At 1000 hPa, rainfall is most strongly correlated with zonal wind over East Africa, with wetter conditions linked to weaker easterlies. The correlation reaches 0.77 (Table 3). A region of significant negative correlation [indicative of stronger easterlies (weaker westerlies)] is also apparent in the Arabian Sea and the eastern Indian Ocean \( (r = -0.69) \). This same pattern of correlation is apparent also at 925 (not shown) and 850 hPa. The correlation at 850 hPa is 0.54 over eastern equatorial Africa and −0.64 over the eastern Indian Ocean.

![Correlation between regional October–December rainfall and concurrent sea surface temperatures for the period 1948–88: (top to bottom) Regions 1–5 with region locations given in the right panels. The 5% significance level is indicated by the dashed–dotted line. Rainfall is also correlated with SST averages for the indicated boxes within the panels with values given in Table 3.](image-url)
2) REGION 5: ANGOLAN COAST

The zonal circulation associated with the wet and dry composites is shown in Fig. 8. The most prominent features are the stronger low-level westerlies in the wet composite and the stronger midlevel easterlies in the dry composite. The contrasts are particularly strong in November. Notably, an analysis of pibal data for the very wet period 1956–61 shows strong westerlies prevailing near Luanda (9°S) in OND and extending to at least 800 hPa (Hastenrath 1973), as did Flohn's (1956) analysis for the wet period 1948–52. Contrasts in the zonal wind are also apparent in the upper troposphere, with the tropical easterly jet being stronger in the wet composite and the midlatitude westerlies of both hemispheres being stronger and extending farther equatorward in the dry composite. The noted contrasts in the vertical structure of the easterlies are similar to those in region 2.

The zone of ascending motion that marks the rain belt is markedly stronger in the wet case, with omega in the midtroposphere being roughly twice as great in the wet
case as in the dry (Fig. 9). It is also notably broader, spanning some $10^\circ$ of latitude in the dry case but over $15^\circ$ of latitude in the wet case. These contrasts are more evident in October.

Rainfall in region 5 is strongly positively correlated ($r = 0.54$; Table 3) with low-level winds across the equatorial Atlantic and in West Africa (Fig. 10). This indicates that rainfall is associated with a weakening of the easterly trades that prevail in the central and western equatorial Atlantic, consistent with the weakening of the subtropical highs. The positive correlation also indicates an intensification (weakening) of the westerlies that prevail nearer the continent, consistent with the wet (dry) composites of Fig. 7.

The correlation of rainfall with 200-hPa winds is negative and extends throughout the Atlantic sector from $15^\circ$N to roughly $15^\circ$S. It reaches $-0.53$ north of the equator in the central equatorial Atlantic and $-0.55$ south of the equator in the eastern equatorial Atlantic (Table 3), indicating that weaker westerlies (stronger easterlies) are linked to higher rainfall.

b. The global context

The analyses presented so far show strong evidence of links between ENSO and rainfall in western equatorial Africa and, in many cases, clear associations with more local effects. These analyses do not allow us to distinguish between remote and local forcing or to determine whether ENSO directly forces interannual variability. This section will consider these questions in greater detail by examining the global tropical circulation anomalies associated with the wet and dry composites.

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FIG. 7. Standardized SST anomalies (°C) for the (left) wet composite and (right) the dry composite of regions (top) 1, (middle) 2, and (bottom) 5. Anomalies are based on the period 1948–88.
FIG. 8. Latitude–height cross sections of zonal winds (m s$^{-1}$) for regions 2 and 5 during (top two rows) October–December and (bottom two rows) November only for (left) wet and (middle) dry conditions. Zonal wind is averaged over 25°–30°E and 7.5°–15°E for regions 2 and 5, respectively. Areas of easterly winds are shaded. (right) The difference between the wet and dry composites; shading indicates areas where the difference is significant at 5% level.
FIG. 9. As in Fig. 8, but for omega ($10^{-2}$ Pa s$^{-1}$).
1) REGION 2: EASTERN ZAIRE BASIN

The clear association of wet and dry conditions in region 2 with ENSO and Indian Ocean SSTs suggests control by the large-scale tropical atmosphere, the atmospheric bridge discussed by Alexander et al. (2002, 2004) and Klein et al. (1999). To examine links to the tropical circulation, analyses of large-scale zonal wind and omega fields are carried out.

