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The intensity, location and structure of the tropical rainbelt over west Africa as factors in interannual variability

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ABSTRACT: This study examines the nature of the tropical rainbelt over west Africa in 4 years corresponding to the four most common patterns of rainfall anomalies in the region. These include 2 years that were anomalously wet in the Sahel, 1955 and 1950, and 2 years, 1983 and 1984, that were anomalously dry. The year 1955 is ubiquitously wet, while a rainfall dipole prevails in 1950, with abnormally high rainfall in the Sahelian latitudes but drought conditions in the Guinea Coast latitudes to the south. The year 1983 is ubiquitously and 1984 is a year with a rainfall dipole but opposite in phase (i.e. Sahel dry, Guinea Coast wet). The main results of the study are that the contrast between wet and dry years is associated with a weakening and contraction of the tropical rainbelt. In addition, a north/south displacement of the rainbelt is associated with the dipole patterns, with a northward/southward shift bringing good rains to the Sahel/Guinea Coast. These shifts are associated with north/south shifts in the latitude of the African Easterly Jet (AEJ) over west Africa. The latitudinal position and extent of the rainbelt correspond to the latitudinal position and extent of an immense ‘tongue’ of strong ascending motion. The core of the ascending motion is bound by the axes of the AEJ on the north and the Tropical Easterly Jet (TEJ) in the south. This importance of these two jets in determining the character of the summer rainy season implies that the Sahelian region provides the link between the Sahel and global scale phenomena. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Rainfall variability in west Africa has several striking characteristics (Figure 1). One is the exceedingly strong interdecadal signal, with rainfall in the 1950s and early 1960s being at least 50% greater than in the subsequent dry periods. Two others are the vast spatial scale and the zonal symmetry of the largest anomalies. The time series in Figure 1 approximately describes the variability throughout the semi-arid region from 10°N to 18°N and 15°W to 30°E (the region henceforth referred to as the ‘Sahel’). In some years dry conditions prevail between the Sahara and the Guinea Coast of the Atlantic and extend inland from the west Coast to at least Chad and the western Sudan around 25°E. In few areas of the world is interannual variability so spatially coherent.

Because of the spatial coherence, two basic spatial patterns describe most of the rainfall variability (Nicholson, 1980, 1981, 1986; Janowiak, 1988; Nicholson *et al.*, 1988; Janicot, 1992a; Nicholson and Palao, 1993; Moron, 1994; Ward, 1998; Nicholson and Grist, 2001). The most common pattern is one with rainfall anomalies of the opposite sign in equatorial and subtropical regions (i.e. the Guinea Coast vs. the semi-arid Sahel to the north)

(Figure 1 for location). This pattern is generally referred to as a ‘dipole’ in the literature. The node of the dipole is well defined and rather consistently lies near 10°N. The transition is so abrupt that, in many years, station anomalies either north or south of that latitude are almost ubiquitously of the same sign (Nicholson, 1980). The second pattern is characterized by anomalies of the same sign throughout these regions. These zonally-symmetric patterns are so fundamental that they are evident on seasonal, annual and decadal time scales and in the historical record of past centuries (Nicholson, 1994, 1995).

The spatial scale, the zonal symmetry, and the small number of spatial modes suggest a certain simplicity in the causal factors governing variability. The ubiquitous feature within the region of coherent rainfall variability is the tropical rainbelt. This zone of high rainfall is commonly, but improperly, referred to as the Intertropical Convergence Zone (ITCZ). Like the ITCZ, it migrates north and south with the seasonal march of the sun. However, the ITCZ is a surface feature and it is defined by wind convergence. Moreover, the relationship between the position of the ITCZ and the location of maximum rainfall is inconsistent. This study focuses specifically on the zone of high rainfall, viewing the ITCZ as but one factor governing its location and character.

Figure 2 shows the annual excursion of the tropical rainbelt over the African continent and its relationship to

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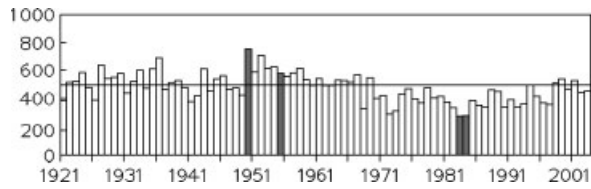


Figure 1. Rainfall in the Sahel 1901–2003, expressed as a regionally-averaged percent standard deviation (as in Nicholson, 1986). The years used in this study are shaded: 1950, 1955, 1983 and 1984.

rainfall seasonality. In each geographical region, a rainy season occurs as the rainbelt traverses it. This passage produces the single rainy season at the subtropical margins of the two hemispheres and the bimodal rainy seasons nearer the equator. The rainbelt integrates the effects of the various dynamical processes influencing the production of rainfall over Africa. Noting its dynamical importance and its role in producing the observed spatial teleconnections,

Nicholson and Grist (2001) proposed that rainfall fluctuations in west Africa can be interpreted in terms of the *position* and *intensity* of the tropical rainbelt. This dichotomy can facilitate the identification of the underlying dynamic factors, such as convergence, vertical motion, latent heat release, dynamic stability and vorticity, which regulate the interannual variability. This in

turn will link the variability to atmospheric features at the synoptic, regional and planetary scale.

The current study builds upon the work of Nicholson and Grist (2001), adding two modifications. The original study did not distinguish between the 'wet dipole' years and the 'wet' years, because the latter is apparent in only a few years of the 20th century. The current study does make this distinction. The 'wet' and 'wet dipole' years are examined separately, in order to test whether the hypothesized intensification of the rainbelt is evident in the 'wet' years. An examination of this pattern is further useful for understanding rainfall variability in the past or future, when it may occur more frequently, and for providing insight into dynamic mechanisms of variability.

A corollary of the conceptual model is that, in order to understand rainfall variability over west Africa, two key questions must be answered: what causes a shift in the position of the tropical rainbelt from year to year and what causes a change in the intensity and amount of rainfall associated with this zone. In other words, where does it rain and how much does it rain?

