Variability of the Intertropical Front (ITF) and Rainfall over the West African Sudan–Sahel Zone

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ABSTRACT

The Intertropical Front (ITF) is a fundamental feature of the atmospheric circulation over West Africa. It separates the wedge of warm moist southwesterly monsoon flow off the tropical Atlantic from much hotter and very dry northeasterly wind from the Sahara Desert. Here, the daily temperature, humidity, and rainfall data for 1974–2003 are analyzed to document the northward advance and southward retreat of the ITF between boreal spring and autumn, and assess its role in Sudan–Sahel (10°–20°N) rainfall patterns. Using largely dekadal (10 day) and monthly resolutions, analyses are performed for the 30-yr-average seasonal time scale and sets of extreme years, with a major focus on concurrent monthly ITF–rainfall relations. The seasonal rainfall predictive potential of the early season ITF latitude is also investigated, as is the secular variation of ITF latitude–weather system–rainfall associations during 1974–2003.

The northward advance of the ITF across the Sudan–Sahel from April to early August is relatively slow, averaging 0.8° latitude dekad⁻¹ (8.8 km day⁻¹). The southward ITF retreat between mid-August and mid-November is almost twice as fast, averaging 1.4° latitude dekad⁻¹ (15.5 km day⁻¹). Coupled with the ITF advance, the monsoon rainbelt migrates northward and intensifies. However, its northern boundary (1 mm day⁻¹ monthly average isohyet) lags 100–250 km south of the ITF, while the most useful rainfall for society (≥3 or 4 mm day⁻¹ monthly average) generally occurs more than 400 km south of the ITF. There, the monsoon wedge is thickest and the horizontal velocity and moisture convergence are maximized in a regional ITCZ. The rapid ITF retreat during September–October is preceded by a similar rainbelt displacement. During both ITF advance and retreat, rainfall over the Sudan–Sahel region is positively related to the ITF’s latitude. The association is strongest during the early (April–June) and late (October) rainy season months (linear correlation, \( r = 0.74 \) to \( +0.81 \), when the ITF is located to the south and rainfall is low. It is weaker during the July–September rainy season core when the ITF is farthest north (\( r = 0.50 \) to \( +0.58 \)). This concurrent rainfall dependence on ITF latitude is established further by contingency analyses for the 30-yr study period and by investigation of several extremely dry and wet individual seasons. The April ITF latitude anomaly is a moderately consistent indicator of the subsequent ITF latitude and associated rainfall anomaly through the first core rainy season month (July). This seasonal prediction potential does not persist into the rainy season peak (August), when the concurrent ITF–rainfall relationship is weakest (\( r = +0.50 \)), the monsoon wedge is thickest, and rain-producing mesoscale dynamical processes are developed fully. However, because the ITF tends to retreat early (late) in seasons when it advanced early (late), the April ITF latitude specification of the September–October ITF latitude and rainfall (negative) is almost as consistent as that for July (positive). The secular variation of ITF latitude during 1974–2003 strongly influenced mesoscale weather systems and rainfall variability on decadal time scales.

1. Introduction

For at least 65 years, the Intertropical Front (ITF) has been recognized as a fundamental feature of the atmospheric circulation over West Africa (Hamilton and Archbold 1945; Eldridge 1957; Hare 1977, but first appeared in 1943). The ITF is a west–east-oriented quasistationary discontinuity that separates the warm and moist southwesterly monsoon flow off the tropical Atlantic from the much hotter, very dry, and frequently dust-laden northeasterly Harmattan air from the Sahara Desert. At the surface, the wind direction discontinuity is characterized by pronounced temperature and humidity gradients.
that migrate seasonally northward then southward, lagging somewhat the zenith angle of the sun in the northern tropics. Between the surface and about 700 hPa, the ITF slopes upward to the south at inclinations between 1:100 and 1:400 (Hastenrath and Lamb 1977; Hastenrath 1991, 166–174) and is the upper boundary of the meridionally migrating wedge of monsoon air. The coincident zones of maximum horizontal velocity and moisture convergence and rainfall that are the West African manifestations of the intertropical convergence zone (ITCZ) occur a few hundred kilometers south of the ITF, where the monsoon wedge is deeper.

Today, the ITF is considered to be important for not only the seasonal-to-interannual climate variability of West Africa, but also for the incidence of the region’s most serious and vector-borne infectious diseases (malaria, meningitis) and its desert locust plagues that can devastate pastures and crops. Much remains to be learned about the terrible diseases of malaria and meningitis. However, it is clear that meningitis outbreaks occur in the harsh, dry conditions north of the ITF (Moore 1992; Molesworth et al. 2003; Sultan et al. 2004, 2005; Thomson et al. 2006) and that malaria infections in individuals originate in the warm and moist environment south of the ITF (Breman 2001; Breman et al. 2004). Furthermore, the equatorward retreat of the ITF occasionally is accompanied by a massive southward migration of desert locusts that breed near the ITF (Drake and Farrow 1988; Roffey and Magor 2003; Maiga 2005; Tipping 2009).

This study uses daily temperature, humidity, and rainfall data for the April–October periods of 1974–2003 to document the northward advance and southward retreat of the ITF across the West African Sudan–Sahel zone (10°–20°N), and to assess the relation of rainfall patterns there to the ITF migrations. These analyses are performed for the 30-yr average seasonal time scale and sets of extreme years. The major focus is on concurrent ITF–rainfall relationships within the April–October rainy season. However, we also explore whether early season (April–May) anomalies in the ITF’s advance predict the wetness of subsequent months, including the July–September core of the West African monsoon, and similarly we assess the predictability of the timing of the ITF’s retreat. Finally, we document the secular variation of these associations during 1974–2003. This paper complements Bell and Lamb (2006), which used daily rain gauge data for 1950–98 to document the variability of West African Soudano–Sahel mesoscale convective weather systems (MCWSs) during that period. Here, we add a key aspect of the regional circulation context to the understanding of that MCWS variability.

