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A revised picture of the structure of the “monsoon” and land ITCZ over West Africa

Sharon E. Nicholson

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Abstract This article presents an overview of the land ITCZ (Intertropical Convergence Zone) over West Africa, based on analysis of NCAR–NCEP Reanalysis data. The picture that emerges is much different than the classic one. The most important feature is that the ITCZ is effectively independent of the system that produces most of the rainfall. Rainfall linked directly to this zone of surface convergence generally affects only the southern Sahara and the northern-most Sahel, and only in abnormally wet years in the region. A second feature is that the rainbelt normally assumed to represent the ITCZ is instead produced by a large core of ascent lying between the African Easterly Jet and the Tropical Easterly Jet. This region corresponds to the southern track of African Easterly Waves, which distribute the rainfall. This finding underscores the need to distinguish between the ITCZ and the feature better termed the “tropical rainbelt”. The latter is conventionally but improperly used in remote sensing studies to denote the surface ITCZ over West Africa. The new picture also suggests that the moisture available for convection is strongly coupled to the strength of the uplift, which in turn is controlled by the characteristics of the African Easterly Jet and Tropical Easterly Jet, rather than by moisture convergence. This new picture also includes a circulation feature not generally considered in most analyses of the region. This feature, a low-level westerly jet termed the African Westerly Jet, plays a significant role in interannual and multidecadal variability in the Sahel region of West Africa. Included are discussions of the how this new view relates to other aspects of West Africa meteorology, such as moisture sources, rainfall production and forecasting, desertification, climate monitoring, hurricanes and interannual variability. The West African monsoon is also related to a new paradigm for examining the interannual variability of rainfall over West Africa, one that relates changes in annual rainfall to changes in either the intensity of the rainbelt or north–south displacements of this feature. The new view presented here is consistent with a plethora of research on the synoptic and dynamic aspects of the African Easterly Waves, the disturbances that are linked to rainfall over West Africa and spawn hurricanes over the Atlantic, and with our knowledge of the prevailing synoptic and dynamic features. This article demonstrate a new aspect of the West Africa monsoon, a bimodal state, with one mode linked to dry conditions in the Sahel and the other linked to wet conditions. The switch between modes appears to be linked to an inertial instability mechanism, with the cross-equatorial pressure gradient being a critical factor. The biomodal state has been shown for the month of August only, but this month contributes most of the interannual variability. This new picture of the monsoon and interannual variability shown here appears to be relevant not only to interannual variability, but also to the multidecadal variability evidenced in the region between the 1950s and 1980s.

Keywords ITCZ · African climate · Tropical rainfall · West African monsoon · Interannual variability

1 Introduction

The Intertropical Convergence Zone, or ITCZ, is one of the most widely known concepts of tropical meteorology. It appears not only in meteorological references, but also in educational literature as diverse as middle school science

S. E. Nicholson (✉)
Florida State University, Gainesville, FL, USA
e-mail: sen@met.fsu.edu

textbooks and college texts on geography, tropical agriculture or environment. The typical resident of the tropics is highly familiar with the concept: it rains when the ITCZ comes. Hence, seasonal forecasting has commonly focused on predicting the excursion of the ITCZ, especially over West Africa. Interannual variability there is commonly explained in terms of its anomalous displacements.

The classic definition of the ITCZ is the convergence of the trade winds of the two hemispheres. This zone is characterized by low pressure, rising motion, clouds and precipitation (Fig. 1). From the viewpoint of the global atmosphere, the ITCZ forms the ascending branch of the Hadley circulation. Regionally, this viewpoint is oversimplified, especially over the land. Over West Africa, the prevailing image of the ITCZ is based on an outdated 1950s model and it is actually erroneous. This has serious consequences for the interpretation of climatic variability and for weather and climate prediction in this region.

Figure 1 describes what some term the “marine ITCZ”, although even over many oceans regions the picture is quite different. Over the continents the trade winds are generally not well developed and the ITCZ is essentially the loci of cloud clusters associated with tropical wave disturbances (Holton et al. 1971). Many feel that the term ITCZ should not be used over land (Houze, personal communication). Indeed, that is generally the view of those working with South American meteorology and climate (Satymurty et al. 1998). However, climatologists dealing with Africa stick closely to the classical ITCZ paradigm, as do most meteorological agencies in West Africa and researchers from other disciplines who study Africa. A case in point is the FEWS (Famine Early Warning System) ITCZ monitoring site (http://www.cpc.noaa.gov/products/fews/ITCZ/itcz.html). It serves as one of the most importance sources utilized for seasonal forecasting of rainfall over West Africa.

This article presents an overview of the monsoon and ITCZ over West Africa and describes a picture much different than the one that prevails in much of the literature dealing with the region’s climatology. The most important feature is that the ITCZ, i.e., the surface wind convergence zone, is effectively independent of the system that produces most of the rainfall. Rainfall linked directly to the West African ITCZ generally affects only the southern Sahara and the northern-most Sahel, and only in abnormally wet years. This revised picture has implications not only for climatological studies, but also for numerous other studies concerned with the climate of West Africa, such as ecology, desertification, and paleoenvironment.

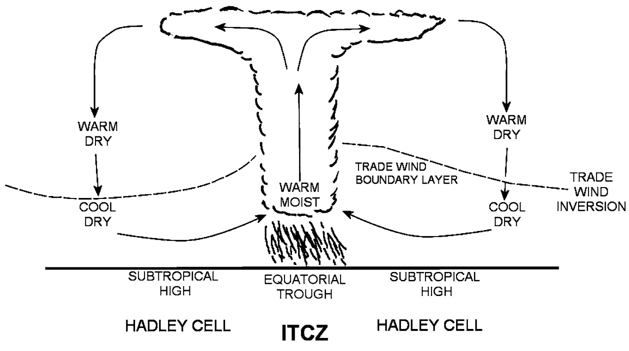


Fig. 1 Classic picture of the ITCZ

The view presented here is well known to the relatively small research community that specializes in West Africa. It is described, for example, in the excellent overviews by Zhang et al. (2006) and Mohr and Thorncroft (2006). It is consistent with a plethora of research on the synoptic and dynamic aspects of the African Easterly Waves, the disturbances that are linked to rainfall over West Africa and spawn hurricanes over the Atlantic (e.g., Reed et al.1988; Pytharoulis and Thorncroft 1999; Nitta and Takayubu 1985; Thorncroft and Hodges 2001). The West African model described here is also consistent with the prevailing synoptic and dynamic features (e.g., Kanamitsu and Krishnamurti 1972; Burpee 1974; Reed et al. 1977; Mikayoda et al. 1982).

The purpose of this article is to highlight the gap between our knowledge of these aspects of West African meteorology and the concepts pervasive in climatological studies of the region. In particular, the results shown here underscore the need to distinguish between the ITCZ (i.e., the zone of surface convergence) and the feature better termed the “tropical rainbelt”. The latter is conventionally used in remote sensing studies to denote the surface ITCZ (e.g., Ba et al. 1995; Adler et al. 2000; Sultan and Janicot 2003). Thus, the term ITCZ is ambiguous: it sometimes refers to surface wind convergence and sometimes to the zone of maximum precipitation. Consistent terminology needs to be established.

The results presented are part of a much larger study. They are limited to August, the month of maximum rainfall. However, the picture of the atmosphere that emerges is applicable for the entire boreal summer. The most important message is that rainfall in the region is not driven by surface features, such as the ITCZ and moist southwest “monsoon” flow, but by features in the upper-level circulation that override the lower-level factors. The circulation aloft is nonetheless influenced by the surface, so that surface gradients and characteristics of the ocean do play an important role.

2 Data and methodology

The data used in this study are NCEP Reanalysis Data (Kalnay et al. 1996; Kistler et al. 2001), Reynold’s reconstructed SST data set (Smith et al. 1996), and rainfall data from the African archive created by the author (e.g., Nicholson 1986, 1993, 2008). That rainfall archive has been incorporated into virtually all other global archives, such as GHCN (Peterson and Vose 1997), the New/Hulme data set (Hulme 1994; New et al. 1999, 2000, see also Rowell 2003), and Legates and Willmott (1990) and it has been continually updated with gauge data from the African meteorological services. It includes monthly data for roughly 1,300 station records, most of which begin before 1920 and extend to 1998.

The NCEP data set includes daily and monthly values of various dynamical parameters. For most variables, the data set covers the years 1948–2005. The parameters to be utilized include wind speed, zonal wind, vertical motion and specific and relative humidity. From the winds, we have calculated additional parameters: divergence, absolute vorticity, and moisture convergence.

The use of NCEP Reanalysis Data for historical analyses has been questioned by some. In particular, it has been suggested that a discontinuity occurred around 1968 or 1970 (Poccard et al. 2000; Janicot et al. 2001; Kinter et al. 2004; Chelliah and Bell 2004). This was coincidently a discontinuity in the Sahel rainfall record: the onset of the multidecadal dry conditions (Nicholson 2000a, 2008; Grist and Nicholson 2001). There appears to be a consensus that NCEP estimates of wind fields are relatively reliable, but that there are difficulties in tropical divergent circulations and rainfall (Poccard et al. 2000; Kinter et al. 2004). It is nevertheless routinely used in long-term studies. In such a study, Grist and Nicholson (2001) used West African pibal and rawinsonde reports to verify conclusions based on NCEP. In other analyses in which we utilized NCEP (e.g., Grist and Nicholson 2001; Nicholson and Grist 2001, 2002; Nicholson and Webster 2007), coherent and physically reasonable results emerged from a mixture of data sources.