Figure 11 shows the difference in zonal wind between the wet and dry composites. At 200 hPa, easterly anomalies appear over Africa and most of the Atlantic, the western Indian Ocean, and the Pacific during wet years, while westerly anomalies are evident over South America and the eastern Indian Ocean. The anomalies at 850 hPa are the opposite of those at 200 hPa, suggesting a change in the east–west zonal circulation.
The patterns of upper-level divergence and vertical motion reflect these changes. The wet-minus-dry composite shows strong divergence at 200 hPa over North Africa (Fig. 11). The vertical motion (omega) anomalies are consistent with this pattern (Fig. 12). Anomalous rising motion corresponds to areas of easterly (westerly) anomalies at 200 (850) hPa. Anomalous subsidence corresponds to areas of westerly (easterly) anomalies at 200 (850) hPa.

The long-term mean omega during OND season shows the regions of actual rising–sinking motion (Fig. 13). The vertical motion anomalies for the wet and dry composites (Fig. 12) show that rainfall anomalies in region 2 are clearly related to global changes in the east–west zonal circulation cells. In the wet composite for OND, the zonal cells are weaker over all three oceans. A weakened Pacific cell is consistent with El Niño conditions, but in this case the Pacific cell is also displaced westward and vertical motion anomalies are weak along the South American coast. Hence, the El Niño SST pattern is not strongly developed. The vertical motion contrasts are notably greater over the Indian Ocean than over the Pacific. The increased ascent over the western Indian Ocean and the increased subsidence over the eastern Indian Ocean are indicative of the Indian Ocean dipole mode. The result is enhanced ascent extending across the equatorial latitudes of Africa, consistent with higher rainfall in the eastern Zaire basin.

In the dry case, anomalies are weak over most of the Pacific and the Atlantic. However, the enhanced (weakened)
subsidence in the eastern (western) Pacific is consistent with La Niña–like conditions. Positive anomalies (i.e., increased subsidence) prevail across the entire Indian Ocean, indicating that the Indian Ocean dipole mode does not come into play. The positive anomalies extend across equatorial Africa, consistent with the dry conditions in the Zaire basin. The strongest anomalies are over the eastern Indian Ocean and western Pacific and are of opposite sign, with increased ascent over the western Pacific. This contrasts with the wet case, in which anomalies are in phase in the western Pacific and eastern Indian Oceans.

It is noteworthy that the wind anomalies at both 200 and 850 hPa (Fig. 11) and the global omega anomalies (Fig. 12) are very much the opposite in the wet and dry cases. This suggests that changes in the east–west circulation govern both wet and dry conditions and are the dominant forcing of interannual variability in region 2 during the OND season.

2) REGION 5: THE ANGOLAN COAST

The analyses in section 5 suggest that OND rainfall along the Angolan coast is linked to both local and remote forcing. Abnormally wet (dry) conditions are associated with well-developed La Niña(El Niño)–like patterns but are also clearly linked to abnormally high (low) SSTs in the eastern equatorial Atlantic.
The remote forcing is evident in the zonal wind and divergence anomalies in the wet-minus-dry composites (Fig. 14). The zonal wind anomalies at 200 hPa over the Pacific and Indian Oceans are the opposite of those for region 2: westerly anomalies over the Pacific and western Indian Ocean and easterly anomalies over the Atlantic and eastern Indian Ocean. As with region 2, the anomaly pattern is reversed at 850 hPa. Over Africa the wet-minus-dry composites show easterly anomalies at 200 hPa, particularly in West Africa, but westerly anomalies at 850 hPa. There is also a strong divergence anomaly at 200 hPa in the eastern Atlantic and along the Angolan coast.