The regional climate motivation for this investigation was substantial. In particular, over the 30 yr since the Sahel drought began to emerge as the world’s most pronounced regional climate change of the last half of the twentieth century (Fig. 1; see also Bell and Lamb 2006), there has been debate over the role of the ITCZ–ITF latitude for that rainfall anomaly. Using a range of regional atmospheric circulation evidence, but not formal West African ITCZ–ITF delineation, most early studies suggested that Sudan–Sahel drought (rainfall abundance) was linked to a reduced (an enhanced) northward excursion of the ITCZ–ITF (e.g., Winstanley 1973a,b; Kraus 1977a,b; Glantz 1977; Lamb 1978a,b, 1983; Hastenrath 1984). Further indirect support for this positive dependence of Sudan–Sahel rainfall on the ITCZ–ITF’s latitude emerged from diverse subsequent studies (e.g., Hastenrath 1990, 2000; Lamb and Peppler 1991, 1992; Janicot 1992a,b; Fontain and Janicot 1992; Palmer et al. 1992; Kapala et al. 1998; Camberlin et al. 2001; Adejwun and Odekunle 2004). Conversely, other papers did not support this relationship, suggesting or implying that the ITCZ–ITF latitude was not necessarily a major determinant of Sudan–Sahel seasonal rainfall (e.g., Miles and Folland 1974; Tanaka et al. 1975; Nicholson 1980, 1981, 2008; Dennett et al. 1985; Citeau et al. 1989; Le Barbé and Lebel 1997; Grist and Nicholson 2001; Nicholson and Grinst 2001, 2003). Again, very few of these studies involved formal West African ITCZ–ITF delineation.

Until recently, the only direct and focused investigation of possible ITF latitude control on Sudan–Sahel rainfall coincided with, but understandably did not recognize, the onset of the above Sudan–Sahel drought...
conditions (Ilesanmi 1971). However, this study was confined to Nigeria during 1961–65, for which it found a statistically significant positive ITF latitude–rainfall relationship on monthly and annual time scales. Our much larger inquiry spans almost all of the West African Sudan–Sahel for 1974–2003 and treats time scales extending from 10 days to multidecadal.

2. Data and methods

a. Rainfall data

Daily rainfall totals for the April–October periods of 1974–2003 are used for 82 stations in the Sudan–Sahel zone (approximately 10°–20°N) between 12°W and 24°E (Fig. 2, Table 1). This dataset was distilled from digitized records obtained from 111 stations. Most of these data were provided by the Directions de la Meteorologie Nationales/National Weather Services (DMNs/NWSs) of Mali, Burkina Faso, Ghana, Benin, Niger, Nigeria, and Chad. DMN/NWS practices caused the shorter durations of the datasets for Nigeria (lack of digitization) and Chad (lack of observations due to political unrest). For Nigeria, daily totals also were obtained for additional stations used in Tarhule and Woo (1998). The necessary daily data were not available for the westernmost Soudano–Sahel nation (Senegal), for which the ITF is less well defined because of the maritime influence of the northeast trades over the adjacent Atlantic Ocean.

All data were quality controlled, with values beyond physically reasonable limits being excluded. The majority of the station records were incomplete, with considerable variation in the length of continuous observations and the distribution of gaps in the records. Since no attempt was made to estimate missing values, the 82 stations selected had records that were the most complete and seemingly most reliable (Table 1).

b. Temperature data

Digitized daily minimum temperature (Tmin) data for the April–October periods of 1974–2003 were obtained from the same DMNs/NWSs as the daily rainfall totals, but only for synoptic stations, which reduced the original number of stations involved to 83 (Table 1). Also, only 3 yr of these data could be obtained from the Nigerian Meteorological Department because of that country’s lack of digital daily data. After applying the same quality control and station selection procedures as for the above rainfall data, the final Tmin dataset included 62 stations (Fig. 2, Table 1). The lack of digitized daily temperature and (see next subsection) relative humidity data prior to 1974 was the reason the study period started in that year.

c. Relative humidity data

A daily maximum relative humidity (RHmax) dataset was developed for the same time periods and 62 stations as the Tmin data, using identical digitized sources and procedures (Fig. 2, Table 1). Comparison of this dataset with its Tmin counterpart confirmed that these diurnal cycle extremes generally are coincident or occur within an hour of each other early in the morning (0500–0700 local time), as was expected.

d. Dewpoint temperature computation

We calculated dewpoint temperature (Td) from the above Tmin and RHmax data, because the Td data available for the study region (generally nomogram derived) had not been digitized. Several empirical equations are available to convert RH and T to Td. Here, for each station day, the Td corresponding to the Tmin and RHmax was computed using the standard U.S. Advanced Weather Interactive Processing System (AWIPS) empirical algorithm for Td estimation (information online at http://meted.ucar.edu/awips/validate/dewpoint.htm). This calculation involved several steps. First, the saturation vapor pressure (es) corresponding to the Tmin was computed using an integrated form of the Clausius–Clapeyron equation. Second, the resulting es was used with the RH max to obtain the corresponding vapor pressure (e). Finally, this e was employed in the calculation of Td using the AWIPS empirical formula.

It was not possible to use the basic Clausius–Clapeyron equation to calculate e because it required station pressure data that were not available for most stations. However, in a validation of the integrated Clausius–Clapeyron equation that we performed for the study region, the resulting hourly Td estimates for April–October 2004 at Niamey, Niger (Figs. 2 and 3), essentially were identical.
to values obtained from the basic Clausius–Clapeyron equation.

e. **ITF delineation**

Following Eldridge (1957) and Ilesanmi (1971), we use the 15°C $T_d$ isodrosotherm to delineate the surface ITF. This criterion is in widespread operational use in West Africa, often in combination with a zero meridional wind component criterion. That hybrid delineation also has been adopted operationally by the Africa Desk of the National Oceanic and Atmospheric Administration/National Weather Service’s (NOAA/NWS) Climate Prediction Center (information online at http://www.cpc.ncep.noaa.gov/products/fews/ITCZ/itcz.shtml), the results of which are used in a minor way in section 3b. Although the zero meridional wind criterion has been used in pervious research (e.g., Hastenrath 1990, 2000; Grist and Nicholson 2001; Sultan and Janicot 2003) to locate the ITF adjacent to and over West Africa, including when equated with the ITCZ, we decided not to employ it here to delineate the West African surface ITF. This decision reflected concerns about the representativeness of surface wind observations and the greatly increased data and data-processing requirements for this less reliable indicator.