The Reanalysis data utilized in this study are primarily "A variables", those strongly influenced by observational data and hence most reliable (Kalnay et al. 1996). These include, for example, wind and pressure fields. Less reliable are the B variables, the derivation of which is about equally dependent on observations and modeling. The only B variables utilized here are specific and relative humidity; some validation was carried out using upper air data. The other B variables, such as divergence, the divergent and rotational wind components, and vorticity are not taken from NCEP Reanalysis. They are instead calculated directly from NCEP winds. Rainfall is a C variable (largely model dependent) and NCEP rainfall is known to be unreliable over Africa (Poccard et al. 2000). For that reason the author's gauge archive was utilized.

In the Sahel 80% of the annual rainfall occurs during the 3-month period July–September. Throughout the region August is the wettest month and it contributes disproportionately to the interannual variability (Dennett et al. 1985; Nicholson and Palao 1993). For the sake of brevity, this study is limited to August. Our preliminary analyses indicate that this is an efficient approach that does not compromise much detail.

3 The classic picture of the ITCZ over Africa

Climatologically speaking, the ITCZ over Africa is conceptualized as a band of rainfall, analogous to that shown in the satellite photo of Fig. 2. This band "follows the sun", advancing into the northern hemisphere in boreal summer and retreating into the southern hemisphere in austral summer (Fig. 3). This is a simple and convenient concept that readily explains the latitudinal gradient of precipitation over West Africa, as well as the seasonality of rainfall throughout tropical regions of the continent. The length of the rainy season is equivalent to the length of the ITCZ's influence and maximum precipitation occurs with its passage (Fig. 4).

The prevailing view of the ITCZ's detailed structure over West Africa is depicted in Fig. 5. This picture was developed by British and French colonial meteorologists working in West Africa in the 1950s and 1960s (Dettwiller 1965; Germain 1968; Hamilton and Archbold 1945; Sansom 1965; Walker 1957; Hastenrath 1995) and it has not changed since that time. A zone of wind convergence develops where the southwest "monsoon" flows into the center of the Saharan heat low and meets the dry desert air. A marked discontinuity in temperature and dewpoint also occurs at the point of convergence, leading the French to prefer the term "Front Intertropical" (FIT).

This classic picture shows the ITCZ sloping toward the equator with height, so that the depth of the moist layer rapidly increases equatorward. Accordingly, convergence and uplift occur all along this zone, but strong precipitation

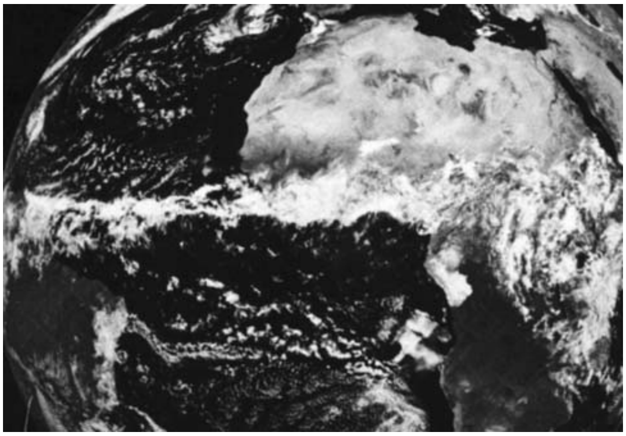


Fig. 2 Meteosat satellite photo (7 July 1979) showing case of continuous "ITCZ" over the Atlantic and West Africa

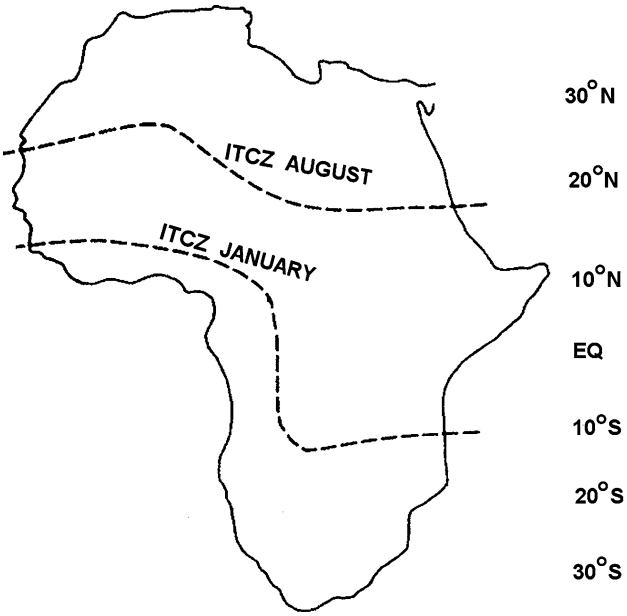


Fig. 3 Maps of the mean position of the ITCZ over Africa in January and August (based on Goudie 1996; Rasmusson 1988; van Heerden and Taljaard 1998; and others)

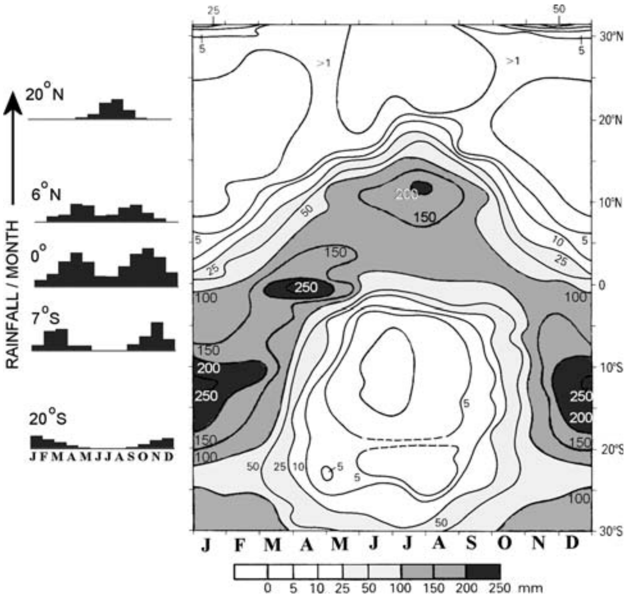


Fig. 4 Rainfall as a function of month and latitude over Africa, following the seasonal excursion of the ITCZ (modified from Flohn 1965). On the left, seasonal cycle of rainfall at select African stations at the indicated latitudes

occurs only where the moist layer is sufficiently thick to support deep clouds and convection. This puts the cloudiness and precipitation maxima well equatorward of the surface convergence (Fig. 5), in contrast to the idealized, “classical” picture ITCZ (Fig. 1), in which they coincide. These historical sources suggest the displacement is about 500 km.

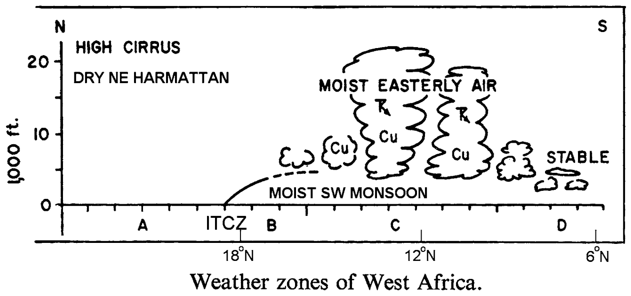


Fig. 5 Classic picture of ITCZ over Africa (based on Dettwiller 1965; Germain 1968; Hamilton and Archbold 1945; Sansom 1965; Walker 1957; and others)

4 The view of the West African ITCZ from reanalysis data

The above describes the basic understanding of the ITCZ held not only by the climatologist, but also the geographer, ecologist, agriculturalist, paleoclimatologist and others concerned with environmental science. Unfortunately, much of this picture is wrong. The surface patterns do fit the classical picture. The meridional (i.e., north–south) components of the wind converge at the latitude of the Saharan heat low (Fig. 6a). This surface convergence is the true ITCZ over West Africa. It includes the convergence into the heat low, as described by Hagos and Cook (2007). However, it extends well to the east of the Saharan heat low so that the two are not synonymous. The convergence also marks the transition in the zonal winds from the easterly flow of the Harmattan to the westerly flow of the low-level monsoon (Fig. 6b). Relative humidity, specific humidity and dew point at the surface increase rapidly equatorward from the surface position of the ITCZ (Fig. 7). In contrast, the situation aloft shows a structure that differs considerably from the one described in Sect. 2. Notable contrast includes the depth of the moist layer, the role of the upper-level flow in producing the structure of the monsoon layer, and the relationship between the surface convergence and the rainfall maximum.

4.1 Vertical structure of the wind field

The southwesterly monsoon flow is associated with the equatorial crossing of the southeast trade winds that arise on the equatorward flank of the subtropical high. Thus the monsoon flow is distinguished by a clear southerly component. The vertical cross-section of the meridional wind in Fig. 6b suggests that the monsoon flow is confined to the lowest levels of the troposphere. The southerly component decreases rapidly above 900 hPa, generally disappearing by 850 hPa. In contrast the westerly component of the flow has a maximum at 850 hPa, where the southerly component approaches zero. There the westerly speed reaches 6 ms^{-1} in the long-term mean.