We deal with these issues in a quintet of papers. This article is the most fundamental and takes the broadest view. It sets the groundwork for the other four and for this reason it is intentionally limited in scope. Here the focus is on the role of the tropical rainbelt and on a conceptual model put forth to link the

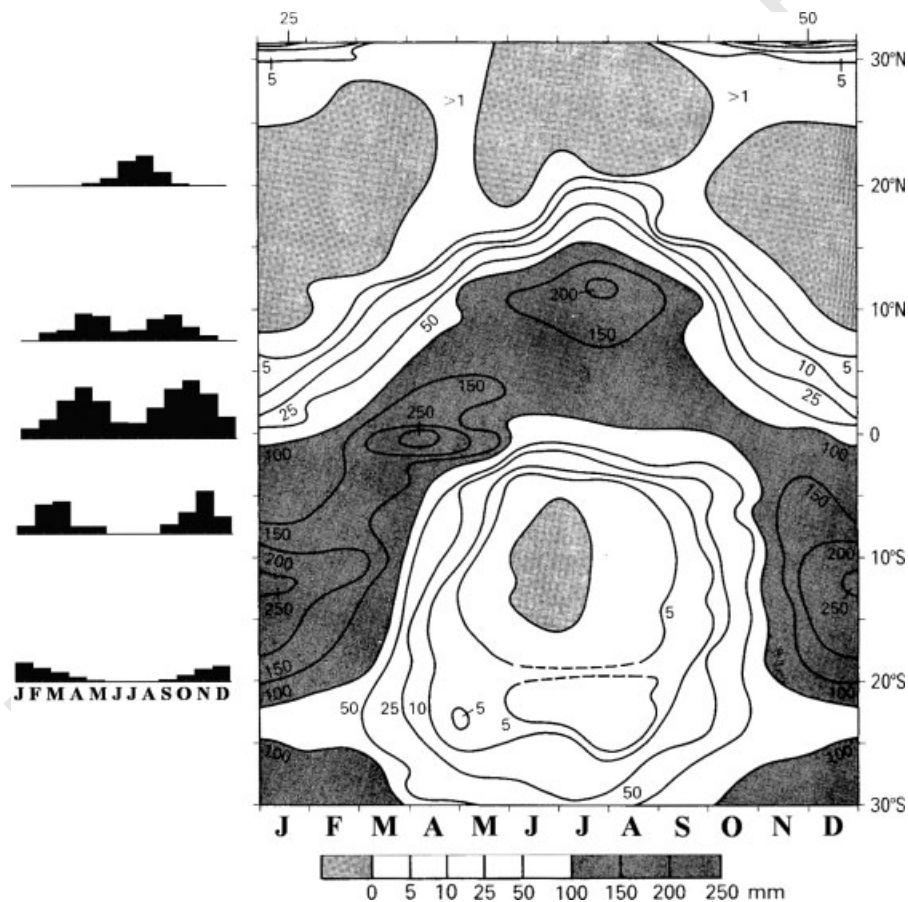


Figure 2. Annual excursion of the tropical rainbelt across the African continent and the associated patterns of rainfall seasonality as a function of latitude (adapted from Flohn, 1964).

rainbelt to interannual variability. Four case studies of individual years are used to define and initially justify the conceptual model. Further validation via composites is the subject of two additional articles. One (Nicholson and Webster, 2006) addresses the causes of the north-south displacement of the 'tropical rainbelt', focusing on inertial instability and off-equatorial convection. The other (Nicholson, 2006) addresses what causes changes in the intensity of rainfall within the tropical rainbelt, essentially the efficiency of the precipitation process in this region. It considers, among other things, wave dynamics. Two other articles (Nicholson *et al.*, 2006a,b) are modelling studies of the dynamics of easterly waves and these utilize the individual years described in the current article.

2. The Conceptual Framework

2.1. The spatial patterns of rainfall variability

The spatial patterns of rainfall described above, the dipole and the ubiquitous negative or positive anomalies, are illustrated in Figure 3. Because the two patterns have a negative and a positive phase, the net result is the four modes shown in the figure. To facilitate the discussion, these will be labeled 'wet' and 'dry' according to the sign of rainfall anomalies in the Sahel. The dipole patterns will henceforth be termed 'wet dipole' and 'dry dipole'. The remaining patterns will simply be termed 'wet' and 'dry'.

An analysis of annual rainfall (Nicholson *et al.*, 1988) showed that during the period 1920–1997, anomalies in 54 of the 77 years could be described by one of the four modes in Figure 3. Of these 29 were dipole years. These configurations were more prominent during the 30 year period 1968–1997: the dipole was well defined in 11 years and the uniform negative or positive anomalies of the wet and dry modes were apparent in 12 years (Nicholson and Grist, 2001).

A number of studies have shown that dry years with and without the rainfall dipole differ with respect to both circulation anomalies over west Africa and sea surface temperature (SST)-rainfall associations (Semazzi *et al.*, 1988; Janicot, 1992b; Fontaine and Bigot, 1993; Fontaine *et al.*, 1995; Janicot *et al.*, 1996; Ward, 1998). Nicholson and Grist (2001) hypothesize that the dipole and dry

patterns have fundamentally different causes. [Note that the term no-dipole was used for the latter in that paper.] According to their conceptual model, the dipole is associated with factors that influence the 'position' of the tropical rainbelt, while ubiquitous negative or positive anomalies are associated mainly with factors that influence its 'intensity'. This would mean that in the dry years the tropical rainbelt is abnormally weak but in its usual position. Further according to the model, in the dry dipole years the rainbelt is displaced anomalously far to the south but no change in intensity is apparent.

2.2. Dynamical aspects of large-scale rainfall patterns

In the conceptual model the dynamic factors deemed most important in determining these anomaly patterns are the location of the African Easterly Jet (AEJ) and the shears associated with it (Grist and Nicholson, 2001; Nicholson and Grist, 2001; Grist *et al.*, 2002). The latitudinal position of the jet over West Africa distinguishes between a wet and dry regime, while other factors determine whether the dipole prevails. This contrasts with past attempts to explain variability of Sahel rainfall via such mechanisms as the position and intensity of the ITCZ, the Hadley and Walker circulations, and the strength of the AEJ.

The essence of this paradigm might be viewed as a dichotomy related to the mean position of the AEJ. In one dynamic mode, which will be termed the 'Sahel' mode to facilitate discussion, the jet lies in its poleward 'track' over the Sahel, with a core at roughly 15°N during the months of June through September. In this case, the rain-bearing disturbances tend to traverse the Sahelian latitudes. This mode is also marked by strong, deep and extensive equatorial westerlies. The other dynamic mode is termed the 'Guinea Coast' mode. In this case the jet is further equatorward (with its core at roughly 10°N) and to the south of the Sahel. Thus, the disturbances pass to the south of the Sahel and bring rain to the Guinea Coast region.

3. Data and methodology

The framework discussed above serves as a working hypothesis in this study. In essence, the latitudinal position of the rainbelt determines whether the Sahel is wet or dry, while the intensity of the rainbelt determines if the dipole pattern prevails. Further, the position of the rainbelt is strongly correlated with the latitude of the AEJ. Parts of this hypothesis have been confirmed in earlier work, based on annual rainfall patterns. In this article the entire framework will be examined, using the anomalies of the Sahel rainy season. This change is made because when annual anomalies are considered, the causes of variability in the Guinea Coast become much more complex and mask the factors creating the characteristic patterns of the Sahel rainy season.

