Vol. 7: 71–83, 1996 | CLIMATE RESEARCH Clim Res | Published August 22

African wave disturbances and precipitation at Niamey during July–August 1987 and 1988

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ABSTRACT: The contribution of African wave disturbances (AWD) to the interannual variability of precipitation in the Sahel is considered. Synoptic circumstances associated with the occurrence of precipitation at Niamey (Niger) during July–August 1987 and 1988 are investigated using European Center for Medium Range Weather Forecasts (ECMWF) gridded analyses and Niamey station observations of several meteorological variables. AWD are detected as oscillations in time series of 700 mb meridional winds and as inverted U-shaped cyclonic circulations on latitude-longitude analyses of the 700 mb wind field over West Africa. Spectral analyses of the time series indicate several prominent AWD periods with peaks ranging from 3 to 6 d, with somewhat different results for Niamey radiosonde data and the co-located ECMWF winds. Three passages of AWD at Niamey are examined in detail and the circumstances associated with ample precipitation during the first two are contrasted with the factors that led to a deficiency of rainfall during the third AWD. The study provides evidence that rainier seasons in the Sahel do not necessarily experience a greater number of AWD or even more intense AWD than drier summers. Occasional heavy precipitation can result from uplift driven by upper tropospheric divergence unrelated to AWD. On the other hand, AWD can provide an important trigger mechanism for convective rainfall during an otherwise dry spell.

KEY WORDS: African waves · Sahel · ECMWF analyses

1. INTRODUCTION

Summer monsoon rainfall over Africa's Sahel is characterized by squall lines or cloud clusters (Payne & McGarry 1977, Rowell & Milford 1993). Rowell & Milford (1993) list the required conditions for deep moist convection in this region as conditional instability, lower tropospheric wind shear and a moist lower layer topped by drier air. Release of the instability can be triggered by surface heating, orography, moisture sources, African wave disturbances (AWD) or other circulations that encourage large-scale convergence. In addition to localized deep convection, Kamara (1986) refers to widespread and prolonged monsoon rains over West Africa south of 15° N which occur during periods of large-scale surface convergence. According to Kamara, '...the massive uplift of air that produces this widespread rainfall has baffled meteorologists...', but it may be caused by upper tropospheric divergence associated with the Tropical Easterly Jet.

Westward propagating areas of cloud cover, high humidity (from observations analyzed by Thiao & Scofield 1993) or precipitation (in simulations by Xue & Shukla 1993 and Druyan & Hall 1996) have been identified with traveling AWD, although similar patterns could result from westward moving squall lines and cloud clusters unrelated to AWD. Moreover, Druyan & Hall (1996) found that some heavy precipitation simulated by a GCM (general circulation model) for the Sahel region during June and July lacked westward movement for periods of several days, implying the

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influence of (a) non-propagating triggering mechanism(s), perhaps analogous to the prolonged monsoon rains described by Kamara (1986). The sub-Saharan precipitation regime is further complicated by the circumstance that some AWD circulations may not be accompanied by significant precipitation during part of their lifetime (Druyan & Hall 1996).

The composite of 8 AWD based on observations from August-September 1974 by Reed et al. (1977) included a rainfall maximum southwest of the wave apex. Payne & McGarry (1977) found that the region between one-eighth and one-quarter of a wave length ahead of wave troughs was the preferred, but by no means the exclusive region for the generation of squall lines. The squall line cluster studied by Fortune (1980) was generated east of an AWD trough, but experienced rapid growth when it moved into the trough. Duvel (1990) determined that AWD over the northern fringe of the Sahel (17.5° N) were more likely to organize moist convection east of troughs, while AWD at more southerly latitudes (7.5° N) seemed to be rainy more often at and west of troughs. However, since Duvel (1990) used Meteosat infrared imagery as a proxy for precipitation observations, some of these conclusions may require additional examination.

Rowell & Milford (1993) investigated the circumstances of squall line generation and longevity over the part of West Africa bounded by 2.5° W-14° E, 9.5° N-22° N, using Meteosat infrared imagery from August 1985. Although they detected a slight preference for the generation of long-lived squall lines both near the maximum northerlies west of troughs and near the maximum southerlies east of troughs, no *statistically significant* preferential locations relative to AWD structure were identified. For example, wave troughs were not favored for squall line generation nor were ridges favored for their decay. This result may be peculiar to the study area since AWD tend to intensify as they approach the Atlantic coast. This paper did not discuss what proportion of the August 1985 squall lines may have occurred independent of AWD activity in their vicinity.

Reed et al. (1988) evaluated the performance of the ECMWF (European Center for Medium Range Weather Forecasts) operational analysis and forecast system's representation of AWD during August-September 1985. Physical parameterizations in the ECMWF model used in the study had previously been revised and resolution had been increased to T106 (equivalent to 1.1° horizontal resolution). Some 20 AWD were identified and tracked using satellite cloud patterns in addition to the gridded circulation analyses. The biggest data gaps over the continental portion of the study area were east of 10° E and parts of the Sahara. The relatively skillful forecasts of AWD propagation that were documented imply that ECMWF analyses, based on 6 h forecasts as their first guess fields (Trenberth 1992), are generally reliable for detecting AWD, despite chronic shortages of observational data over northern Africa. Reed et al. (1988) did not relate AWD behavior to precipitation or humidity patterns.

Druyan & Hall (1994, 1996) have analyzed AWD simulated by 2 generations of climate models at NASA/Goddard Institute for Space Studies (GISS) at 4° latitude by 5° longitude resolution. Composites in these GCM studies showed modest precipitation enhancement within the southerly circulation east of AWD troughs.

The present study investigates the synoptic circumstances associated with the occurrence of precipitation at Niamey (Niger) during the height of a rather dry summer, July-August 1987, and during a rainier parallel period the following year, using gridded ECMWF analyses and Niamey station observations of several meteorological variables. At Niamey, the 1950-1990 mean July-August precipitation is 342 mm (SD = 106 mm). In July-August 1988, some 320 mm rainfall were recorded, while only 244 mm occurred at Niamey during the same months of the previous year. These interannual differences were more impressive on a regional scale. For example, the FAO Niger national rainfall index for 1987 was more than 2 standard deviations (base period 1960 to 1993) lower than for 1988 (Gommes & Petrassi 1994). (This index represents the average rainfall of some 205 stations throughout Niger, weighted by the long-term means.) In addition, the planetary circulations during 1987 and 1988 were contrasted by strong El Niño/La Niña signals (Druyan & Hastenrath 1994). The objective of the current study is to determine the role, if any, of AWD in producing the contrasting Niamey precipitation accumulations during these seasons.

2. DATA

In order to facilitate comparisons between previous and future GISS GCM results and observational evidence, analyses of relevant meteorological variables are made here from ECMWF observational data sets interpolated to a 4° latitude by 5° longitude horizontal resolution grid.

Precipitation accumulations observed at Niamey (13° N, 2° E) during July-August 1987 (JA87) and 1988 (JA88) were assigned to the synoptic time closest to their observation, at 6 h intervals in 1987 and at 12 h intervals in 1988. Other variables from radiosonde ascents at Niamey include the precipitable water and winds at the standard pressure levels.

3. RESULTS

3.1. Precipitation and meridional winds

ECMWF gridded meridional wind components at 700 mb (v7) were compared to concurrent Niamey radiosonde observed values for JA87 and JA88. While raw station data are building blocks for gridded analyses, spatial smoothing and adjustments for 3-dimensional consistency occurring in the ECMWF analysis cycle can make the gridded representation more meaningful for certain climate applications. On the other hand, all potential sources of observed meteorological data in a given region may not necessarily be assimilated into the ECMWF analysis for a given synoptic time due to unavailability or transmission errors. The more data-sparse a region is, the less accurate will be the ECMWF analysis representation of its current atmospheric state.

This study therefore refers to both sources of wind data, each offering a slightly different perspective on the local circulation. Fig. 1 shows that at 14° N, 0° there was a consistent phase lag of ECMWF v7 oscillations relative to the Niamey v7 and relative to the data 5° further east. On the other hand, v7 values at 14° N, 5° E were more often in phase with the station data. Time lags in v7 peaks at the more westerly location relative to those at 14° N, 5° E reflect the westward propagation of wave-like circulation features. The closer fit of Niamey meridional winds to the analyzed (presumably more distant) values east of the station is an apparent peculiarity of the analysis procedure. Fig. 1 also shows that the amplitudes of ECMWF v7 oscillations are often smaller than for Niamey v7, in keeping with the effects of spatial smoothing on the gridded data.