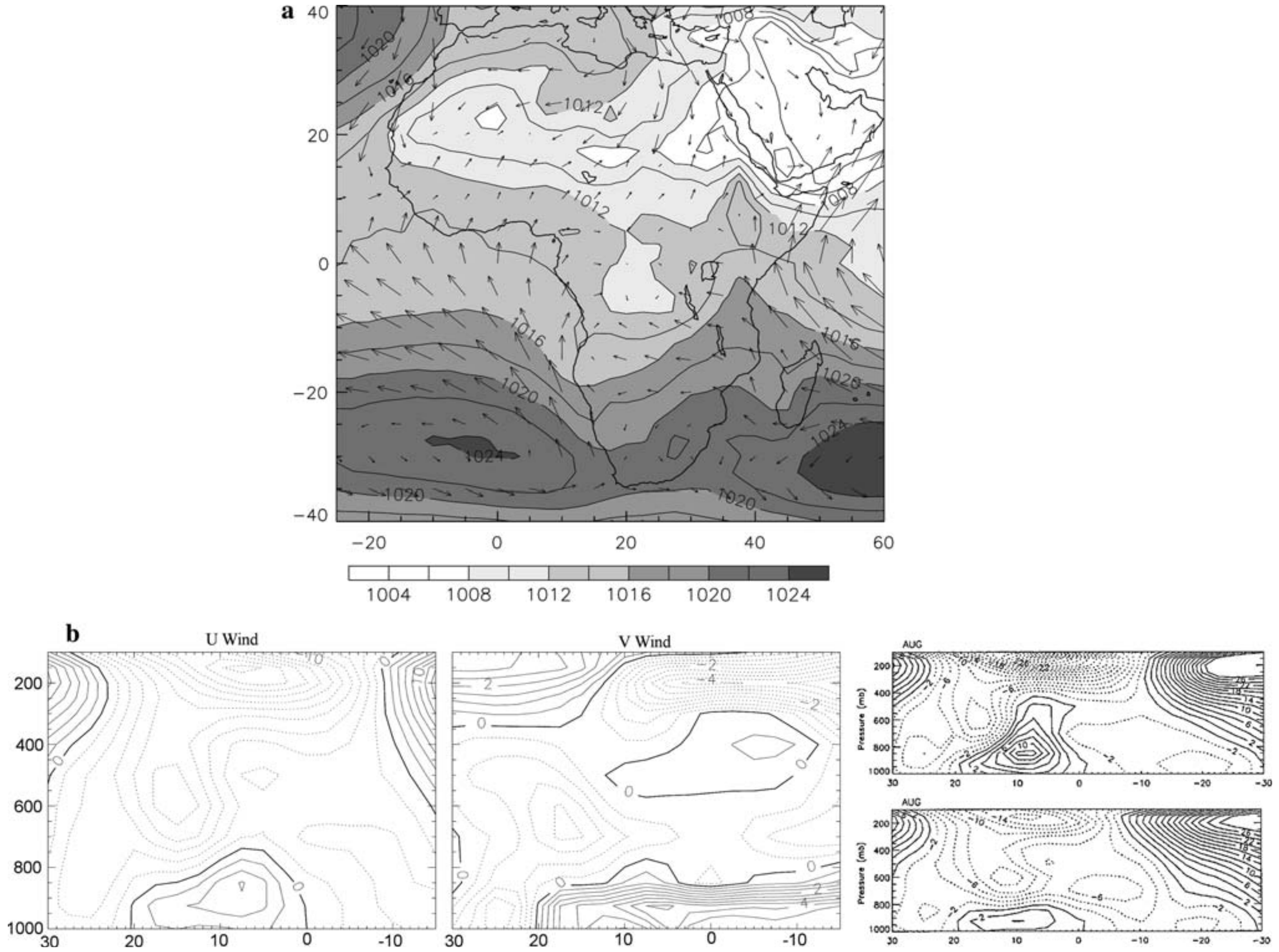


Fig. 6 Long-term mean surface pressure and wind over West Africa in August. **a** Vector wind and surface pressure (mb). **b** Vertical cross-sections of the u (*left*) and v (*center*) components (m s^{-1}). On the right is u for wet and dry years. Averages are for the region 10°W to 10° and for the years 1958 to 1997 (based on Nicholson and Grist 2003). In **a**, the length of the wind vectors is proportional to wind speed

The mean zonal winds shown in the middle panel of Fig. 6b are deceiving, as they mask a bimodal state. In one mode (Fig. 6b, top of right panel) only the low-level monsoon flow is evident in the equatorial westerlies. In the other mode (Fig. 6b, bottom right panel), the westerly jet (henceforth termed the African westerly jet or AWJ) is very strongly developed with core speeds at 850 hPa as high as 10 ms^{-1}. In such a case, the westerly flow typically extends well into the mid-troposphere (Grist and Nicholson 2001; Nicholson and Webster 2007). This bimodality is strongly linked to the interannual variability of rainfall, discussed later in Sect. 4.6.

Tomas and Webster (1997) suggest that such a westerly jet arises not as part of the monsoon, but as a result of an inertial instability mechanism that leads to off-equatorial convection (see also Tomas et al. 1999). A strong surface anticyclone (the South Atlantic high) lies just to the south of the equator during the boreal summer. The cross-equatorial pressure gradient drives anticyclonic vorticity across the equator, resulting in cyclonic vorticity north of the equator. To create a balance in the flow, there is acceleration of the wind, vortex tube stretching and convergence in the lower levels. The resultant unstable atmosphere promotes convection.

Nicholson and Webster (2007) confirm that this situation exists over West Africa during August in at least some wet years. The occurrence of the westerly maximum above the southerly monsoon flow is consistent with this idea. It disappears in dry years. The AWJ's development appears to be controlled by the surface pressure gradient over the tropical Atlantic, as a strong cross-equatorial gradient is needed to produce inertial instability. There is a strong correlation between the surface pressure gradient between 20°N and 20°S and the speed of the jet (Fig. 8a). The weak gradients occurred without exception during the relatively dry years post-1969 and the strong gradients occurred primary during the wet years prior to that. Thus the speed of the westerly jet is also well correlated with rainfall in the

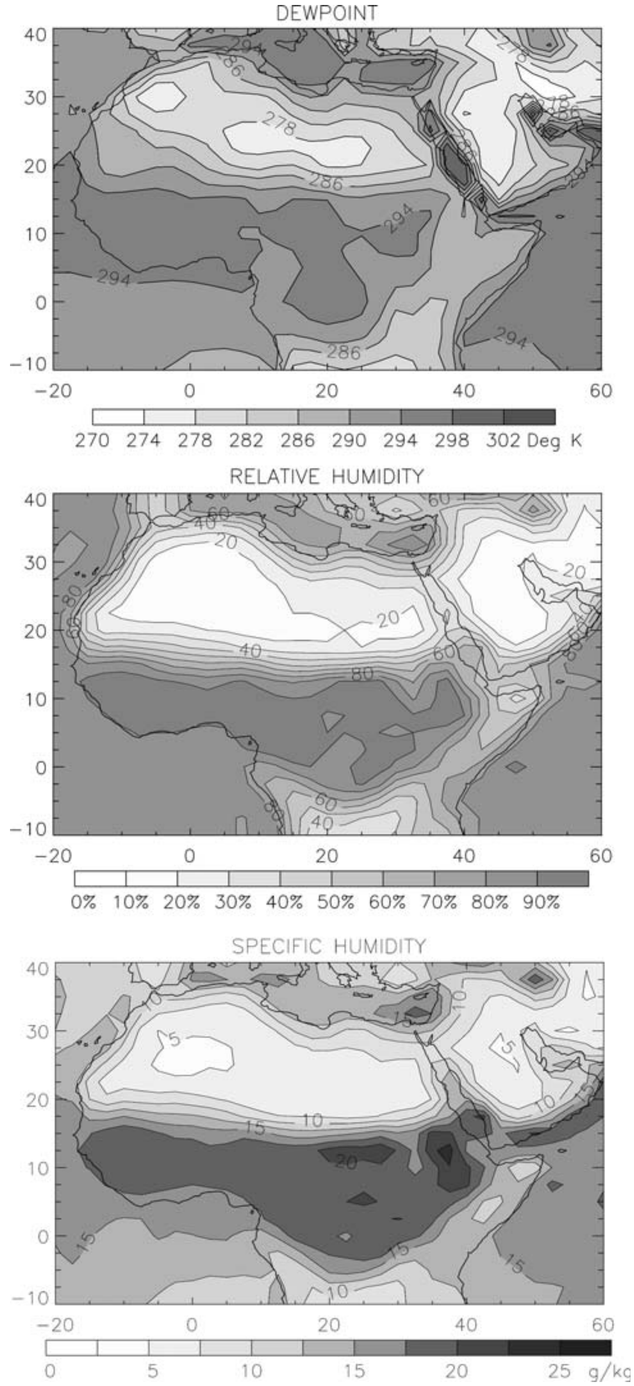


Fig. 7 Mean surface dewpoint (°C), relative humidity (%) and specific humidity (g kg^{-1}) over West Africa in August

Sahel (Fig. 8b). Geostrophic arguments cannot account for the existence of the low-level African westerly jet and its link to the pressure gradient, given the low latitude and the absence of the jet in dry years. Also, the pressure gradient shown in Fig. 8a is a surface gradient, while the AWJ is at 850 hPa.

