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Variability of Sahelian disturbance lines and rainfall during 1951–1987

PETER J. LAMB, MICHAEL A. BELL & JONATHON D. FINCH

Co-operative Institute for Mesoscale Meteorological Studies and School of Meteorology, The University of Oklahoma, Norman, Oklahoma 73019, USA

e-mail: plamb@ou.edu

Abstract This paper reviews the variability of the characteristics of Sahelian Disturbance Lines on decadal, seasonal, and interannual time-scales for the last half of this century. The relations between this Disturbance Line variability and the behaviour of the distinctive West African tropospheric wind field will also be presented. Those analyses will, in addition, be used to assess the predictability of the start of the Sahelian rainy season with a 1-3 month lead time. The above investigations will be based on unique sets of daily rainfall totals and individual rawinsonde soundings for the Sahel.

INTRODUCTION

Since the 1950s, there has been a progressive and widespread decrease in annual rainfall totals in Sahelian West Africa, resulting in almost continuous drought conditions since the early 1970s, with shorter periods of particularly extreme dryness (Lamb, 1982; Ropelewski *et al.*, 1993). Almost all rainfall in the region is produced by westward-moving disturbance lines (DLs) that are generally oriented north to south, have much larger north–south (10^2–10^3 km) than west–east (10–10^2 km) dimensions, and occur during the June–September monsoon season (Hastenrath, 1991). Therefore, a better understanding of the variability of these rainfall systems should lead to a better understanding of what has caused the decline in monsoon season and annual rainfall totals. The DLs receive their moisture from the low-level southwesterly monsoon flow and are steered westward by the easterly flow above the monsoon layer in which their bases are embedded. The most prominent features of that easterly flow are the African Easterly Jet (AEJ) near 700 mb and the Tropical Easterly Jet (TEJ) near 200 mb. Indices that describe the horizontal extent and intensity of the DLs have been previously developed, and this paper reviews how these DL characteristics have varied on the interannual and decadal time scales. This paper also discusses the possibility of predicting the seasonal onset of agriculturally-sufficient rains in the Sahel, based upon the pre-rainy season evolution of AEJ-related shears and their relation to the intraseasonal variation of DL size and intensity. Although the results presented here extend only to 1987, the work is ongoing and the findings for 1988–1997 will be available shortly.

DATA AND METHODS

Disturbance line characteristics were inferred from a daily rainfall data set supplied by Dr M. V. K. Sivakumar for 1951–1990 that includes records from ~530 stations in Senegal, Mali, Burkina Faso, and Niger. Data for June–September were used to generate DL-related time series for four square catchments, each approximately 440 km by 440 km and centred upon Dakar, Senegal (14°44 N, 17°25 W; 64 possible stations), Bamako, Mali (12°38 N, 8°02 W; 70 possible stations), Kindi, Burkina Faso (12°26 N, 2°02 W; 109 possible stations), and Niamey, Niger (13°30 N, 2°08 E; 39 possible stations). The catchments and rainfall stations are located in Fig. 1. Square catchments were used in order to accommodate the linear nature of the westward-moving DLs, and were centred on rawinsonde stations (except for Kindi) to facilitate comparison of their rainfall statistics with closely associated tropospheric wind characteristics.

Two basic DL index time series for 1951–1987 were developed for each catchment from its daily rainfall totals, to use as a basis for characterizing the DLs. The Daily Disturbance Extent Index (*DDEI*; Bell & Lamb, 1994) is simply the percentage of available stations within a given catchment that received rainfall above a trace for each day from June to September in each year. The *DDEI* thus represents the horizontal extent and/or degree of organization of the DLs. Several DL-related statistics were then generated from the 1951–1987 *DDEI* time series for each catchment: (a) number of days per season when $DDEI \geq 70\%$ (frequency of large and/or well-organized DLs); (b) number of days per season when $0\% < DDEI \leq 30\%$ (frequency of small and/or poorly organized DLs); (c) number of days per season when $DDEI = 0\%$ (frequency of total DL absence); and (d) average non-zero *DDEI* value per season (average DL size).

