Saharan Air Outbreaks over the Tropical North Atlantic

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1. Introduction

Among Bergeron's many interests were climatology, the characteristics of the intertropical convergence zone and mineral dust in the atmosphere, the last because of the importance of soil particles in the process of ice nucleation. Perhaps it was because of these interests that Bergeron was drawn to the study of the meteorology of North Africa where the climate in many regions is dominated by the behavior of the intertropical convergence zone and where dust is ubiquitous and abundant indeed. These interests and his humanitarian instincts converged to produce at least two papers (Bergeron, 1960, 1968) which dealt with the possibilities of employing weather modification techniques to increase rainfall in the arid and desert regions of North Africa.

In our paper we will present a review of the characteristics of Saharan air outbreaks, a term we have applied to synoptic scale masses of hot, dry, dust-laden air which periodically emerge from the coast of Africa. The air in these outbreaks has meteorological properties that are very different from those which one would expect for the 'normal' marine atmosphere over the tropical North Atlantic. Because of these characteristics, the outbreaks have distinctive circulation features.

We will begin by focusing on the most striking feature of the outbreaks, viz. the presence of extremely high concentrations of dust. After discussing the large scale meteorological controls and climatology of dust transport over the Atlantic, we will describe the structure and dynamics of the outbreaks.

2. Phenomenology of Saharan dust transport

It has long been known that large quantities of soil dust are transported out of the arid and desert regions of North Africa into the atmosphere of the tropical North Atlantic. Often the concentration of dust is so great as to cause dense hazes. Mariners have noted

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this phenomenon in reports dating back some 2000 years. Indeed, the region off the west coast of North Africa was once known to voyagers as the ‘dark sea’ because the haze frequently restricted visibility so severely as to make navigation difficult. Darwin, on the voyage of the Beagle, observed a dust outbreak while in the region of the Cape Verde Islands (15°N/23.5°W) in January 1833 and was so impressed by the magnitude and persistence of the event that he was moved to speculate that eolian (wind) transport might be an important mechanism for supplying material found in deep sea sediments (Darwin, 1846).

Subsequent studies have shown that African dust is transported across the Atlantic into the Caribbean. This was first noted in 1965 by Delany et al. (1967) who were engaged in an experiment to measure the concentration of cosmic spherules in the trade winds at a site on the coast of the island of Barbados, West Indies (13°10′N, 59°30′W). Much to their consternation, they found that their collectors were often overloaded with huge amounts of red-brown dust which they later deduced to be derived from Africa. In 1966 one of us (JMP) established a continuous aerosol study on Barbados, a program which continues to this day.

The mineral dust concentration in the trade winds at Barbados (Fig. 1) varies according to a clearly defined seasonal cycle; the greatest dust concentrations occur in the summer months, the winter concentrations being at least an order of magnitude lower (Prospero and Nees, 1977). The day-to-day variations in dust concentration at Barbados are also quite large. This can be seen in Fig. 2 (Savoie and Prospero, 1977) which presents daily aerosol concentration data for Barbados and for two other stations (Sal Island, Cape Verde Islands, and Miami, Florida) during the summer of 1974. These sites were part of a University of Miami aerosol network of eight ships and four land stations that was incorporated in the Global Atmospheric Research Program Atlantic Tropical experiment (GATE). The sharp increase in dust concentration at these stations coincided in each case with the arrival of a dust-laden air mass. By tracing the progress of the dust peaks in Fig. 2 and noting the arrival time differential between stations, it can be inferred that the transit time from the coast of Africa to the

![Image of graph showing mean monthly mineral aerosol concentration, Barbados, West Indies. Dust concentrations for the period August 1965–April 1966 were calculated from data presented in Delany et al. (1967); concentrations for the period May–September 1966, were calculated from unpublished data supplied by A.C. Delany. The curve depicts the 3-month moving average.](image-url)
Caribbean is about 5–7 days. Even in Miami the principal insoluble aerosol constituent during the summer is Saharan dust.