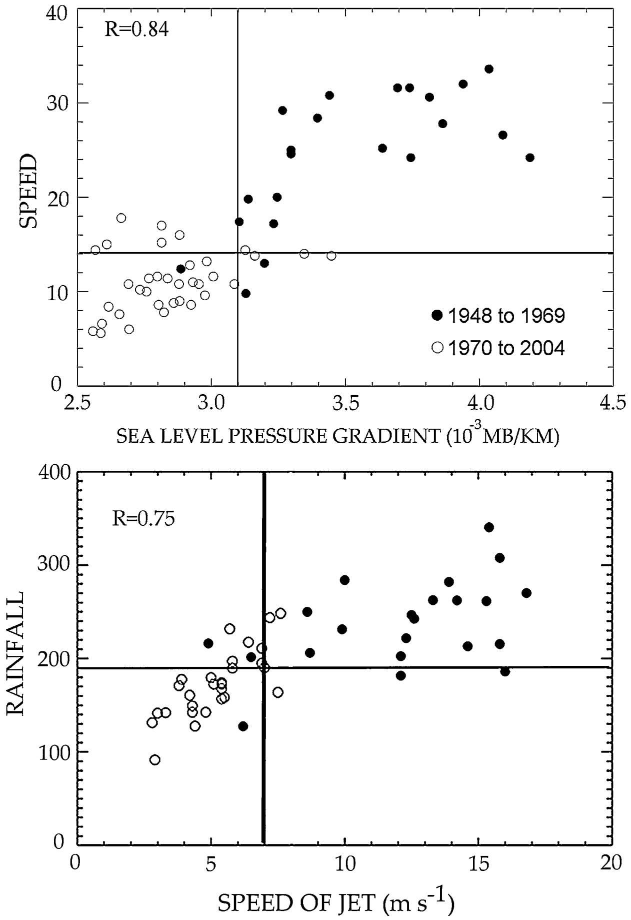
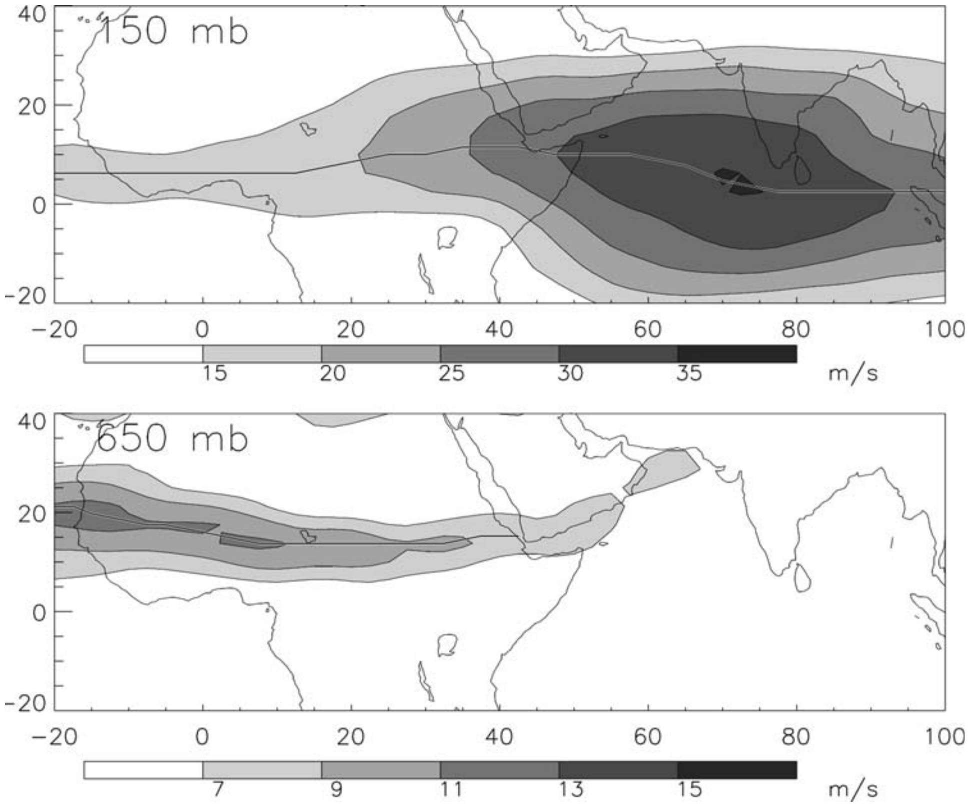


Fig. 8 (a) Speed of the westerlies (m s^{-1}) at 850 hPa versus surface pressure gradient for August of the years 1948–2004 (from Nicholson and Webster 2007). Data are averaged for 5°W to 5°E and the pressure gradient is calculated between 20°N and 20°S. The open circles represent the years 1948–1969 and the *solid circles* represent the years 1970–2004. **b** Annual rainfall in the Sahel (averaged within the sector 10–18°N and from the Atlantic coast to 30°E) versus speed of the westerly jet at 850 hPa

Two other elements of the winds aloft are the African Easterly Jet (AEJ), with its maximum near 600 hPa in the mid-troposphere, and the Tropical Easterly Jet (TEJ), with its maximum near 150 hPa in the upper troposphere (Fig. 9). Both features are clearly apparent in the vertical structure of the wind field over West Africa during the summer monsoon (Fig. 6b) (Nicholson and Grist 2002). The AEJ has long been implicated as the primary factor in the development and propagation of wave disturbances over West Africa (e.g., Burpee 1972) and in the interannual variability of rainfall (e.g., Kanamitsu and Krishnamurti 1978; Newell and Kidson 1984; Fontaine and Janicot 1992). Until recently the role of the TEJ has been largely ignored, but Nicholson and Grist (2001) and Nicholson (2008) suggest that it plays a pivotal role in interannual variability.

Fig. 9 Mean winds (m s^{-1}) in August at 600 and 150 hPa, showing the African Easterly Jet and Tropical Easterly Jet, respectively



4.2 Convergence zones over West Africa

The meridional winds associated with the AEJ and TEJ, together with the surface convergence zone, produce a divergence field that is considerably more complex than that suggested by the simple ITCZ concept. Figure 10 shows the mean August divergence fields at the surface and at the levels of the AEJ and TEJ. At the surface, two zones of convergence are evident. The most intense lies at roughly 20°N and corresponds to the surface position of the ITCZ. The other straddles the Guinea Coast of the Atlantic and corresponds to the frictional convergence of the sea breeze. These two merge along the West Coast at about 15°N.

At 650 hPa, near the AEJ level, the ITCZ convergence is replaced by weak divergence. This suggests a cell of meridional overturning extending from the surface ITCZ to the anticyclonic side of the AEJ in the mid-troposphere. Just to the south is weak convergence, centered near 5–10°N on the cyclonic side of the AEJ.

At the TEJ level of 150 hPa the picture is reversed. Divergence prevails over West Africa from roughly 15ºN–5ºN, while convergence prevails around 15–25°N. This suggests a second cell of meridional overturning that links the mid- and upper troposphere. Lying just to the south of the lower meridional cell, this cell extends from the cyclonic side of the AEJ to the anticyclonic poleward flank of the TEJ. The associated patterns of convergence and divergence are evident in the meridional flow fields associated with these jets (Fig. 6b).

Clearly, the Hadley-type overturning envisioned in Fig. 1, extending from the surface ITCZ to the upper troposphere, is not present over West Africa during the summer monsoon season. Instead two apparently independent meridional cells of Hadley-type overturning prevail. One is associated with the surface convergence of the ITCZ and extends to the mid-troposphere. The second, some 5°–10° of latitude further south, links the AEJ in the mid-troposphere to the TEJ in the upper troposphere. A much shallower cell of overturning is also visible in the divergence field. This extends along the West African coast, with strong convergence at 1,000 hPa and strong divergence at 850 hPa. This is presumably the shallow sea-breeze circulation cell. The vertical motion analysis in the following section suggests it is nevertheless an important feature in the larger-scale dynamics of the region.