The anomalies in the omega fields for the wet and dry composites are consistent with the wind anomalies (Fig. 14). Easterly (westerly) anomalies at 200 (850) hPa roughly correspond to anomalous ascent and vice versa. In the wet composite (Fig. 15), the zonal circulation cell over the Pacific is anomalously strong. The Atlantic cell is anomalously weak, but the changes are small. Over the Indian Ocean, the ascending branch of the zonal circulation is abnormally weak, while the descending branch is abnormally strong but displaced eastward. The result is increased subsidence over the entire expanse of the equatorial Indian Ocean but increased ascent or decreased subsidence across equatorial Africa and in the eastern equatorial Atlantic. This is consistent with the reduced intensity of the subtropical highs over the Atlantic and increased rainfall in equatorial Africa from the Atlantic coast to roughly 30°E. This situation is also consistent with the upper-level zonal wind anomalies.

In the dry case, the omega anomalies are considerably weaker. The most apparent change in the east–west zonal circulation is an anomalously intense cell over the Atlantic. This is consistent with the cold SST anomalies in the Gulf of Guinea and along the Angolan coast. The
net result is increased subsidence in the eastern Atlantic and across equatorial Africa to ~30°E. Also evident is a weakening of the cell over the Indian Ocean, indicative of a weak positive Indian Ocean dipole. The same pattern is apparent in the wet composite for region 2. The weak intensification of the cell over the Pacific in the dry composite is consistent with the El Niño–like SST anomalies in the Pacific (Fig. 7). The strong correlations with zonal winds over the Atlantic (Fig. 10 and Table 3), together with the weak changes in the zonal circulation over the Pacific and Indian Oceans shown in Fig. 14, suggest that the Atlantic is the major control on the development of dry conditions in region 5.

7. Discussion

a. Local versus remote forcing

The analyses in sections 5 and 6 have shown a strong statistical association between local Atlantic SSTs and rainfall along the Angolan coast and a somewhat weaker association between rainfall in the eastern Zaire basin and local SSTs along the coast of East Africa. Here we develop the argument that most of these changes are at least partially remotely forced by the global circulation changes described in section 6.

The link is clear for the zonal wind anomalies over the region. Figures 11 and 14 show these to be part of basin-scale anomalies over the Atlantic. A possible mechanism can be induced by analogy with the Indian Ocean. It is well known (e.g., Hastenrath et al. 2010) that changes in the east–west zonal circulation over the Indian Ocean modulate the intensity of the low-level equatorial westerlies over the Indian Ocean and that the strength of these westerlies is inversely proportion to rainfall over coastal regions of East Africa. A similar but reverse effect appears to occur over the Atlantic. The weakened Atlantic east–west zonal cell enhances equatorial westerlies in the eastern Atlantic. An alternative mechanism of development is the inertial instability mechanism described by Nicholson and Webster (2007). The major prerequisite for the formation of a low-level westerly jet, as clearly seen in Fig. 8 for the wet case of region 5, is a strong cross-equatorial pressure gradient. The pressure anomalies related to wet and dry conditions (Fig. 6) are consistent with this (not shown).

The local SST anomalies noted in the equatorial and eastern Atlantic are forced by the large-scale pressure and wind fields over the Atlantic. These anomalies are particularly strong along the African coast from just north of the equator to roughly 20°S: that is, in the region of the southward-flowing Angola current (Meeuwis and Lutjeharms 1990). In a fashion analogous to the Pacific El Niño, the weakening of the high results in weaker trade winds over the equatorial Atlantic, allowing a Kelvin wave to propagate eastward in the Gulf of Guinea (Moore et al. 1978; Adamec and O’Brien 1978). This brings with it warm water, resulting in higher SSTs in the region of the Angola current running from roughly 2°N to 20°S along the African coast. In the dry composite, when the subtropical high is more intense, negative SST anomalies are apparent in the equatorial Atlantic and in this coastal sector.