The Daily Disturbance Intensity Index (*DDII*) is defined for each day with rainfall above a trace from June to September 1951–1987, as follows:

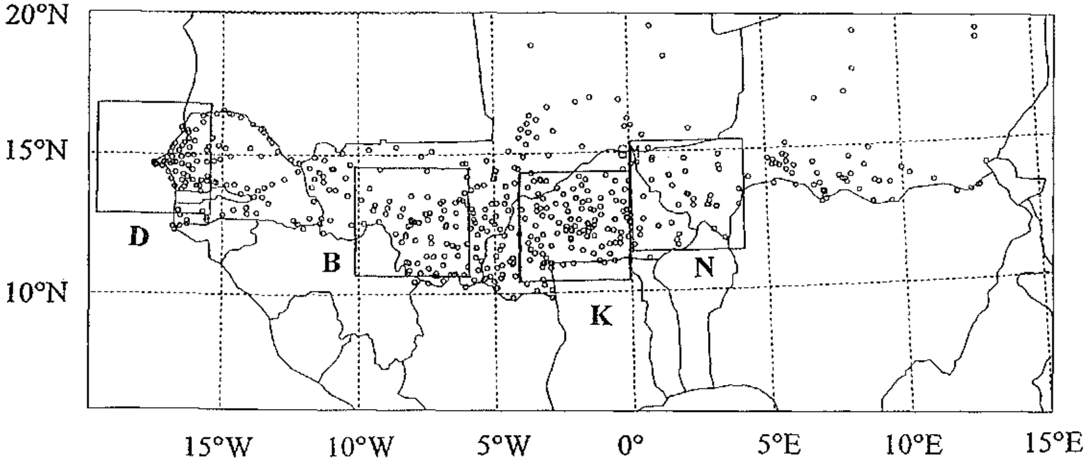


Fig. 1 Location of daily rainfall stations in the Sivakumar data set (unfilled dots) and regional catchments (large squares) used in analyses. Letters indicate stations on which catchments are centred (D = Dakar; B = Bamako; K = Kindi; N = Niamey). Rawinsonde data were also used for D, B and N.

$$DDII_j = \frac{1}{N_j}\sum_{i=1}^{N_j}\frac{r_{ij} - \bar{r}_i}{\sigma_i} \tag{1}$$

where r_{ij} is the daily rainfall value (>trace) on Julian day j at station i in a particular season, $\bar{r}_i$ is the long-term (1951–1990) mean of the five-day moving average daily rainfall value for the period centred on Julian day j at station i, σ_i is the 1951–1990 standard deviation of the five-day moving average rainfall value on Julian day j at station i, and N_j is the number of available rainfall stations within the catchment that received rainfall (>trace) on Julian day j. The *DDII* is thus not defined on those days when all available stations within a catchment did not receive rainfall above a trace, and so the index is a true measure of intensity. Standardized anomalies were used because of the strong south–north seasonal rainfall gradient in the region. This index does not include the seasonal cycle. Several DL-related statistics were then generated from the *DDII* time series for each catchment: (a) number of days per season when $DDII \geq +0.4\sigma$ (frequency of strong disturbance lines); (b) number of days per season when $DDII \leq -0.4\sigma$ (frequency of weak disturbance lines); and (c) average *DDII* value per season (average DL intensity).

The Daily Disturbance Intraseasonal Intensity Index (*DDIII*) is defined (Finch, 1998) for each day with rainfall above a trace from June to September, 1951–1987, as follows:

$$DDIII_j = \frac{1}{N_j}\sum_{i=1}^{N_j}\frac{r_{ij} - [\bar{r}]_i}{[\sigma]_i} \tag{2}$$

where r_{ij} is a daily rainfall value (>trace) on Julian day j at station i in a particular season, $[\bar{r}_i]$ is the long-term (1951–1990) mean of all available June–September daily rainfall values (>trace) at station i, $[\sigma_i]$ is the 1951–1990 standard deviation of all available June–September daily rainfall values (>trace) at station i, and N_j is the number of available stations within the catchment that reported rainfall (>trace) on Julian day j. For each day from June–September in each season, the *DDIII* represents the catchment averaged standardized rainfall anomaly with respect to the long-term (1951–1990) average and standard deviation of all rain day amounts from June–September at the individual stations. Like the *DDII*, this index is defined only on those days when at least one station received rainfall above a trace. In contrast to the *DDII*, this index retains the seasonal cycle and is used to trace intraseasonal variations in rainfall intensity.

Two sets of daily rawinsonde data were also utilized in this study. Both data sets were kindly provided by Dr D. L. Cadet. The first data set includes up to 4-times-daily mandatory level geopotential height, wind, temperature, dewpoint depression, and mixing ratio data, with values between the mandatory levels interpolated every 25 mb for Dakar (1950–1951, 1953–1955, 1957–1961, 1964–1969, 1971–1978), Bamako (1967–1979) and Niamey (1950–1951, 1953–1979). The second data set includes once- or twice-daily significant, standard, and mandatory level geopotential height, wind, temperature, dewpoint depression, and mixing ratio data for the same locations for 1980–1984.

