On the Generation of African Squall Lines

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ABSTRACT

Squall lines (SLs) form an important component of the meteorology of northern Africa, and in particular, contribute substantially to rainfall totals. Their generation requires the existence of a potentially unstable low-level supply of moisture overlain by dry desert air and vertical wind shear beneath the midlevel African easterly jet. The instability may be released (and an SL initiated) by factors such as surface heating, topography, African waves, or surface evaporation. The relative importance of each of these factors and the means by which they impact on SL generation is reviewed. This is followed by a detailed analysis of one month of satellite imagery and surface data for August 1985 over a portion of central northern Africa.

The novelty of our study lies in the temporal resolution of the satellite imagery, which with 21 images per day allows the identification of a large number of short-lived SLs (4-h duration or less). On the southern fringes of the Sahara these are likely to contribute significantly to rainfall totals, and so cannot be neglected. The analysis is also entirely objective, an important feature if future studies are to produce a homogeneous SL climatology. Our results show, for the period and area of study, a preference for SLs to generate during the midafternoon, with generation probability also enhanced by above-average low-level westerly flow and by surface features such as the Air Mountains, the Jos Plateau, and the northernmost section of the river Niger. African waves and the strength of the African easterly jet were not found to affect SL generation for the period and region studied. Where these results do not support previous studies, we speculate that this may be due to differences in location or time of year, but only a more extensive analysis will resolve these issues.

1. Introduction

Squall lines (SLs) are responsible for the majority of rainfall in the African Sahel and a significant, but lesser, proportion of the rainfall in much of the remainder of sub-Saharan North Africa. They consist of an organized line of convective cells, oriented in a north–south direction, which may be up to 1000 km in length. They travel more or less westward, often faster than the wind speed at any level, and may last for many hours. On average over half the rainfall occurs during the first 30 min, though this varies considerably as the convective cells are of small-scale and widely ranging intensities. The line of convection is followed by the "anvil," consisting firstly of middle-level cloud that gives rise to more homogeneous but lighter precipitation, followed by a high-level cirrus shield.

Such a sequence of events is evident from both surface-based observations and space-based observations. Studies of the former category were pioneered by Hamilton and Archbold (1945) and Eldridge (1957), whose work has since been developed and added to by later workers such as Bolton (1981, 1984) and Omotosho (1984). More sophisticated measurement techniques were applied during the COPT81 field program (Convection Profonde Tropicale), where Doppler radar was employed to investigate the internal dynamics and steady-state behavior of West African SLs (e.g., Sommeria and Testud 1984; Chong et al. 1987; Chalon et al. 1988; and Roux 1988). Placing these results in a larger-scale context has been substantially advanced by the advent of satellite observations that have provided a better understanding of the entire evolution, life cycle, and behavior of SLs (e.g., Aspliden et al. 1976; Martin and Schreiner 1981; and Desbois et al. 1988).

Since SLs account for significant proportions of rainfall in much of sub-Saharan North Africa, an increased understanding of their generation, dynamics, and decay is crucial both to enlarge our broader understanding of African meteorology and also to further the more practical issue of forecasting for the region, particularly at shorter time scales. The diabatic heating associated with these small-scale weather systems is one of the main driving forces behind the North African circulation, and so an understanding of their behavior and their interaction with the environment is also an important component of climate studies. Much effort

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has been placed on assessing the interannual variability of Sahel rainfall (reviews by e.g., Druyan 1989; Lamb and Peppler 1991), but little progress has been made on the difficult task of investigating the interactions between this variability and the smaller space–time-scale variations that make up the regional climate. This paper contributes to these efforts by concentrating on the generation of SLs and its relationship to their determining factors, both those with known spatial or temporal variability (e.g., topography, diurnal solar cycle) and those with more "random" variability (i.e., synoptic-scale weather systems and the large-scale flow regime).

We first provide a review of current knowledge on the generation of African SLs and the various "external" factors involved. This is followed by new results and analysis, using satellite data to observe the behavior of SLs during a one-month period. Note that the importance of this analysis lies not only in its results, but also as a pointer for the methodology of future studies. Only through a much more detailed and extensive analysis of SL climatology may the aims of this paper be fully realized.

2. Review of current knowledge

Squall lines may develop from relatively isolated deep convective events or from cloud clusters that are often the decaying remnants of a previously active SL. Mesoscale dynamic and diabatic feedbacks then enable the convective activity to develop further and become far more organized and persistent than much smaller convective events. The conditions required for generation and development are: conditional instability, vertical wind shear in the lower troposphere, and a moist lower layer with dry air at middle levels. The release of the instability may be triggered by factors such as surface heating, topography, large-scale convergence (e.g., African waves), or surface moisture sources.

The following subsections refer in turn to these factors that influence SL generation. First, a comparison is made of the SL definitions used in the papers to be reviewed and the data available to each study, since these can significantly affect the results.

a. Definitions of a squall line

Table 1 presents the comparison of SL definitions used in the studies referred to in sections 2b to 2f. Also shown is our own definition, described in more detail in section 5 and used in the analysis presented in section 6. Even when differences of data length, area covered, and the time of year are considered, there is still a wide variety in the number of cloud clusters and SLs found by different authors, largely as a result of differences in the definition of a cloud cluster or SL. The main differences include the following:

(i) The use of synoptic data or satellite data: SL definitions and analyses based on these two data types do not compare well.

(ii) Differences in the minimum lifetime or size of a cloud cluster or SL.

(iii) Confusion between a cloud cluster and an SL: a cloud cluster may contain one or more SL life cycles within its own life cycle and is inclusive of the post-SL phase. An active SL can no longer be recognized as such when its leading edge looses its sharpness, that is, when new convective cells are no longer actively developing ahead of the maturing cells. This distinction between SLs and cloud clusters particularly affects results on the lifetime of systems.

(iv) Most definitions rely on a high degree of subjectivity (perhaps inevitable when using satellite imagery in a photographic rather than digital format). Typical is the definition of Payne and McGarry (1977): "Squall clusters were characterized by explosive growth, high brightness, and a distinct and generally convex shaped leading edge." This inevitably involves human judgement, and may in part give rise to discrepancies between authors.