Fig. 2 offers a closer inspection of the 2 time series of v7 and their relationship to precipitation events at the station. Periodic oscillations of v7 contain wave energy even when v7 does not become positive (southerly), but only waves that include at least a small sector of v7 > 0 are easily identifiable on 2-dimensional streamflow analyses (discussed below). Using v7 > 0 as a criterion to identify well developed waves, Fig. 2 shows that some 19 AWD traversed Niamey during JA87, although ECMWF data could detect only 12 of them. During JA88, 16 AWD are discerned at Niamey, but again only 12 based on ECMWF winds. Niamey precipitation accumulations were >5 mm in 11 events in JA87, 14 events in JA88. Thus, the number of significant rain events is only about 70% of the number of AWD. Moreover, the rainier season experienced about 16% fewer AWD. Examples of AWD with and without precipitation at Niamey are analyzed below.

Examination of Fig 2 indicates that a number of AWD traversed Niamey without causing significant precipitation. Whether or not an AWD causes rainfall

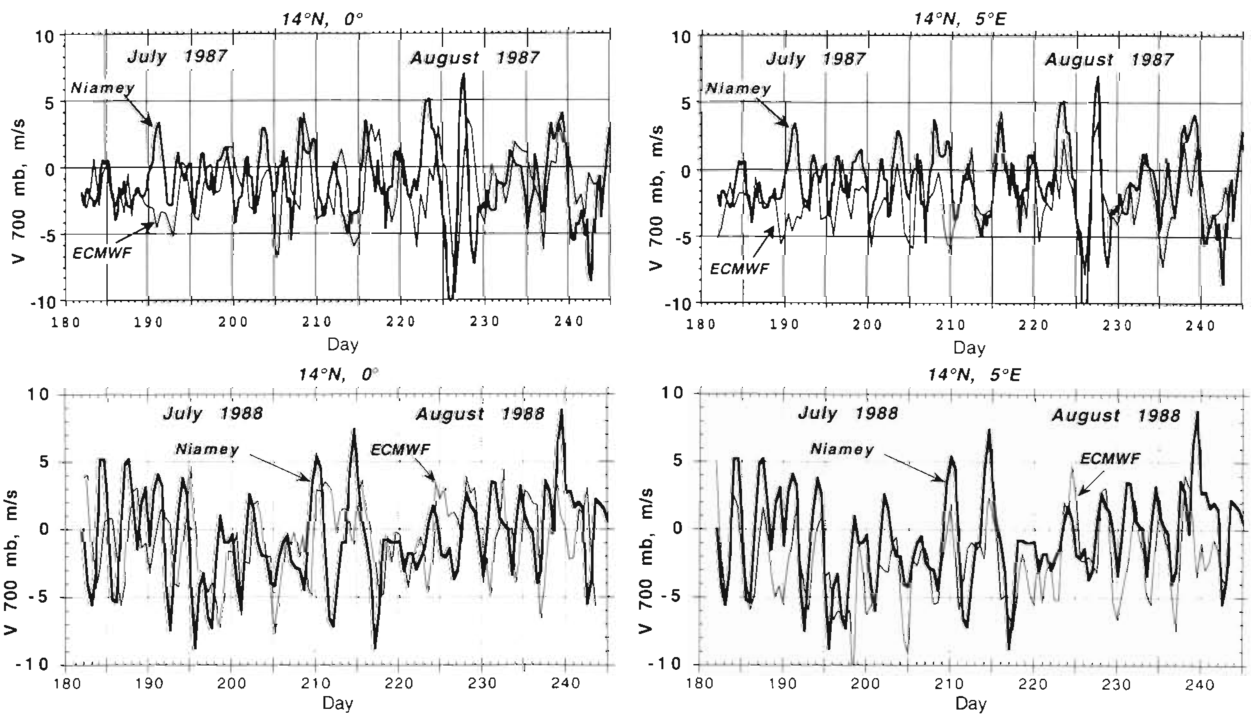

Fig. 1. Time series of 700 mb meridional wind components during July–August 1987 and 1988, for Niamey radiosonde data (13° N, 2° E) and ECMWF-gridded data at 14° N, 0° and 14° N, 5° E

at a particular station may be related to the time of day at which the most unstable category of the wave passes the station or with other, as yet undetermined factors that inhibit precipitation. Of course, a wave not producing heavy rainfall at Niamey could very well trigger precipitation elsewhere during its lifetime. Additional evidence that AWD sometimes do not trigger heavy precipitation was offered by GCM simulations described by Druyan & Hall (1996).

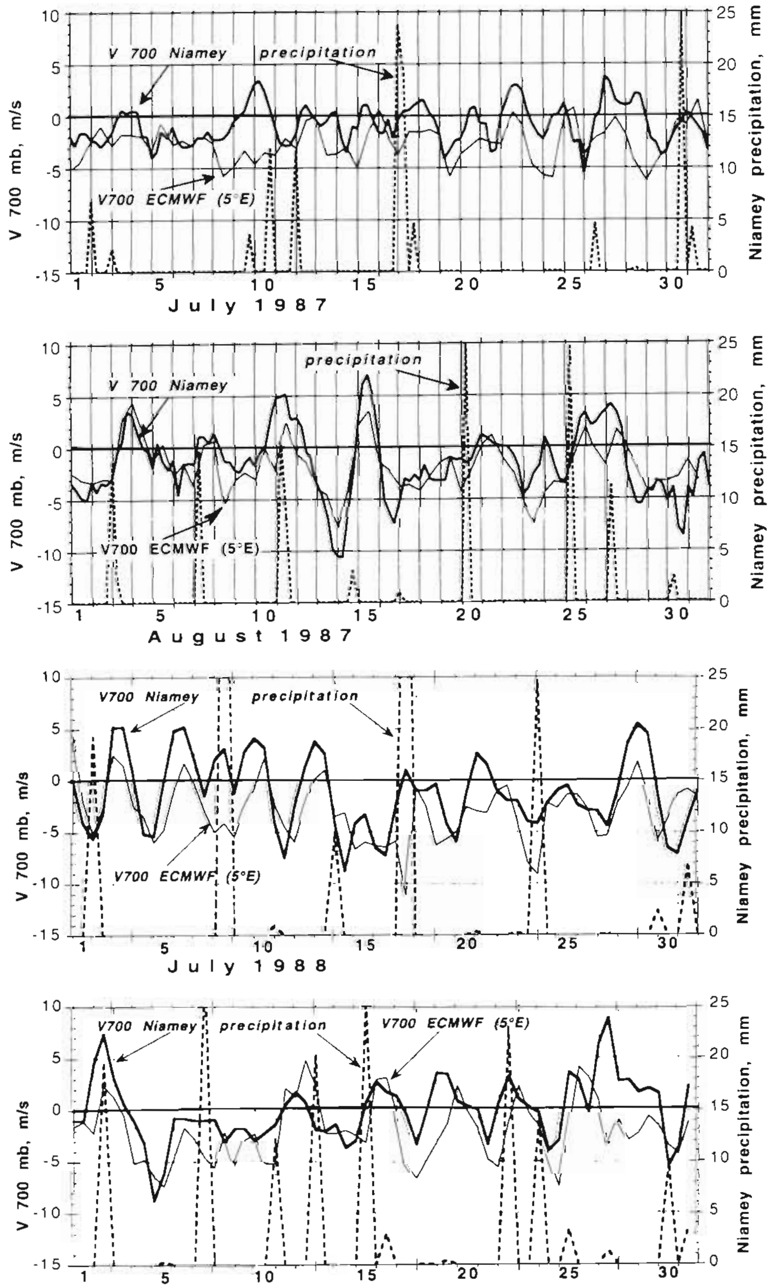

Fig. 2. Niamey precipitation accumulations plotted on the same expanded time scale as time series of Niamey and ECMWF (14° N, 5° E) 700 mb meridional wind components during July–August 1987 and 1988

Fig. 2 also shows that 23 of the 25 events with Niamey rainfall >5 mm occurred within 2 d before or after v7 > 0. One exception was the case of heavy rainfall on 24 July 1988 at 00:00 h GMT which occurred more than 2 d after v7 was previously positive and some 4 d before it next became positive. In the second example, rainfall on 7 August 1988 at 12:00 h GMT occurred in the middle of an 8 d period during which v7 at Niamey was negative. This episode is discussed in more detail below.