Because of the large concentration of dust in the outbreaks, the atmosphere is often quite turbid even in the Caribbean and in south Florida (PROSPERO et al., 1979). As a consequence, the progress of the dust outbreaks often can be followed by means of satellite imagery (PROSPERO et al., 1970; CARLSON and PROSPERO, 1972; LUSHINE, 1975; MAYFIELD, 1975; BRANDLI and ORNDORFF, 1977; and CARLSON, 1979). In some cases the dust storms can be observed from the time of their inception over the desert. Over West Africa, the dust storms are most easily followed using infra-red imagery; because of its altitude, the airborne dust radiates at a cooler temperature than the surface and, consequently, the area of the storm has a uniform gray appearance as contrasted to the black appearance of the hot desert surface. Over the oceans, the dust outbreaks are best followed with visible spectrum imagery. Examples of visible and infra-red imagery of dust storms are shown in Figs. 3 and 4.
Figure 3
SMS-1 infra-red satellite imagery showing a dust storm in an early stage of evolution at 1300 GMT, 29 July 1974. The dust storm is visible as an elongated gray region extending from about 23°N, 9°W to 26°N, 2°E. The storm first appeared on the 1100 GMT image and attained maturity in about one hour. An identical dust storm had occurred in the same region on the previous day.

The seasonal cycle in dust concentration at Barbados apparently is not attributable to a corresponding seasonal cycle in dust transport out of Africa. Indeed, the frequency of occurrence of dust-haze along the west coast of North Africa is much greater in the winter than during the summer (McDonald, 1938); however, the winter haze distribution is shifted about 10° to the south of the summer distribution. This shift is consistent with the southward shift of the large scale atmospheric circulation in winter. The continued dust activity in Africa during the winter and the consequent haze distribution at sea suggested that the principal dust transport trajectories might be found in the latitudes south of Barbados. This was indeed shown to be true in an aerosol study which has been carried out in Cayenne, French Guiana (4°50'N, 52°22'E), since December 1977 (Prospero et al., 1981). The maximum monthly mean aerosol concentrations at Cayenne in the two years of record (Fig. 5) occur in March, whereas in Barbados the maximum occurs during the months of June, July or August (with the interesting exception of 1977 when there were essentially two annual maxima, one in March). Also, the Cayenne maximum monthly means in the annual cycle were 23 and 28 µg m⁻³ (in 1978 and 1979 respectively), whereas the maxima at Barbados during the
years 1976–79 were in the range of 15–18 μg m⁻³. As was the case with the Barbados aerosol samples, the Cayenne samples were traced unambiguously to an African origin by making use of our aerosol network and satellite imagery (PROSPERO et al., 1981).

The annual cycle in dust concentration at Cayenne is quite similar to that which we have observed in Dakar, Senegal, in an aerosol monitoring program which the University of Miami has maintained since 1974 in cooperation with scientists at the University of Dakar. The monthly mean dust concentrations at Dakar are, of course, much greater than at Cayenne, the annual monthly mean maxima ranging from 130 μg m⁻³–206 μg m⁻³; in all cases, the maximum occurred in March. The Dakar dust concentrations are invariably at a minimum in July and August, the months when the Barbados values are at a maximum. The geographical and temporal variations in dust concentration are consistent with our studies of satellite photographs which suggest that in the summer months, dust outbreaks generally emerge from the coast of Africa between about 15° and 20°N. During the winter, the main paths of the outbreaks appear to pass over this same coastal region and also further to the south. It is
not clear from whence these dust outbreaks originate but the character of the wind field suggests that the principal sources are in the deep Sahara in Mauritania, northern Mali and central Algeria.

Another major center of dust storm activity in West Africa is found in western Niger and northern Chad (Hamilton and Archbold, 1945; Dubief, 1979; Bertrand et al., 1974; Domergue, 1980). However, the maximum dust concentration in this region occurs between December and February (i.e., a cycle different from that observed at Dakar) when dust laden air masses, known as the harmattan, penetrate to the Gulf of Guinea. The dust is carried by winds to the west and southwest, the movement being readily tracked by the day-to-day variations in surface-level visibility (Bertrand et al., 1974). At this time of year, the maximum monthly mean dust concentration in Ivory Coast is in the range of 53–166 μg m⁻³ (Domergue, 1980). It is perhaps significant that the time of the peak dust activity in this region of West Africa occurs at the time of minimum dust transport to the region of French Guiana. This suggests that the massive transport of dust into the tropical Atlantic and the Gulf of Guinea must be terminated by fairly complete removal, most likely in the regions of high precipitation that are characteristic of the ITCZ.