The main findings of the various studies are now summarized.

b. Diurnal cycle

The strong influence of the diurnal solar cycle on SL and cloud-cluster generation and decay has been noted by many authors, e.g., Hamilton and Archbold (1945), Aspliden et al. (1976), Martin and Schreiner (1981), and Duvel (1989). A peak in generation is seen during the mid- or late-afternoon hours when conditional instability of the boundary layer reaches a maximum. The release of this instability may be triggered by surface heating, which reaches a maximum in the early afternoon, as well as by orography or by large-scale convergence (see below). It should be emphasized, however, that SL generation may occur at any time of day, and merely shows a preference for the mid- to late-afternoon hours. The SLs then grow rapidly during the following hours, with maximum convective activity not occurring until midnight or later in some areas (McGarry and Reed 1978; and Reed and Jaffe 1981).

c. Geographical features

Several authors have noted that high ground and areas of high surface moisture enhance SL and cloud-cluster generation [e.g., Eldridge (1957), Martin and Schreiner (1981), Omotosho (1984), Kamara (1986), and Desbois et al. (1988)]. Regions identified by these authors include the Jos Plateau (northern Nigeria); Air Mountains (near Agadez, Niger); Darfur Mountains (Chad); the Cameroon mountains; the southern part of Adrar des Iforas (Mali); the headwaters of the rivers Niger, Gambia, and Senegal; the plain north of

TABLE 1. Comparison of the definitions of cloud clusters (CCs) and SLs used by authors under whose results are reviewed in section 2. Also shown is our definition used in section 5.

Author(s)	Data	Resolution		Type of weather system	Subjective/ objective definition	Minimum life-time	Minimum value of max. size	Data period (* includes nonactive periods)	Area within 5–20°N (10^6 km^2)	Number of CCs or SLs found	Notes/details of definition
		Spatial (km)	Temporal								
Hamilton and Archbold (1945)	Surface + upper air	—	—	Disturbance Line (=SL) & local thunderstorms	Subjective	—	—	—	—	—	No formal definition given. Text is mainly descriptive. Includes some statistics of wind squalls greater than 30 mph.
Eldridge (1957)	Surface	50–200	—	Disturbance Line (=SL)	Subjective	6 h	16 km	365 days (1 Jan.–31 Dec. 1955)	5.1 (land)	283	Phenomena of the thunderstorms or squall type, with a degree of regular movement.
Aspliden et al. (1976)	GOES SMS-1 IR + VIS	8 (IR) 4 (VIS)	0.5–3 h	CC	Subjective	6 h	2° by 2°	63 days (3 periods during Jun–Sept. 1974.)	4.2 (land) 3.5 (Ocean)	176	Brightest clouds, determined from photographic images. Referred to as disturbance lines.
Payne and McGarry (1977)	GOES SMS-1 IR + VIS	8 (IR) 4 (VIS)	3 h	CC, SL	Subjective	6 h	1° by 1°	28 days (23 Aug–19 Sept. 1974)	4.2 (land) 3.0 (Ocean)	92 CCs 48 SLs	Cloud Cluster: distinct cloud mass containing deep convection during some part of its life. Squall episode: explosive growth, high brightness and convex leading edge.
Martin and Schreiner (1981)	GOES SMS-1 IR + VIS	8 (IR) 4 (VIS)	3 h	CC, SL	Subjective	—	1° by 1°	85 days (27 Jun–19 Sept 1974)	2.5 (land) 2.9 (Ocean)	526 CCs 55 SLs	Cloud Cluster: as Payne and McGarry (1977) SL cluster: explosive growth, compact oval shape and very high brightness.
Bolton (1981, 1984)	Surface (8 stations) supplemented with GOES SMS-1	100 (surface)	1 min (surface)	SL	Quasi-objective	—	—	823 days* (Jun. '74 to Aug. '76)	0.3 (land)	80	*Guide* to SL existence: 1) Max. squall speed > 12 m s^{-1} 2) Rain ⩾ 5 mm; 3) Storm duration ⩾ 3 h 4) Pressure jump ⩾ 0.5 mb (one station)
Omotosho (1984)	Surface (40 stations)	100–500	1 min	SL	Objective	—	—	1827 days* (Jan. '71–Dec. '75)	2.6 (land)	—	Wind squall (by WMO definition). May not always be associated with a rainfall event. Identified only at individual stations, size and lifetime not analyzed.
Desbois et al. (1988)	Meteosat IR	30	3 h	SL	Quasi-objective	12 h	—	62 days (Jul '83 and Jul '85)	9.6 (land) 3.0 (Ocean)	50	Cold cloud < −40°C. Sharp edge on west side. Long lifetimes (up to 84 h) indicate definition may incorporate whole cloud cluster, not just active SL phase.
Duvel (1989, 1990)	Meteosat IR	30	3 h	SL	Quasi-objective	12 h	—	93 days (Jul '83, '84, '85)	4.2 (land)	49	Same definition and data anaylsis as Desbois et al. (may be CCs, not just SLs).
This study	Meteosat IR	5	1–1.5 h	SL	Objective	2.5 h	None	31 days (1–31 Aug. 1985)	2.1 (land)	186	1) Area of cold cloud <−60°C 2) Leading edge has < 40 km between −40°C and −60°C contours. 3) Nonzero average speed

the river Niger between 5° and 10°W; the northernmost part of the river Niger; and the region around Lake Chad.

Orography tends to enhance the likelihood of SL generation by acting as a trigger for the release of low-level instability. This may occur either through the forced ascent of moist air, or because surface temperature over high ground is large relative to the vertical temperature profile, or due to the effects of boundary-layer convergence lines [the latter being described by Wilson and Schreiber (1986)].

Marshlands or other areas of high surface moisture in the midst of arid or semiarid regions may trigger SL generation by supplying the water vapor necessary for the development and maintenance of convective activity. Also, the associated spatial discontinuities or gradients of surface evaporation may result in the development of mesoscale circulations (Ookouchi et al. 1984), thus triggering deep convection.

d. African waves

African (or easterly) waves are synoptic-scale disturbances that travel westwards across tropical northern Africa, into the eastern Atlantic, and often on into the Caribbean. They have wavelengths of around 2500 to 3000 km, propagation speeds of 7 to 8 m s^{-1}, and a period of 3 to 4 days (e.g., Carlson 1969; Reed et al. 1977; and Duvel 1990). Their modulation of rainfall, cloudiness, and SL generation has long been recognized. Schove (1946) found that SLs often occurred slightly ahead of or behind the wave trough, and Carlson (1969) and Burpee (1974) found that cloudiness or heavy rainfall was more likely to occur at, or just behind, the trough.