In most cases the amplitudes of the 700 mb wind speed maxima were larger for Niamey. An occasional peak in the Niamey time series is completely absent in the ECMWF data, implying that the station data are sometimes not assimilated into the analysis cycle. Missed peaks may change the distribution of spectral amplitude versus wave period in time series of v7 and can change the composited AWD characteristics as well. The correlation coefficient between v7 at Niamey and the corresponding ECMWF v7 at the grid point northeast of the station is 0.53 for both JA87 and JA88, but much lower (0.23 and 0.11 respectively) when considering ECMWF data northwest of the station.

3.2. Power spectra of meridional wind

Since the variability of v7 during JA87 and JA88 (Figs. 1 & 2) is somewhat different for the Niamey radiosonde as compared to the nearby ECMWF grid point, it is not surprising that their power spectra (Fig. 3) also differ. Table 1 summarizes the characteristics of the major spectral peaks that appear in Fig. 3. During JA87 both sources of data indicate peaks at 3.8 d and near 5.0 d, but the station data imply that much power is also present at periods up to 7.0 d. The ECMWF spectrum for JA88 highlights contributions from 3.2 and 4.0 d period waves with a sharp drop toward longer and shorter periods. The Niamey spectrum for the same period also has peak power concentrated over a somewhat smaller range than its counterpart for JA87, with spikes at the same periods as ECMWF, 3.2 and 4.0 d, in addition to fairly high amplitudes for waves with periods up to 5.5 d.

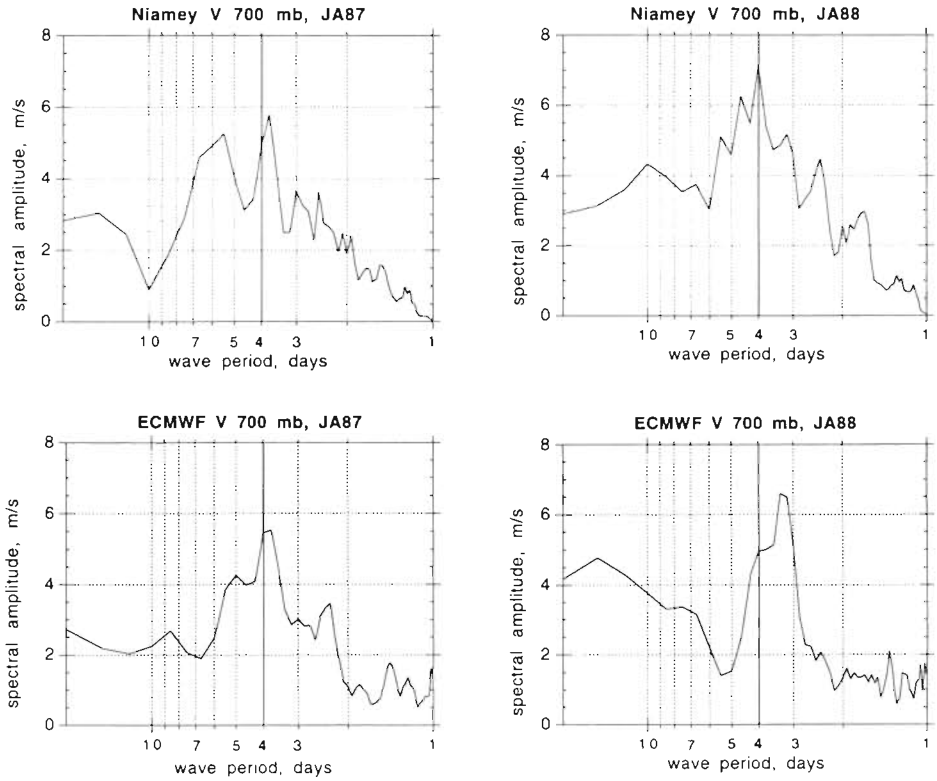

Fig. 3. Smoothed power spectra for Niamey and ECMWF (14° N, 5° E) 700 mb meridional winds for July–August 1987 and 1988

Fewer spectral peaks for ECMWF v7 is consistent with the occasional exclusion of Niamey radiosonde data by ECMWF (see Fig. 1) and with the spatial smoothing inherent in ECMWF analyses. The additional peaks for Niamey v7 represent longer period energy for both years. Interannual differences for both sources of data imply that wave energy favored longer periods (perhaps slower AWD) in JA87, which was less rainy than the following year. We do not know whether the predominance of slower AWD is a cause of the lower rainfall totals.

Table 1. Peaks for the (3-point) smoothed spectra of v7 plotted in Fig. 3

Data source	Spectral peak ($m\ s^{-1}$)	No. of SD above mean	Period (d)
Niamey JA87	5.8	2.6	3.8
Niamey JA87	5.2	2.2	5.5
ECMWF JA87	5.5	2.8	3.8
ECMWF JA87	4.3	1.8	5.0
Niamey JA88	7.1	2.5	4.0
Niamey JA88	6.3	2.0	4.6
Niamey JA88	5.2	1.4	3.2
ECMWF JA88	6.6	2.8	3.3
ECMWF JA88	6.5	2.8	3.2
ECMWF JA88	5.0	1.8	4.0

3.3. AWD modulation of rainfall

One method of compositing AWD assumes that the entire season's record of winds is composed of an uninterrupted series of waves (Rowell & Milford 1993, Druyan & Hall 1994). Each wave is segmented into 8 categories so that an event occurring even 2 d before or after an AWD trough traversal is still considered to be associated with some part of the wave structure. The categories are usually defined as follows (Reed et al. 1977, Druyan & Hall 1994): 2, maximum northerlies; 4, trough; 6, maximum southerlies; 8, ridge; with intermediate categories 1, 3, 5 and 7 between these positions. We divided the v7 time series at Niamey into discrete waves, where each wave included one interval of v7 > 0. Each precipitation event was then assigned to one of the 8 wave categories.

During JA87, about 75% of the total precipitation accumulation (Fig. 4) in 65% of the rain events occurred near an AWD trough, in categories 3 to 5. The single rainiest category (3) corresponded to the northerly circulation just west of the troughs, similar to AWD composites from other observational studies (Reed, et al. 1977, Duvel 1990). Only 9% of the JA87 accumulation (in 13% of the rain events) occurred in categories 8, 1 and 2. In distinct contrast, during JA88 only 23% of the total rainfall (Fig. 4) in 23% of the rain events occurred near the troughs, while 32% of the rainfall (in 38% of the events) occurred between the

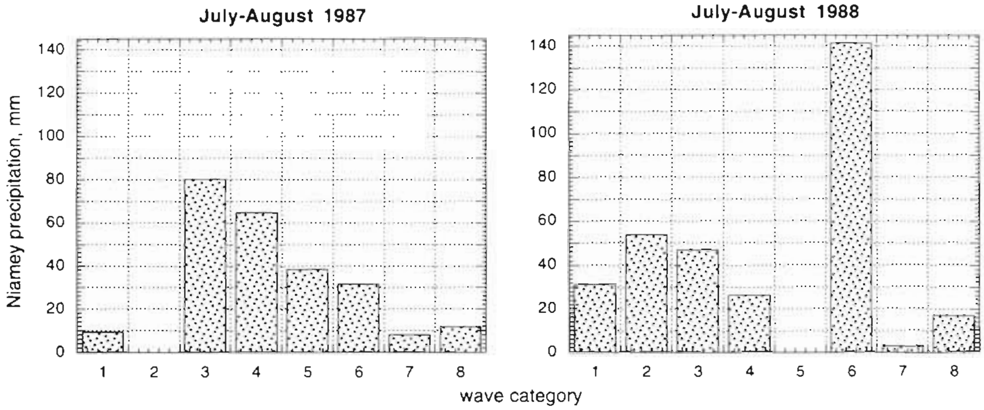

Fig. 4. Niamey precipitation accumulations for each of 8 categories of AWD traversing the station. (a) July-August 1987, (b) July-August 1988. Categories: 2, maximum northerlies; 4, trough; 6, maximum southerlies; 8, ridge; 1, 3, 5, 7: the intermediate categories

western ridge (category 8) and the maximum northerlies (categories 1 and 2). Fig. 4 also shows that the largest proportion (45%) of the JA88 precipitation totals was associated with moisture laden southerlies east of the trough (categories 6 and 7). The concentration of precipitation near troughs during JA87 emphasizes the role of uplift related to AWD vorticity advection during that relatively dry season. During JA88, on the other hand, one-third of the rainfall occurred nearer AWD ridges, when the negative vorticity would not be especially helpful in triggering moist convection. In those cases, other triggering mechanisms were apparently effective, as was the southerly monsoon circulation which could have been periodically strengthened by traversing AWD. Precipitable water measured by the Niamey radiosonde did not vary appreciably between the different wave categories.