Moncrieff & Miller (1976) and several other authors (e.g. Frank, 1978; Weisman *et al.*, 1988; Rowell & Milford, 1993) have suggested that there is a crucial dependence of tropical squall line development and longevity upon the environmental vertical wind shear. Omotosho (1990) developed environmental wind shear criteria (associated with the African Easterly Jet) for the lower and middle Sahelian troposphere that were considered to be critical for the occurrence of convective storms at Kano in northern Nigeria. Based upon these shear criteria, Omotosho (1990) suggested a scheme to predict the onset of significant convective rainfall—i.e. the start of the rainy season—several weeks in advance. The prediction scheme has the following steps: (a) on a daily basis, calculate the differences in the *u*-component wind between the surface and 700 mb (ΔU_L) and between 700 mb and 400 mb (ΔU_M); (b) average each of these shears over successive 7-day periods; and (c) when the two 7-day average shears simultaneously meet the conditions: $-20 \leq [\Delta U_L] \leq -5$ and $0 \leq [\Delta U_M] \leq 10$ m s^{-1}, for three continuous weeks, rainy season onset is predicted to occur five to six weeks after these conditions were first met.

Following the work of Omotosho (1990), in an initial effort to test the applicability of his predictive scheme across the entire Sahel, *u*-component wind data from 400 mb, 700 mb, and the surface (for 1980–1984) or 950 mb (for 1950–1979) were used to examine the development of ΔU_L and ΔU_M before the rainy season onset and during the course of the subsequent monsoon season. Seven-day and 10-day averages of these shear values were calculated for each year, and then averaged over the available record length at each of the three rawinsonde stations. The annual cycles of the 1951–1987 averages of the 7- and 10-day mean values of the *DDEI* and *DDIII* were compared to the long-term average of the 7- and 10-day mean ΔU_L and ΔU_M values, respectively, to see what relationship exists between the rainfall and shear characteristics on this long-term average basis. It was considered important to test the Omotosho (1990) prediction scheme in this long-term climatological mode as a step towards validating it on the interannual time-scale.

RESULTS

The results obtained from the time series of *DDEI* and *DDII* characteristics for the present square catchments (Fig. 1) were quite similar to those found for circular

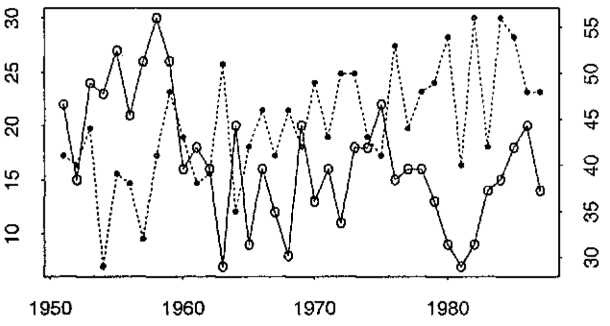


Fig. 2 Variation in frequency of large and small DLs during 1951–1987 for the Bamako catchment. Heavy solid line gives number of days per season when *DDEI* $\geq$ 70% (large DLs; *left-hand* ordinate); light broken line gives number of days per season when 0% $<$ *DDEI* $\leq$ 30% (small DLs; *right-hand* ordinate).

