The Diurnal and Seasonal Cycles of Wind-Borne Dust over Africa North of the
Equator

G. N’TCHAYI MBOROU
Faculté des Sciences, Université des Sciences et Techniques de Masuku, Franceville, Gabon

J. J. BERTRAND
Faculté des Sciences, Université de Niamey, Niamey, Niger

S. E. NICHLSON
Department of Meteorology, The Florida State University, Tallahassee, Florida

(Manuscript received 12 February 1996, in final form 23 September 1996)

ABSTRACT

This article presents a study of the diurnal and seasonal cycles of dust over North Africa, using surface visibility as an indicator of dust. The diurnal cycle shows a reduction of visibility during the daytime hours in the areas where dust is generated, a consequence of the elimination of the nocturnal inversion. The annual cycle reveals that, at latitudes from 5° to 16°N, there is a latitudinal increase in the duration of the presence of aerosols over the course of the year. The presence of aerosols diminishes in the latitudes from 20° to 35°N, indicating that the aerosol content of the Saharan air is lower than that over the semiarid sub-Saharan zones, such as the Sahel. A comparison of three periods, 1957–61, 1970–74, and 1983–87, shows a continually increasing presence of dust, particularly in the western Sahel. The interannual variability of the dust and its annual cycles in these three periods throughout North Africa bear a strong relationship to rainfall fluctuations in the Sahel. Overall, the results indicate that over the last few decades the Sahel region has replaced the central Sahara as the source of atmospheric aerosols over most of North Africa.

1. Introduction

In the desert regions of the Sahara and its borders, aeolian processes mobilize and suspend in the atmosphere considerable quantities of aerosols. Of the total global production, estimates of which vary between 1000 and 3000 Tg yr\(^{-1}\) (Andreae 1995; Duce 1995), more than half generally originates over West Africa (Schütz et al. 1981). These fine particles of mineral dust are transported great distances westward by the winds. The dust appears in episodic, large-scale outbreaks that persist for long periods of time. A veritable dust cloud, with a horizontal extent on the order of millions of square kilometers and reaching to several kilometers in altitude, forms above the African continent (Bertrand et al. 1973; Vvor 1991). These outbreaks are associated with dense hazes at the surface and extensive surface deposition. A high concentration of iron in the soils gives the dust a yellow or reddish hue that is maintained even at great distances from the source (Dessens and van Dinh 1990).

Controversy exists concerning the source of the African dust. Traditionally, the Sahara was considered to be the source (Kalu 1979; d’Almeida 1986), particularly the four regions of northern Mauritania, the Spanish Sahara, the central Sahara of Niger, and the northern Sudan. The situation is, however, considerably more complex (Reiff et al. 1986). The excellent inverse correlation between Sahel rainfall and dust transport across the tropical North Atlantic suggests a Sahelian source (Prospero and Nees 1986; Prospero et al. 1993; Prospero 1996), as does the seasonal displacement of the “Saharan” dust plume, moving some 10° latitude southward in winter (Prospero 1995). Airmass trajectories and the composition of particles also point to the Sahel as a source of dust outbreaks in the Canary Islands (Bergametti et al. 1989).

Recent modeling studies have also underscored the importance of the Sahel in the dust transport over the Atlantic. Using the Goddard Institute of Space Sciences general circulation model with an aerosol tracer and “natural” conditions of soil and vegetation over West Africa, Tegen and Fung (1994) also showed a Saharan
origin of the dust plume and could not simulate the seasonal shift in its latitude. When the model allowed for “disturbed” soils in the Sahel as a result of the long series of recent drought years (Nicholson et al. 1996) and changes in land-management practices, a more realistic, seasonally migrating plume resulted (Tegen and Fung 1995). In fact, the study suggested that disturbed sources resulting from climate variability, cultivation, deforestation, and wind erosion contribute some 30% to 50% of the total atmospheric dust loading. This suggests another way in which human activities can influence global climate, because the effect of the mineral dust on the atmospheric radiation balance is considerable (Fouquart et al. 1987). The mineral dust modifies both the shortwave solar radiation transmitted through to the surface and the longwave infrared radiation emitted to space. It is an effective absorber of longwave radiation; model results suggest that the absorption is sufficient to evoke a greenhouse-type warming of the atmosphere at least locally and thereby modify atmospheric dynamics (Andreae 1996; Tegen et al. 1996). The dust both scatters and absorbs solar radiation, but the scattering effect dominates in the visible portion of the spectrum (Li et al. 1996; Tegen et al. 1996). The scattering of the visible wavelengths provides a simple way to monitor the dust, using the reduction in visibility it produces.