3.4. Vertical motion

ECMWF analyses include arrays of computed vertical motion (ω, mb s^{-1}) at standard pressure levels. We examined ω at 500 mb to monitor the large-scale uplift conducive to precipitation. Inspection of the data shows that ω often becomes more negative at 12:00 h GMT, presumably due to the midday convection prompted by surface heating. Precipitation at Niamey was not well correlated with the time series of ω at nearby grid points. Several periods of sustained uplift (negative ω) did not produce rainfall while several rain episodes did not coincide with ω minima. Moreover, longitude-time sections of ω did not show any westward propagation or correspondence with AWD trajectories.

3.5. Lower tropospheric convergence

The composite AWD by Reed et al. (1977) included a distinct spatial arrangement of divergence at 850 mb and 200 mb. The divergence computed using ECMWF

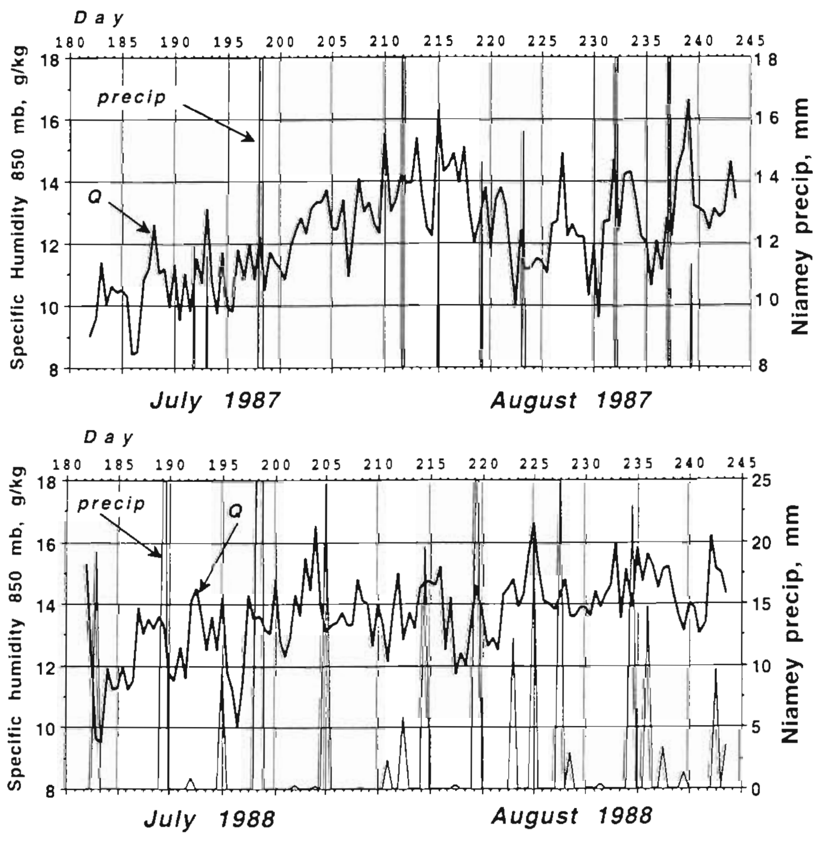

Fig. 5. Time series of 850 mb specific humidity during July-August 1987 and 1988 at 14° N, 5° E from ECMWF gridded analyses. Vertical spikes indicate the precipitation accumulation recorded at Niamey

zonal and meridional wind components at 850 mb had a positive correlation (0.32 and 0.38 for JA87 and JA88) with 700 mb meridional winds, implying that convergence (divergence) is often associated with northerlies (southerlies) west (east) of AWD troughs. Examples are shown below. Correlations of 850 mb divergence time series during JA87 and JA88 with ω were also positive, but weaker. Although uplift in the mid troposphere often corresponds to lower tropospheric convergence, it is by no means rare for such convergence not to be translated into deep large-scale convection.

3.6. Precipitation and specific humidity

Precipitation observations at Niamey were compared to concurrent time series of ECMWF-analyzed 850 mb specific humidity (Q850) at the grid location 14° N, 5° E (Fig. 5). The data plotted in Fig. 5 show that most precipitation events corresponded to peaks in Q850 (or Q at 700 mb or Q850 at the grid point west of the station; not shown), but many peaks in Q had no associated precipitation event. The correspondence was not improved by averaging values at the 2 closest grid locations or by averaging Q at 850 and 700 mb.

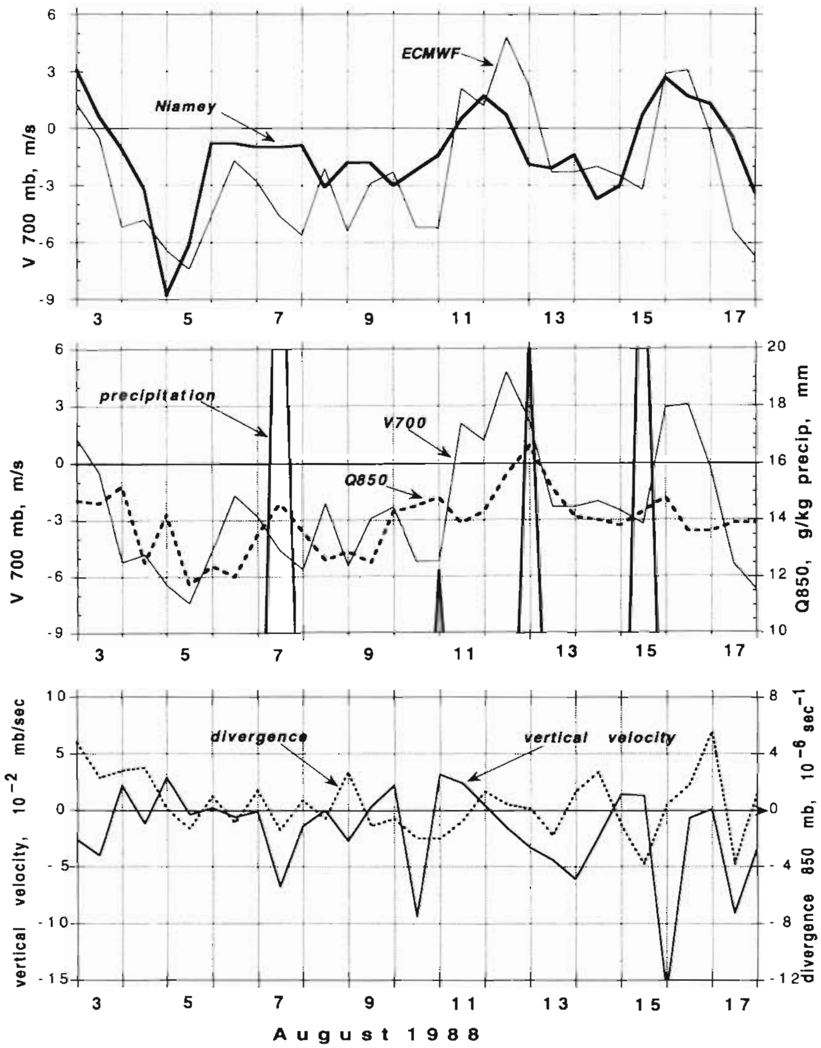

Fig. 6. Time variation of meteorological variables at or near Niamey during the period 3 to 17 August 1988. Top: meridional wind component; middle: specific humidity and precipitation; bottom: 850 mb divergence and 500 mb vertical velocity. Vertical grid lines indicate 00:00 h GMT

The number of rainy days during JA87 and JA88 was similar, but JA88 experienced 9 days with accumulations >19 mm (including 58 mm on 17 July) compared to only 5 such days for JA87. This may be related to the generally more humid environment of JA88 (mean Q850 = 14 g kg^{-1} compared to 12 g kg^{-1} for JA87). Lamb (1983) found that the humid layer at 13° N was deeper during previous rainy seasons than during droughts. The mean Q850 near Niamey at the synoptic times closest to significant rain events (>5 mm) was higher than each seasonal mean by one-third of the respective standard deviations for both JA87 and JA88.