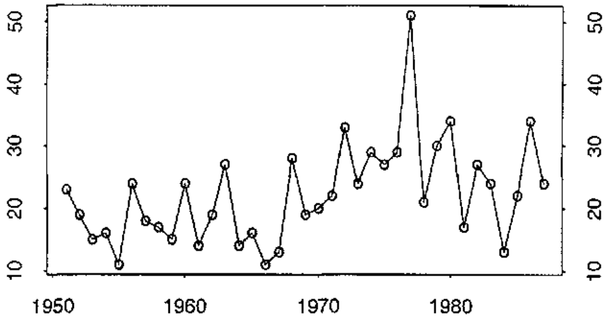
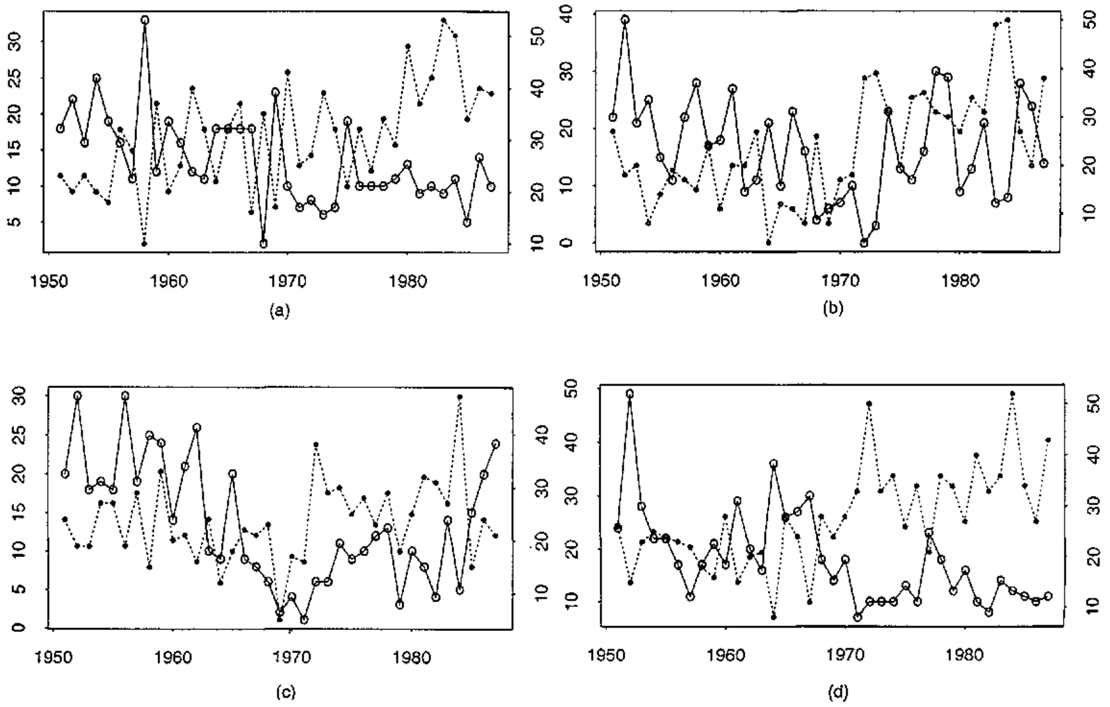


Fig. 3 Variation in frequency of DL absence during 1951–1987 for the Dakar catchment. Line gives number of days per season when *DDEI* = 0%.

catchments (with the same "diameter") by Bell & Lamb (1994). Because of space limitations, the figures included here are for only one of the four catchments, but that catchment's results are representative of those for the other catchments.

Most notably, it was found that the dramatic decline in seasonal rainfall totals in the West African Sahel after 1950 was the result of: (a) a pronounced and progressive zone-wide decrease (increase) in the frequency of large and well-organized (small and/or disorganized) DLs throughout the period (see Fig. 2); (b) a



(a) (b) (c) (d)

Fig. 4 Variation in frequency of strong and weak DLs during 1951–1987 for (a) Dakar, (b) Bamako, (c) Kindi, and (d) Niamey catchments. Heavy solid line gives number of days per season when *DDII* ≥ +0.4σ (strong DLs; *left-hand* ordinate); light broken line gives number of days per season when *DDII* ≤ -0.4σ (weak DLs; *right-hand* ordinate).

post-1965 increase in the frequency of DL absence (see Fig. 3); (c) a general zone-wide increase in the frequency of weak DLs for the period as a whole, but with considerable interannual variability (see Fig. 4); (d) a general decrease in the frequency of strong DLs throughout the period for the extreme westernmost (Dakar) and easternmost (Niamey) catchments, whereas this decrease reversed after the early-1970s for the two central (Bamako, Kindi) catchments (Fig. 4); and (e) pronounced and progressive zone-wide decreases in the seasonal average DL size and DL intensity throughout the period (Fig. 5). Note that there is an overall positive relationship between DL size and intensity from daily to interannual time scales, as illustrated in Figs 6 and 7.

Figure 8 compares the annual cycles of (a) the long-term average 10-day mean ΔU_L and ΔU_M shears and (b) the long-term average 10-day mean *DDEI* and *DDIII* values for the Niamey catchment. These curves show that, in a long-term average annual cycle sense, the tropospheric low-level shear (ΔU_L) strengthens (becomes more negative) until the end of June (at all three stations) and then begins to slowly weaken. Towards the end of June, the size and intensity of DLs begins to quickly increase. Near the centre of the mid-rainy season ΔU_L weakening, there is a slight

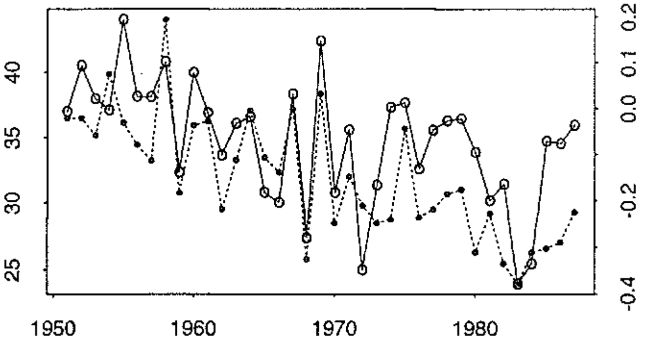


Fig. 5 Variation in average size and intensity of DLs during 1951–1987 for the Dakar catchment. Heavy solid line is seasonal mean of non-zero *DDEI* values (average size; in percent; *left-hand* ordinate); light broken line is average of *DDII* values (average intensity; σ; *right-hand* ordinate).