4.3 Vertical motion and convection

Figure 11 shows a vertical cross-section of vertical velocity, as a function of latitude. A striking feature is the narrow column of rising air near 10°N. It is bound on the north by the AEJ axis and on the south by the TEJ axis. The core of maximum ascent is at about 600 hPa, i.e., near

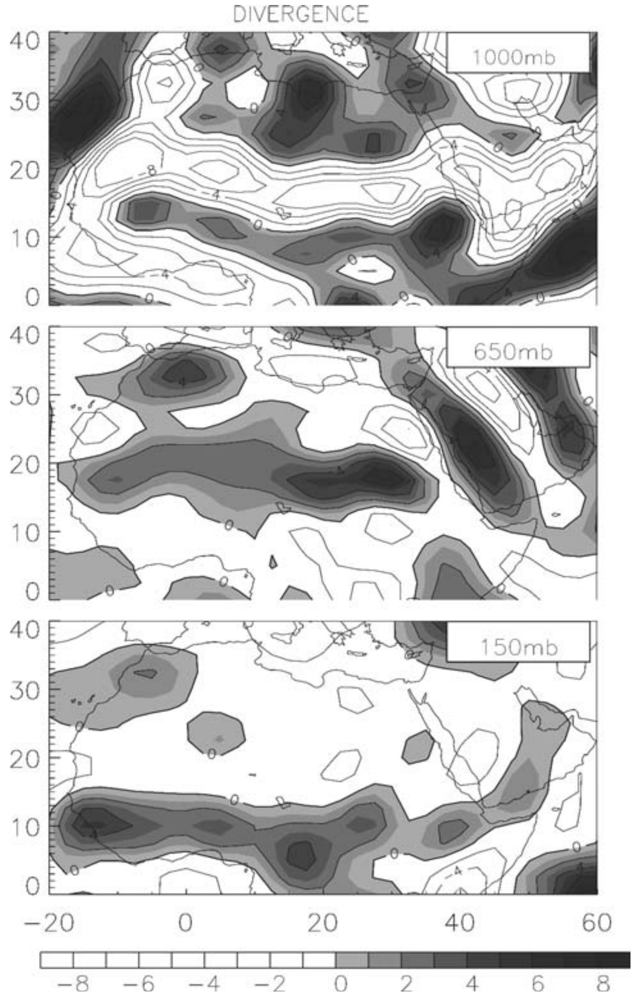


Fig. 10 Mean divergence (10^{-6} s^{-1}) in August at 1,000, 650 and 150 hPa

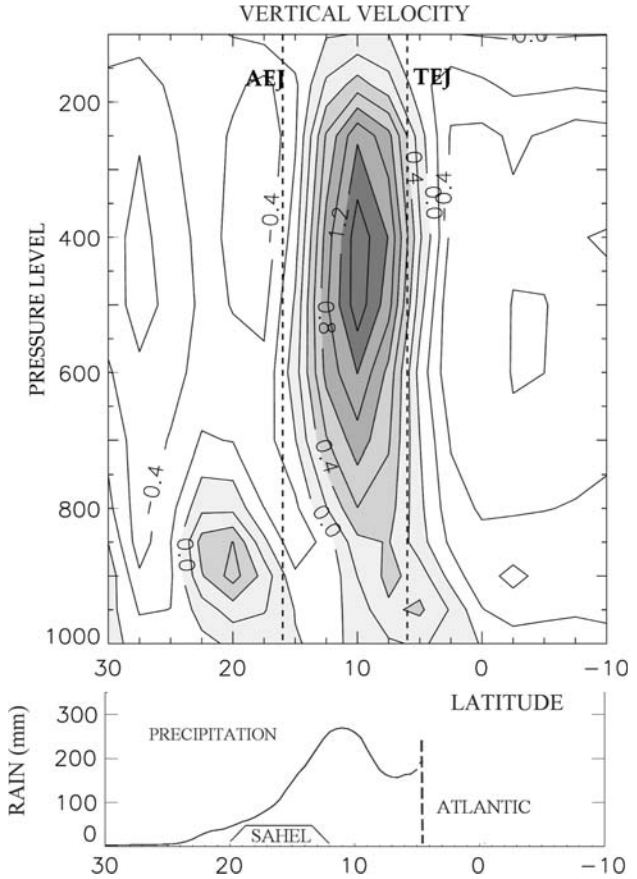


Fig. 11 Vertical cross-section of mean vertical velocity (10^{-2} m s^{-1}) in August. Axes of the AEJ and TEJ are superimposed, respectively, to the left and right of the column of strong vertical motion. Mean August rainfall (mm $month^{-1}$, averaged for 10°W to 10°E) as a function of latitude is indicated as a *solid line*

the core of the AEJ. Here the mean vertical velocity exceeds 1.2×10^{-2} ms^{-1}. The strong ascent produces the column of humid air extending into the upper troposphere.

Two shallower regions of ascent near the surface lie at 20 and 5°N (Fig. 11). The northern-most corresponds to the surface ITCZ and the meridional cell from the surface to the mid-troposphere, as described in Sect. 4.2. The more southern surface region of ascent corresponds to the frictionally induced uplift as the southwest monsoon encounters the coast of West Africa. It coincides with the coastal meridional sea-breeze circulation seen in Fig. 10. Interestingly it merges with the strong column of ascent lying between the jet axes.

Figure 11 also shows mean August precipitation as a function of latitude. The bulk of the rainfall is clearly associated with the deep core of ascent lying between the axes of the AEJ and the TEJ. This zone of precipitation is termed the "tropical rainbelt" by Nicholson (2008). Maximum rainfall, which reaches nearly 300 mm $month^{-1}$ in the long-term mean, is coincident with maximum ascent. The coastal cell is too shallow to support the development of large-scale precipitation, except in areas of topographic uplift, such as the highlands of Guinea and Sierra Leone. The ascent associated with the ITCZ lies over the western Sahara and also brings only insubstantial amounts of rainfall.

An important aspect of this new picture of the ITCZ over West Africa is that the ITCZ is dissociated from the main region of precipitation. A region of moderate subsidence separates the cell of ascent linked to the ITCZ from the cell associated with the rainfall maximum. In the mean, this subsidence lies over the Sahel. The shift from the subsidence to the ascent within a few degrees of latitude accounts for the strong gradient of precipitation in the region. In contrast, the ascent linked to the tropical rainbelt is coupled with the lower-level ascent near the coast, suggesting that the mesoscale processes associated with the sea-breeze circulation have some influence on the larger-scale dynamics and rainfall formation.

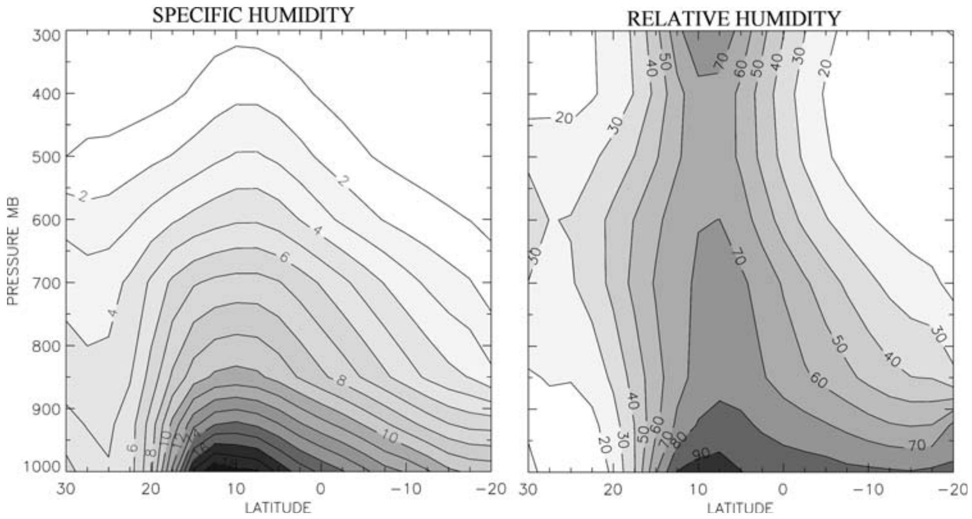


Fig. 12 Vertical cross-sections of mean specific (*left*) and relative humidity (*right*) over West Africa. Specific humidity is in units of g kg^{-1}; relative humidity is expressed in %

4.4 The moisture field of the West African monsoon

The moisture field over West Africa is portrayed in Fig. 12 via vertical cross-sections of relative and specific humidity. The most striking feature is the deep core of moist air extending from the surface to the upper troposphere and centered at roughly 8–10°N. In this core relative humidity exceeds 60% throughout the troposphere, compared to less than 40% over the Sahara and most of southern Africa, above the boundary layer.

This core coincides with the region of strong ascent lying between the axes of the AEJ and TEJ (Fig. 11) and the very humid air is essentially limited to the region of ascent. The juxtaposition suggests that the vertical motion associated with the tropical rainbelt transports surface moisture throughout the troposphere. However, the specific humidity field indicates a more complex situation. The differences between the specific and relative humidity fields reflect the strong gradient of temperature between humid Guinea Coast of the continent and the Sahara desert.

The specific humidity shows that the actual amount of vapor in the atmosphere is relatively constant with latitude between roughly 5 and 18°N. Consequently, the moisture convergence (Fig. 13) essentially reflects the wind convergence. The relatively small moisture gradients seem counterintuitive, in view of the strong precipitation gradient in the region. This implies that atmospheric dynamics rather than low-level moisture control the precipitation regime over West Africa. Specific humidity decreases sharply to the north, as the Sahara is approached, and gradually equatorward, in progressing from the continent to the ocean. This suggests that much of the moisture in the monsoon layer is recycled water, i.e., derived from local evaporation over the continent, rather than transport from the Atlantic. This is in agreement with several published estimates of recycling in this region (Brubaker et al. 1993; Savenije 1995; Trenberth 1999).