While peaks in lower tropospheric Q seem to be a necessary condition for heavy rainfall, they are not sufficient to guarantee significant precipitation; many of the Q850 peaks in Fig. 5 do not correspond to precipitation events. In fact, Q850 near Niamey had about 10 peaks without heavy rainfall at the station during July–August of each of the 2 years. Thiao & Scofield (1993) found that westward propagating cloud systems over the Sahel in September 1992 correlated well with NMC (U.S. National Meteorological Center)-analyzed specific humidity maxima at 688 mb and with trough axes based on NMC-analyzed winds at 688 mb. We will show below, however, that for the ECMWF analyses considered here, Q850 (or Q700) maxima do not move westward with each AWD.

The ambiguity of the Q versus precipitation relationship can probably be explained by the analogy of Q to an electric charge in a capacitor, with precipitation the discharge mechanism, in this case a sink for atmospheric humidity. Our data do not have enough time resolution to always detect decreases in Q that should

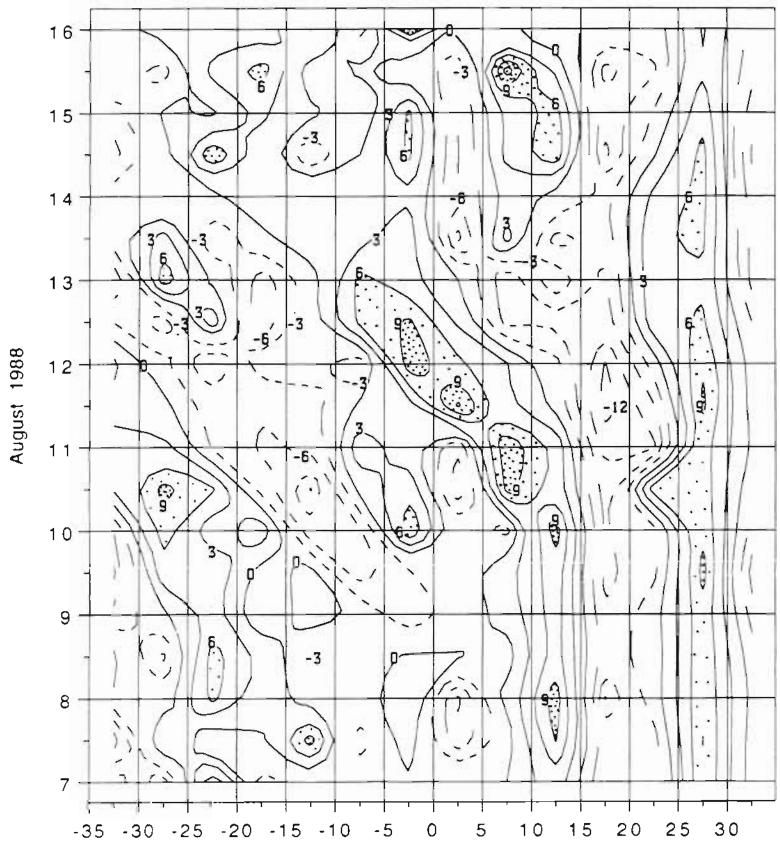

Fig. 7 Time-longitude cross section, 7 to 16 August 1988, of vorticity due to the zonal gradient of the 700 mb meridional wind (units: 10^{-6} s^{-1})

occur after rainfall (in the absence of strong moisture convergence). Moreover, frequent precipitation associated with traveling AWD reduces atmospheric humidity at irregular intervals. This is probably why Q maxima do not follow AWD trajectories.

3.7. Details of 6 to 17 August 1988

We next examine the evolution of the synoptic circulation during the period 6 to 17 August 1988, during which there were 4 significant rain events at Niamey and 2 well-documented passages of AWD. Fig. 6 shows the time trends of important meteorological variables near Niamey during these 12 days. Both ECMWF (at 14° N, 5° E) and the Niamey radiosonde observations indicate that v7 remained northerly over that station until 11 August. The 700 mb circulation gained a southerly component at 12:00 h GMT on 11 August but became negative again on the 13th. The transition from northerlies to southerlies that occurred on 11 August suggests the passage of a wave disturbance that is accompanied by shift from 850 mb convergence to divergence. A similar sequence of v7 and lower tropospheric divergence occurs on 15-16 August. Heavy rainfall was recorded at Niamey close to 12:00 h GMT on 7 August, some 4 d before the wave, as well as close to 00:00 h GMT on August 11, 00:00 h GMT on August 13 and 12:00 h GMT on 15 August. Fig. 6 shows that the 850 mb specific humidity (Q850) peaked during each of these 4 rain events.

The veering of the wind direction from west to east across an AWD trough is conveniently represented by the positive vorticity due to zonal gradients of v: $\zeta = \Delta v/\Delta x$, where Δx is the zonal grid spacing. Fig. 7 shows the time-longitude variation of ζ based on v7 at 14° N. Several swaths of positive ζ (cyclonic troughs) are seen to propagate westward, although vorticity maxima remain stationary along 27.5° E and, between 7 and 10 August, along 12.5° E. The trajectory of the 11 August AWD is represented by the swath of positive ζ which advances westward from 12.5° E on 10 August at 00:00 h GMT to 7.5° W on 13 August at 00:00 h GMT, at an average speed of 6.7° longitude d^{-1} (8.4 m s^{-1}). The ζ maximum related to the second AWD that appears on Fig. 7 moved from 12.5° E at 12:00 h GMT on 14 August to 7.5° E 24 h later (5° longitude d^{-1} = 6.3 m s^{-1}). Fig. 7 shows that during the 12:00 h GMT 7 August rain event at Niamey (2° E), the 700 mb circulation was anticyclonic, far removed in time and distance from any cyclonic vorticity. The events of 00:00 h GMT on 11 August and 12:00 h GMT on 15 August also occurred within anticyclonic circulation (evidenced by a ζ minimum), but strong positive ζ associated with an approaching AWD was only 5° longitude east of Niamey in each case (Fig. 7). Rainfall on 13 August occurred after the AWD had passed, during the transition between cyclonic and anticyclonic circulation.

Fig. 8 shows a time-longitude plot of the 850 mb divergence field, also at 14° N. Lower tropospheric convergence can be initiated by the westward propagating vorticity maxima associated with AWD. Diagonal swaths of negative values in Fig. 8 indicate westward propagating areas of convergence, such as described by the trajectories of the AWD of 11 and 15 August, which are indicated based on the analysis in Fig. 7. Note that the convergence was displaced about 7.5° westward of the vorticity maxima between 11 and 13 August (west of Niamey), while the conver-