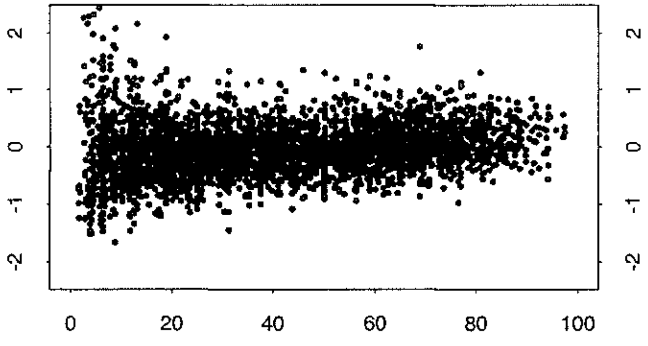


Fig. 6 Relation of DL size to DL intensity for the Bamako catchment on a daily basis for 1951–1987. Abscissa is *DDEI* (size; %) and ordinate is *DDII* (intensity; σ).

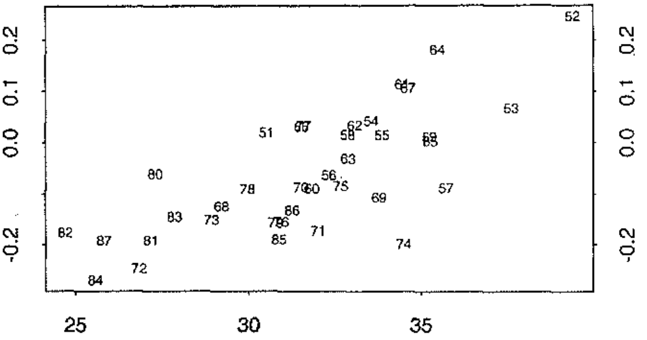


Fig. 7 Relation of DL size to DL intensity on a seasonal basis for 1951–1987 for the Niamey catchment. Abscissa is average non-zero *DDEI* (size; %) and ordinate is average *DDII* (intensity; σ). Numbers give last two digits of year.

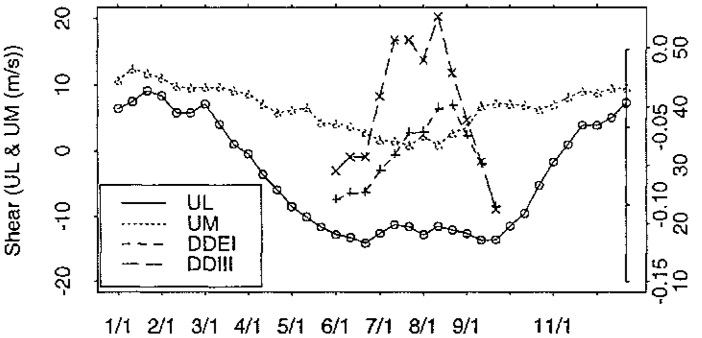


Fig. 8 Seasonal variation in long-term average 10-day mean tropospheric wind shears and size and intensity of DLs for the Niamey catchment. UL and UM respectively denote the ΔU_L and ΔU_M shears defined in the text, while the *DDEI* and *DDIII* are as defined in the text.

temporary strengthening of the ΔU_L which coincides at all three stations with a drop in the *DDEI*, and at least a plateau, if not a drop, in the value of the *DDIII*. After this mid-season strengthening, the low-level shear weakens again slightly, and then strengthens once more (except at Dakar) as the *DDEI* and *DDIII* values fall at the end of the rainy season. After the *DDEI* and *DDIII* have diminished greatly by the end of the rainy season, the low-level shear again weakens through the end of the year. Finally, Fig. 8 suggests that the above shear criteria of Omotosho (1990) work well, on a long-term average annual cycle basis, in diagnosing when the size and intensity of DLs begin to quickly increase. This is particularly true of the Bamako and Niamey catchments. Therefore, it appears possible that these shear criteria could have predictive value for rainy season onset on a seasonal basis across much of the Sahel.

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