In an earlier paper (N’Tchayi Mbourou et al. 1994), we used this approach to show that a general increase in Sahelian dust has occurred over the last several decades, paralleling and probably as a consequence of the long decline in rainfall. In this article we emphasize the diurnal and seasonal aspects that can provide some insight into causes and source regions of the dust. Included is a comparison for three periods: 1957–61, 1970–74, and 1983–87. These periods are chosen on the basis of rainfall conditions in the Sahel (Fig. 1). The first is toward the end of a long sequence of rainy years, the second corresponds to the first severe drought of the early 1970s, and the third begins at the onset of the second intense period of the drought. Comparisons with rainfall during these periods and with the long-term temporal evolution of rainfall for the region as a whole are also presented. Overall, our results provide further observational evidence that the Sahelian region is a major source of atmospheric dust, exceeding that of the Sahara in recent decades.

2. The climate of West Africa

The climate of Africa north of the equator is characterized by pronounced seasonal contrasts, regulated by the intertropical convergence zone (ITCZ). The ITCZ is made manifest at the surface by the transition zone between the dry harmattan air and the moist air from the equatorial regions. This transition is marked by discontinuities in wind, dewpoint, and temperature. Figure 2 shows surface pressure and winds and the surface position of the ITCZ during the boreal summer and winter. The ITCZ advances rather quickly northward between February and June or August, when it attains its maximum latitude, then retreats rapidly southward until December. It seldom attains a position farther north than 25°N. North of the ITCZ the dry northeasterly harmattan winds prevail, their southward advance over the Sahara occurring in tandem with the retreat of the ITCZ. From year to year this meteorological situation recurs, with some variations in the timing of the excursions and the latitudinal positions of these features (Nicholson 1980).

The rainy seasons are a function of the displacements of these features, with the annual march of rainfall paralleling the movements of the ITCZ. For areas south of the Sahara, the mean annual rainfall is a function of the length of time that the region lies in the humid air south of the ITCZ. This annual march of meteorological controls also determines the dust content of the atmosphere. Locally, the amount of dust in the atmosphere is a function of local generation, scavenging by precipitation, dry deposition processes such as sedimentation and impaction, and advection of dust by winds. The local generation is a dry season phenomenon, while the scavenging by precipitation takes place early in the rainy season. Over West Africa the advection is generally linked to the northeasterly harmattan winds blowing from the Sahara across the semiarid Sahel toward the Guinea coast of Africa. The thus-transported mineral dust produces frequent dry hazes over the Gulf of Guinea and adjacent lands (Bertrand et al. 1973; Prospero 1981).
The dust clouds extend far into the atmosphere (Carlson and Benjamin 1980), reaching to 5 km or higher in the midtroposphere. Much of this dust is advected out of the region by the upper-level winds. The African easterly jet, a summer wind maximum in the midtroposphere, is embedded in the Saharan dust layer. Due to its strength and stability, it exports dust as far as the Caribbean and South America (Prospero and Nees 1986). Over West Africa, for example, there is a good correlation between vertical and horizontal extinction produced by desert dust (Ben Mohamed et al. 1986; d’Almeida 1987, Legrand et al. 1983). This correlation can be attributed to a certain uniformity of the vertical structure of the aerosol cloud at a given location.

It should be noted, however, that horizontal visibility is not a perfect indicator of aerosol loading. Occasionally there is good horizontal visibility at the surface despite low atmospheric transmittance. Photometric measurements in Niamey, Niger, and in Tamanrasset, Algeria, have shown that this situation may occur in the vicinity of the ITCZ, where the dust layer overrides the humid, dust-free monsoon layer (Ben Mohamed et al. 1988; d’Almeida 1985).