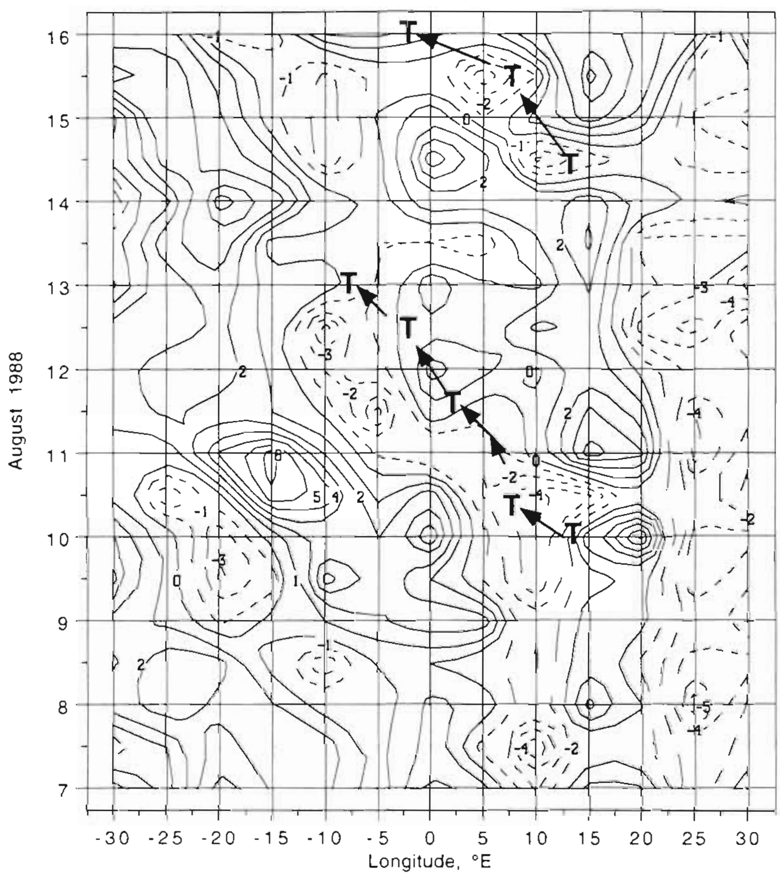

Fig. 8. Time-longitude cross section, 7–16 August 1988, of divergence of the 850 mb circulation (units: 10^{-6} s^{-1}). Trajectory of troughs based on Fig. 7 is marked by **T**

gence was closer to the troughs east of the station. Since convergence results from time increases of vorticity, it favors a position ahead of AWD where air is being overtaken by cyclonic circulation. Closer proximity of 850 mb convergence to AWD troughs is indicative of slower moving or quasi-stationary intensifying disturbances.

Although the Q850 field responds to changes in the circulation, centers of maximum humidity do not move westward with AWD. This is further emphasized by examining the time-longitude plot of Q850 (not shown) for 7 to 16 August 1988 which includes a persistent Q850 maximum over 10–15° E and occasional quasi-stationary maxima along the Atlantic coast, but no swath of high Q850 along the trajectories of the AWD discussed above.

Additional insight regarding the relationship of AWD to meteorological events at Niamey is gained by examining spatial patterns of relevant variables at several synoptic times during the interval under study.

12:00 h GMT, 7 August (Fig. 9): The spatial pattern of Q850 is shown superimposed on the 700 mb circulation field. A tongue of high humidities appears along the Atlantic coast and a maximum east of Niamey at 10° E. Q850 at Niamey was about 14.5 g kg^{-1} and heavy rainfall was reported within 6 h of 12:00 h GMT. The circulation at 700 mb was northeasterly and cyclonic circulation can be discerned at 10° N, 15° E, just southeast of the Q850 maximum. At 500 mb, ω was a minimum (maximum upward velocity) near Niamey and ω was also negative within a wide area coinciding with Q850 > 14 g kg^{-1}, east and southeast of the station. In addition, the divergence at 200 mb analyzed by ECMWF near Niamey peaked during 6 to 8 August, reaching a maximum for the month at 00:00 h GMT on 8 August. These circumstances indicate that the 7 August precipitation event was associated with large-scale uplift, probably driven by upper tropospheric divergence, as described by Kamara (1986).

12:00 h GMT, 8 August (Fig. 10): Q850 at Niamey decreased to below 13 g kg^{-1} as strengthening northeasterlies advected drier air towards the station and the vertical velocity weakened. A wave disturbance whose trough axis lies along 12.5° E was clearly defined by the circulation, and the Q850 maximum lay within this trough and to its west. The trough is marked by the ζ maximum in Fig. 7.

12:00 h GMT, 9 August: The wave trough remained near 12.5° E, with the Q850 maximum near the apex. Northeasterlies at Niamey kept Q850 below 13 g kg^{-1}.

12:00 h GMT, 10 August (Fig. 11): The wave trough reached 7.5° E, with the humidity maximum still analyzed over 10° E, although Q850 had begun to increase at Niamey (Fig. 6).

00:00 h GMT, 11 August (Fig. 12): Significant rainfall was recorded at Niamey (Fig. 6). The 700 mb wave trough was at 6° E, reaching the station's longitude about 12 h later. Fig. 12, as well as the sequence of meridional wind directions (Fig. 6), suggests that rainfall occurred west of the 700 mb trough where v7 was northeasterly and cyclonic circulation at 850 mb created convergence and moisture advection toward Niamey. The relative position of precipitation and lower tropospheric convergence southwest of the wave apex fits the composite of 8 AWD described by Reed et al. (1977). The moderate increases in Q850 (from about 12.5 g kg^{-1} to about 14.8 g kg^{-1}) that occurred at Niamey as the trough approached during the 36 h period ending at 00:00 h GMT on 11 August were

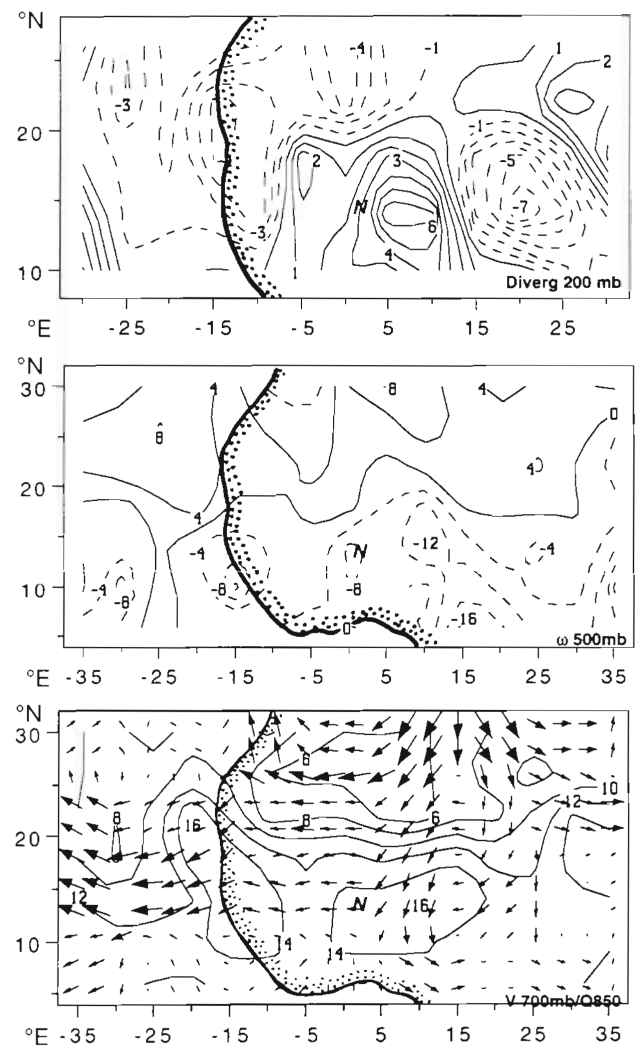

Fig. 9. Distributions of meteorological variables at several vertical levels over West Africa on 7 August 1988 at 12:00 h GMT, based on ECMWF gridded analyses. From top to bottom: divergence of the 200 mb winds (10^{-6} s^{-1}); vertical motion at 500 mb (10^{-2} mb s^{-1}); circulation at 700 mb and specific humidity at 850 mb (10^{-3} g kg^{-1}). The location of Niamey is indicated by *N*

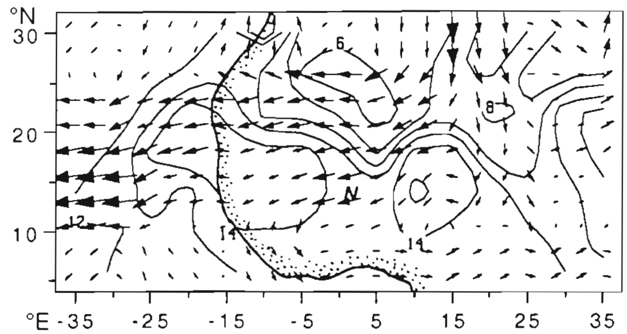

Fig. 10. Circulation at 700 mb and specific humidity at 850 mb (10^{-3} g kg^{-1}) over West Africa on 8 August 1988 at 12:00 h GMT based on ECMWF gridded analyses. The location of Niamey is indicated by *N*

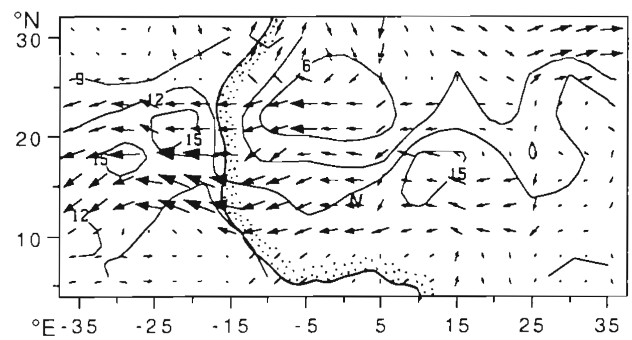

Fig. 11. Circulation at 700 mb and specific humidity at 850 mb (10^{-3} g kg^{-1}) over West Africa on 10 August 1988 at 12:00 h GMT based on ECMWF gridded analyses. The location of Niamey is indicated by *N*

undoubtedly related to the pattern of moisture advection toward Niamey shown in Fig. 12. The 850 mb circulation became divergent over Niamey (Fig. 6) after the trough passed, but ω was already positive (downward) at 00:00 h GMT on 11 August, implying subsidence near the time of rainfall.