Using data from GATE and from the SMS-1 geostationary satellite, Payne and McGarry (1977) presented a more detailed study of the influence of African waves on cloud-cluster and SL generation. Cloud-cluster genesis was found to be independent of wave position (determined from filtered 700-mb wind data) during the third phase of GATE (23 August–19 September 1974). SLs, however (which may occur once or more within the lifetime of a cloud cluster), were found to have preferred generation about ⅛ to ¼ of a wavelength ahead of the trough, and preferred termination immediately behind the ridge (Fig. 1). Note, however, that not insignificant numbers were also found to generate or decay in other parts of the wave. In an earlier study, using data from all three phases of GATE (27 June–19 September 1974), Aspliden et al. (1976) showed that cloud clusters were most likely to generate slightly ahead of the cyclonic wave axis. In a more recent study, Duvel (1990) used Meteosat data and ECMWF analyses to show that SLs in July (1983, 1984, 1985) generated most frequently just ahead of the northerly wind maximum.

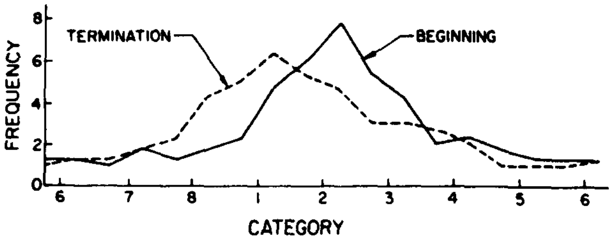

FIG. 1. Frequency distribution of the leading edge of SLs versus wave phase, for their generation (solid line) and termination (dashed line) (23 August to 19 September 1974). The graph has been smoothed with a 3-point running mean extending over 1.5 wave categories: 4 represents the trough axis, 8 the ridge, and 2 and 6 the maximum northerly and southerly wind components, respectively (from Payne and McGarry 1977).

These results may be explained by the composite wave picture built up by Reed et al. (1977). This shows the region just ahead of the trough to be characterized by the ideal thermodynamic conditions for SL generation (a shallow moist layer with dry air aloft), as well as by large-scale low-level convergence.

Bolton (1981, 1984), however, found that there appeared to be "no clear connection" between African waves (determined from the 700-mb meridional wind component) and the occurrence of SLs at Minna, Nigeria (9°,37′N; 6°34′E). It may be that Bolton used too small a sample, taking upper-air data from just one station during the period 1–23 September 1974, and that he also was using a fairly narrow definition of SLs. Alternatively, it may be a real effect that the waves provide little modulation of SL generation in the region of Minna.

e. Large-scale flow

Another important aspect of the flow is the existence of low-level vertical wind shear. In North Africa this is associated with the midlevel (about 650 mb) African easterly jet, which arises as a consequence of the reverse thermal gradient to the south of the Sahara. Numerical studies have demonstrated the importance of the large-scale kinetic (and thermodynamic) state of the environment, by initializing three-dimensional models with a profile typical of that preceding an African SL (e.g., Bolton 1981, 1984; Dudhia et al. 1987; Weisman et al. 1988; and Lafore and Moncrieff 1989). This approach has simulated SLs having much in common with those observed. Bolton's results are particularly relevant here, as he has also experimented with a number of idealized profiles. In particular, he found his results to be sensitive to lapse rate, such that appreciable buoyancy at the level of maximum mean flow was required in order that the system travel faster than the flow at any level. This suggests that only the midlevel African easterly jet can be important in this respect and that the upper-level tropical easterly jet is too high for its shear to impact on SL development.

Observational evidence of the impact of the wind profile is lacking and has only been concerned with conditions ahead of (or behind) SLs already at a mature stage. Using a diagram of the time evolution of the vertical profile of zonal wind, Bolton (1981) showed that SLs only passed when there was a strong maximum of the midlevel easterly jet of at least 8 m s^{-1}, and normally 12 m s^{-1}. He also presented the mean profiles of westerly wind before and after an SL had passed and compared these with the profile on non-SL days (Fig. 2). The 700-mb jet was on average significantly stronger prior to an SL passage, by about 5 m s^{-1}, and also weakened slightly after the SL had passed (but not significantly). He concluded that not only should low-level shear be present, but that for most SLs it should be stronger than average. In the east tropical Atlantic, Mansfield (1977) also found an association between enhanced 700-mb easterly flow and the passage of four fast-moving SLs during the period 2–17 September 1974.

f. Atmospheric moisture content

Another essential ingredient for SL development is the existence of a moist lower layer with dry air at middle levels. Conditions during northern summer in the Sahelian and Soudan regions of North Africa are ideal in this respect, being characterized by a moist southwesterly monsoon flow undercutting the dry northeasterly "Harmattan." Case studies over West Africa (e.g., Lemaitre and Testud 1986; Chalon et al. 1988; and Chong and Hauser 1989) and over the tropical Atlantic (e.g., Zipser 1977), as well as the modeling studies referred to above, have shown that evaporating precipitation cools the dry air aloft, generating downdrafts on both the mesoscale and convective scale. Dynamical forcing of the downdrafts may also be important (Miller and Betts 1977). This descending cold air produces a "gust front" at the leading edge of the SL, which, acting as a density current, lifts the warm moist air ahead, encouraging the development of new convective cells and accelerating the propagation of the SL.

The importance of the moisture profile is also discussed by Bolton (1981), whose composite tephigrams show that ahead of SLs at Minna the surface layer was on average warmer and slightly moister than on non-SL days, with somewhat drier air aloft. In the same way, the moisture profile also determines the latitudinal and intraseasonal variability of SLs. In southern parts of West Africa this gives rise to a bimodal annual cycle of SL occurrences (since the dry middle layer is often absent at the height of summer), but produces a single-peaked distribution north of about 12°N (Omotosho 1984). Studies of interannual variations over the West African Sahel have also found that the depth of moisture supply may be related to rainfall totals (Lamb 1983).

Finally, the influence of recent convective activity on the probability of further SL generations should also be considered. Since the effect of deep convection is to overturn the troposphere through much of its depth, an SL passage is often (but not always) followed by a period of inactivity (e.g., Eldridge 1957; and Bolton 1984). The time scale on which the local atmospheric profile recovers the capability to support another SL probably varies substantially depending upon the large-scale flow regime and upon local factors.