The first step in the surface ITF delineation was the calculation of individual station $T_d$ averages for each dekad (10–11-day period) during April–October 1974–2003, for which the final dekads of May, July, August, and October included 11 days. These station dekadal $T_d$ averages then were used to interpolate the spatial position of the 15°C isodrosotherm for each individual dekad, via a kriging (Cressie 1991, 119–134) isoplething algorithm in the SURFER software package (information online at http://www.goldensoftware.com). The northward and then southward progression of this isodrosotherm between April and October indicated the ITF’s advance and retreat during each season. Further averaging of the individual station dekadal $T_d$ means across 1974–2003, and then application of the same interpolation procedure, gave the 30-yr climatological pattern of ITF migration on the dekadal time scale.

Comparison of the 1974–2003 spatial patterns of ITF location and rainfall amount was performed on a monthly basis. The long-term average monthly ITF position was established using the above interpolation procedure after averaging the individual station $T_d$ values for the three dekads of each month. ITF delineation likely was less precise north of 16°N, because of the reduced number of Tmin and RH stations there (Fig. 3). Similarly, dekadal station rainfall totals (Fig. 2) for each month were averaged over the 30 yr, from which isohyetal patterns of daily rainfall rate were produced using the same isoplething algorithm.

f. **Statistical ITF–rainfall associations**

The statistical relationships between time series of ITF latitude and rainfall amount were assessed for a range of time scales: dekadal, monthly, July–September rainy season core, and the entire April–October season. Results were obtained for the study region as a whole (10°–20°N, 12°W–24°E; Fig. 2), after area and time
averaging was performed for both parameters as indicated next.

For the ITF latitude for each dekad, a value first was estimated for each 4° longitude strip (delineated in Fig. 2) using the above kriging interpolation algorithm. The nine 4°-strip values then were averaged to give a dekadal ITF latitude representative of the entire 12°W–24°E sector. The resulting 1974–2003 time series of dekadal ITF latitude positions provided the basis for the analyses presented in section 3. To address the time-scale dependence issue, time averaging of the values in this dekadal time series transformed it into additional time series with monthly and seasonal resolutions. Also, averaging of the dekadal time series across years produced mean seasonal cycles of ITF latitude for sets (composites) of six very wet and six very dry years and for the entire 1974–2003 period. The same procedure was used to generate the time series and mean seasonal cycles of area-averaged rainfall amount for the entire 10°–20°N to 12°W–24°E region, using a different initial step. That initial step involved spatial averaging of the dekadal rainfall totals for the stations in each 4°-longitude strip (Fig. 2). This yielded the dekadal 4°-strip rainfall totals that subsequently were processed in the same manner as the above 4°-strip ITF latitude estimates to produce the required area-averaged time series and seasonal cycles of rainfall amount. The averaging of station totals rather than normalized station departures (often performed because of the strong northward rainfall gradient) was prompted by Bell and Lamb (2006) obtaining essentially the same results for this region when using both approaches. However, very limited use also is made of time series of area-averaged normalized station departures.

Statistical associations between the above time series of the ITF latitude and rainfall amount are established through correlation analysis, comparison of patterns for individual extreme years and the 6-yr composites of such years, and the use of contingency tables. Following Bell and Lamb (2006), several approaches are employed to estimate significance levels and confidence limits for the
correlation coefficients and extreme year–composite comparisons, respectively. For correlation coefficients, the standard two-tailed Student’s $t$ test (Wilks 2006, 131–135) is used to assess their statistical significance. The Student’s $t$ distribution also is exploited to attach confidence limits to 1974–2003 dekadal means against which individual year values and composite averages are compared (Keeping 1995, 183–184). Further, standard deviations are provided for the dekadal mean values that contribute to the 6-yr composite dekadal averages.

3. Results

a. Spatial ITF and rainfall patterns

Figure 3 documents the long-term (1974–2003) average northward advance and southward retreat of the ITF on the dekadal time scale for the entire West African Sudan–Sahel rainy season. The northward advance across the Sudan–Sahel begins in early April, by which time the ITF has migrated to north of 10°N (Fig. 3a) from its late winter position near the Gulf of Guinea coast. This advance proceeds quite rapidly in April to reach 13°–14°N, except across Chad in the extreme east. However, the ITF’s progress is slower in May–June, especially in the eastern half of the study region across Niger and Chad. As a result, by the end of June the ITF has a distinct west-northwest to east-southeast (WNW–ESE) orientation. This alignment is enhanced as the ITF proceeds more rapidly northward during July, when the Saharan surface heat low intensifies, to reach its most poleward location (~20°N) in early August. However, the absence of data from Mauritania and Algeria may have affected
slightly the July–August ITF orientation in northwestern Mali and northwestern Niger. Evidence of the ITF’s distinctive WNW–ESE tilt during the July–September rainy season core first was noted by Eldridge (1957) and later by Ilesanmi (1971). The same alignment also characterizes the long-term annual average isohyetal pattern for the region (e.g., Nicholson 1980, Fig. 2).

Overall, the northward ITF advance is relatively slow, averaging only 0.8° latitude dekad\(^{-1}\) (8.8 km day\(^{-1}\)). The southward ITF retreat across the Sudan–Sahel occurs almost twice as fast, taking place between mid-August and mid-November (Fig. 3b) at an average rate of 1.4° latitude dekad\(^{-1}\) (15.5 km day\(^{-1}\)). Through October, this withdrawal proceeds most rapidly in the western half of the study region, which returns the ITF to a near-zonal orientation. By late November, the ITF has retreated south of 10°N at all longitudes in Fig. 3.

Ilesanmi (1971) obtained similar rates of northward

**Fig. 5.** Relationship between ITF latitude and total rainfall for early (April–June) and late (October) rainy season months in the West African Sudan–Sahel zone. (left) Time series (1974–2003) of 10-day (dekad) averaged ITF latitude (°N, solid line, left ordinate) and 10-day area-averaged total rainfall (mm, broken line, right ordinate) for domain between 10°–20°N and 12°W–24°E (Fig. 2). (right) The corresponding scatter diagrams and linear correlation coefficients, all of which are significant at the 1% level (indicated by two asterisks) according to a two-tailed Student’s \(t\) test (Wilks 2006, 131–135). Time series consist of three dekad values per month for each year between 1974 and 2003, with the abscissa labeled in yr. Correlation coefficients in parentheses are for time series with seasonal cycles removed, where each dekad value was the departure from the 1974–2003 dekad mean.
advance and southwest retreat in his limited 1961–65 ITF study for Nigeria.