At a given station, aerosol loading is a function of both the local source strength, which is dependent on the local factors controlling dust mobilization, and on dust transport via advection and mixing. The ambient concentration is a function of these factors, as well as the processes that remove dust from the atmosphere, scavenging by clouds and precipitation (“wet” deposition), and dry deposition. There is considerable uncertainty in estimates of dry deposition and, hence, in the relative importance of wet and dry deposition (Prospero 1995). Clearly, the relative importance of dry deposition is greater in the drier seasons and also decreases with increasing distance from the source. Nevertheless, in West Africa precipitation scavenging is a major mechanism for the removal of dust. Thus, the distribution of mineral dust over West Africa is complex, but it is controlled to a large extent by the conditions of rainfall, particularly rainfall in proximity to the station.

4. Methodology

Ideally, dust would be directly assessed by way of photometric measurements or satellite methods. However, few such measurements exist in West Africa, and these are limited to relatively short time periods. Likewise, satellite measurements extend back only as far as the early 1980s and, hence, do not cover the earlier years, when rainfall conditions in the Sahel were good. For this reason, visibility is utilized as a proxy indicator of dust. The methodology is more thoroughly described in N’Tchayi Mbourou et al. (1994).

Visibility is measured hourly at the main meteorological stations in West Africa. The data utilized in this solar radiation reaching the surface. When the layer is sufficiently dense, these aerosols can reduce daily global radiation by 38% and reduce the direct beam by 80% but increase diffuse radiation by 150% (Dehainsala 1990). In the horizontal plane the optical diffusion by the suspended particles reduces the visibility.

The horizontal visibility is thus an indication of the intensity of attenuation of radiation by the suspended particles (Chepil and Woodruff 1957; Carlson et al. 1968; Noll et al. 1968). Over West Africa, for example, there is a good correlation between vertical and horizontal extinction produced by desert dust (Ben Mohamed et al. 1986; d’Almeida 1987, Legrand et al. 1983). This correlation can be attributed to a certain uniformity of the vertical structure of the aerosol cloud at a given location.

It should be noted, however, that horizontal visibility is not a perfect indicator of aerosol loading. Occasionally there is good horizontal visibility at the surface despite low atmospheric transmittance. Photometric measurements in Niamey, Niger, and in Tamanrasset, Algeria, have shown that this situation may occur in the vicinity of the ITCZ, where the dust layer overrides the humid, dust-free monsoon layer (Ben Mohamed et al. 1988; d’Almeida 1985).

At a given station, aerosol loading is a function of both the local source strength, which is dependent on the local factors controlling dust mobilization, and on dust transport via advection and mixing. The ambient concentration is a function of these factors, as well as the processes that remove dust from the atmosphere, scavenging by clouds and precipitation (“wet” deposition), and dry deposition. There is considerable uncertainty in estimates of dry deposition and, hence, in the relative importance of wet and dry deposition (Prospero 1995). Clearly, the relative importance of dry deposition is greater in the drier seasons and also decreases with increasing distance from the source. Nevertheless, in West Africa precipitation scavenging is a major mechanism for the removal of dust. Thus, the distribution of mineral dust over West Africa is complex, but it is controlled to a large extent by the conditions of rainfall, particularly rainfall in proximity to the station.
study are derived from 53 stations, as indicated in Table 1, and cover the years 1970–74 and 1983–87. For some analyses, data for 1957–61 are also utilized, but these data are available only for a smaller network of stations. Visibility data at each location have been sampled at 3-h intervals, namely at 0300, 0600, 0900, 1200, 1500, 1800, 2100, and 2400 UTC. As part of standard observing procedure, each case of visibility below 10 km includes an annotation indicating its cause (e.g., fog, smoke, wet haze, dust haze, blowing sand, etc.). These meteorological annotations are utilized to eliminate cases in which reduced visibility is not a result of dust. This required rejection of as much as 85% of the low-visibility data in southern areas but only about 5% of the data in the Sahel.