3. Structure and dynamics of Saharan air outbreaks

The transport of dust (i.e., its concentration in the atmosphere and its geographical distribution) depends on a complex way on meteorological and climatic conditions in the
source regions and on the wind fields over the Atlantic. The environmental conditions associated with the generation of dust storms in North Africa have been the subject of a number of papers (see, for example: Bertrand et al., 1974; Burns, 1961; Dubief, 1979; El-Fandy, 1953; Hamilton and Archbold, 1945; Kalu, 1979; Morales, 1979; Samways, 1976; Wilson, 1971; Yaalon and Ganor, 1979). Here, we will deal

Figure 6
Schematic diagram of typical soundings in the region of a Saharan air outbreak. (a) Over the eastern tropical Atlantic at about 17°N, 23°W. (b) Over the eastern Caribbean (Diaz et al., 1976).
with the dust generation phase only to the extent necessary for understanding the evolution of the subsequent transport phases. Also, we confine our description to dust outbreaks that occur in the summer months. To our knowledge, there have been no meteorological studies of dust transport over the oceans during any other time of year.

As stated in the previous section, satellite photographic analysis suggests that during the summer the major dust outbreaks that emerge into the Atlantic are initiated over the desert expanse that stretches from the coast of Mauritania and Spanish Sahara into central Algeria. The intense heating of the land surface, which typically attains a temperature of 60°–65°C in the daytime, results in extremely unstable conditions; as a consequence, a very deep isentropic mixing layer develops and the high velocity, gusty winds generate dust which is carried to the top of the mixing layer which may be as high as 500 mb. The dust storms generally appear to develop very rapidly during the mid- to late morning. This suggests to us that the dust generation may be associated with the coupling of the convective layer with an upper level jet.

The hot (potential temperature about 45°C), dry (mixing ratio 2–4 gm/kg), dust-laden air emerges from the coast of Africa in meso- to synoptic scale outbreaks that usually follow the passage of the trough of an easterly wave. As these outbreaks emerge from the coast, they are undercut by the cool, moist, northerly coastal winds thereby generating a sharp inversion at about 850 mb. A typical idealized sounding that one might expect to see off the coast of Africa during the passage of a dust outbreak is

![Graph](image)

**Figure 7**

Measurements of temperature ($T$), dewpoint ($T_d$), winds, and dust concentration made aboard a NOAA DC-6 aircraft en route northward to Dakar at flight level 790 mb (about 2000 meters) on 3 July 1974. Shown at the top of the figure are observers notes on the occurrence of dense haze and the location of the southern boundary of the haze. Dust concentrations were computed from aerosol measuring devices.
shown in Fig. 6a. Because of the strong inversion at the base of the outbreak, the cloud tends to be quite suppressed and clouds are predominantly stratiform. Indeed, the absence of cumulus clouds in the region of a dust outbreak is one of the features that stands out so clearly in satellite photographs. The temperature just above the inversion at the base of the dust outbreak may be 5°–10°C warmer than air at an equivalent altitude near the equator. However, the top of the outbreak parcel is generally a degree or two cooler than air at an equal altitude in an equatorial sounding. Also, the outbreak is capped by a weak mixing inversion. The potential temperature between the inversions is nearly isentropic. Because of the unusual temperature, dew point and aerosol properties of the outbreaks and because the outbreaks assume a layer-like structure over the ocean, it is possible to characterize such a structure as being a Saharan air layer.

The large horizontal gradients in temperature, dew point and aerosol concentrations between the Saharan air layer and the equatorial region is graphically displayed in Fig. 7, which presents data collected during a flight in GATE when the aircraft was returning to Dakar on a track with a terminus at 9°N, 24°W. Note the rapid increase in temperature and decrease in dew point along the return track. These steep boundary gradients are maintained as the outbreaks cross the Atlantic as has been shown in research flights in the eastern Caribbean (CARLSON and PROSPERO, 1972; PROSPERO and CARLSON, 1972).