This ITF evidence of West African monsoon development across the Sudan–Sahel being much slower than its rapid demise is consistent with the findings of Bell and Lamb (2006, Fig. 7) concerning the size and intensity of the monsoon’s MCWSs in the present study region. The growth of these distinctive MCWSs proceeds slowly and monotonically through late August, and their rainfall rates maximize slightly earlier in early to mid-August. Thus, the peak MCWS development continues 1–2 dekads after the ITF starts to retreat southward. Both the MCWS’s size and intensity then decrease rapidly following these maxima, to the point where their late September values are similar to those of early June. Segele and Lamb (2005) found that the counterpart Kiremt monsoon for the extreme east of the Sudan–Sahel zone (Ethiopia) also withdraws equatorward approximately twice as fast as it previously advanced northward. Also consistent with these results is Camberlin and Diop’s (2003) finding that the interannual variability of the rainy season onset in Senegal (extreme west of the Sudan–Sahel zone) exceeds that of its cessation dates. The reasons for this fundamental seasonal asymmetry of the entire Sudan–Sahel monsoon system from the Atlantic Ocean to the Red Sea, have not been elucidated and invite numerical model experimentation.

The spatial relationship of West African Sudan–Sahel rainfall to the ITF migration is shown in Fig. 4 on the monthly mean time scale for 1974–2003. From April through August, the rain belt advances northward and intensifies, but its northern boundary (1 mm day$^{-1}$ isohyet) generally lags 100–250 km south of the ITF position through July, especially across Mali. This separation more than doubles in Niger and western Chad in August, when it likely is even larger in Mali. Moreover, beginning in May the most societal useful rain rates (>3–4 mm day$^{-1}$) generally occur more than 400 km south of the ITF. Those rains increase strongly farther southward in July–August, to more than 10 mm day$^{-1}$ in the extreme south. The rapid equatorward retreat of the ITF during September–October is preceded by a similar

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**Fig. 6.** As in Fig. 5, but for core rainy season months (July–September) and with correlation coefficients being significant at the 5% level (single asterisk).
displacement of the rainbelt. By October, rain rates exceeding 3 mm day\(^{-1}\) have migrated south of 10\(^\circ\)N, from whence they do not return until May. The isohyetal patterns in Fig. 4 generally exhibit the WNW–ESE orientation of the ITF.

**b. Concurrent statistical ITF–rainfall associations**

The long-term (1974–2003) average concurrent dependence of Sudan–Sahel rainfall amount on ITF latitude is documented in Figs. 5–8 and Tables 2 and 3. These displays employ a range of time scales and seasonal periods, for which the rainfall and ITF data were processed as described in section 2f. All analyses are for the study region as a whole.

Figures 5 and 6 use the three dekadal averages for each month to assess the seasonal variation of the ITF latitude–rainfall association. The statistical significance of all linear correlations obtained is high. This relationship is positive for all months, indicating that rainfall increases with the extent of anomalous northward ITF penetration, irrespective of the rainy season stage. However, the strength of the association has a pronounced seasonal cycle. It is very strong in the early (April–June) and late (October) rainy season months (Fig. 5), when the ITF is located farther south and rainfall is much lower than during the intervening rainy season core. The correlations for May, June, and October are between +0.78 and +0.81, which are highly statistically significant, and the April correlation is almost as strong (+0.74). Also, when the seasonal cycles are removed from the time series, these correlations are weakened only slightly for May, June, and October (6%–10% variance reductions; see Fig. 5), and not excessively for April (17%).

This ITF latitude control on rainfall amount is reduced markedly during the July–September rainy season core, when the correlations are in the +0.50 to +0.58 range (Fig. 6) but remain statistically significant. The association is weakest and of lowest statistical significance in August, when the ITF is farthest north (and least precisely located due to reduced station density), the southwest monsoon layer is thickest, and the resulting rainfall is maximized. This reduced ITF influence during July–September presumably stems from the thicker monsoon layer permitting a wider range of mesoscale dynamical processes to contribute to the development (or suppression) of the region’s distinctive MCWSs. It is another finding that should help focus numerical model experimentation. Note that the removal of the seasonal cycles from the time series did not reduce the August correlation in Fig. 6. The weakening of the July and September correlations by this process primarily resulted from variability at the very start (July, first dekad) and end (September, third dekad) of the rainy season core.

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**Fig. 7.** Seasonal variation of linear correlation between dekadal-average ITF latitude and measures of dekadal mean Sudan–Sahel rainfall for the same domain (10\(^\circ\)–20\(^\circ\)N, 12\(^\circ\)W–24\(^\circ\)E) as in Figs. 5 and 6. For 1974–2003, the boldface solid line gives the ITF correlation with area-averaged raw rainfall totals (from Figs. 5 and 6), the dashed–dotted line is for the ITF correlation with time scores of the first unrotated PC of the station rainfall totals, and the dashed line is for ITF correlation with area-averaged \(\log_{10}\) transformed raw rainfall totals. The boldface broken line is similar to the solid line but for 1988–2003 only (see text). Dotted line gives 1988–2003 correlation between the CPC Africa Desk ITF latitude and the raw rainfall totals used to produce the broken line correlation. According to a two-tailed Student’s \(t\)-test (Wilks 2006, 131–135), all April–June and October (July–September) correlation coefficients are significant at the 1% (5%) level, except for the CPC ITF correlation (1% level for all months).
The above monthly correlations obtained using raw dekadal rainfall totals (Figs. 5 and 6) essentially were duplicated when those rainfall data were subject to additional processing (Fig. 7). This sensitivity analysis was prompted by the well-known skewness of the short-term rainfall totals and its possible effects on statistical analyses of such data (e.g., Richman and Lamb 1985, and references therein). The additional processing produced time series of (i) log_{10} transformed station totals and (ii) scores of the first unrotated principal component (PC) of the raw station totals. However, except for the April PC correlation, the resulting curves in Fig. 7 follow closely
that derived from the raw rainfall totals. While the use of ITF latitudes obtained from 1988–2003 operational analyses by the NOAA/NWS Climate Prediction Center (section 2e) produced higher monthly correlations with raw rainfall for June–September (by 0.05–0.17) than when the raw rainfall-present ITF correlations were recalculated for the same period, the August minimum correlation also occurred (Fig. 6). The PoDs are in the 53.33%–58.89% range, which is only about 10% lower than for April–June and October. For July and September, TCEs occurred only for 5.00%–6.66% of months. However, TCEs were more frequent (18.33%) for the maximum rainfall month of August, when the minimum correlation also occurred (Fig. 6).