From these data two indices are derived. As in
N’Tchay Mbourou et al. (1994), the “dust index” (DI) is a measure of the number of hours when visibility falls below 10 km and the “severe dust index” (SDI) is a measure of the number of hours with visibility below 5 km. In various studies of optical depth and turbidity over West Africa, these two thresholds are shown to correspond roughly to aerosol optical depths of about 0.3–0.5 and 0.6–0.9, respectively. For 500 nm, specifically, the DI and SDI correspond to optical depths of 0.5 and 0.9, respectively (ben Mohamed and Frangi 1986).

Despite the care taken to ensure that these indices are based on visibility reduction due to airborne dust, the determination remains partially subjective. However, in most cases the dust is readily distinguishable from such phenomena as smoke. Smoke, for example, scatters in the blue, while dust has a near-neutral extinction. Moreover, the dust hazes are dense and persistent, and the dust producing them is quite palpable. The dust outbreaks also lead to extensive dust deposition. Numerous studies demonstrate the linkage between meteorology, dust storms, and the long-range transport of hazes (Pye 1987). In the absence of sophisticated observing instruments, visibility has traditionally served as a means of studying African dust in extensive research dating back to the early 1980s or earlier (e.g., Legrand et al. 1983).

The close correspondence between the temporal and spatial patterns of dust over the continent and over the Atlantic Ocean, where the dust is clearly established as mineral dust, further supports the validity of using the visibility measurements as a means of monitoring dust outbreaks.

5. Results

a. Diurnal variation

To characterize the diurnal cycle of the occurrence of desert dust, we have calculated the annual number of days when the visibility is reduced to below 5 and 10 km at each synoptic hour at nine stations distributed from the equator to North Africa (see location in Fig. 3). The results of this analysis for the year 1987 are presented in Fig. 4, which shows that the diurnal cycle of desert dust varies from station to station.

For the stations of Douala, Conakry, Ziguinchor, and Oran, situated far from the source zone of the dust, the frequency of visibility reduction by dust varies weakly as a function of hour. There is, however, a combined aerosol-relative humidity effect that results in an increased frequency of reduced visibility in the morning hours.

Much larger hourly variations characterize stations in the source regions. In general, the minima occur during the late morning to midafternoon hours. At the Sahelian stations of Tombouctoo, in northern Mali (d’Almeida 1985), and Agadez, in northern Niger (Bertrand et al. 1973; d’Almeida 1985), the difference between the minimum values observed at night and the maximum daytime frequencies is particularly pronounced. The maximum is registered at 1200–1500 UTC at Tombouctoo and at 0900–1200 UTC at Agadez. At the stations situated within the source zones of the Sahara, the maxima are also observed at midday, between late morning and midafternoon, but the diurnal cycle is much smaller than at Sahelian stations. Examples are in Salah and Zouer-
ate; in the source region that extends through the territories of Morocco, Algeria, Mauritania, and Mali, roughly between 20° and 30°N (d’Almeida 1985); and Hassi Messaoud in the source region of eastern Algeria (Bergametti 1987). In general, the frequency of dust, as assessed by either the DI or SDI, is considerably higher at Sahelian stations than at those in the Sahara.

The midday maximum in the above areas can be explained by the fact that the deflation of soil dust is essentially linked to the speed and turbulence of the wind. From sunset onward, because of the cooling of the surface layer, atmospheric stability favors the deposition of dust on the surface, thereby improving the visibility at night. In the morning the nocturnal temperature inversion disappears and the surface layers of the atmosphere become unstable; wind speed and turbulence increase. In the afternoon the increased height of the mixed layer and the reduction of wind speed at the surface account for the observed decrease in the occurrence of dust.

b. Seasonal variation

1) MEAN MONTHLY DURATION OF REDUCED VISIBILITY

Figure 5 presents the latitudinal variation of the mean number of hours per month, with visibility reduced below 5 and 10 km during the period 1983–87 at selected stations. Those on the left extend from the Guinea coast to the northern Sahel; all have a tropical rainfall regime with the rainy season occurring during the high-sun (summer) season. Except for Abidjan, the rainfall maximum occurs in the June–September period. Stations on the right extend from the southern Sahara to the Mediterranean coast; all but Tessalit have an extratropical rainfall regime with winter rainfall.