In the Sahel 80% of the annual rainfall occurs during the 3 month period July–September. Throughout the

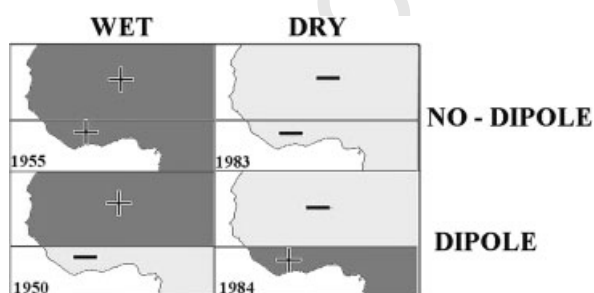


Figure 3. Schematic illustrating the four most common rainfall anomaly patterns over west Africa. Light shading indicates below normal rainfall; dark shading indicates above normal rainfall.

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region August is the wettest month and it contributes disproportionately to the interannual variability (Dennett *et al.*, 1985; Nicholson and Palao, 1993). In view of these statistics this study is limited to the July–September period (Figure 4) but focuses most strongly on August.

Four ‘case studies’ will be conducted, using 1 year to represent each of the spatial patterns shown in Figure 3. To determine dipole years, rainfall anomalies were spatially-averaged for sectors north and south of 9°N and years with particular strong anomalies in the Guinea Coast and Sahel were chosen to represent the wet and dry dipole patterns. Nicholson and Grist (2001) gives a list of dipole and no-dipole years. The 4 years used in this analysis are evaluated in the companion papers that deal more specifically with wave activity, sea-surface temperatures, and dynamical processes. The years 1950 and 1955 represent the wet dipole and wet patterns, respectively. The years 1983 and 1984 represent the dry dipole and dry patterns, respectively. These years are indicated in Figure 1 to underscore the dramatic contrast in annual rainfall between the wet years and dry years. The rainfall conditions during the July–September season are represented in Figure 5 as regionally averaged % departures from the long-term mean.

This study utilized individual years instead of the commonly used composite method, in order to provide a common thread throughout our work. The wave studies

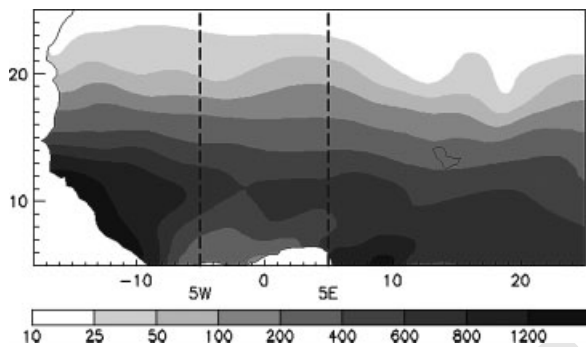


Figure 4. Map of long-term mean rainfall in the boreal summer (July–September) and map of stations used for the map and this study. Area between the dashed lines is used for latitudinal cross-sections.

(modelling and observational), for example, do not lend themselves to composite analysis. Moreover, composites often mask differences among the years forming them, suggesting general features that may or may not exist in all years of the composite.

The case studies are used as a diagnostic tool to identify individual major contrasts in the basic state of the atmosphere during years with contrasting rainfall patterns and to provide initial validation of our hypotheses. Although the four case studies provide only limited support for the generality of our results, composites used in further work will provide such support. The applicability of our results to interdecadal variability will also be examined in further work.

The data sets to be used consist of the author’s African precipitation archive (e.g. Nicholson, 1986) and the national centre for environmental prediction (NCEP) reanalysis data set (Kalnay *et al.*, 1996). The NCEP data set includes daily and monthly values of various dynamical parameters. For most variables, the data set covers the years 1948–2003. The parameters to be utilized include wind speed, zonal wind, and vertical motion. The NCEP data set has become a standard analysis tool. It was used in our previous work and the reliability of its wind estimates over Africa was validated in Grist and Nicholson (2001).

A map of rainfall stations in the archive is shown in Figure 4. Most records extend from around 1920 to 1997 and have been updated continually with data from the local meteorological services. Reliance on locally-obtained data has provided continuity in the station records. This archive also contains a larger number of African stations than some of the new, global data sets (e.g. New *et al.*, 1999, 2000) and is more homogeneous, since the data source and station network generally changed in the 1970s or 1980s in the other data sets. A rough estimate of the data set’s spatial resolution is 1° by 1° (e.g. Nicholson *et al.*, 2003), assuming that five stations per grid box are needed to provide a representation spatial average (Xie and Arkin, 1995). Although the New/Hulme data set is gridded at 0.5°, the criterion utilized is one station within 450 km of

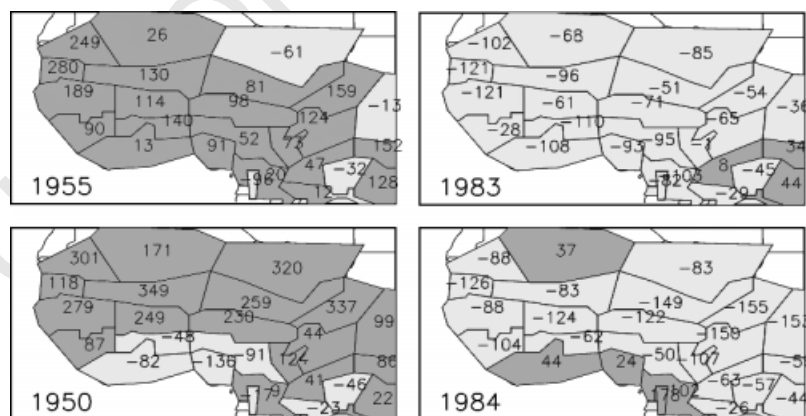


Figure 5. Regional rainfall anomalies for the July–September season for 1950, 1955, 1983 and 1984. Anomalies are expressed as a % of the standard departure from the mean for the 30 years 1968–1997 (as in Nicholson, 1986).

1 the gridpoint (New *et al.*, 2000). This is equivalent
2 to approximately a 5°-spatial resolution in data-sparse
3 regions of Africa.

4 Interpreting our working hypothesis on a year-to-year
5 basis suggests the following situations to explain the
6 rainfall anomalies in each of the four years. The years
7 with abnormally 'wet' conditions in the Sahel, 1950 and
8 1955, are presumably linked to a northward displacement
9 of the rainbelt and the AEJ. The displacement brings
10 heavy rainfall into Sahelian latitudes. The wet conditions
11 in the Guinea Coast in 1955 are then a result of an
12 overall intensification of the rainbelt. The years with
13 abnormally 'dry' conditions in the Sahel, 1983 and 1984,
14 are presumably linked to a southward displacement of
15 the rainbelt and the AEJ. As a consequence, the major
16 rain-bearing systems are south of the Sahel, producing
17 drought. Although this displacement means that the
18 rainbelt lingers along the Guinea Coast region in the
19 boreal summer, this region is nevertheless abnormally
20 dry because of an overall weakening of the rainbelt.

21 To test these ideas, we evaluate the location and
22 intensity of the rainbelt directly using station rainfall
23 data and indirectly using vertical motion from the NCEP
24 reanalysis data. The importance of this comparison is
25 that the two data sets are completely independent. The
26 latitudinal location of the AEJ is also examined, as are
27 other characteristics of the upper-level winds.