The ITF latitude–rainfall amount relationship is quantified further in Fig. 8 on seasonal time scales. For the July–September rainy season core as a whole, the association between the raw time series is much stronger when the two parameters are averaged over dekadal periods (Fig. 8a; $r = 0.67$) than when monthly means are used (Fig. 8b; $r = 0.47$). However, removal of the seasonal cycles from these time series reduced the dekadal correlation substantially (+0.41), whereas the monthly correlation weakened only slightly (+0.45). The dekadal-based raw July–September correlation of +0.67 also exceeds the counterpart values obtained when these months were treated separately (+0.50 to +0.58; Fig. 6). Furthermore, Figs. 8b and 8c suggest that use of ITF averages and normalized rainfall departures for the entire April–October rainy season does not weaken the relationship beyond that obtained for July–September from

Table 2. Contingency table indicating concurrent tercile associations between monthly averages of dekadal ITF latitude and total rainfall values in Fig. 5 for early (April–June) and late (October) rainy season months in the West African Sudan–Sahel (10°–20°N, 12°W–24°E). For ITF latitude, $\Delta$South ($\Delta$North) denotes the southern (northern) displacement terciles. PoD of corresponding tercile, bolded, and TCE tercile, italics. See section 3b for further explanation.

<table>
<thead>
<tr>
<th>ITF latitude</th>
<th>Total rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Below avg</td>
</tr>
<tr>
<td>Apr</td>
<td></td>
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<tr>
<td>$\Delta$South</td>
<td>23</td>
</tr>
<tr>
<td>Near avg</td>
<td>3</td>
</tr>
<tr>
<td>$\Delta$North</td>
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</tr>
<tr>
<td>Total</td>
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</tr>
<tr>
<td>PoD</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>$\Delta$South</td>
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<tr>
<td>Near avg</td>
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<td>$\Delta$North</td>
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<td>Total</td>
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<tr>
<td>PoD</td>
<td>71.11%</td>
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<tr>
<td>Jun</td>
<td></td>
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<tr>
<td>$\Delta$South</td>
<td>24</td>
</tr>
<tr>
<td>Near avg</td>
<td>5</td>
</tr>
<tr>
<td>$\Delta$North</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
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</tr>
<tr>
<td>PoD</td>
<td>66.67%</td>
</tr>
<tr>
<td>Oct</td>
<td></td>
</tr>
<tr>
<td>$\Delta$South</td>
<td>21</td>
</tr>
<tr>
<td>Near avg</td>
<td>9</td>
</tr>
<tr>
<td>$\Delta$North</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
</tr>
</tbody>
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| PoD          | 64.44%   | TCE      | 0.00%    

Table 3. As in Table 2, but for the core rainy season months (July–September) in Fig. 6.

<table>
<thead>
<tr>
<th>ITF latitude</th>
<th>Total rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Below avg</td>
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<tr>
<td>Jul</td>
<td></td>
</tr>
<tr>
<td>$\Delta$South</td>
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</tr>
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<td>$\Delta$North</td>
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<tr>
<td>Total</td>
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<tr>
<td>PoD</td>
<td>58.89%</td>
</tr>
<tr>
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</tr>
<tr>
<td>$\Delta$South</td>
<td>18</td>
</tr>
<tr>
<td>Near avg</td>
<td>5</td>
</tr>
<tr>
<td>$\Delta$North</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
</tr>
<tr>
<td>PoD</td>
<td>54.44%</td>
</tr>
<tr>
<td>Sep</td>
<td></td>
</tr>
<tr>
<td>$\Delta$South</td>
<td>17</td>
</tr>
<tr>
<td>Near avg</td>
<td>11</td>
</tr>
<tr>
<td>$\Delta$North</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
</tr>
<tr>
<td>PoD</td>
<td>53.33%</td>
</tr>
</tbody>
</table>
TABLE 4. Documentation of extreme seasons used in interannual (Fig. 9) and composite (Fig. 10) analyses. Study region mean Jul–Sep departures (for stations in Fig. 2) are relative to 1974–2003 averages, whereas West African mean April–October departures (from Fig. 1) are relative to 1941–2000 averages. Seasons shown were driest/wettest in the study region during 1974–2003, except for 1978 which had better data coverage than the slightly wetter 1974 and 1975.

<table>
<thead>
<tr>
<th>Year</th>
<th>Study region mean Jul–Sep rainfall departure (s)</th>
<th>No. of Jul–Sep (Jun–Sep) dekads when study region ITF south of average</th>
<th>West African Apr–Oct rainfall departure in Fig. 1 (s)</th>
<th>Year</th>
<th>Study region mean Jul–Sep rainfall departure (s)</th>
<th>No. of Jul–Sep (Jun–Sep) dekads when study region ITF north of average</th>
<th>West African Apr–Oct rainfall departure in Fig. 1 (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most extreme</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>−1.19</td>
<td>8 (11)</td>
<td>−1.25</td>
<td>1999</td>
<td>+1.33</td>
<td>8 (8)</td>
<td>+0.70</td>
</tr>
<tr>
<td>1983</td>
<td>−0.90</td>
<td>7 (10)</td>
<td>−1.26</td>
<td>1994</td>
<td>+1.26</td>
<td>5 (7)</td>
<td>+0.32</td>
</tr>
<tr>
<td>1987</td>
<td>−0.80</td>
<td>7 (8)</td>
<td>−0.89</td>
<td>1998</td>
<td>+0.79</td>
<td>9 (9)</td>
<td>+0.26</td>
</tr>
<tr>
<td>1982</td>
<td>−0.68</td>
<td>3 (6)</td>
<td>−0.82</td>
<td>2003</td>
<td>+0.69</td>
<td>8 (8)</td>
<td>+0.47</td>
</tr>
<tr>
<td>1990</td>
<td>−0.52</td>
<td>9 (9)</td>
<td>−0.71</td>
<td>1988</td>
<td>+0.62</td>
<td>8 (10)</td>
<td>+0.11</td>
</tr>
<tr>
<td>Less extreme</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>−0.37</td>
<td>3 (6)</td>
<td>−0.88</td>
<td>1978</td>
<td>+0.27</td>
<td>3 (8)</td>
<td>−0.07</td>
</tr>
<tr>
<td>Avg</td>
<td>−0.74</td>
<td>6.17 (8.33)</td>
<td>−0.97</td>
<td>Avg</td>
<td>+0.83</td>
<td>6.83 (8.33)</td>
<td>+0.30</td>
</tr>
</tbody>
</table>