Having reviewed current understanding of the

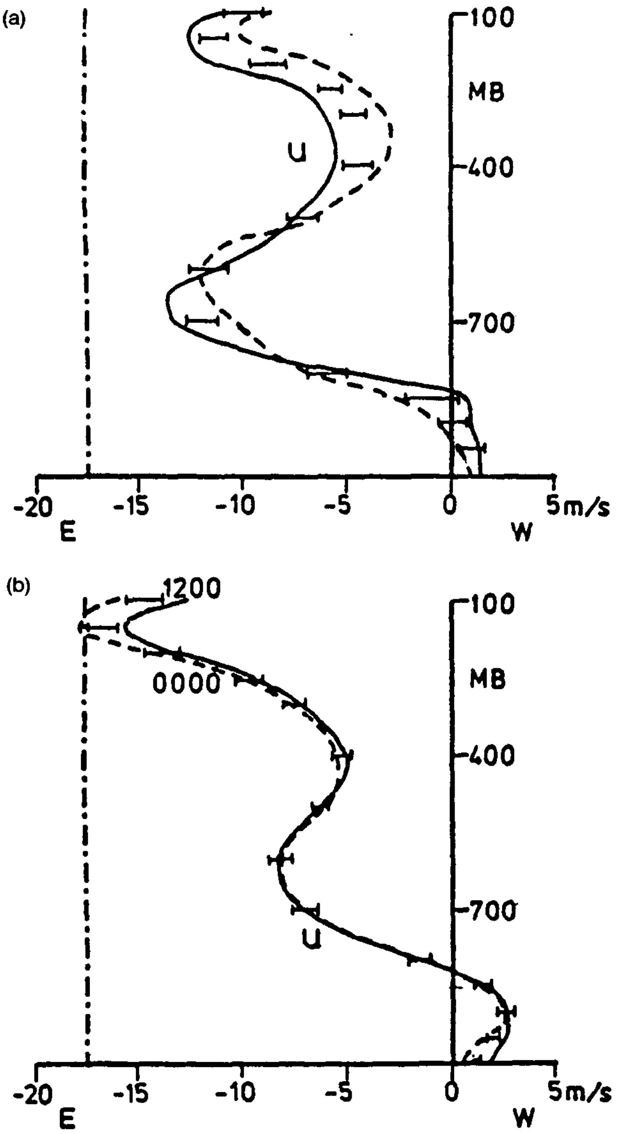

FIG. 2. Minna mean profile of "westerly" wind component (m s^{-1}) (actually the component along the GATE mean direction of SL motion, i.e., from 083°): (a) before (full line) and after (dashed line) an SL passage (each data pair 12 h apart) (July 1974 to August 1976); (b) on non-SL days at 1200 UTC (full line) and 0000 UTC (dashed line) (July to September 1974). Dashed–dot line: mean speed of SLs. Bars denote one standard error (e). Two means are significantly different with 95% confidence if they differ by at least 2e (from Bolton 1981).

mechanisms involved in the generation of African SLs, we now present our own analysis of one month of Meteosat imagery. Details of the data are first outlined, and then the period of study is placed into its climatological context.

3. Data

a. Meteosat imagery

Thermal infrared data were obtained for the month of August 1985 for an area covering much of Niger and parts of Mali, Burkino Faso, and Nigeria (2.5°W to 14°E, 9.5°N to 22°N). Twenty-one images were available each day, spaced at 1-h intervals from 0530 to 2030 UTC, and at 1.5-h intervals during the night hours. This temporal resolution is essential for tracking the SLs that can both generate and decay very rapidly. The spatial resolution of the data was about 5 km, and each image was collocated using a number of easily identifiable surface reference points. Images were color-coded according to brightness temperature at 20°C intervals, allowing the SLs to be easily identified as areas of rapidly growing cold cloud with a sharp leading edge (large temperature gradient) and approximately westward motion. An objective definition is given in section 5.

b. Wind observations and analyses

The generation site of each SL relative to the phase of an African wave (section 6d) was determined using ECMWF 700-mb streamline analyses, available at 6 hourly intervals at 1.875° resolution. Rowell (1988) and Reed et al. (1988) have shown the analyses of wave positions to be of useful quality.

Although model analyses of the location of synoptic systems over tropical North Africa are of reasonable quality, analyses of the precise magnitude and direction of the lower-tropospheric winds are liable to significant errors (Rowell 1988). Raw data, available over the GTS from pilot balloons and radiosondes, was, therefore, employed to study the influence of the magnitude of the lower-tropospheric flow on SL generation (section 6e). No data are available for the period 1200 UTC 24 August to 1800 UTC 30 August, during which there was a fault in the GTS. Presumably this also affected the quality of the ECMWF analyses, and so in section 6d wave positions were only compared to SL generation sites for the period 1–23 August.

4. Climatological context

In order to place the present study in context, we now describe its temporal location within the seasonal cycle and the long-term climate. Considering the former, the annual march of rainfall across sub-Saharan Africa is well known, with our chosen month (August) being the wettest as far south as about 10°N (e.g., Nicholson 1981; and Nicholson et al. 1988) and also the month of maximum SL activity (Omotosho 1984).

However, with regard to the *year-to-year* variability, little effort has so far been directed towards assessing fluctuations in SL behavior [except for the work of Desbois et al. (1988), in their study of very long-lived SLs]. Here, our concern is whether the SLs to be studied in section 6 are typical of other years. To assess this a gridded dataset of monthly mean rainfall was used provided by Hulme (1991, personal communication) and constructed using the methodology described by Hulme (1992). These data have the advantage that a consistent reference period was used for each rainfall station and that measurements were transformed to a regular grid (2.5° latitude by 3.75° longitude), giving fairly homogeneous data coverage in both space and time. Rainfall anomalies were computed at each grid box for August 1985 (relative to two climatological periods: 1951–80 and 1971–90), and then averaged over the area of interest, with an appropriate weighting for boxes falling partly outside the area. Those boxes with no rainfall data were discarded, representing the northern 42% of the area where rainfall amounts are small. The computations show rainfall during August 1985 was 70% of the 1951–80 August mean and 85% of the 1971–90 mean (equivalent to the fourth driest August during the former period, but only the tenth driest during the latter period). Thus, the SLs to be studied in section 6 occurred during a moderate drought relative to the long-term climate, but a near-average month relative to the recent long-running drought [see, for example, Ward (1992) for a long time series of rainfall data].

5. Definition of a squall line and measurements made

For the purposes of this study, an SL required each of the following:

(i) An area of cold cloud with a brightness temperature less than −60°C;

(ii) a sharp leading edge, defined as less than 40 km between the −40°C and −60°C contours, on the forward side of the cloud;

(iii) nonzero average speed of the leading edge (relative to the land surface);

(iv) duration of at least 2.5 h.