These figures show that the annual cycle of desert dust is clearly dependent on latitude. In the three stations of the sub-Saharan region, below 15°N, aerosols are concentrated in the months from October to April (at Abidjan, they are limited to December through March). The annual duration of the dusty conditions at the surface generally increases with latitude. At the latitude of Abidjan (5°N), the dense dust haze (i.e., with visibility less than 10 km) is frequently present from December to February, and at Dori (14°N) it is present from October to May. The maxima are observed in December and January at all three stations. With increasing latitude, at the stations of Tombouctoo in the northern Sahel and Tessalit in the southern Sahara, the desert dust is present all year round. The maximum occurs around June or July. At stations farther north (the three Saharan stations of Adrar, El Golea, and Touggourt, and the coastal station Oran) the dense hazes become increasingly rare, while the thin hazes, which reach a maximum in summer, occur more
persistence, haze frequency overall reaches a minimum near Touggourt at 33°N.

Figure 6 shows the seasonal distribution of rainfall at these stations. The relationship between dust and the rainy season is significantly different for the tropical (Fig. 6a) and extratropical (Fig. 6b) groups. For Abidjan, Bobo Dioulasso, and Dori, all south of the Sahara, frequent dust outbreaks are confined to the dry season—December to February at Abidjan and October to April elsewhere. There is no increase in dustiness at Abidjan during the "summer" dry season, presumably because of the brevity of the period and the high rainfall in previous months do not favor local mobilization of dust.

At stations farther north the seasonal relationship between rainfall and dust is less clear. At Tombouctoo and Tessalit dust attains a maximum during the rainy season, synchronous with the maxima at the stations farther south. The reasons for the timing of this maximum are not clear. It might be a result of increased dust generation during the rainy season as a consequence of the disturbances passing through the region. So far northward, these disturbances often bring turbulent winds but little or no rain and, hence, serve to mobilize dust but are insufficient to scavenger it.

At the stations in the Sahara (Adrar, El Goléa, and Touggourt) there is no dust-free season. The minima in the indices correspond to the rainy season, but the annual cycle in dust loading is considerably larger than the annual cycle in rainfall. Moreover, the indices are lower with increasing distance from the central Sahara, but rainfall does not change considerably. The seasonal cycle of dust at these stations may reflect both local generation during the dry season and advected dust from the Sahel. The maximum in the northern Sahel (Tombouctoo) and southern Sahara (Tessalit) likewise occurs during the summer rainy season. This suggests that the dust occurrences in July through August may be a residual from the prior Sahel dry season and would thus reflect the rainfall conditions in the Sahel during the previous year. Further evidence of this is presented in section 5b(3).

Further north at Oran, beyond the desert and along the Mediterranean coast, the DI increases, but the SDI continues to decrease. This is possibly a consequence of the higher rainfall at Oran, compared to the desert stations.

2) Spatial Distribution during the Season

In order to examine the spatial variation of desert dust on a seasonal basis, we illustrate the dust duration at each station with circles drawn in proportion to the number of hours with visibility reduced below 5 km (Fig. 7). This helps us to visualize the importance of the dust and its seasonal distribution, with the four parts of the figure representing January to March (Fig. 7a), April to June (Fig. 7b), July to September (Fig. 7c), and October to December (Fig. 7d) for the period 1970–74. The data are also presented numerically in Table 1.

From January to March the aerosols are present nearly everywhere, even along the Guinea coast. The regions where they are most important are eastern Niger and stations downstream from there in western Mauritania. The maximum is in eastern Niger. For the stations of Bilma, Agadez, Zinder, Maine Soroa, and N’guigmi, the mean daily frequency of occurrence of visibility below 5 km is 5 h. For Atar and Nouakchott, the frequency is 4 h. For lower latitudes this approaches 3 h for the stations of Dori, Niamey, Ouagadougou, Kandi, Parakou, and Bobo Dioulasso, and 1 h for the region near the coast consisting of the stations Abidjan, Lome, Cotonou, and Douala. In the north the values are much lower. For the stations of Bechar, Hassi-Messaoud, El Goléa, In Salah, and In Amenas, the mean daily frequency during this season is about 1 h. These results show that the frequency of dust in January through March is higher in the southern Sahara than in the northern. The presence of dust over most of the continent is explained by the fact that the ITCZ occupies its southernmost position during this period of the year (Fig. 2), and the harmattan winds transport southward the dust from sources in the Sahara and Sahel.