The local SST anomalies along the coast of East Africa in association with rainfall fluctuations in region 2 are also part of basin-scale anomalies that appear to be linked to the Indian Ocean dipole mode (Webster et al. 1999; Clark et al. 2003). The signature of the dipole is well developed in both the correlation with SSTs and sea level pressure (Figs. 5, 6) and in the wet composite of Fig. 7.

Once the local SST anomalies are established, they probably have some impact on rainfall. The likely mechanisms are an influence on static stability of the lower atmosphere or advection of moisture. In the cases evaluated here, the latter effect is unlikely. An analysis of specific humidity (not shown) indicates little or no contrast between the wet and dry composites, suggesting that increased moisture availability does not play a role. Some impact on static stability is likely. However, in the case of the Angolan coast, the impact of higher SSTs cannot be separate from that associated with the concurrent weakening of the subtropical high.

b. The central Zaire basin as a transition zone

Regions 2 and 5, the eastern Zaire basin and the Angolan coast, both show strong associations with global SSTs in the tropics. The association is strongest with cold anomalies (i.e., La Niña–like conditions), which are linked to wet conditions along the Angolan coast, but dry conditions in the eastern Zaire basin (Fig. 7). A weaker association is evident between warm SSTs in the tropical sections of the Pacific and Indian Oceans and drier conditions along the Angolan coast (wetter conditions in the Zaire basin).

Our results suggest that the year-to-year variability of rainfall is generally out of phase in western and eastern portions of equatorial Africa. This is consistent with numerous studies of rainfall variability in the region (e.g., Nicholson 1986). The relatively weak links of the other three regions to SSTs and SLP are a consequence of their geographical location, between regions 2 and 5. This makes them a transition zone, sometimes reacting in phase with region 2 and sometimes with region 5. Consequently, the linear correlations with SSTs and SLP are weak.
The three regions of the central Zaire basin (regions 1, 3, and 4) all extend from roughly 15° to 25°E. Several arguments can be made for this being a region of strong transition with respect to rainfall variability. For one, within this span an abrupt shift between prevailing rising motion and prevailing subsidence occurs (Fig. 13). Subtle zonal shifts in the east–west circulation cells can have a large impact. The links between rainfall and low-level zonal winds also suggests that this is a transition zone (Fig. 10). The central Zaire basin lies at the eastern edge of the sector where rainfall in region 5 is correlated with winds over the equatorial Atlantic and at the western edge of the sector where rainfall in region 2 is correlated with winds over equatorial East Africa.

The relationships to SSTs and sea level pressure are also indicative of the region being a transition zone. The pattern of correlation with both SSTs and SLP (Figs. 5, 6) is similar for regions 1 and 2 but much weaker for region 1, suggesting that similar factors play a role but perhaps affect region 1 in only some years. A similar argument can be made for regions 3 and 4: SST correlation patterns and to a lesser extent SLP correlation patterns are similar to those for region 5 but notably weaker.

Other factors may also play a role in the very weak correlations between the large-scale forcing and rainfall in the three regions of the central Zaire basin. Region 1 provides an example of this, but similar results (not shown) were obtained for the other two regions. The wet and dry SST composites for region 1 (Fig. 7) suggests a nonlinear response to both ENSO and to the Indian Ocean dipole. Wet conditions appear to be linked to El Niño but a link between dry conditions and La Niña is not evident (in contrast to regions 2 and 5). A strong Indian Ocean dipole is evident in the dry composite for region 1, but not in the wet composite.

It should also be noted that local factors play a large role in the rainfall regime in the central Zaire basin (Jackson et al. 2009; Vondou et al. 2010). The annual and diurnal cycles of convection suggest a major orographic influence of the surrounding highlands. Any large-scale forcing would manifest itself by way of its influence on these orographic effects.

**8. Summary and conclusions**

One of our clearest results is the inverse relationship between the eastern and western sectors of equatorial Africa during the OND season. This opposition is apparent in the anomalies of SSTs, sea level pressure, and east–west zonal circulation anomalies linked to both wet and dry composites in the two regions. The eastern sector appears to be part of a region of coherent variability that extends throughout eastern equatorial Africa (i.e., east of the Rift Valley highlands) during the “short rains” (Nicholson 1996).