The time of origin was defined as the time of the image in which the SL was first observed, though it is recognized that it may have generated up to 1 or 1.5 h prior to this. The position of origin was taken as the center of the cold cloud area. The initial growth rate was averaged from the first to the third images on which the SL appeared. Last, the time of decay was defined as the time of the final image on which the SL had a sharp leading edge, and the position of decay as the central point on this leading edge.

A small proportion of SLs failed to follow a simple pattern of generation, propagation, and decay: 22 resulted from the merger of one or more SLs, 2 split into a pair of separate SLs towards the end of their life, a few redeveloped from previously decayed SLs (i.e., from the remaining anvil or cirrus shield), and a few more developed close to the time of a missing image (of which there were 10 out of the 651 for the month). In all cases, objective and consistent rules were used to define their characteristics, or (for growth rate) no measurements were made.

As the results of this study are to be compared with the work of other authors, it is pertinent to comment on how our definition compares with those used by others (Table 1). Three important differences should be noted.

(i) The minimum lifetime used here includes a large number of short-lived SLs that would be excluded by most other authors, who generally used a minimum lifetime of at least 6 h.

(ii) Some authors (see Table 1) consider cloud clusters that include within their lifetime the cirrus shield remaining after the decay of the active SL, and may include further SL events. Our requirement to maintain a sharp leading edge means that we analyze only individual, active SL events.

(iii) The definitions used in this study have been made as objective as possible, so as to reduce the variations of human judgement. This introduces the possibility that the process may be automated, if it is desired to process much larger amounts of data. In contrast, the definitions of other authors rely on a degree of subjectivity.

6. Results

In the following sections we first describe the broader aspects of the frequency and behavior of SLs during August 1985 (between 2°W and 14°E), and then set out the detailed findings under the same factors as were described in section 2.

a. General observations

A total of 157 SLs generated and decayed within the specified area during August 1985, and a further 29 either generated or decayed outside the area of study. The distribution of lifetimes of those in the former category is illustrated in Fig. 3. The existence of a large number of short-lived SLs is not an aspect of the regional meteorology noted by other authors and has only become apparent here due to the high temporal resolution of the data available. Their short lifetime and small size indicates that their precipitation was probably much less than their longer-lived counterparts, although they may have made a significant contribution to seasonal rainfall totals in some or many areas. Since the reason for their short lifetime and small size may be linked to dynamical or geographical differences in their environment, we have divided the SLs into two types: those with lifetimes of 4 h or less, and those with lifetimes greater than 4 h (giving roughly equal numbers of each type; 64 and 93, respectively). Some of the analysis in the following subsections is carried out separately on each of these types to investigate whether they respond differently to the various factors affecting their generation.

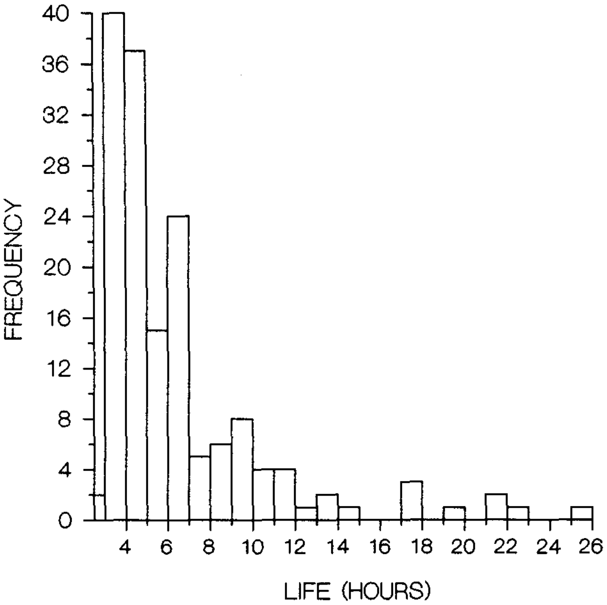

FIG. 3. Histogram showing the frequency of SLs with a given lifetime.

Figure 3 also shows that few SLs lasted more than several hours, even though the cloud clusters that encompass them may exist for some days (e.g., Martin and Schreiner 1981). Payne and McGarry's (1977) results are similar, with a mean duration of 10.1 h for SLs lasting longer than 6 h, which compares well with a mean of 9.8 h when we apply a similar minimum duration. Note, however, that some SLs were excluded from Fig. 3 because their entire life cycle was not contained within the area of study, giving rise to a bias against long-lived SLs of 25% or more (depending on the threshold of minimum lifetime).

Table 2 shows the mean and standard deviation of the life, average speed, and initial growth rate of both long and short-lived SLs (hereafter defined as above; lifetimes of 4 h or less, or greater than 4 h). Short-lived SLs averaged slightly lower initial growth rates (significantly different at the 5% level), although the variability in each category is large. There is no significant difference in mean speed between the two types.

Table 3 illustrates the distribution of SL generation with latitude during August 1985 (including 30 additional generation sites of SLs later merging with some of those counted above). The number of generations decreases steadily northward as moisture availability

TABLE 2. Mean characteristics of long- and short-lived SLs.

Type of SL	Characteristic	Sample size	Mean	Standard deviation
Long-lived	Life (h)	93	8.1	4.4
	Speed (m s^{-1})	93	14.7	3.7
	Initial growth (10^3 km^2 h^{-1})	104	4.4	3.6
Short-lived	Life (h)	64	3.4	0.5
	Speed (m s^{-1})	64	15.2	3.9
	Initial growth (10^3 km^2 h^{-1})	63	3.5	2.1

in the low-level monsoon flow gradually lessens. Their mean lifetime, and the percentage of long-lived SLs, also tends to decrease over the northern Sahel (north of about 14°N), where the SLs can rarely travel for more than a few hours before reaching an area of insufficient moisture.

b. Diurnal cycle

Figure 4 illustrates the number of long and short-lived SLs that generated and decayed at different stages of the diurnal cycle. The histogram of generation of long-lived SLs is broadly similar to the results of other authors, but peaks approximately 2 h earlier. This is probably because the higher temporal resolution of our data is able to capture the SLs at an earlier stage of development. The decay of long-lived SLs has a broad peak from evening to early morning (1800 to 0300).

The generation of short-lived SLs peaks during the late afternoon, slightly later than for long-lived SLs. It may be that SLs developing later in the day are more likely to be short lived because they have not developed sufficiently to become selfsustaining after the decline of surface heating. The peak in decay of short-lived SLs is simply about three hours later than the peak in generation.