Because of the large temperature gradients, a strong wind shear exists along the southern boundary of the Saharan air layer in accordance with thermal wind balance. A middle level easterly jet, typically 20–25 m s⁻¹, is generally present near 650 mb, the altitude where the positive horizontal temperature gradient between the Saharan air and the equatorial (non-Saharan) air tends to vanish. A major difference between the characteristics of the Saharan air layer over the Cape Verde Islands and those over the eastern Caribbean (Fig. 6b) is that the layer thickness (i.e., the distance between the upper and lower inversions) decreases to the west. The layer usually has a top near 500 mb and a base at 850 mb over the eastern Atlantic whereas over the Caribbean the top is at about 550 mb and the base is at about 750 mb. The westward transport of dust takes place primarily within the nominal isentropic layer; dust is transferred downward to the moist layer by convective erosion of the base of the Saharan air layer and by the settling-out of large particles through the lower inversion. Aircraft aerosol measurements over the eastern Caribbean (PROSPERO and CARLSON, 1972) and off the coast of Africa (PROSPERO, unpublished data) have shown that the mineral dust concentration in the SAL is at least several times greater than in the boundary layer air.

A three-dimensional conceptual model of the Saharan air layer in the summer is shown in Fig. 8 (KARYAMPUDI, 1979) as it would appear to an observer looking toward the west from a position over Africa. In the figure, the outbreak has emerged from the coast of Africa following the passage of an easterly wave whose axis is shown close to 40°W; in the foreground is the West African surface thermal low. The Saharan air is shown ‘sliding’ over the trade wind inversion which is shown rising to the west. Note
Figure 8
A Saharan dust plume model (KARYAMPUDI, 1980).

also that the southern portion of the Saharan air is also lifted from the surface, in this case by the southwest monsoon winds. Over the Atlantic, low-level trade wind flow beneath the Saharan air will transport dust into the ITCZ where rapid removal by precipitation is expected.
Cloud and dust/haze (Visibility less than 10 km) patterns based on combined ground observations and a SMS-1 satellite photograph at 1200 GMT, 9 July 1974. Contours represent isopleths of turbidity (optical depth, $I_0$) at wavelength $\lambda = 0.66 \mu m$ as determined from the brightness pattern in a NOAA-3 VHRR satellite photograph at 1114 GMT (CARLSON, 1979). Compare this figure with the photograph of the dust outbreak of 30 July (Fig. 4).

Anticyclonic trajectories are shown within the Saharan air layer behind the wave axis in Fig. 8. This circulation appears to develop as a consequence of the decrease in the thickness of the Saharan air layer with distance from the coast. Because of the Saharan layer depth decrease, horizontal divergence must occur to satisfy mass continuity. Consequently, the layer expands in the horizontal plane and takes on an anticyclonic curvature to conserve its potential vorticity (DIAZ et al., 1976). The effects of anticyclonic flow and divergence are often visible in satellite photographs; dust plumes crossing the coast are generally relatively narrow (less than 5°) but once over the ocean, the plumes turn clockwise as they move to the west, broadening to produce a layer of 10°-15° of latitude wide.

The middle level easterly jet is shown along the southern boundary of the Saharan layer. The jet is a characteristic feature of the layer. It is present in the Saharan layer even over the Caribbean. Although some trajectories are shown crossing the wave axis, the anticyclonic flow field tends to keep the dusty air mass behind the wave axis. Even in the Caribbean, the arrival of a dust outbreak is generally preceded by the passage of an easterly wave. An actual example of the distribution of dust and cloud in association with an easterly wave is shown in Fig. 9.
4. Dust, weather and climate

Saharan dust appears to have a significant impact on the circulation of the equatorial Atlantic through its interaction with the radiation field in the solar and long wave (terrestrial) regions of the spectrum. The dust alters the vertical distribution of radiative heating, thereby altering the thermodynamic forcing of the atmosphere. The optical properties of Saharan aerosols have been determined directly in laboratory studies (Carlson and Caverly, 1977; Patterson and Gillette, 1977; Patterson et al., 1977) and indirectly by inversion techniques using radiation data gathered in GATE (Carlson and Caverly, 1977). All data sets show strong absorption below 0.6 μm wavelength (Carlson and Caverly, 1977). Computed radiative heating rates (Carlson and Benjamin, 1979) show that the combined solar and longwave heating rates during typical dust outbreaks average from 1–2°C over a 24-h period over a considerable area of the eastern Atlantic. The radiative forcing by the instantaneous heating rate is about 3–4 times greater than those averaged on the entire 24-h day. Furthermore, the presence of dust seems to result in a cooling of the surface due to radiation flux divergence. The end effect of the heating aloft and the surface cooling is to increase the atmospheric stability.