30 4. The tropical rainbelt

31 Figure 6 shows the tropical rainbelt as a function of lati-
32 tude as it migrates north and south over west Africa dur-
33 ing the course of the year. This is shown for each of the
34 4 years corresponding to the four spatial configurations
35 in Figure 2. The results suggest that the framework sug-
36 gested by Nicholson and Grist (2001) is not quite applica-
37 ble. A northward displacement of the rainbelt is evident
38 in the wet dipole case, consistent with the hypothesis, but
39 not in the wet case. In the wet dipole case, its core lies
40 at roughly 12–13°N in August, when it reaches its northern-
41 most latitude. In the wet case, the core lies at roughly
42 10°N, i.e. near its mean position. Similarly, an equator-
43 ward displacement to roughly 7 or 8°N is evident in the
44

dry dipole year. However, in the dry year the core lies 45
near its mean August position, as in the wet year 1955. 46

47 Thus, the location of the rainbelt explains the rainfall
48 patterns of the wet and dry dipole years. However, the
49 contrast between the ubiquitously wet and dry years, 1955
50 and 1983, cannot be so explained. Instead, in these years
51 contrast is apparent in the intensity and latitudinal extent
52 of the rainbelt. In the core, rainfall exceeds 200 mm/mo
53 in 1955, but only 100 mm/mo in 1983. In August the
54 zone in which rainfall exceeds 100 mm extends from 8°N
55 to 15°N in 1955, but in 1983 it is limited to the latitudes
56

57 These points are further illustrated via a direct com-
58 parison between 1950 and 1984 and between 1955 and
59 1983. In July and August peak rainfall occurs markedly
60 further north in 1950 than in 1984 (Figure 7(a)). Thus a
61 marked north-south displacement of the tropical rainbelt
62 distinguishes the 2 years. In August the rainbelt is also
63 considerably stronger in 1950 than in 1984. In September
64 some contrast in intensity is still apparent, but there is
65 little contrast in intensity in either June or July. The situ-
66 ation is quite different for 1983 and 1955 (Figure 7(b)).
67 The latitudinal profiles in all months are similar in the
68 2 years, but at all latitudes there is more rainfall in 1955
69 than in 1983. The only exception is the Saharan latitudes
70 in June. Thus, the differences in the intensity of the rain-
71 belt account for the wet *versus* dry conditions throughout
72

73 Figure 7 also shows that rainfall conditions in June are
74 relatively constant year to year. No association is
75 apparent between high rainfall in June and high rainfall
76 during the other months. Thus, conditions in June are not
77 a precursor to those of the subsequent rainy season and
78 provide little forecast value.

79 It is further interesting to note that within each year the
80 latitudinal profile of rainfall remains essentially constant
81 during the 3 month season of July–September (Figure 8).
82 An important exception to the above occurs in 1950,
83 when rainfall increases tremendously in August. This is
84 interesting, in that August is responsible for the most of
85 the contrast between wet and dry years (Dennett *et al.*,
86 1985; Nicholson and Palao, 1993). This feature likewise
87 underscores the difficulty of seasonal forecasting from
88

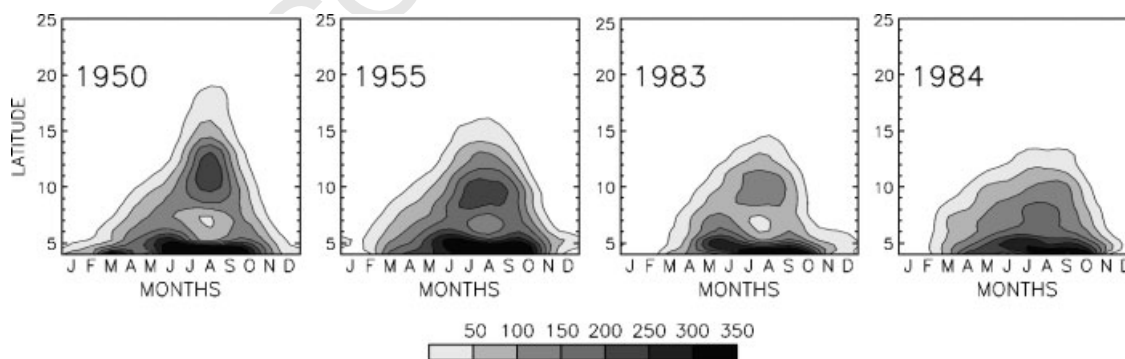


Figure 6. Rainfall as a function of month and latitude over West Africa in the years 1950, 1955, 1983 and 1984. Rainfall is in mm/mo and is averaged for the region 5°W–5°E (refer Figure 4).

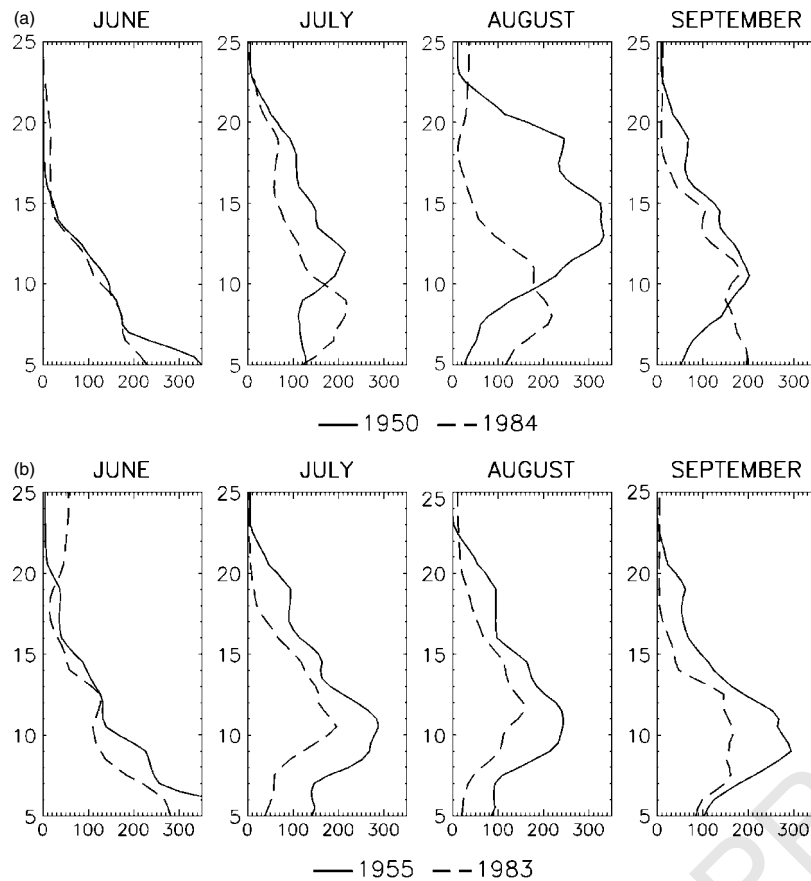


Figure 7. Rainfall as a function of latitude in the months of June through September. (a) a comparison of 1950 and 1984, the two dipole years. (b) a comparison of 1955 and 1983, the non-dipole years.