The main difference in the situation during the following season, April to June, is the absence of aerosols in latitudes south of 14°N. The aerosols are concentrated along the periphery of the Sahara. There is a large quantity of dust in northeast Niger, southwestern Mali, and the northern Sahara. The highest values are at Bilma, where the daily frequency of occurrence of strong visibility reduction (visibility less than 5 km) is 7.8 h at Bilma, 4.4 h at Kiffa, and 3.2 h at Adrar. From July to September the area of frequent visibility reduction is displaced farther northward, suggesting that desert dust is generally absent in latitudes below 16° or 17°N. The region of the greatest frequency of visibility reduction is near Atar.

From October to December the situation is once again similar to that of January to March, but with a somewhat lower frequency of dust in parts of the Sahel and Guinea coast. As in January to March, the highest frequency of occurrence is in the central Sahel.

These seasonal changes in the geographical pattern of dust reflect both the seasonal excursion of the ITCZ (Fig. 2) and the seasonal cycle of rainfall (Fig. 8). An inverse relationship between dust and rainfall is clearly apparent in a comparison of Figs. 7 and 8. As the monsoon penetrates the continent and the ITCZ moves northward, the dust is pushed farther aloft and is scavenged by the clouds and rainfall. Thus, the southern boundaries of the dust occurrences in April to June and July to September reflect the northern limits of the rain belt, which moves progressively northward. As the ITCZ and rain belt move southward from October to
December, the dustiness increases; near the coast, where rainfall still occurs, the increased dustiness probably reflects the southward movement of Sahelian air with the retreat of the ITCZ and further southward penetration of the harmattan. Overall, maximum visibility reduction occurs in January to March, when rainfall is limited to stations fairly close to the coast.

It is interesting to compare the spatial distribution of dust during 1970–74 with that of the period 1983–87, a later drought interval, and with that of the period 1957–61 (Fig. 9), the end of a long wet spell in the Sahel (Fig. 1). Unfortunately, data for the earlier period were unavailable for the western Sahel, but the observations are complete for the later period.

The occurrence of dust is dramatically lower during 1957–61 nearly everywhere and during all seasons except January–March. This is the only season with particularly frequent dust occurrence. The greatest changes are apparent in the October–December season, just subsequent to the Sahel rainy season. This is strongly indicative of reduced dust generation in that region during the 1957–61 period, compared to the period 1970–74. The increased dust in all seasons in the 1983–87 period is likewise striking, particularly in the Sahel (Fig. 10).
This further underscores the importance of the Sahel for dust production.


An examination of the monthly means of the DI and SDI for the three periods 1957–61, 1970–74, and 1983–87 further underscores the nearly ubiquitous increase of dust since the 1950s. The first period corresponds to relatively wet conditions throughout the region (Fig. 1) and the subsequent periods to major periods of drought within a long dry episode. Between the periods 1957–61 and 1970–74, the increase in dust frequency is particularly marked at stations in the Sahelian zone (e.g., Niamey). Between the periods 1970–74 and 1983–87, this increase, reflected in both the seasonal prevalence and intensity of the dust (Fig. 11), is apparent at the ensemble of sub-Saharan stations situated in the west and in the Niger basin (e.g., Gao, Niamey, and Abidjan). Farther north at the edge of the Sahara, the stations of Agadez and Bilma exhibit a large increase in dust between 1957–61 and 1970–74. However, the increase in the 1980s noted farther south is not evident. In fact, a slight reduction of the monthly frequency of dust is evident between 1970–74 and 1983–87, particularly at the more northern station of Bilma. At the Saharan stations of In Salah and El Golea, an overall increase in the DI is apparent from the 1950s to the 1980s, but the SDI shows a different evolution. At both stations, it is lowest during the period 1970–74, suggesting relatively weak dust loading compared to the periods 1957–61 and 1983–87.