The presence of large concentrations of dust and the ensuing increased heating rates may result in an increase in the ascending motion (Karyampudi, 1979) especially where the dust concentration is greatest – generally at 700 mb close to the ridge of the easterly wave and north of the middle level easterly jet. Weak compensating sinking motions are found in the equatorial region south of the Saharan air layer and also just east of the trough axis. Thus, a direct Saharan air circulation regime appears to develop primarily as a consequence of dust-induced heating effects. This circulation regime is shown schematically in Fig. 10.

Saharan dust may also play an important role in the cloud microphysics of the tropical North Atlantic. Allee et al. (1976) found that the concentration of ice nuclei was extremely high in dust outbreaks with values in the range 10–100/l (at −20°C) being typical. In contrast, the cloud condensation nucleus concentration appeared to be relatively low within the Saharan air layer, generally less than 100/cc. The impact of Saharan dust on cloud processes can extend over very large regions. During cloud seeding experiments in South Florida in 1975, the measurement of maximum ice nucleus concentrations appeared to coincide with the incursion of Saharan air parcels into the area (Allee et al., 1976).

Thus, Saharan air outbreaks in general and dust in particular may have a pronounced effect on the atmospheric processes occurring over a large area. However, dust is itself a product of weather and climate. In this regard it is important to note that the dust concentrations over the tropical North Atlantic as implied by the Barbados measurements (Fig. 1) were much greater during the early 1970’s than they were during the 1960’s or in the later 1970’s (Prospero and Nees, 1977). The period of greatest dust concentrations coincided with the time of severe drought in the Sahel. It is not clear
SAHARAN AIR CIRCULATION

Figure 10
Schematic illustration of the internal Saharan air circulation as it would appear to a person looking to the northeast from a position on the equator near 40°W. The heavy dust region coincides with the ridge of the easterly wave whose trough is near 35°W. Warm air in the vicinity of the ridge rises (partially in response to warming due to the radiative heating of the dust) whereas relatively cooler air sinks in the region south of the middle level jet and to the east of the trough axis. The hatched area indicates the dimensions of the Saharan air layer (Karyampudi, 1979).

at this time whether the increase in dust transport was purely a consequence of natural processes or if land use practices (such as overgrazing) could have played a role. Nonetheless, the fact remains that a climatic episode in Africa made itself felt over an area that extended to regions over 4000 km away.

5. Conclusion

Although Saharan dust transport has been the most thoroughly studied case of long-distance aerosol transport, it is by no means a unique phenomenon. It appears that many arid and desert regions are capable of supplying large quantities of mineral aerosol to the atmosphere (Prospero, 1979; Prospero, 1981a,b). Most dramatic is recent evidence that there is a very substantial flux of soil dust out of Asia into the North Pacific (Duce et al., 1980). During the initial phase of a five month aerosol study on Enewetak Atoll (11°N; 162°E), large concentrations of mineral aerosol were measured. Meteorological analyses indicate that the soil dust was derived from arid regions in the People’s Republic of China. This result was somewhat unexpected as Enewetak lies well within the easterly tradewind regime. Asian dust also appears to affect the optical properties of the atmosphere at least as far to the east as Hawaii (Bodhaine et al., 1981), and it is believed to be the cause of hazes in the Arctic (Rahn et al., 1977).
Thus, there is evidence that soil aerosols may play a more important role globally than was originally suspected. The extent of the transport and the magnitude of its impact remain to be determined through continued research. In this respect, the Saharan outbreak studies will provide a conceptual framework for the investigation of soil aerosol transport in other regions.

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