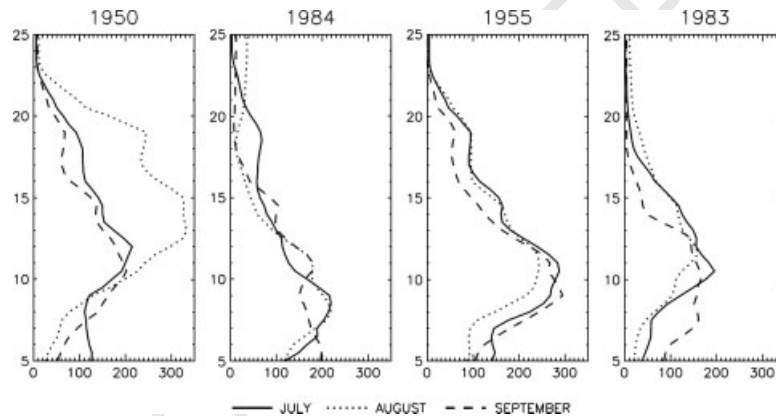


Figure 8. Rainfall as a function of latitude over west Africa in the months July, August and September. Refer Figure 4 for location of the area used for the cross-section.

1 Collectively, these results show that anomalous dis- 12
 2 placements of the tropical rainbelt account for the two 13
 3 dipole years, 1950 and 1984, but weakening and inten- 14
 4 sification of the rainbelt, respectively, account for the 15
 5 ubiquitously wet year 1955 and the ubiquitously dry 16
 6 year 1983. However, a strong enhancement of rainfall in 17
 7 August in the Sahelian latitudes contributes to the occur- 18
 8 rence of the dipole in 1950. Overall these results are 19
 9 consistent with those of a much earlier study (Nicholson, 20
 10 1981). That study found, for example, that in many years 21
 11 with drought in the Sahel, the rainbelt lay in its normal

position. It also concluded that an anomalous displace- 12
 ment of the zone was more likely to be a cause of wet 13
 years than dry ones. These conclusions belie the once 14
 common notion that an equatorward displacement of the 15
 ITCZ is the major cause of Sahel drought. 16

5. Winds Aloft and the AEJ

Our working hypothesis was that a northward/southward 21
 shift in the AEJ would be evident during the years 22

1 1950/1984. Such a shift in the location of the rainbelt
 2 in August was observed. To test this, cross-sections of
 3 mean zonal wind in August as a function of latitude were
 4 derived for each of the 4 years. These are presented in
 5 Figure 9.

6 Two consistent differences are apparent between the
 7 two wet years and the two dry years. In the wet years
 8 there are strong westerly jet in the boundary layer just
 9 north of the equator and the tropical easterly jet (TEJ) is
 10 exceedingly strong. In the dry years the jet is replaced by
 11 shallow equatorial westerlies of the south west monsoon
 12 and the TEJ is markedly weaker. Grist and Nicholson
 13 (2001) showed these same contrasts between multi-year
 14 wet and dry composites for the region. As for the
 15 anticipated north/south displacements of the AEJ in the
 16 wet/dry years, no consistent association is evident. The
 17 AEJ is displaced to roughly 18°N in the wet dipole year
 18 1950, but lies at 14°N (near its mean position) in 1955.
 19 The AEJ lies 2 or 3° further south during the two dry
 20 years, but its location cannot account for the occurrence
 21 of the dipole in 1984 *versus* ubiquitous dry conditions in
 22 1983.

23

24

25 6. Vertical Motion

26

27 Figure 10 shows the mean vertical motion as a function
 28 of latitude during August of each of the 4 years. Areas
 29 of strong ascent are highlighted and directly compared
 30 in Figure 11. An obvious result is a strong but narrow

31 tongue of ascending air in the low latitudes. It extends
 32 from the lower to the upper troposphere. Maximum
 33 ascent occurs in the mid-troposphere, i.e. near the AEJ,
 34 in three of the four cases. Two smaller and shallow areas
 35 of ascent are evident. One lies over the central Sahara at
 36 about 20°N. This corresponds to the well-known heat low
 37 over the western Sahara. The second area, at roughly 5°N,
 38 is much shallower and weaker. It probably represents the
 39 frictional uplift at the coast as the low-level southwest
 40 'monsoon' passes over the shoreline. In general, the three
 41 areas appear to be independent and presumably have
 42 different origins. However, they appear to be merged in
 43 August of 1950, the case in which maximum vertical
 44 motion lies nearest the surface.

45 A comparison of the vertical motion fields in the
 46 4 years supports the conclusions in Section 3, based on
 47 the rainbelt itself. Clearly the maximum vertical motion is
 48 displaced northward in 1950, when it spans the latitudes
 49 from roughly 12–20°N, and southward in 1984, when
 50 it lies at 8 or 9°N. This confirms that the two dipole
 51 patterns are associated with north-south displacements
 52 of the rainbelt. Somewhat surprisingly maximum vertical
 53 motion occurs at roughly 10–11°N in both the ubiquitous
 54 wet case (1955) and the ubiquitous dry case (1983).
 55 The contrast in rainfall is associated with contrast in the
 56 intensity of the vertical motion and the reduced latitudinal
 57 extent of the ascending air mass.

58 Thus emerges a picture in which two features of the
 59 vertical motion field represent the main contrast between
 60 the two wet years and the two dry years (Figure 10). In 60