An explanation for the described evolution of the dust layer is not readily apparent. However, changes in the geographic sources of the dust, and perhaps the patterns of dust advection, are likely. At the Sahelian stations of Niamey and Gao, the changes in dust occurrence between the 1950s and the 1980s clearly reflect changes in the intensity of the rainy season and, to a lesser extent, the length of the dry season (Fig. 11). However, at Gao there is an interesting shift in the timing of maximum dust frequency from the dry “winter” season to the summer rainy season. This suggests enhanced mobilization of dust as aridity increases, but a failure of the meager rains to scavenge the dust during the rainy season and, hence, a steady build-up of dust in the northern Sahel. At coastal Abidjan the changes in dust are commensurate with a reduction in rainfall, but advected dust from the Sahel (with the southward penetration of the harmattan) is also likely because the dry season there begins well before the onset of the dust events.

The patterns are more complex in the northern ex-
treme of the Sahel (Agadez) and at the southern margin of the Sahara (Bilma). There maximum dust occurrence is during the brief rainy season, but there is a reduction beginning in July or August, the months of peak rainfall. Surprisingly, dust occurrence is less frequent there than farther south, and it is lower in 1983–87 than during 1970–74. Both of these trends may reflect a combination of reduced source strength and reduced mobilization. This far north, rain-bearing disturbances, with their high winds, occur much less frequently; the soils are also thinner, less spatially continuous, and contain less fine material capable of being mobilized.

As aridity increases over time, the fine dust-forming particles are eroded away. By the 1983–87 period, following two decades of increasingly arid conditions, most of the finer surface particles may have been eroded away. A less frequent occurrence of disturbances this far north during the most recent drought years is also a possibility.

At stations in the central and northern Sahara (In Salah and El Golea), the evolution and seasonal distribution of dust is more difficult to explain in terms of rainfall since these areas experience little systematic change in rainfall and annual rainfall is very low. This
increase in dust frequency from 1957–61 to 1983–87 is likely a manifestation of increased dustiness over the Sahel, with the high frequency of weaker dust events reflecting the distance from the source.

6. Discussion

Our clearest result is the generally parallel trends of increasing dust and decreasing rainfall over Sahelian West Africa. Clearly, the lower rainfall was accompanied by reduced soil moisture (Nicholson et al. 1997) and vegetation cover (Tucker et al. 1991). This would enhance the potential for dust mobilization. The long decline in rainfall over West Africa is part of a major shift in climate that might be accompanied by other meteorological changes in the region, such as in the strength of the Hadley circulation, in the synoptic disturbances, or in the strength and position of the African easterly jet (Newell and Kidson 1984; Nicholson 1989; Fontaine and Janicot 1992). The fundamental processes affecting the mobilization and transport of the dust are poorly understood (Westphal et al. 1987, 1988), but an influence from such changes cannot be ruled out. Nevertheless, evidence suggests that there has been neither a change in the number or size of wet season disturbances nor a systematic shift in such major synoptic features as the ITCZ (Nicholson 1989). Furthermore, the African jet is most active after the atmospheric dust has waned in the summer. Thus, circulation changes are not likely to be the cause of the increased dustiness over West Africa.

Overall, our results suggest a scenario in which the Sahel region as a whole increasingly becomes a source of dust for most of West Africa. The increasing aridity
enhances the erodibility of the surface, promoting dust generation after the rainy season. This process would be further accelerated by the disturbed soils and vegetation cover in the Sahel, as a result of increasing population pressure (Tegen and Fung 1995). Farther north, where the thinner soils and sparser vegetation cover make the surface even more prone to deflation, most of the erodible soil material may have been mobilized during the dry years of the 1970s. This would suggest that the temporal evolution of dust in much of the region better reflects Sahelian rainfall than local conditions.