Factors affecting the decay of SLs have received little attention in the published literature but are nevertheless important. Figure 5 presents some further analysis of our data, illustrating the diurnal variability of decay likelihood, but masking out its dependence upon generation. It shows the conditional probability that an SL decays within the next 3 h, given that it has already been in existence for at least 2.5 h. This is fairly constant at around 50%, except during the early afternoon hours when it drops to about 10%; that is, the diurnal cycle has little impact on decay likelihood, except for the few SLs present at midday that have a much higher probability of survival.

TABLE 3. The influence of latitude on the frequency of SL generation and duration.

Latitude (°N)	Number of SLs generating	Mean life (h)	Percent of long-lived SLs
9.5–9.9	10	6.7	100
10.0–11.9	69	6.8	68
12.0–13.9	49	6.6	57
14.0–15.9	44	5.6	54
16.0–17.9	22	5.1	47
18.0–19.9	8	3.6	29
20.0–21.9	1	3.0	0
Total/Average	203	6.2	59

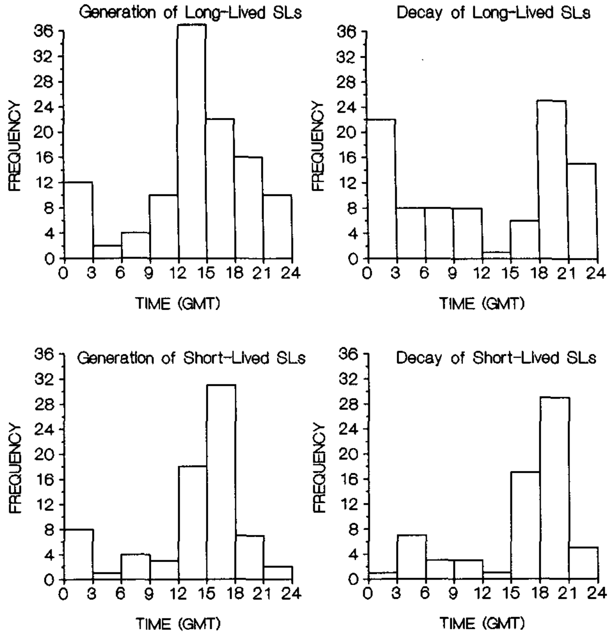

FIG. 4. Histograms showing the diurnal cycle of the origin and decay of long and short-lived SLs.

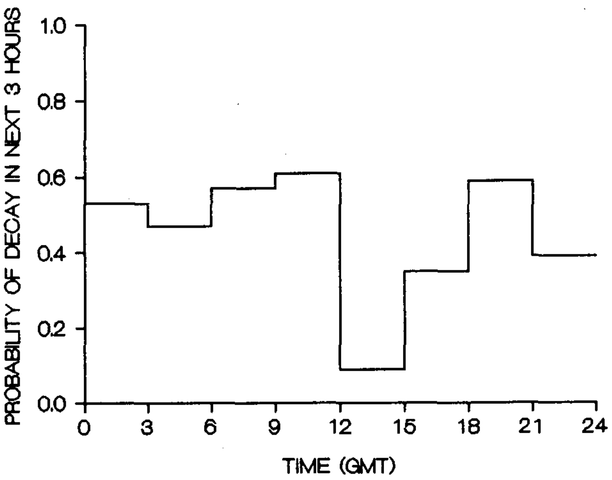

FIG. 5. Diurnal variation of the conditional probability of an SL decaying in the next 3 h, given that it has already lived for at least 2.5 h.

c. Geographical features

Figure 6 shows the geographical locations of the origins of both long and short-lived SLs during the 30-day period. The tendency for a lesser proportion of long-lived SLs farther north is apparent, as already noted in section 6a and Table 3. No longitudinal biases towards the relative proportions of long and short-lived SLs are evident, but a number of regions of higher total-generation density stand out, suggesting the influence of topographic and other surface features. These include the following:

(i) At latitudes 16° to 19°N there is an area of enhanced generation (of mainly short-lived SLs) just west of the Air Mountains (7° to 9°E). Although their life is too short to be considered by many of the studies in section 2, they may account for the majority of rainfall in this area.

(ii) Three SLs developed just west of the Adrar des Iforas Mountains (20°N, 2°E).

(iii) Preferred generation also seems to occur around the northernmost part of the river Niger. We speculate that these SLs were aided by the river and surrounding areas acting as a moisture source at a latitude where surface evaporation is generally lacking.

(iv) Further south, a higher density of SL origins was found over the Jos Plateau area (9° to 12°N, 7° to 10°E).

These observations are, however, purely subjective, and so are now tested for statistical significance. Each 1° square was classified as either orographic, riverine, or other. Orographic squares are defined as those containing more than 30% of land above 500 m, as a simple indication of hilly or mountainous areas. Riverine squares are defined as those through which the river Niger passes, or for which the river is less than 0.5° farther east (to allow for SLs generating and propagating for up to 1 h at 15 m s^{-1} before their first appearance on an image). Two 2° latitude bands were selected (10° to 12°N and 16° to 18°N), and Table 4 compares the number of SLs generating in each of the geographical classes during August 1985. First, it is seen that many more SLs generate within the southern-latitude band than the northern band (cf. Table 3). To aid comparison, this effect is removed in the lower half of Table 4 by showing the fraction of SLs generating in squares of a particular type to those generating in "other" squares, weighted by the number of squares of each type. The main conclusions are as follows:

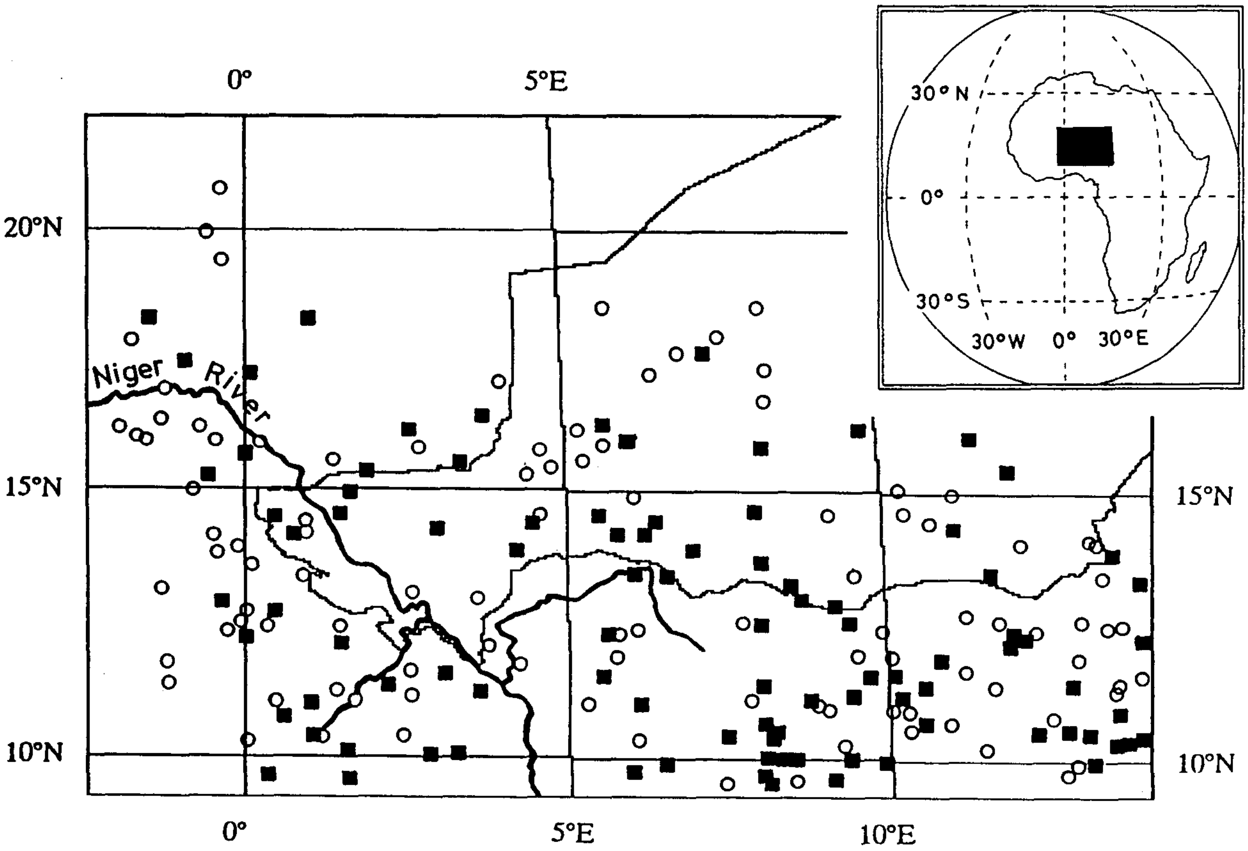

FIG. 6. Geographical distribution of long- (■) and short- (O) lived SL generation sites. Thin solid lines mark the national boundary of Niger, and thick solid lines the major rivers. The inset shows the location of the analysis region within the African continent.

TABLE 4. The influence of surface features on SL generation. See text for definitions of "Orographic" and "Riverine" squares. Weighted ratio = (ratio in top half of table)/(ratio for "Other" squares).

	Latitude	Orographic	Riverine	Other
Ratio of number of SLs/	16–18°N	6/6	9/5	7/21
number of squares	10–12°N	32/11	3/3	34/18
Weighted ratio	16–18°N	3.0	5.4	1.0
	10–12°N	1.5	0.6	1.0

(i) The enhancement of SL generation around the Air Mountains between 16° and 18°N was significant at the 2% level. A χ^2 test was used, based on the null hypothesis that the orographic squares and other squares had the same impact on SL generation.

(ii) Over five times as many SLs generated in the region of the northernmost part of the river Niger, when compared to other areas of the same latitude (a significant impact at the 1% level).

(iii) The Jos Plateau area between 10° and 12°N also appears to have increased the likelihood of SL generation, but this is significant only at the 10% level.

(iv) The southern part of the river Niger (10° to 12°N) had no significant impact on SL generation. Moisture availability is less restricted at this latitude so the river provides little advantage.

d. *African waves*

Following Payne and McGarry (1977), African waves (in the 700-mb ECMWF analyses) were subdivided by eight numbered boundaries that were allowed to vary with latitude, where boundary 2 represents the axis of maximum northerly wind component, boundary 4 the trough, boundary 6 the axis of maximum southerly wind component, and boundary 8 the ridge. Boundaries 1, 3, 5, and 7 occupy intermediate positions. The resulting regions were of approximately equal area, and waves were identified on all days so there were no uncategorized areas.

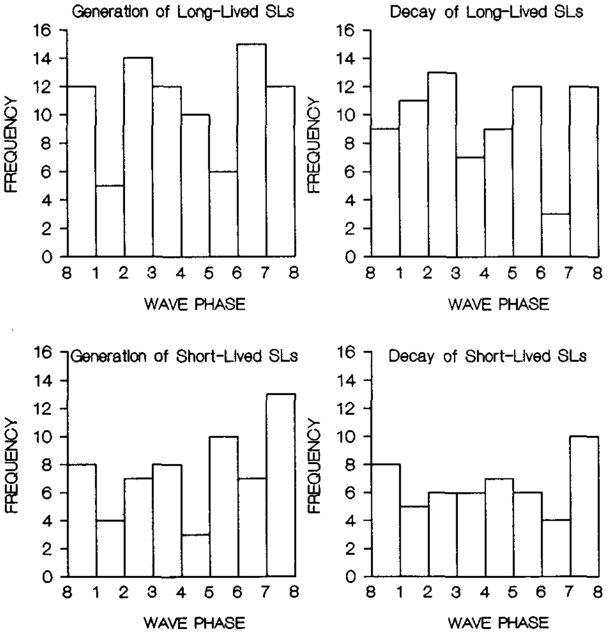

FIG. 7. Histograms showing the influence of African waves on the origin and decay of long and short-lived SLs. Boundaries between categories are defined in the text.

The effect of African waves on the generation and decay of long and short-lived SLs is illustrated in Fig. 7. None of these distributions was significantly different from the null hypothesis that the waves had no impact on SL generation (using a χ^2 test). This is in apparent contrast with the results of other studies (section 2d), and may be because our region of study is farther east than those used by other authors. African waves are known to grow more intense towards the coast of West Africa (Albignat and Reed 1980), and so it is plausible that their impact on SL generation may only become noticeable to the west of our region. More work is needed to investigate the impact of wave intensity on SL generation.

e. *Large-scale flow and moisture content*

The influence of the zonal wind profile on SL generation was also investigated. Ascents by pilot balloon and radiosonde were classified into (i) those with an SL generating within 2° and 6 h, and (ii) those for which there were no SL generations and no existing SLs within 3° and 12 h. The mean and standard deviation of the 850-mb and 700-mb zonal winds, and a measure of the shear between these levels, are shown in Table 5 for the two datasets ("All SLs" and "No SLs"). There is little difference between them, and we suggest that this is because observations both ahead and behind the newly generated SLs are included: other authors such as Bolton (1981, 1984) and Lafore and

TABLE 5. The influence of 850- and 700-mb zonal winds (u) on SL generation. The categories represented by each column are defined in the text: n = sample size, SD = standard deviation.