In fact, the April–October seasonal correlation based on the average normalized rainfall departure for the study region (+0.66; Fig. 8c) is essentially the same as the July–September correlation based on dekadal rainfall totals (+0.67; Fig. 8a).

c. Analysis of extreme years

This section examines the dekadal-time-scale dependence of Sudan–Sahel rainfall amounts on ITF latitude for the six wettest and six driest July–September rainy season cores in the study region during 1974–2003. Table 4 quantifies the rainfall departures for those years.

Figure 9 documents the relationship for the seasons characterized by the region’s two driest (1984, 1983) and two wettest (1999, 1994) July–September cores during 1974–2003. Note that 1983 and 1984 were the two driest entire Sudan–Sahel rainy seasons for all of West Africa since 1941, whereas 1999 and 1994 are not nearly as wet as many years during the 1950s (Fig. 1). Also, the two drought years differed substantially concerning both their basin-scale sea surface temperature (SST) causation and resulting regional West African rainfall anomaly patterns. During 1983, for which the key SST forcing emanated from the pronounced tropical Pacific El Niño event (Lamb and Peppler 1992), the drought extended from the Sudan–Sahel equatorward to the Gulf of Guinea coast (Ward 1998; Nicholson and Grist 2001; Nicholson and Webster 2007; Nicholson 2008). In contrast, the 1984 Sudan–Sahel drought was associated with a classic tropical Atlantic dipole SST anomaly pattern [negative (positive) departures north (south) of ~10°N; Lamb and Peppler (1992)] and a dipole West African rainfall anomaly pattern in which the Gulf of Guinea rainfall was above average (Ward 1998; Nicholson and Grist 2001; Nicholson and Webster 2007; Nicholson 2008).

For the study region, the 1984 southward displacement of the ITF was especially pronounced from late June through late August (2°–3° latitude), when rainfall was reduced substantially to up to half of the 1974–2003 average (Fig. 9). These anomalies were weaker during 1983, except from mid-August to early September. Thus, the southward ITF displacement and associated Sudan–Sahel rainfall suppression in the study region were more pronounced in 1984 when the SST forcing was more immediate and the drought did not extend farther south. For the wettest season of 1999, the ITF and rainfall departures generally are the opposite of 1983, and not as sustained or (except for a dekad or two) as pronounced as for the 1984 drought (Fig. 9). During the other wet year (1994), the northward ITF displacement and associated rainfall enhancement were delayed until early August, when they were especially pronounced, after which these anomalies prevailed through the rest of the season except for late September.

The above dry-versus-wet contrasts were reinforced when seasonal cycles of ITF latitude and rainfall were composited for the full sets of six dry and six wet years in Table 4. Composite results are presented in Figs. 10 and 11. The composite patterns in Fig. 10 (left panels) are very similar to, but less pronounced than, those for the most extreme seasons in Fig. 9. For the dry composite, the southward ITF displacement persists consistently through June–August at close to 1° latitude and also strongly characterizes mid- to late October (Fig. 10). The associated rainfall deficit increases from mid-June to a late August maximum of ~20 mm dekad−1, after which it returns to near average. For the wet composite, the northward ITF displacement is delayed until July and persists through October with 1°-latitude maxima. The associated rainfall excess also extends across July–October, with early and late August maxima of ~15 mm dekad−1.
The wet–dry composite representation in Fig. 10 emphasizes the August through mid-September rainfall difference, a more extended period of ITF contrast that spans mid-July through mid-September, and a mid- to late October latitude separation that is associated with only a small difference in total rainfall because of the low rainfall at this season end (Fig. 4). The above dry (wet) rainfall anomalies are documented further in Fig. 11 by pronounced southward (northward) displacements of key isohyets, the latitudinal separation of which maximizes between 2° and 4°.

d. Seasonal predictability

The moderate-to-strong concurrent ITF latitude–rainfall relations established in sections 3b and 3c prompted investigation of whether the early season ITF latitude can be used to predict core and late season Sudan-Sahel rainfall. This inquiry necessarily also involved documentation of the seasonal persistence of ITF latitude anomalies. Results are presented in Fig. 12 and Table 5.

There are three major outcomes of these predictability assessments. First, the early season ITF latitude is a moderately consistent indicator of the ITF latitude and associated rainfall in the first core season month of July. In particular, Fig. 12 shows that the April ITF latitude has a correlation of +0.55 (+0.53) with the July ITF latitude (rainfall), which is surprisingly close to the concurrent July ITF latitude–rainfall correlation (+0.56; Table 2, Fig. 6). Table 5 indicates that the associated PoDs of the April ITF latitude tercile specifying the corresponding July ITF latitude (rainfall) tercile is 48.89% (42.22%), and the likelihood of TCEs is only 6.67% (10.00%). Most of these values also are close to their
concurrent July ITF latitude–rainfall counterparts of 58.89% and 5.00% (Table 3). Interestingly, these July predictability results based on the April ITF latitude are slightly stronger than those derived from the more immediately preceding May and June ITF latitudes (e.g., Fig. 12). Thus, April ITF latitude and associated rainfall anomalies tend to persist through July. However, such persistence generally is not sustained into the peak rainy season month of August, which is the second principal outcome of this predictability assessment. The correlations of August ITF latitude and rainfall with the ITF latitude during preceding months all are near zero (Fig. 12). Furthermore, Table 5 indicates that the PoDs of the April ITF latitude specifying the corresponding August ITF latitude (31.11%) and rainfall (33.56%) are around the climatological value (33.33%), with TCEs occurring 40.00% and 36.67% of the time, respectively. In fact, these PoDs (TCEs) are slightly smaller (larger) than equivalents computed using the opposite matrix diagonals (extreme terciles) in Table 5. Similar PoD and TCE percentages were obtained when the May ITF latitude tercile was used to predict the August ITF latitude and rainfall (not shown). So, not only is the concurrent ITF latitude control on rainfall weaker for August than for all earlier months, but the August ITF latitude and rainfall often are uncoupled from the ITF latitude anomaly sustained to that point in the rainy season evolution. This further uniqueness of August is another finding that invites numerical model experimentation.