4.5 The ITCZ and wave dynamics

It has long been known that there are two main tracks of easterly waves over West Africa during the boreal summer (Burpee 1974; Reed et al. 1977, 1988; Pytharoulis and Thorncroft 1999; Thorncroft and Hodges 2001). One is centered at roughly 20°N, i.e., coincident with the surface ITCZ. The other is somewhat variable, with tracks concentrated between 5 and 15°N (Thorncroft and Hodges 2001). Analyses of individual years indicate that the southern track was centered near 11°N in 1974 (Reed et al. 1977) and near 10°N in 1985 (Reed et al. 1988), but around 8°N during 1961 (Baum 2006). The southern track is associated with the region of ascent between the AEJ and TEJ. The two tracks merge at the West Coast near Dakar and become a single track at roughly 15°N over the tropical Atlantic. The point of merger is coincident with the merger of the convergence linked to the coastal cell and the ITCZ at the West African coast.

Through streamline analysis, Burpee (1974) discovered the existence of two cyclonic circulation centers, one on each side of the jet. He concluded that the northern one is associated with the semi-permanent east-west oriented line of minimum surface pressure near 20°N, while the southern one was related to the rainy zone at latitudes near 10°N. Reed et al. (1977), applying a composite analysis to GATE easterly waves, likewise found that two circulation centers were present at the surface. The southern circulation center was located below the 700 hPa wave (i.e., at about 11°N and south of the AEJ) and the northern circulation center was located at about 20°N (i.e., poleward of the AEJ).

Figure 14 brings this picture further into focus. The northern wave track and the cyclonic center poleward of the AEJ, both lying near 20°N, are associated with the surface ITCZ, the Saharan heat low, and the meridional overturning arising there. Several studies have shown that

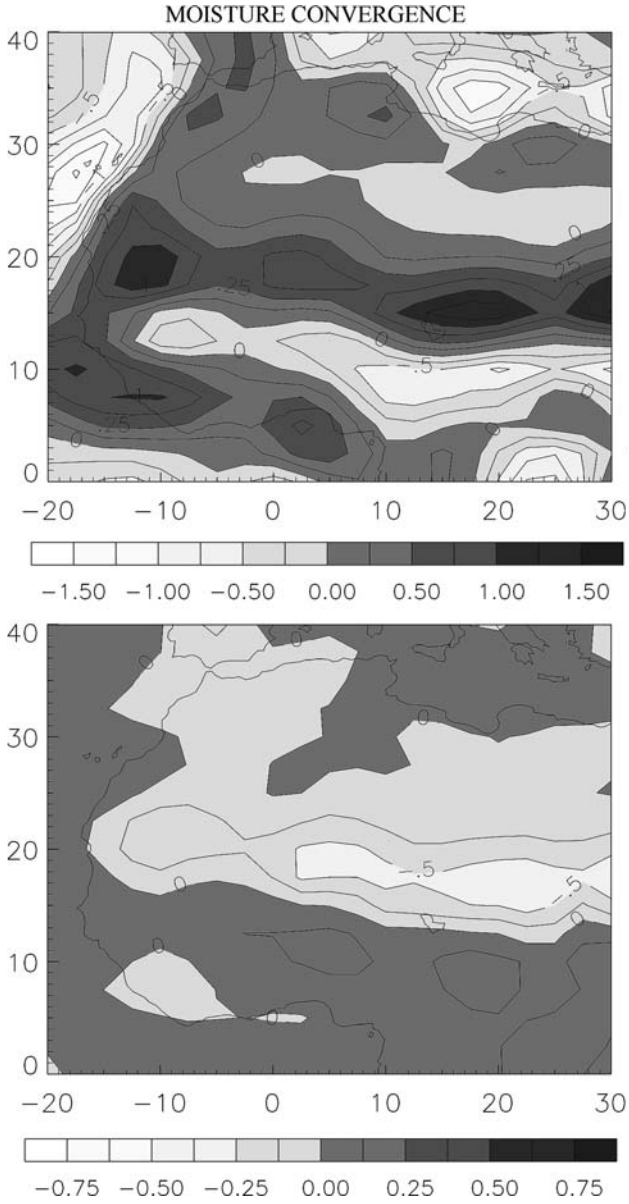


Fig. 13 Mean moisture convergence (10^{-7} s^{-1}) at 1,000 and 650 hPa

the location of this wave track is relatively fixed and that the waves are generally not associated with strong convective activity (Thorncroft and Hodges 2001). In view of the link to fixed geography, the relative invariance of this track is understandable.

The southern track is associated with the tropical rainbelt and the cyclonic circulation center south of the AEJ. The waves in this track, and associated squall lines, are generally limited to the region between the axes of the two jets (Tourre 1979). The latitudinal location of the AEJ axis is relatively variable from year to year (Grist and Nicholson 2001), accounting for the variability in the location of the southern wave track.

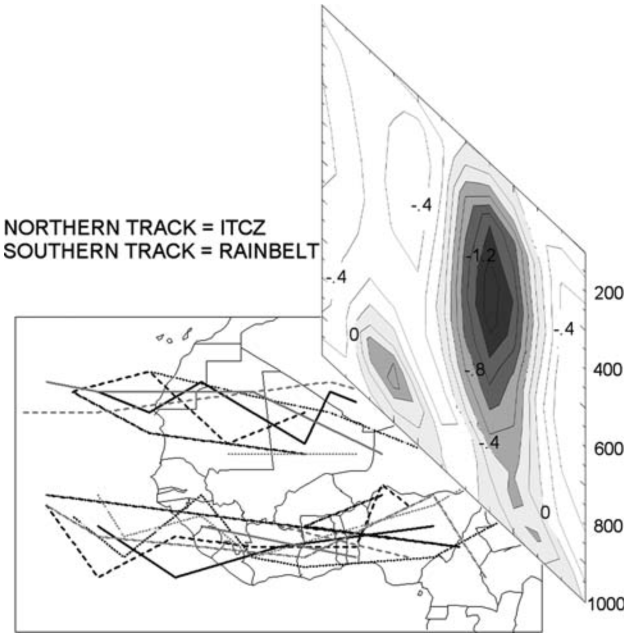


Fig. 14 The relationship between tracks of African Easterly Waves and the vertical motion fields over West Africa (based on Baum 2006; Nicholson 2008). The tracks are illustrated using waves of August 1982

4.6 Interannual and multidecadal variability

In a series of articles, commencing with Nicholson and Grist (2001), the author developed a new paradigm for understanding the interannual variability of rainfall over West Africa. Interannual variability is the net result of changes in the intensity, location and latitudinal extent of the tropical rainbelt over West Africa. Latitudinal displacements of the rainbelt create the well-known rainfall dipole, with anomalies of the opposite sign north and south of roughly 10°N (Nicholson 2008; Nicholson and Webster 2007). Changes in intensity are associated with anomaly patterns of like sign throughout the region.

The changes in the West African monsoon that are associated with these two basic patterns of variability are quite different. The north–south displacement is forced mainly by the development or absence of the AWJ. A northward displacement of this jet results in a commensurate displacement of the African Easterly Jet (Nicholson 2008; Nicholson and Webster 2007). The main column of ascending motion and the core of the rainbelt lie between the axes of the AEJ and the TEJ (which exhibits little latitudinal displacement), so that the tropical rainbelt is also displaced to higher latitudes (i.e., into the Sahel). This brings about wet years in the Sahel. In such years, the rising motion associated with the ITCZ in the vicinity of the Saharan heat low merges with the main column of ascent. This produces a broader rain belt, which further serves to increase rainfall by increasing the length of the rainy season.

In contrast, the intensity of the rainfall is governed primarily by the intensity of the Tropical Easterly Jet (Nicholson 2009). Its impact on the region is manifested by changes in the upper-level divergence, vertical motion within the rainbelt and nature of the easterly wave activity (Nicholson et al. 2008). Also, waves occasionally form on the TEJ and these are often associated with very intense precipitation events in the Sahel (Nicholson et al. 2007).

The studies described above were based on various sets of individual years. A complete analysis of multidecadal variability is beyond the scope of this article. However, a simple analysis of key circulation features shows that the factors governing multidecadal variability appear to be the same as those governing annual variability. A comparison of the 1950s and the 1980s decade, an exceedingly wet and an exceedingly dry decade, respectively (Fig. 15), illustrates this. The mean u wind patterns for the two decades (not shown) are nearly indistinguishable from those shown in Fig. 6b for wet years and dry years. In the 1950s, the ascending motion over the surface ITCZ/Saharan heat low was much more intense than in the 1980s (Fig. 16). In contrast to the mean conditions shown in Fig. 6, the circulation cell over the Sahara is merged with the main column of ascent during the 1950s and the subsidence over the Sahel is not evident. During the 1950s mean annual rainfall was 100 mm in the vicinity of the heat low. In such a case, the ITCZ may in fact be a component of the rainfall regime over West Africa.

The relationships between surface pressure gradient and the speed of the AWJ and between rainfall and the speed of the AWJ, shown in Fig. 8a, suggest a possible bimodal state. There appears to be threshold pressure gradients and jet speeds, above/below which rainfall is very likely to be above/below average in the Sahel. This would further support the hypothesis of inertial instability switching the system between a wet mode and a dry mode. If that is the case, a bimodal distribution of various circulation parameters should be evident.

Figure 17 presents histograms illustrating the frequency distribution of the latitude of the AEJ over West Africa, the speed of the AWJ, and Sahel rainfall. Data cover the period 1948–2004. A bimodal distribution is evident in all three parameters. The maximum speed of the AWJ is typically 5 or 6 ms^{-1} or it ranges between 9 and 16 ms^{-1}. The two latitudinal maximum for the AEJ lie at 14–15 and 16–17°N. The two maxima in the distribution of annual rainfall in the Sahel lie at 160–220 and 280–300 mm. These results do support the concept of two independent dynamic modes governing rainfall variability in the region. A dynamic instability mechanism triggering the shift to the wet mode is consistent with this concept.