	All SLs	No SLs	Upstream of SL	Downstream of SL
850 mb u (m s^{-1})				
n	57	80	23	21
Mean	−0.2	−0.4	1.2	−2.3
SD	4.9	4.1	3.8	6.1
700 mb u (m s^{-1})				
n	41	62	13	14
Mean	−8.1	−8.4	−7.3	−8.9
SD	4.0	5.2	4.9	3.7
700 mb u minus 850 mb u				
n	41	62	13	14
Mean	−7.8	−7.5	−8.6	−5.7
SD	5.3	5.1	5.8	5.7

Moncrieff (1989) have demonstrated that the profile is considerably modified by the SL passage.

The ascents close to an SL were, therefore, further subdivided, and the following steps were used:

(i) The ascent was "moved" forward or backward at the SL's average speed to a relative position at the time of the SL generation.

(ii) If the ascent was moved backward more than 1.5 h it was no longer considered, since this new time preceded the SL generation.

(iii) The ascents were then categorized according to their new positions:

(a) observation close upstream of the SL (by 0.2° to 2.0° longitude, with <2.0° of latitude difference); and

(b) observation close downstream of the SL (by 0.2° to 2.0° longitude, with <2.0° of latitude difference).

Observations within 0.2° of the SL were not categorized because of the uncertainty in locating SL generation sites.

Results for these new categories are also displayed in Table 5. Their significance was computed using a *t*-test on the null hypothesis that they are samples from the same population as the sample "No SLs." Only the zonal flow at 850 mb, before an SL generation, achieved significance (at the 5% level). On average this was westerly prior to SL generation (or just ahead of a newly generated SL), as opposed to slightly easterly when no SL formed, implying that the moist southwesterly monsoon layer was on average somewhat deeper. This agrees well with other observations of the environment in which SLs are likely to be found (section 2f).

At the 700-mb level, our results show that the easterly flow need be no stronger than average prior to SL generation. This is in contrast to Bolton's results (Fig. 2) and may indicate that at the more northerly latitudes of our study the impact of the African easterly jet is of secondary importance compared to that of the depth of the monsoon flow. Alternatively, it may be that the 700-mb flow was little different from average only prior to the generation of the short-lived SLs that predominate in this study; a longer period of data would be required to test the possibility that the long-lived SLs require a stronger 700-mb flow.

7. Conclusions

We have provided a review and further insights into how atmospheric and surface variability in the Sahel influences the generation of SLs. A methodology for further investigations has also been provided, and perhaps for the production of a detailed climatology of the generation and behavior of SLs. The novel aspects of our study have been the high temporal resolution of satellite imagery used to track these rapidly changing mesoscale systems, and also the highly objective manner in which we have defined the SL life cycle and surveyed the links with other available data. The availability of almost hourly imagery, along with a low definition of minimum lifetime, has enabled the identification of a large number of SLs during a period of only one month. This included a large number of short-lived SLs (lifetimes of 4 h or less), which probably contribute significantly to seasonal rainfall totals in some regions, and are, therefore, an important component of the climatology of tropical Africa. These events were found to have a different generation distribution to the longer-lived SLs relative to the diurnal cycle and to latitude, and also slightly smaller initial growth rates. However, no significant differences were found in terms of their mean speed, preferred phase of African wave, and preferred longitude. Further analysis is needed to determine how these relationships between SLs and their environment are dependent on the SL lifetime.

Although our analysis has been based upon only a single month of data, it has provided a reasonable sample from which to work. However, one must still be cautious about generalizing the results of this and other studies that have utilized relatively short periods of data. Our most important findings are now summarized.

(i) The expected decrease of SL frequency towards the fringes of the Sahara has been demonstrated, and also a decrease in their mean lifetime to just a few hours.

(ii) Further evidence has been presented for the well known and easily understood dependence of SL generation upon the daily solar cycle, with the modal time of generation being during the midafternoon. However, the diurnal cycle has much less influence on the likelihood of an SL decaying.

(iii) African wave disturbances were not found to have a significant impact on SL development during the period and region of study: it is suggested that only as the wave disturbances grow more intense, as they move westward, do they have a noticeable impact on SL generation.

(iv) Significantly enhanced SL generation around the Air Mountains, the Jos Plateau, and the northernmost section of the river Niger has been demonstrated.

(v) Increased depth of the moist southwesterly monsoon flow has been shown to be linked with a greater likelihood of SL generation.

(vi) No link was found with the strength of the 700-mb African easterly jet for the period and region studied. The required low-level shear was apparent, but the relationship between its strength and SL generation may vary with location and season.

Some of these results do not support the findings of other authors, and we have speculated that this may be partly due to the differences in the period and location of the studies. This emphasizes the need to carry out a far more extensive analysis of the generation, growth, movement, and decay of SLs. In particular, there is a need to investigate the geographical and intraseasonal variability of the links between all aspects of SL behavior and their determining factors. This would enhance our understanding of small-scale variability and predictability over North Africa, and may also help those seeking to model and understand the mechanisms of climate change in the region. If such a study of SL climatology is to be undertaken, it should ideally be based upon at least hourly satellite imagery covering much of sub-Saharan North Africa, and a number of entire seasons. Its analysis should be made as objective as possible, so as to reduce or eliminate the systematic and random influences of human judgement. This objectivity would also enable the production and analysis of an SL climatology to be automated; a great advantage with such potentially large quantities of data.

One missing link, however, in this optimistic view of future possibilities, is the lack of synoptic data on a temporal and spatial resolution corresponding to that of the space-based observations. Reliable analyses of the detailed daily (or subdaily) synoptic meteorology at tropical latitudes are still lacking, so that precise determination of the position and intensity of wave disturbances or of the midlevel jet, for example, will remain difficult. However, modeling centers are now placing an increasing emphasis on the analysis and prediction of the tropical flow, and the quality of such output is continually improving (e.g., Tiedtke et al. 1988).

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