The third major outcome of this predictability assessment is that the above independence of the August ITF latitude and rainfall from the early season ITF latitude often is part of a July–September transition to the opposite ITF latitude anomaly. This transition reflects a moderate tendency for the ITF to retreat southward early (late) in seasons when it advanced northward early
For example, Fig. 12 shows that the correlation of the April ITF latitude with (i) the September ITF latitude (rainfall) is $-0.31 (-0.50)$ and (ii) the October ITF latitude (rainfall) is $-0.50 (-0.23)$. Consistent with this situation, the PoDs of the April ITF latitude tercile specifying the corresponding September and October ITF latitude (rainfall) terciles are only 18.89% (16.67%) and 22.22% (24.44%), respectively, and the associated TCEs are 48.33% (55.00%) and 50.00% (43.33%) (Table 5).

The July–September transition to the opposite ITF latitude anomaly is sufficiently frequent that use of the April ITF latitude to predict September and October ITF latitudes and rainfalls gave much larger PoD equivalents (40.00%–46.67%) and much smaller TCE equivalents (10.00%–21.67%) when they were computed using the opposite matrix diagonals and opposite extreme terciles, respectively, in Table 5. As noted above, the August results in Table 5 show a slight tendency for this transition to begin in that month. Thus, taking into account this midseason ITF latitude anomaly transition, the April ITF latitude specification of the September–October ITF latitude and rainfall is almost as consistent as that for July (Table 5).

Similar correlations and PoD–TCE percentages were obtained when the May ITF latitude was used to predict the September and October ITF latitude and rainfall (not shown). Again, numerical model experimentation is needed to explore the causation and predictability of this further distinctive ITF seasonal cycle of behavior.

e. Secular variation

The pronounced multidecadal variation of West African Sudan–Sahel rainfall since the early 1950s has been recognized for about 20 yr and was documented in Fig. 1. Recently, Bell and Lamb (2006) showed that consistent multidecadal variations characterized the size and intensity of the MCWSs that produced this secular rainfall pattern. This section places the 1974–2003 ITF variability within the same multidecadal context.

Figure 13 juxtaposes 3-yr running mean versions of (i) time series of the study region’s April–October mean ITF latitude and rainfall (Fig. 13a from Fig. 8c) and July–September dekadal ITF latitude and rainfall (Fig. 13b from Fig. 8a) with (ii) Bell and Lamb’s (2006, Fig. 15) time series of June–September average MCWS size and intensity indices for three subareas of the present study.
gradually reversed. The ITF showed a strong tendency to advance farther north, MCWSs increased in size and intensity, and the resulting seasonal Sudan–Sahel rainfall recovered to the level of the late 1970s (but not yet the early 1950s; see Fig. 1). The multidecadal associations between ITF latitude and MCWS size–intensity were particularly strong for Burkina Faso and Niger (Figs. 13d,e).

4. Summary and discussion

This study completes a pair of papers dealing with the West African atmospheric conditions that were most immediately associated with the pronounced rainfall changes (especially severe drought) in the Sudan–Sahel zone (10°–20°N) since the mid-1950s. Previously, Bell and Lamb (2006) documented the 1951–98 variability of the westward-propagating mesoscale convective weather systems (MCWSs) that deliver rain across the Sudan–Sahel zone. Here, we added a key aspect of the regional circulation context to our understanding of MCWS and rainfall variability: the 1974–2003 behavior of the Intertropical Front (ITF), which is the leading edge of the southwest monsoon flow into West Africa. In both papers, the focus was on identifying the final links in the teleconnection chain between global- and basin-scale sea surface temperature (SST) anomalies and Sudan–Sahel seasonal rainfall totals. This association with SST has been established strongly on interannual- to multidecadal time scales (e.g., Lamb 1978a,b; Folland et al. 1986; Palmer 1986; Lamb and Peppler 1992; Palmer et al. 1992; Ward 1998; Giannini et al. 2003; Hoerling et al. 2006; Nicholson and Webster 2007).

Here, we analyzed daily temperature, humidity, and rainfall data for 1974–2003 to document the northward advance and southward retreat of the ITF between boreal spring and autumn, and to assess its role in Sudan–Sahel rainfall. Using largely dekadal (10 day) and monthly resolutions, analyses were performed for the 30-yr-average seasonal time scale and sets of extreme years, with a major focus on concurrent monthly ITF–rainfall relations. Also investigated were the seasonal rainfall predictive potential of the early season ITF latitude, and the secular variations of ITF latitude–MCWS–rainfall associations during 1974–2003.