5 A modified picture of the West African monsoon

The results in Sect. 4 suggest a revised picture of the West African monsoon that is summarized in Fig. 18. The most notable contrast with Fig. 5 is that the ITCZ is associated with a cyclonic circulation center and a shallow cell of meridional overturning, but little rainfall. In the mean the "tropical rainbelt" over West Africa is decoupled from the surface "ITCZ". Also notable is that the rainfall maximum is some ten degrees of latitude, or 1,000 km, south of the ITCZ, rather than 500 km.

Equatorward of the ITCZ, the moist layer does not have a gentle slope, but instead deepens rapidly at a rate of roughly 1 km/100 km (Fig. 7). The moisture gradient is relatively flat from 5°N to nearly 20°N. However, it is somewhat deeper at the latitude of the precipitation maximum, where a column of air with high relative humidity extends into the upper troposphere. Instead of continually deepening toward the equator, this layer rapidly becomes shallower from about 5°N to 10°S, i.e., from the African coast to the south equatorial Atlantic. This structure further supports the suggestion (see Sect. 4.4) that local evaporation rather than moisture from the Atlantic is the moisture source for the monsoon.

In the classic picture of the West African monsoon, the explanation for the rainfall being south of the surface convergence is that a certain depth of humid air is required to sustain the convection. That is not the case, since the depth of the monsoon is relatively constant from 5°N to nearly 20°N. The location well equatorward of the surface convergence is instead due to the dynamic link between the

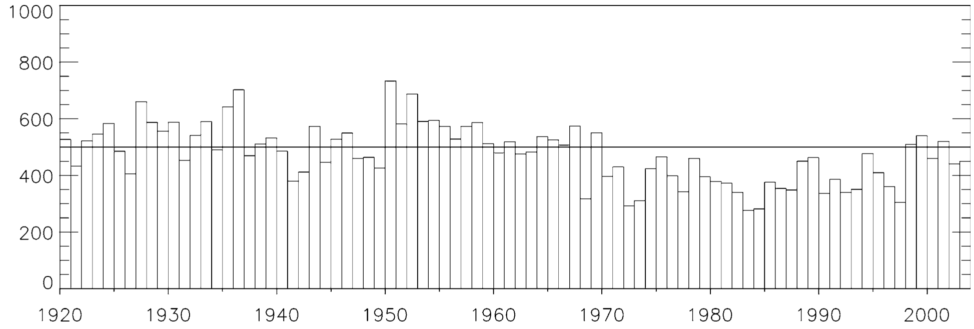


Fig. 15 Mean annual rainfall in the West African Sahel, 1921–2004 (from Nicholson 2005)

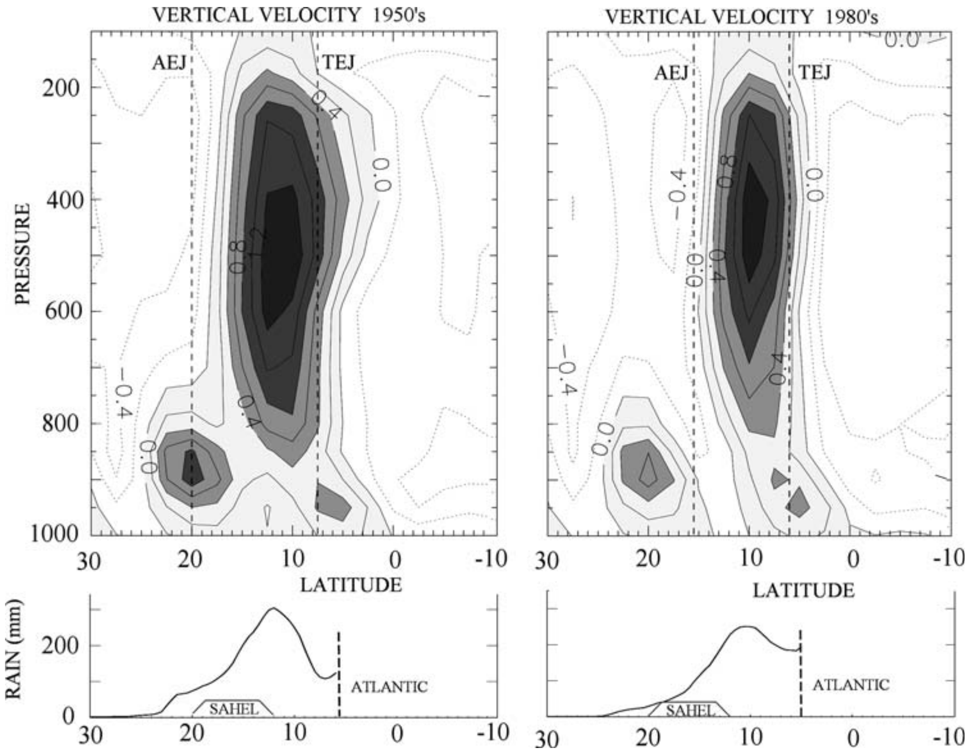


Fig. 16 As in Fig. 11 but averaged for the 1950s and the 1980s

AEJ, TEJ and tropical rainbelt. The position of the surface ITCZ is relatively constant from year to year, coinciding with the heat low over the western Sahara. The core of the AEJ migrates some 10° of latitude, so that the latitudinal displacement between the ITCZ and rainbelt is quite variable.

In this revised view, the low-level westerly flow over the continent in the boreal summer is only partially due to a monsoon system. Above the southwesterly monsoon flow lies an elevated westerly maximum, essentially a low-level westerly jet (Nicholson 2008; Nicholson and Webster 2007). It is independent of the monsoon but nevertheless an integral part of the precipitation regime and atmospheric circulation prevailing in the boreal summer. This feature is discussed in greater detail in Sect. 4.1.

6 Implications of the results

6.1 Production of rainfall over West Africa and seasonal forecasting

This revised picture has tremendous implications for modeling, seasonal forecasting, climate monitoring, the development of hurricanes, the understanding of interannual variability over West Africa, and the impact of desertification and other land surface changes. Perhaps the most important result is that in the boreal summer season three quasi-independent mechanisms control precipitation development over West Africa: ascent linked to the upper-level jet streams, convergence associated with the surface ITCZ, and a coastal circulation cell linked to sea-breeze effects.

It is generally assumed that the ITCZ is the main mechanism of precipitation in the region. The picture emerging from the Reanalysis Data suggests that, in fact, the surface ITCZ controls rainfall only in the arid northernmost Sahel and southern Sahara (ca. 23–15°N). Also it produces rainfall only when it acts in tandem with the other mechanisms (Nicholson 2008). This generally occurs only in August of the wettest years.

The primary rain-producing mechanism is the strong core of ascent lying between the axes of the AEJ and TEJ. This controls the large-scale tropical rainbelt in the boreal summer. It produces rainfall in the central and southern Sahel (15–10°N), where rainfall is associated with transient easterly wave disturbances. In years when the ascent is displaced equatorward, it also produces rainfall in the Guinea Coast region of West Africa (10–5°N).

Ascent is also associated with the band of convergence where the southwesterly winds meet the land (Fig. 10). In contrast to the ITCZ, this coastal cell generally merges with the deep column of ascent associated with the tropical rainbelt. Presumably the intensity of this convergence has some influence on the intensity of the ascent within the tropical rainbelt and hence on precipitation in much of West Africa. This would suggest that characteristics of the southwesterly African monsoon flow, such as its speed,

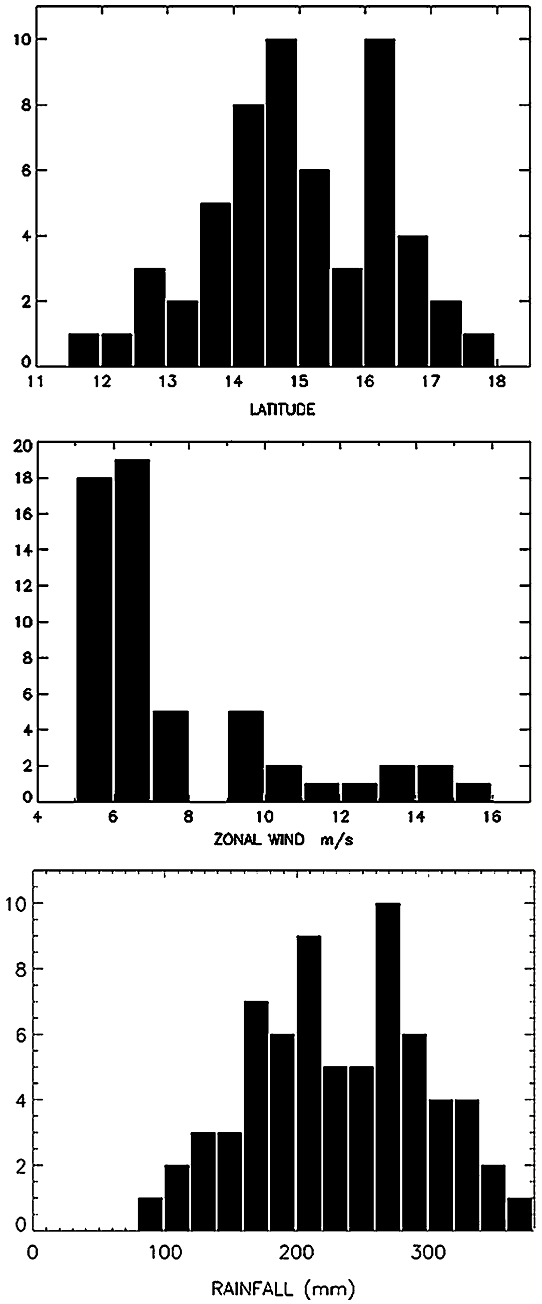


Fig. 17 Histograms showing mean August rainfall, mean speed of the low-level westerly jet in August, and mean latitude of the African easterly jet in August for the years 1948–2004. Wind data are averaged for 5°W to 5°E. Sahel rainfall is averaged for the sector indicated in Fig. 8b

depth and compass direction, influence rainfall over West Africa in the boreal summer.