Even after the AWD trough passed through Niamey, the humidity maximum remained east of the station and Q850 at Niamey held steady. No rain was reported on 12 August as v7 began to veer to the south of east.

00:00 h GMT, 13 August: Heavy rain occurred (Fig. 6), coinciding with large increases in Q850 to more than 16 g kg^{-1}. The wave trough was already 10° west of Niamey (associated with weak convergence), while at the station a trend of increasing 850 mb convergence and upward motion peaked some 12 to 24 h later. At 700 mb the ECMWF wind was southeasterly, but station data already indicated a shift to a northerly component (Fig. 6). The center of maximum Q850 remained well to the east of Niamey (not shown).

12:00 h GMT, 15 August (Fig. 13): A second AWD traversed Niamey on 15 August. Fig. 6 shows a sharp shift in v7 from a northerly to a southerly direction on that day. (According to the Niamey radiosonde, the shift occurred during the first half of the day, according to ECMWF, during the second half.) Very heavy rainfall was recorded at the station within 6 h of 12:00 h GMT, close to the traversal of the AWD trough (Fig. 6). Q850 rose very slightly, immediately behind the trough, and the 850 mb convergence became slightly stronger. The time trend of the 500 mb vertical velocity (ω) near Niamey shows a sharp (positive) peak prior to the trough's arrival, not unlike the sequence discussed above for the AWD of 11 August.

Fig. 13 shows the horizontal distribution of several meteorological variables at different vertical levels.

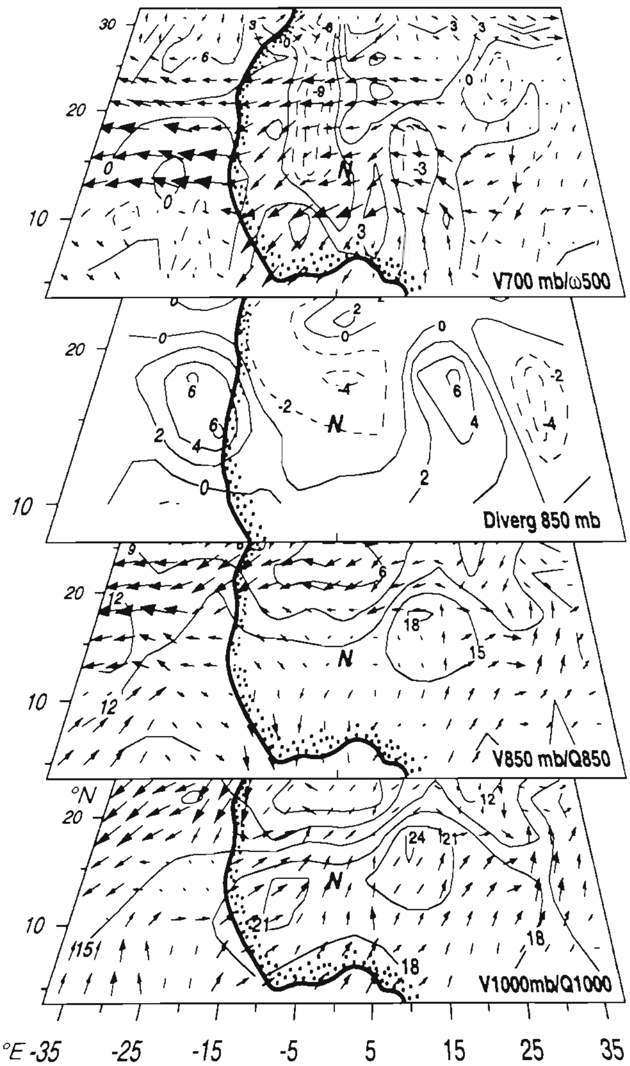

Fig. 12. Distributions of meteorological variables at several vertical levels over West Africa, on 11 August 1988 at 00:00 h GMT, based on ECMWF gridded analyses. From top to bottom: circulation at 700 mb and 500 mb vertical motion (10^{-2} mb s^{-1}); divergence at 850 mb (10^{-6} s^{-1}); circulation and specific humidity (10^{-3} g kg^{-1}) at 850 mb; circulation and specific humidity (10^{-3} g kg^{-1}) at 1000 mb. The location of Niamey is indicated by *N*

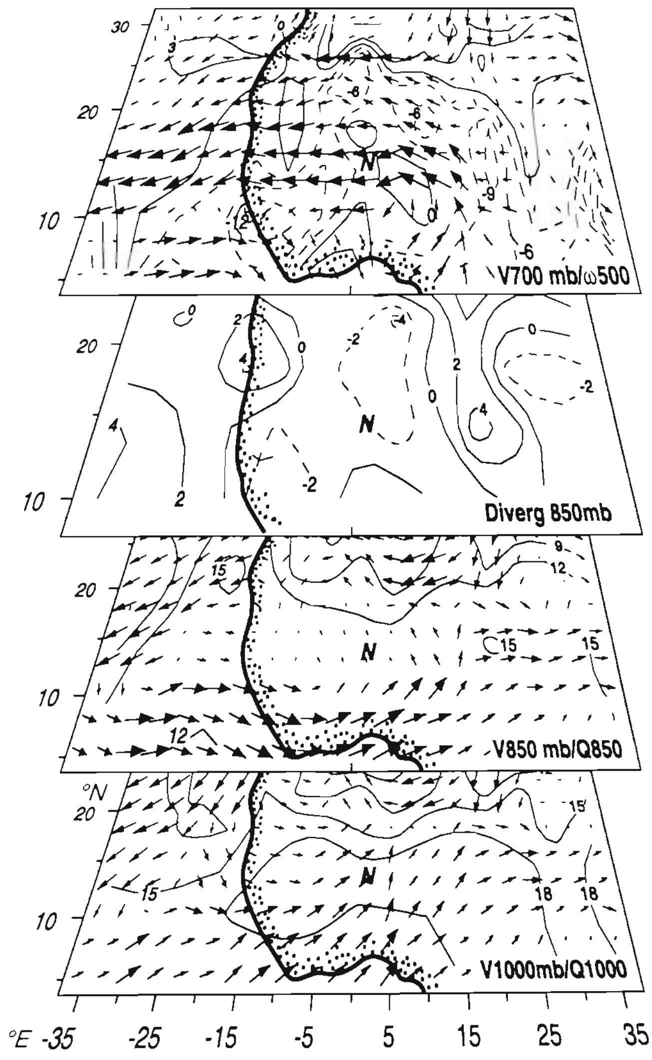

Fig. 13. Distributions of meteorological variables at several vertical levels over West Africa, on 15 August 1988 at 12:00 h GMT, based on ECMWF gridded analyses. From top to bottom: circulation at 700 mb and 500 mb vertical motion (10^{-2} mb s^{-1}); divergence at 850 mb (10^{-6} s^{-1}); circulation and specific humidity (10^{-3} g kg^{-1}) at 850 mb; circulation and specific humidity (10^{-3} g kg^{-1}) at 1000 mb. The location of Niamey is indicated by *N*

The wind shift at 700 mb associated with the AWD trough was east of Niamey within an area of slightly positive vertical velocity. Winds at 850 mb were southerly at Niamey within an area of maximum Q850 and the cyclonic circulation was displaced westward of the 700 mb trough. Near-surface circulation was southwesterly at Niamey and Q1000 exceeded 18 g kg^{-1}. Convergence at 850 mb was again associated with the western side of the AWD although it did not coincide with the areas of large-scale upward motion designated by negative ω.