The northward advance of the ITF across the Sudan–Sahel from April to early August was shown to be relatively slow, averaging 0.8° latitude dekad⁻¹ (8.8 km day⁻¹). The southward ITF retreat between mid-August and mid-November is almost twice as fast, averaging 1.4° latitude dekad⁻¹ (15.5 km day⁻¹). Coupled with the ITF advance, the monsoon rainbelt migrates northward and intensifies. However, its northern boundary

Fig. 12. Seasonal persistence of the ITF latitude and its control on rainfall for the same West African Sudan–Sahel domain (10°–20°N, 12°W–24°E) as in Figs. 5–10. Curves give the linear correlation between the average ITF latitude for the month in the upper-right corner of the panel and the average ITF latitude (boldface solid line) and mean total rainfall (boldface dotted line) during subsequent months. Thin broken horizontal lines give 1% significance levels for correlation coefficients, according to a two-tailed Student’s t test (Wilks 2006, 131–135).

region (panels c–e). Collectively, these diverse representations show that the severe drought conditions of the mid-1980s occurred when the ITF was located farthest south, and MCWS size and intensity was minimized after declining progressively beginning in the mid-1950s. Then, for most of the period from the mid-1980s until the end of the MCWS time series (1998), the situation

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(1 mm day$^{-1}$ monthly average isohyet) lags 100–250 km south of the ITF, while the most societal useful rainfall (>3–4 mm day$^{-1}$ monthly average) generally occurs more than 400 km south of the ITF. There, the monsoon wedge is thickest and horizontal velocity and moisture convergence are maximized in a regional ITCZ. The rapid ITF retreat during September–October was found to be preceded by a similar rainbelt displacement. During both ITF advance and retreat, Sudan–Sahel rainfall is positively related to ITF latitude. The association is strongest during the early (April–June) and late (October) rainy season months (linear correlation, $r = +0.74$ to +0.81), when the ITF is located to the south and rainfall is low. It is weaker during the July–September rainy season core when the ITF is farthest north ($r = +0.50$ to +0.58).

This concurrent rainfall dependence on ITF latitude was established further by contingency analyses for the 30-yr study period and investigation of several extremely dry and wet individual seasons. The April ITF latitude anomaly was shown to be a moderately consistent indicator of the subsequent ITF latitude and associated rainfall anomaly through the first core rainy season month (July). However, this seasonal prediction potential does not persist into the rainy season peak (August), when the concurrent ITF–rainfall relationship is weakest ($r = +0.50$),
the monsoon wedge is thickest, and rain-producing mesoscale dynamical processes are developed fully. Interestingly, it was found also that the ITF tends to retreat early (late) in seasons when it advanced early (late). Because of this situation, the April ITF latitude specification of the September–October ITF latitude and rainfall (negative) was almost as consistent as that for July (positive). In keeping with the above findings, the

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**Fig. 13.** Secular variation of associations between ITF latitude, MCWS size–intensity, and Sudan–Sahel rainfall for 1951–2003. All time series shown were smoothed using a 3-yr running mean. (a) Smoothed versions of April–October ITF and rainfall index time series for 1974–2003 in Fig. 8c (same line signatures and ordinate scales). (b) Smoothed versions of July–September dekadal ITF latitude and total rainfall time series for 1974–2003 in Fig. 8a (same line signatures and ordinate scales). (c) Relations between smoothed ITF latitude (solid line) time series for 1974–2003 in (a) and smoothed MCWS size [daily disturbance extent index (DDEI), broken line] and intensity [catchment average rainfall (CAR), dotted line] time series for Mali for 1951–1998 from Bell and Lamb (2006, Fig. 15). (d),(e) As in (c) but for Burkina Faso and Niger. In (c)–(e), black squares in each inset map locate regions to which MCWS time series pertain. ITF latitude (°N) is along the left ordinate, MCWS intensity (CAR, mm day⁻¹) is along the inside right ordinate, and MCWS size (DDEI, % of stations receiving rain) is along the outside right ordinate. See Bell and Lamb (2006) for details on the DDEI and CAR calculations.
secular variation of ITF latitude during 1974–2003 strongly influenced MCWS and rainfall variability on decadal time scales.

Several of the observational results obtained here invite further investigation, including through numerical simulation. Most fundamental is the pronounced asymmetry between the long-term average rates of seasonal ITF advance (very gradual) and retreat (almost twice as fast) across the Sudan–Sahel. Understanding of this basic difference surely will accelerate progress on the seasonal prediction of the societally unfavorable delayed onsets and abrupt cessations of Sudan–Sahel rainfall. Also requiring substantial inquiry is the relative “decoupling” between the crucial rainfall during the peak month (August) and (i) the concurrent ITF latitude and (ii) the ITF latitude during preceding months. As noted above, this reduced ITF influence presumably stems from the thicker monsoon layer during August permitting a wider range of mesoscale dynamical processes to contribute to the development (or suppression) of the region’s distinctive MCWSs. However, the key mechanisms involved remain to be elucidated.

Not unrelated to the foregoing issues is the seasonal prediction potential found to be offered by the April ITF latitude. This potential exists both for the May–July northward ITF and rainbelt advance (due to the persistence of the ITF latitude anomalies) and, to a lesser extent, the subsequent southward ITF and rainbelt retreat [because the ITF tends to retreat early (late) in seasons when it advanced early (late)]. This situation highlights the need for understanding of the teleconnections and regional processes that influence the April ITF latitude and the persistence of ITF latitude anomalies throughout the rainy season.

Interestingly, Slingo et al. (2008) documented that the special observing period (SOP, 2006) of the African Monsoon Multidisciplinary Analysis (AMMA) project (Redelsperger et al. 2006) had the following characteristics at the representative site of Niamey (located in Figs. 2 and 3): (i) a northward ITF passage that was about a month later than the 1974–2003 average (5 May versus first April dekad), (ii) May–July rainfall that was only 60% of the 1941–2000 mean, (iii) near-average peak season (August) rainfall, (iv) September–October rainfall that was only 53% of the 1941–2000 mean, and (v) a southward ITF passage that occurred in the vicinity of the 1974–2003 average time (29 October versus last October dekad). Note that the 2006 monsoon sequence of characteristics i–iii was fully consistent with the seasonal prediction “model” outlined above, including the decoupling of August rainfall from the ITF and rainfall anomalies of previous months. However, after this August 2006 decoupling, there was no occurrence of the aforementioned tendency for a late ITF retreat (above-average rainfall) to follow the early season’s late ITF advance (below-average rainfall). Instead, the ITF retreat occurred at about the average time and the accompanying rainfall was below average, principally because of extreme October dryness.

Nature thus has provided much potential for analysis of the uniquely detailed AMMA SOP 2006 observations to elucidate the controls on and the role of the seasonal ITF cycle within the West African monsoon system (e.g., Drobinski et al. 2009).

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REFERENCES