Seasonal forecasting requires an understanding of the factors that govern each of these mechanisms. Statistical forecasting, which has had the best success in this region, might be improved by independently considering these mechanisms and the factors that govern them. Clearly the bulk of the precipitation is linked to the AEJ and TEJ and to the wave disturbances associated with them. Successful model predictions thus require adequate simulation of both jets and their variability.

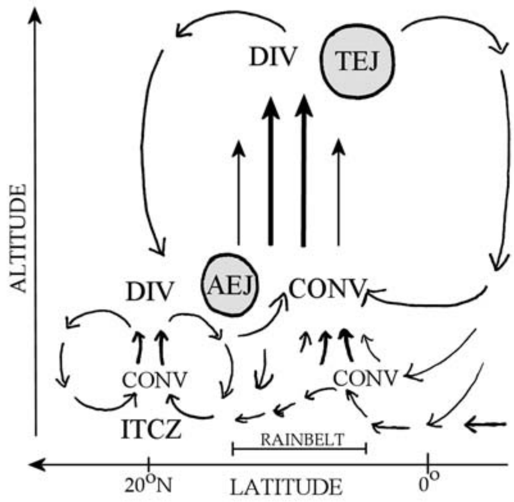


Fig. 18 Schematic illustration of the revised picture of the West African monsoon

6.2 Sources of moisture over West Africa

Our analysis showed the following characteristics of the moisture field over West Africa: a flat meridional moisture gradient over the continent between the Atlantic and the Sahara, more moisture at low levels over the continent than over the Atlantic, and a moisture convergence field that is dominated by the wind field. The implications of this are that the moisture from the Atlantic may play a lesser role during the summer “monsoon” than that evaporated over the continent itself. This is consistent with studies showing that during the boreal summer most of the moisture over West Africa is locally recycled (Brubaker et al. 1993; Savenije 1995).

Although this would appear to underscore the role of land surface processes in modulating rainfall, the importance of moisture is primarily latent heat release at the level of the AEJ (Miller and Lindzen 1992; Thorncroft and Blackburn 1999). This is controlled not by the low-level moisture, but by the intensity of the rising motion transporting that moisture aloft (Nicholson and Grist 2002).

In the context of the role of moisture, it is interesting to note that the water vapor content over West Africa can be higher in wet years than in dry years, even those contrasting in the intensity of the rainbelt (Nicholson 2009). Long ago (Lamb 1983) also noted the lack of contrast in atmospheric moisture between wet and dry years. This underscores an argument for the importance of dry dynamics in governing interannual variability (e.g., Nicholson et al. 2008) and suggests that the link between sea-surface temperatures and Sahel rainfall, noted by many authors (see Sect. 6.3), is not dominated by moisture transport.

6.3 Marine influences

A link between African rainfall and conditions over the surrounding oceans is indisputable. Robust statistical analyses have demonstrated this (e.g., Lamb 1978a, b; Lamb and Peppler 1992; Hastenrath 1990; Rowell et al. 1995; Ward 1998) and numerous model simulations bolster the connection to sea-surface temperatures (Rowell et al. 1992, 1995; Ward 1998; Rowell 2001; Giannini et al. 2003). Nothing in the scenario put forth here contradicts any of the results showing a link between West African rainfall and the global oceans.

Rather, our results suggest a new context in which the role of SSTs should be considered. In particular, it is imperative that we develop an understanding of the links between SSTs and the important features our study underscores: the low-level African Westerly Jet, the African Easterly Jet, the Tropical Easterly Jet and local coastal influences. This appears to be far more important than the links to such factors as moisture transport or location of the surface ITCZ.

Our results further suggest that it may not be the sea-surface temperatures per se that are important but the accompanying pressure patterns. Folland et al. (1986) long ago noted a relationship between inter-hemispheric sea-surface temperature contrast and Sahel rainfall. Our work likewise shows the importance of inter-hemispheric contrast, but the most important mechanism appears to involve the surface pressure gradient. This in no way contracts the earlier work on sea-surface temperatures, but adds a new dimension to the question of causality.

6.4 The desert and desertification

The traditional explanation for the lack of precipitation over the Sahara, despite the intense heat low, is that the heat low is too shallow to support convection. The circulation cell associated with the heat low was equally deep in the 1980s, when minimal August rainfall fell in the region, and in the 1950s, when on average nearly 100 mm fell during August (Fig. 16). This system was markedly stronger in the 1950s. However, the key factor in producing the rainfall in this transition zone appears to be the coupling between the circulation associated with the heat low and the ascent associated with the tropical rainbelt.

Numerous authors have suggested that desertification in the Sahel might influence its climate (e.g., Xue and Shukla 1993; see also Mohr et al. 2003). This point is still controversial but a vast amount of literature does suggest that land surface feedback might influence the region’s rainfall regime (see reviews in Entekhabi 1995, Nicholson 2000b). An extrapolation of the revised view presented here suggests that the critical region may be that between the Saharan low and the tropical rainbelt. It is interesting to speculate that land surface changes in this region might be particularly significant if they influence the degree of subsidence and hence the degree of coupling of these two regions of ascent.

6.5 The question of the ITCZ over West Africa: definition and monitoring

It has become convention to monitor the ITCZ via the rainfall maximum or via proxy indicators of this maximum, such as OLR. This study shows that the surface ITCZ and the rainfall maximum over West Africa are independent features. Also, the latitudinal position of the ITCZ over West Africa is much less variable than is the position of the rainfall maximum, here termed the tropical rainbelt.

While it has, in fact, become common usage to call this zone of rainfall the “ITCZ”, the usage creates confusion by implying a direct connection with the surface convergence. Unambiguous terminology is imperative. Here we propose using the term “tropical rainbelt” to indicate the rainfall maximum that seasonally migrates between the northern and southern hemispheres over Africa. The term ITCZ should be reserved for the surface convergence zone.

7 Summary and conclusions

This article presents an overview of the land ITCZ over West Africa, based on analysis of NCEP Reanalysis data. The picture that emerges is much different than the prevailing one. The most important finding is that the surface ITCZ is effectively independent of the system that produces most of the rainfall. Rainfall linked directly to it generally affects only the southern Sahara and the northern-most Sahel, and only in abnormally wet years in the region. A second finding is that the rainbelt normally assumed to represent the ITCZ is instead associated with a large core of ascent lying between the African Easterly Jet and the Tropical Easterly Jet. This region corresponds to the southern track of African Easterly Waves, which modulate the spatial organization of the rainfall.

Our analyses also suggest, in conjunction with earlier work, that a bimodal state of the monsoon exists and that inertial instability can trigger the shift from one state to the other. One state is associated with wet conditions in the Sahel, the other with dry conditions. This mechanism has been demonstrated for August, the wettest month and the month that contributes most to the interannual variability of rainfall. Further work is needed to demonstrate whether or not this plays a role in other months of the Sahel rainy season, particularly July and September.

This new view is relevant to many other aspects of West African meteorology, such as moisture sources, rainfall production and forecasting, the origin of the Sahara, desertification, climate monitoring, hurricanes and interannual variability. It is consistent with a plethora of research on the synoptic and dynamic aspects of the African Easterly Waves, the disturbances that organize rainfall over West Africa and spawn hurricanes over the Atlantic, and with our knowledge of the prevailing synoptic and dynamic features. This picture also appears to explain much of the multidecadal variability evidenced in the region between the 1950s and 1980s.

The findings presented underscore the need to distinguish between the ITCZ and the feature better termed the "tropical rainbelt". The latter is conventionally but improperly used in remote sensing studies to denote the surface ITCZ over West Africa. The revised view also suggests that the moisture available for convection is strongly coupled to the strength of the uplift, which in turn is controlled by the characteristics of the African Easterly Jet and Tropical Easterly Jet, rather than by moisture convergence.

These findings also underscore the need to modify the understanding of the West African ITCZ that prevails outside of the relatively small scientific community focused on the meteorology of West Africa. The image held in many parts of the climate community and by researchers in other disciplines is more akin to the "marine" ITCZ: a surface zone of convergence that produces ascent and intense convection. While the Atlantic marine ITCZ may, in fact, play a role over West Africa (IRI 2002), the structure of the equatorial convergence zone over West Africa is quite different. A better understanding of the role of each is a pressing research need.

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