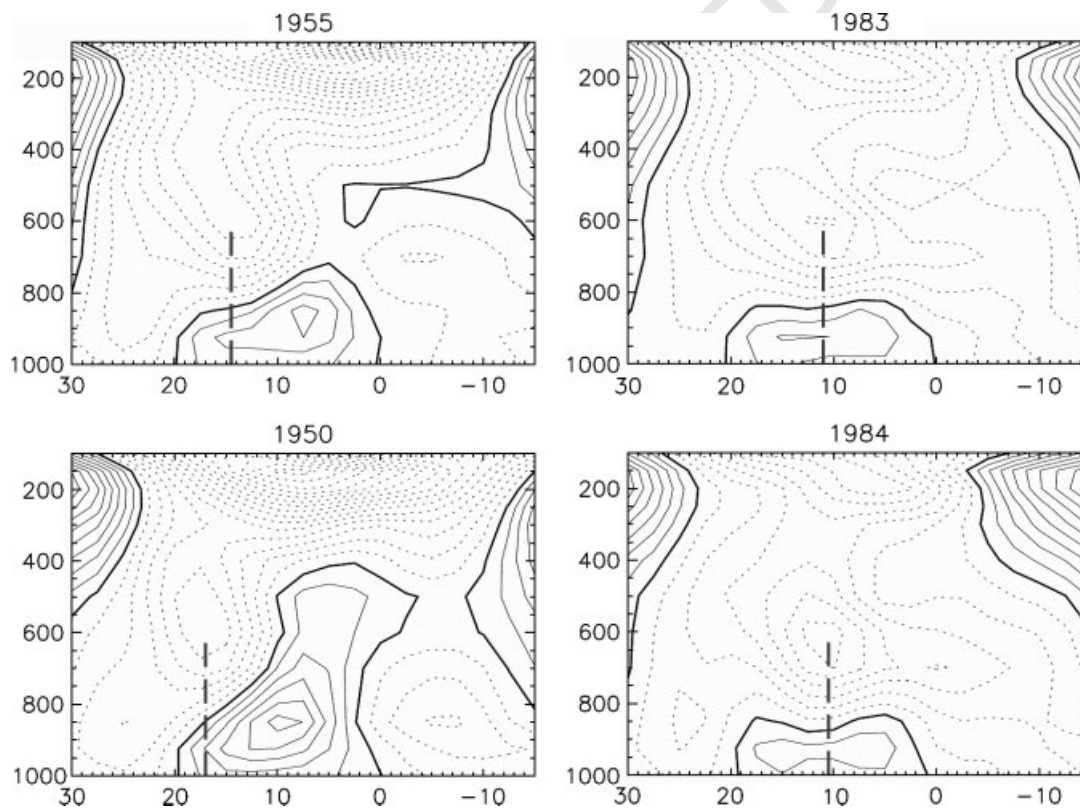


Figure 9. Mean zonal winds (m s^{-1}) in August of the 4 years, averaged for the region 10°W–10°E. Contours are every 2 m s^{-1} , with dashed lines representing easterly winds. Vertical lines represent the core of the African Easterly Jet.

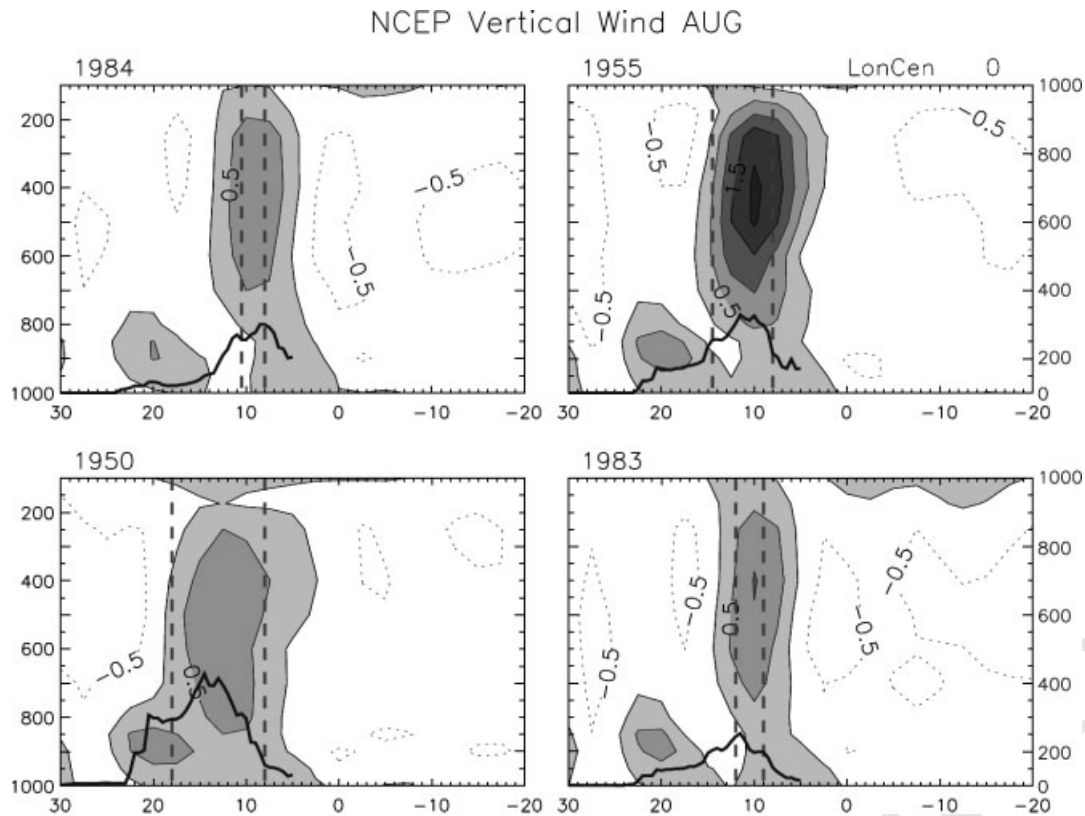


Figure 10. Mean vertical motion in August for the 4 years 1950, 1955, 1983 and 1984. Contours are in m s^{-1} ; areas of ascent are shaded. Mean rainfall as a function of latitude, averaged for the sector shown in Figure 4, is indicated at the bottom; rainfall in mm/mo is indicated on the right hand axis. The vertical dashed lines indicate the axes of the AEJ (left) and TEJ (right).

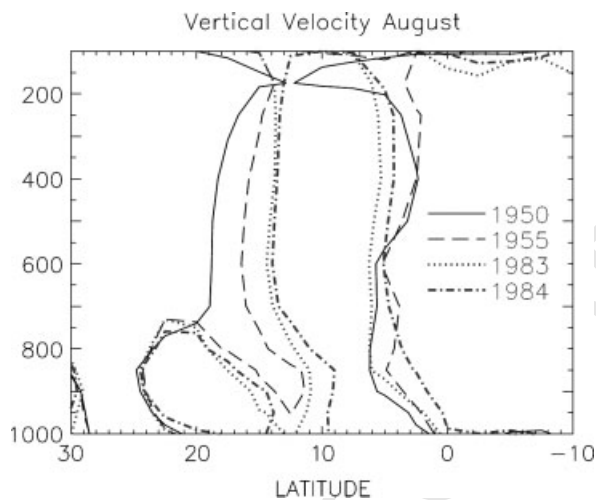


Figure 11. The cores of the tongue of ascending air in each of the 4 years shown in Figure 10. The -2 m s^{-1} contours are shown.

anomalous north-south displacements in the two dipole years appear to be secondary features, but none the less the cause of the dipole patterns.

Other interesting features emerge from Figure 10. The first is that the latitudinal extent of the rainbelt, shown by a solid line at the base of the diagram, shows a strong correlation with the latitudinal extent of the ascending tongue. Also peak rainfall is higher in the 2 years with stronger vertical motion. Finally, the ascending air appears to be roughly bounded by the cores of the AEJ and TEJ, indicated with vertical lines in the figure. This suggests that the ascending motion is linked to the juxtaposition of the two jets and that the relationship between the two is a major factor in the formation of the tropical rainbelt over west Africa. This issue is further explored in the following section.