In general, wet (dry) conditions in the eastern sector are associated with patterns reminiscent of El Niño (La Niña). In the western sector, along the Angolan coast, all three oceans appear to play a role in rainfall variability. Rainfall in this region is strongly correlated ($r = 0.74$) with the difference in SSTs along this coast and in the coastal sector of the Indian Ocean. Wet conditions are associated with La Niña–like conditions and three of the four years comprising the wet composite are La Niña years. All four years of the dry composite are El Niño years. However, strong anomalies in SSTs, winds and vertical motion are also apparent over the tropical Atlantic and tropical Indian Oceans.

Thus, remote forcing appears to be the major control on rainfall variability in both regions 2 and 5. More local factors also play a role for region 5. A pronounced weakening (intensification) of the South Atlantic High is associated with wet (dry) conditions along the Angolan coast. This produces strong positive (negative) SST anomalies along the coast. The SST anomalies may enhance the other factors modulating rainfall in the coastal sector, but they do not appear to be the major factor. Little influence on atmospheric moisture is apparent and stability changes appear to be limited to the atmosphere just above the surface.

Rainfall variability in western equatorial Africa in the OND season is strongly influenced by the east–west zonal circulation cells of the global tropics. Consequently, correlations with zonal wind are stronger than with SSTs or SLP (see Table 3). The easternmost sector, the eastern Zaire basin (region 2), appears to be most strongly linked to conditions over the Indian Ocean. The westernmost sector appears to be most strongly linked to conditions in the Atlantic sector. The other three sectors appear to be transition zones, lying at the edge of the zonal cells over the Atlantic and Indian Oceans. Rainfall in those sectors bears an inconsistent relationship with surface conditions of SSTs or pressure over the tropical oceans.

Changes in the intensity of zonal wind over the continent are also associated with the wet and dry composites. For both the eastern and western sectors, the wet composites compared to the dry have stronger easterlies in the upper troposphere and weaker easterlies in the mid troposphere. In the eastern (western) sector, the largest contrast is in the upper troposphere (mid troposphere). In the western, coastal sector the low-level equatorial westerlies are also markedly different in the wet and dry composites. In the wet composite an elevated westerly jet core contrasts with weak westerlies with
a near-surface maximum in the dry composite. In this sector, the reduced subsidence associated with a weakening of the South Atlantic high in the wet composite favors higher rainfall. However, the presence of the westerlies might further contribute to the wetter conditions by enhancing the orographic influence of the coastal mountains.

There are a number of parallels with factors associated with rainfall variability in this region during AMJ and with summer rainfall in West Africa, the Sahel–Sudan zones (Nicholson 2008; S. E. Nicholson and A. K. Dezfuli 2012, unpublished manuscript). In all three cases, increased rainfall is associated with a stronger tropical easterly jet and weaker easterlies in the midtroposphere. Studies of variability in other sectors of equatorial and East Africa have shown similar changes in the zonal winds in conjunction with wet and dry conditions (e.g., Segele et al. 2009; Camberlin 1995; Vigaud et al. 2007; Todd and Washington 2004). This indicates the ubiquitous importance of the zonal circulation in modulating tropical rainfall throughout Africa and provides a mechanism to explain the strong teleconnections that exist throughout the African continent.

The low-level westerlies appear to be particularly important. A sharp contrast between weak near-surface westerlies in dry years to a distinct westerly jet with a core near 850 hPa in wet years is evident in West Africa and in western equatorial Africa during both the AMJ and OND seasons. Enhanced westerlies have also been associated with higher rainfall in much of East Africa, both for individual rain events and with respect to interannual variability (e.g., Camberlin 1996; Okoola 1999a,b; Pohl and Camberlin 2006; Mapande and Reason 2005). This system and the dynamics governing it deserve much further attention.

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REFERENCES