Some 12 h later the AWD trough moved west of the station. Based on Niamey radiosonde winds (Fig. 6), the trough traversed the station somewhat earlier in the day than implied by the analyses shown in Fig. 13. The ECMWF analysis, which seems to lag in the sequence of events compared with the Niamey data, shows the strongest upward vertical motion at Niamey at 00:00 h GMT on 16 August, after the trough axis had passed (Fig. 6).

The first period of rain (7 August) seems to be unrelated to the approaching wave, and it occurs during a period of 850 mb convergence/200 mb divergence and northeasterly winds. The 11 August rainfall occurs several hours before trough passage, accompanied by strong lower tropospheric convergence. The 13 August event occurs within 12 h of the strongest southerly component winds at 700 mb, increasing convergence and the highest Q850 during the period (undoubtedly connected to the moisture flux by the southeasterlies). On 15 August, precipitation at Niamey coincides with the passage of an AWD trough and the strongest 850 mb convergence of the period.

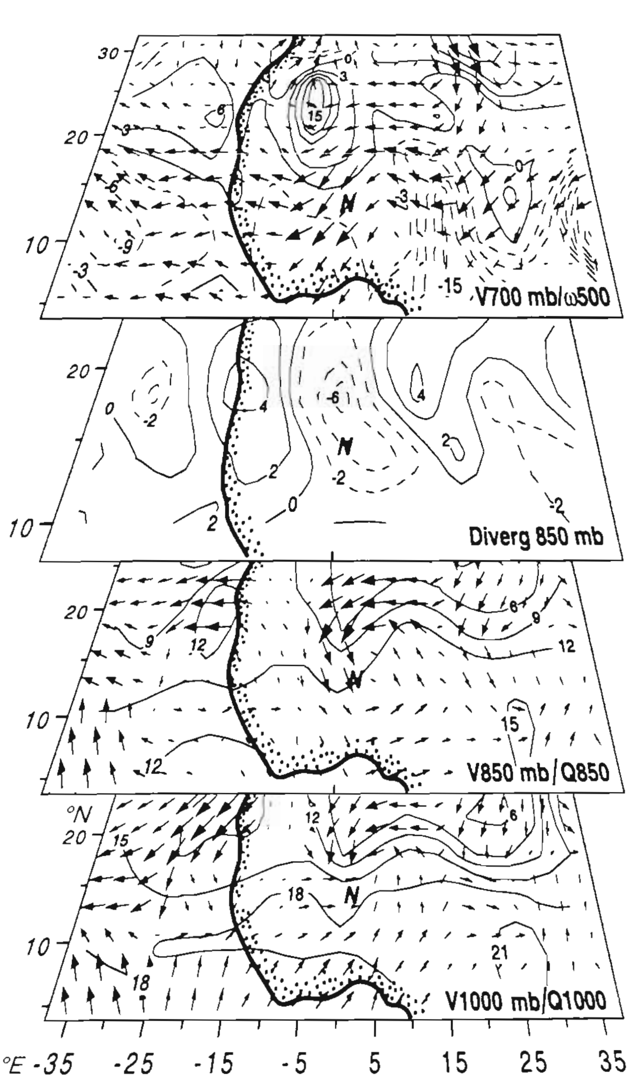

Fig. 14. Distributions of meteorological variables at several vertical levels on 14 August 1987 at 12:00 h GMT based on ECMWF gridded analyses. From top to bottom: circulation at 700 mb and 500 mb vertical motion (10^{-2} mb s^{-1}). Divergence at 850 mb (10^{-6} s^{-1}); circulation and specific humidity (10^{-3} g kg^{-1}) at 850 mb; circulation and specific humidity (10^{-3} g kg^{-1}) at 1000 mb. The location of Niamey is indicated by *N*

3.8. AWD without precipitation at Niamey

A very strong AWD traversed Niamey on 14–15 August 1987 without triggering any significant precipitation (only 3.1 mm at 18:00 h GMT on 14 August). Fig. 14 shows the following at 12:00 h GMT on 14 August:

(1) The wave trough (based on 700 mb winds) was imbedded within a broad area of uplift, but the strongest vertical motion was located some 10° longitude further east.

(2) Strong 850 mb convergence west of the 700 mb trough was associated with rather intense cyclonic circulation, but it advected dry desert air toward Niamey and Q850 was only 12 g kg^{-1}.

(3) Rather weak westerly circulation at 1000 mb kept the near-surface specific humidity below 18 g kg^{-1}.

Compared to the AWD discussed above that were associated with heavy precipitation (on 11 and 15 August 1988, respectively), this system featured much stronger northerlies at 850 mb and lower humidities throughout the lower troposphere.

4. SUMMARY AND CONCLUSIONS

We have studied the interrelationship of meteorological variables over West Africa during July–August 1987 and 1988 (JA87 and JA88, respectively) using gridded ECMWF analyses and station data from Niamey. In addition, we have focused on the role of African wave disturbances in triggering precipitation at Niamey and in determining the seasonal precipitation statistics.

Time series of ECMWF gridded wind analyses occasionally miss extrema associated with AWD so that Niamey radiosonde data detect a wider variety of AWD periodicities. Major spectral peaks mostly fall within the range of 3 to 6 d periods.

There was evidence that about 30% of AWD that traverse Niamey do not cause appreciable precipitation. One such wave was distinguished by strong advection of dry air from the north and by the southerlies south of Niamey being blocked by neutral moisture advection from the west near the surface. AWD that do not produce rain as well as precipitation from non-AWD causes are characteristics of the Sahel summer that were described in a GCM study of the same years by Druyan & Hall (1996).

Extrema of vorticity computed from ECMWF gridded analyses of 700 mb meridional winds and divergence from 850 mb analyzed wind fields show the westward propagation of AWD across the Sahel during July–August. However, extrema of specific humidity and 500 mb vertical motion from these gridded analyses do not propagate with AWD.

ECMWF-analyzed fields of 850 mb divergence and 500 mb vertical motion are not highly correlated with each other or with precipitation occurrence at Niamey. AWD create a rather broad area of 850 mb convergence west (ahead) of their 700 mb troughs. While these dynamics often encourage precipitation by increasing lower tropospheric humidity, they do not automatically initiate mid-tropospheric uplift. Convergence in the lower troposphere associated with AWD can also prompt the advection of dry desert air from the north thereby inhibiting rainfall. In addition, broad areas of uplift not associated with AWD are also evident in ECMWF analyses and can be relevant to significant rain events.

The greater JA88 Niamey rainfall totals cannot be attributed to AWD. This supports earlier findings from a GCM study (Druyan & Hall 1996) which looked at simulated precipitation over a broad area of West Africa. Our analysis shows that JA88 did not have a greater number of AWD than JA87. Since most of the Niamey precipitation accumulation in JA87 occurred as AWD troughs were traversing the station, we conclude that AWD can provide an important trigger mechanism for convective rainfall during an otherwise dry spell. In sharp contrast to the situation during JA87, much of the JA88 rainfall was bolstered by processes unrelated to AWD dynamics, such as large-scale uplift supported by strong upper tropospheric divergence. Other JA88 heavy rainfalls were associated with strong moisture advection by southerly winds that are sometimes strengthened by AWD. Evaluation of data from other years and from other stations will suggest whether these results from 1987 and 1988 are characteristic of the Sahel climate in general.

Acknowledgements. This research is supported by NSF ATM-9407018 and the NASA Climate and Earth Observing System Programs. M.S. was a trainee at the African Desk of the NOAA/NCEP/Climate Prediction Center, supported by the NWS/International Activities through the WMO/Voluntary Cooperation Program. ECMWF data were provided courtesy of Dr C.-K. Park and technical assistance in data handling by S. Kaltenbaugh, both of the NASA/Goddard Space Flight Center. Niamey climatological mean rainfall statistics were graciously supplied by Chris Landsea. Jose Mendoza assisted with the graphics.

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Editor: V. Meentemeyer, Athens, Georgia, USA

Manuscript first received: January 9, 1996
Revised version accepted: May 9, 1996