7. Relationships between rainfall, the AEJ and the TEJ

The AEJ and the TEJ are two of the most prominent circulation features of the tropical atmosphere. These lie, respectively, in the mid- and upper-troposphere. The AEJ's core lies over west Africa (Figure 12); maximum speeds, on the order of $12\text{--}15 \text{ m s}^{-1}$, occur generally around 650 mb. Its importance in the initiation, growth and propagation of Africa easterly waves is well established (Burpee, 1972; Rennick, 1976, 1981). The TEJ's

1 the both types of wet years, the vertical motion is strong,
 2 with maxima in excess of 8 m s^{-1} and large areas in
 3 which the ascent exceeds 4 m s^{-1} . In the two dry years
 4 there is only a small region in which ascent exceeds 3 m s^{-1} .
 5 The second contrast is the latitudinal extent of the
 6 ascending tongue. It extends over $7\text{--}8^\circ$ of latitude
 7 in the two dry years, but twice that in the wet years. A
 8 consequence is that in the Sahelian latitudes descending
 9 air prevails, intensifying the aridity in these latitudes. The

1 core lies much further east; it is markedly stronger and
 2 more extensive than the AEJ. The TEJ figures most
 3 prominently in the Asian monsoon (e.g. Mishra and Tan-
 4 don, 1983; Chen and van Loon, 1987; Mishra, 1987;
 5 Chen and Yen, 1993). Studies of the jet over Africa are
 6 sorely lacking (Chen and Yen, 1993). However, numer-
 7 ous studies have shown that a consistent relationship
 8 exists between the strength of the TEJ and rainfall over
 9 west Africa e.g. (Kanamitsu and Krishnamurti, 1978;
 10 Newell and Kidson, 1984; Grist and Nicholson, 2001).
 11 Moreover, Tourre (1979) showed that the axes of the
 12 two jets confine the region through which squall lines
 13 propagate (Figure 13).

14 The congruence of the jet axes and the core of the
 15 ascending motion (viz. Figure 10) suggests that the jets
 16 may likewise bound the core of the tropical rainbelt.
 17 This implies a definitive role in determining at least the
 18 position and latitudinal extent of the rainbelt. To test this,
 19 the jet axes are superimposed upon the August rainfall
 20 fields for the 4 years (Figure 14). A clear association
 21 between the jet axes and location/extent of the rainbelt is
 22 clearly illustrated. Likewise, in the mean, the positions
 23 of the axes roughly border the core of rainbelt in
 24 August, particularly west of 25°E, where the AEJ is

strong. However, the association is not strong enough
 to distinguish the two dry years on the basis of the AEJ
 axis.

8. Summary and conclusions

This study has examined the intensity, location and
 structure of the tropical rainbelt in 4 years corresponding
 to the anomaly patterns in Figure 2. Two prominent
 differences in the structure of the tropical rainbelt in
 the two wet years and two dry years are identified. In
 the wet years, compared to the dry one, the rainbelt is
 markedly more intense and its core covers a much greater
 latitudinal band. It is weak and contracted in the two dry
 years. As would be expected, the rainbelt corresponds to
 a narrow tongue of ascending motion over west Africa.
 The region of ascent is likewise stronger and broader in
 the wet years than in the dry years. Thus, a fundamental
 question concerning the interannual variability is what
 factors govern the latitudinal extent and intensity of the
 rainbelt and associated vertical motion.

Parallel work suggests that wave activity modulates
 the intensity (Grist, 2002; Grist *et al.*, 2002; Nicholson
et al., 2006a,b). The question of intensity is treated
 more comprehensively in a later article (Nicholson,
 2006). The primary question to be answered is what
 changes the amount of precipitation associated with the
 tropical 'rainbelt' over west Africa. Preliminary analysis
 suggests that the determinants include vertical motion,
 convergence, dynamic instabilities and latent heating. On
 the other hand, the total amount of rainfall occurring
 locally at areas within the tropical rainbelt is determined
 by a combination of this intensity and the latitudinal
 extent of this zone. Our work has shown that the extent
 is governed collectively by the latitudes of the AEJ and
 TEJ, the axes of which bound the tropical rainbelt in
 August.

As for its location, a north-south displacement of the
 rainbelt is apparent only in the two dipole patterns, with
 a northward/southward shift bringing good rains to the
 Sahel/Guinea Coast. The 'tongue' of vertical motion is
 similarly displaced in the dipole years, but not in the
 other 2 years. This displacement appears to be the main
 factor in the development of the rainfall dipole because
 it alters the latitudinal band in which the major rain-
 bearing systems develop and propagate. These shifts
 are associated with north/south shifts in the latitude of
 the AEJ over west Africa. The AEJ also shifts slightly
 northward during the ubiquitously wet year.

Thus a second fundamental question is causes a
 north/south displacement of the tropical rainbelt. Al-
 though the question is beyond the scope of this paper,
 numerous other studies (e.g. Lamb, 1978; Hastenrath,
 1984, 1990; Giannini *et al.*, 2003) that sea-surface tem-
 peratures play a role in determining the location of the
 ITCZ/tropical rainbelt. This issue is further investigated
 in a companion article (Nicholson and Webster, 2006).

This study dramatically underscores the importance of
 both the AEJ and TEJ in determining the character of

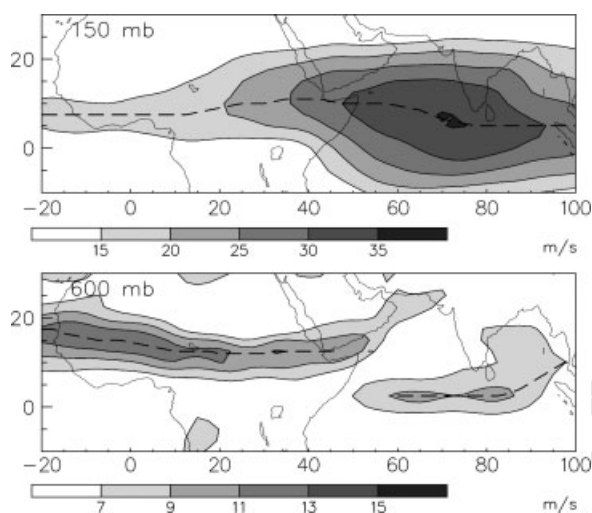


Figure 12. The Tropical Easterly Jet (TEJ) and African Easterly Jet (AEJ) in August. The speeds (m s^{-1}) are derived from NCEP Reanalysis Data and represent a mean for the period 1948–2003.