We have tested this suggestion, using correlations between rainfall and dust occurrence at select stations. At stations Abidjan, Bouake, Bobo Dioulasso, and Niamey, the SDI is correlated both with rainfall averaged for the Sahelian zone as a whole (Nicholson and Palao 1993).
and with local rainfall during the years 1957 to 1987, using data from N’Tchayi Mbourou et al. (1994). For station Gao the total number of days with dust haze was used in lieu of the SDI. The results are shown in Table 2. In all cases the correlation is higher with Sahel rainfall than with local rainfall, but this is particularly true for stations Abidjan and Bouake, well south of the Sahel. In addition, the correlation is generally higher with antecedent rainfall of the previous year than with rainfall in the concurrent year; this agrees with the conclusions of Prospero and Nees (1986) concerning Saharan dust deposited at Barbados. In some cases, the highest correlation is with a multiyear antecedent rainfall average; at Gao in the central Sahel, the correlation with rainfall in the previous three years reaches 0.84. This may be indicative of a long-term buildup of dust in response to the long series of drought years since the 1960s (Fig. 12).

These correlations, and results described earlier, strongly suggest that the Sahel is the source of atmospheric aerosols throughout West Africa. Such a conclusion is counter to the classic ideas (e.g., Kalu 1979) concerning the source regions of Saharan dust. The shift is apparently a consequence of the 20-yr sequence of dry years in the Sahel. This is not to suggest, however, that rainfall is the sole cause of the increasingly dusty atmosphere over West Africa. Land use has changed and population pressure has increased, leading to more intense agriculture and probably to overgrazing in the more northern regions. These processes make the soil more prone to erosion, enhancing the potential source strength. When coupled with drought, these changes become more acute and probably contribute to the increased dust (Tegen and Fung 1995).

It is interesting to speculate on the impact of the dust on the rainfall. The intensity and instability of the African easterly jet are dependent on the atmospheric temperature gradient in the midtroposphere, well within the Saharan air layer. The thermal structure would be altered by the presence of the dust, in view of modification of the atmospheric radiation balance by the aerosols (Fouquart et al. 1987). The development of rain-bearing disturbances, dependent on the instability of the jet, has also been shown to be affected by the presence of the dust (Karyampudi and Carlson 1988). If the feedback that exists is positive—that is, increased dust increases the dynamic stability of the atmosphere—the dust might be a mechanism by which the droughts are intensified and prolonged (Nicholson 1989). This could explain the unique aspects of Sahelian drought, its large intensity, and its multidecadal persistence.

7. Conclusions

At stations in the zone of dust generation in the central Sahel, diurnal changes in the surface thermal inversion and surface winds produce a strong diurnal cycle in dust frequency. There is a pronounced increase around midday. Elsewhere there is only a relatively weak diurnal cycle. At coastal stations a small morning maximum occurs as a consequence of combined dust and humidity effects. Desert stations also show a weak afternoon maximum, as in the Sahel.

The surface fluctuations in the seasonal occurrence of dust are linked to the movements of the ITCZ and the annual march of the rainy season. The ITCZ limits the southward penetration of the dust. Therefore, when the ITCZ reaches its farthest-north position (in July or August), the monsoon winds counter the southward penetration of the dust. Furthermore, rainfall during this season scavenges the dust. In contrast, the ubiquitous presence of the dust, when the ITCZ reaches its southernmost position (December or January), is explained by the influence of the harmattan.

The comparison of the reduction of visibility during the three periods 1957–61, 1970–74, and 1983–87 demonstrates an increase in both the frequency of occurrence and the annual duration of dust conditions at the surface. This is particularly true for stations in the Sahel, which show a tendency toward an increase in the length of the
dry season. This increase is also apparent at stations in the central and northern Sahara that do not show commensurate changes of rainfall. Overall, the results suggest that since the onset of drought in the 1970s the Sahel has become the major source region of wind-borne dust over North Africa.

Acknowledgments. This work was made possible by a grant from the Fond International de Coopération Universitaire de l’AUPELF. We also express our gratitude to the responsible agencies of ASECNA and the national meteorological services for the meteorological information that they furnished, and to AGRHYMET at Niamey for obliging our requests for visibility and rainfall data and numerous other services. Some support was also provided for the participation of SEN by the National Science Foundation through Grants ATM-9024340 and ATM-9521761. We would also like to thank Prof. Joseph M. Prospero of the University of Miami and an anonymous reviewer for helpful comments on the manuscript.

REFERENCES