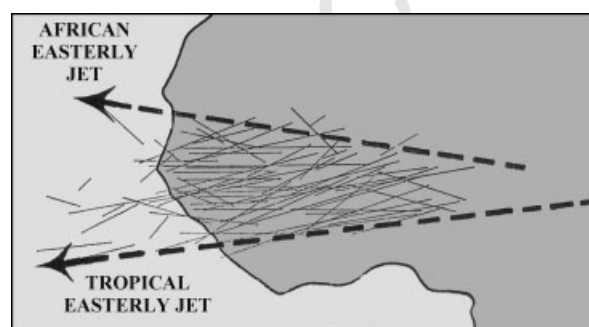


Figure 13. Tracks of squall lines over west Africa in relationship to the axes of the TEJ and the AEJ (Tourre, 1979).

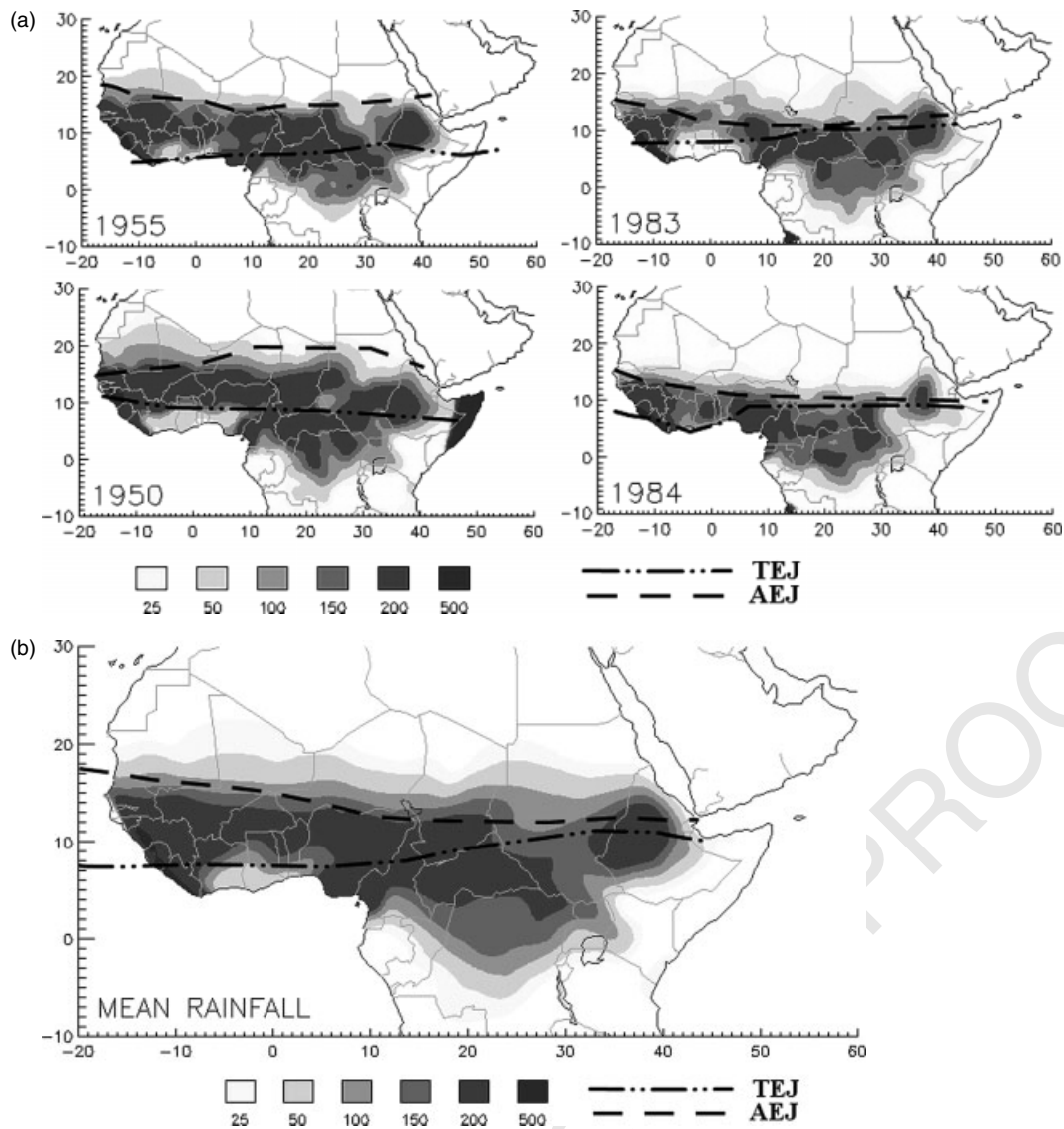


Figure 14. (a) August rainfall (mm) in the 4 years 1950, 1955, 1983 and 1984. The axes of the TEJ and AEJ have been superimposed upon the rainfall field; (b) Mean August rainfall (mm). The mean axes of the TEJ and AEJ have been superimposed upon the rainfall field.

CONCEPTUAL MODEL

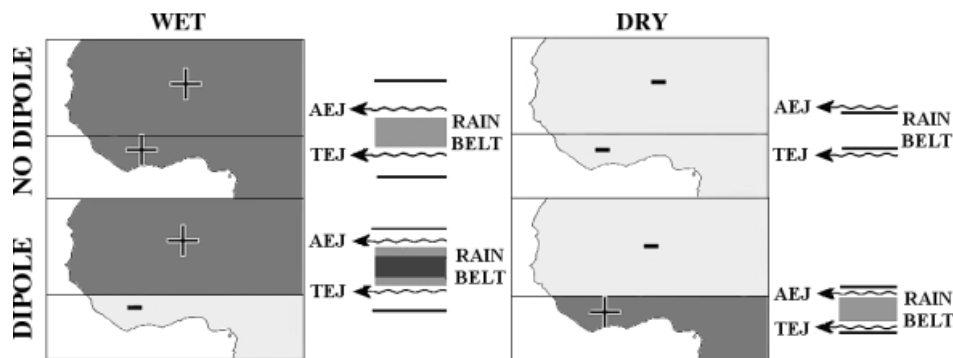


Figure 15. Summary of new conceptual framework of rainfall variability sub-Saharan West Africa, illustrated for August. Variability is a function of the intensity, width and location of the “rainbelt”. The schematic shows the prevailing rainfall anomaly pattern, next to which is a sketch of the width, location and intensity of the rainfall. Intensity is indicated by shading, with the horizontal lines representing latitudes where rainfall exceeds 100 mm/mo, and the light and dark shading indicate rainfall in excess of 200 mm/mo and 300 mm/mo, respectively. The development of the dipole pattern, with contrasting anomalies in the Sahel and Guinea Coast, requires simultaneous shifts in the latitude of the AEJ. No shift is evident in the no-dipole patterns.

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1 the summer rainy season. This implies a link between
 2 the Sahel and global scale phenomena. The relationship
 3 between the jets governs both the extent of the rainbelt
 4 and its intensity (Nicholson *et al.*, 2006a). A related issue
 5 is what causes a relative displacement of the axes of the
 6 two jets with respect to each other. This issue may tie in
 7 Africa to the Asian monsoon system.

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 14 University. We are also grateful to NCAR for providing
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