Dust Concentration in the Atmosphere of the Equatorial North Atlantic: Possible Relationship to the Sahelian Drought

Abstract. *The concentration of insoluble mineral aerosol in the lower troposphere of the western equatorial North Atlantic Ocean has increased by a factor of 3 over the last decade. This increase may be related to the drought in the Sahelian zone of North Africa.*

A severe drought has afflicted a large area of North Africa that lies to the south of the Sahara Desert. The region most affected, the Sudano-Sahelian zone, lies approximately between latitudes 10°N and 20°N and includes portions of the countries of Mauritania, Senegal, Mali, Upper Volta, Niger, Chad, Sudan, and Ethiopia (*1*). Coincidentally with these events in North Africa, we have measured a sharp increase in the mineral aerosol content of the atmosphere over the western equatorial North Atlantic and the Caribbean. We report here on these measurements and discuss their implications.

For almost a decade, we have studied the character of the aerosols in the North Atlantic trade-wind belt. We have found that the principal component of the aerosol is mineral dust, which originates from the desert and the arid and semiarid regions of West Africa (*2–4*). The transport process begins with the lifting of dust by high-velocity, gusty winds (*3*). Because of the intense heating of the air at the desert surface, the vertical mixing is very deep and intense and it carries dust to altitudes of 5 to 7 km. The hot, dry, dust-laden air emerges from the coast of Africa as a large-scale, anticyclonic eddy, which we call a Saharan air outbreak (SAO); these outbreaks move across the Atlantic in a layer that has a base at an altitude of 1 to 2 km and a top at 5 to 7 km. The base of the layer is generated when the trade winds cut beneath the Saharan air as it emerges from the continent. Because the temperature at the base of the Saharan air layer (SAL) may be as much as 5° to 6°C warmer than that of the air in the mixed (surface) layer below, a strong inversion is formed. The SAO's have a latitudinal width of 10° to 15° and move across the Atlantic in the nominal trade-wind belt, the usual transit time for an individual outbreak being 5 to 7 days.

Much of our work took place at Barbados, West Indies (13°10'N, 59°30'W), where an aerosol monitoring program has been in effect since 1965 (*2–5*). Aerosol measurements were made by two different techniques. From 1965 until 1970 the aerosol was collected by means of 1-m^2 nylon meshes suspended normal to the wind (*2, 5*). In 1971 electricity was brought to the coastal site, and all subsequent sampling was performed by drawing air through a cloth filter [Institute for Paper Chemistry (IPC) 1478] at a high rate of flow, 1.5 to 2 m^3/min (*6*). Sampling has been continuous except for equipment failures and several periods of extended shutdown.

The collection efficiency of the meshes was determined by sampling simultaneously with both types of collectors under a wide range of dust concentration conditions. These data (Fig. 1) indicate a mass collection efficiency of 30 percent for particles borne in the air passing through the mesh. The collection efficiency of 30 percent is further validated by comparing the atmospheric dust concentrations measured by using meshes at Barbados with the aerosol concentrations measured by using IPC 1478 filters aboard aircraft participating in the Barbados Oceanographic and Meteorological Experiment (BOMEX) during the summer of 1969 (*3, 4*). We have extracted all of the aircraft dust concentration data for samples collected below an altitude of 1.2 km (that is, in the trade-wind mixed layer) and between latitudes 10°N and 25°N (within the nominal northeast trade-wind belt). The agreement between the Barbados and aircraft data (Table 1) is excellent. The difference in the geometric mean concentrations (*7*) is not statistically significant (Student *t*-test) at the 95 percent confidence level; the 95 percent confidence interval for the estimate of the difference in the true means is −0.70 to 1.82.

The mean monthly concentration of insoluble mineral aerosol at Barbados and the superimposed 3-month moving average (Fig. 2) show two distinct trends. First, there is a pronounced seasonal periodicity, with the highest concentrations usually occurring during the months of June, July, and August. Second, there has been a marked increase in dust concentration during the years 1972 to 1974.

In Table 2, we compare the mean June, July, and August dust concentration on Barbados with rainfall records in the Sahel as reported by Bunting *et al.* (*8*) and by Tanaka *et al.* (*9*). The data of Bunting *et al.* are from five stations in a relatively small area in northern Nigeria and southern Niger between 2°E to 13°E and 12.5°N to 14°N; two stations are on the border of the Sahel and three are actually south of it. Those of Tanaka *et al.* are for eight stations in the area 13°N to 16°N and 14°W to 25°E; these stations also lie along the southern portion of the Sahel. There are no coherent long-term rainfall data for the vast area of the Sahel that lies to the north of these stations. Although there are some differences between these two records, it is clear that the deficits and their cumulative effects became most severe in the period 1971 to 1973; the drought is generally considered

Table 1. Mean aerosol concentration ± standard deviation (S.D.) in the mixed layer of the northeast trade winds during May, June, and July 1969 as measured on Barbados by using the mesh technique and aboard an aircraft by using IPC 1478 filters. The aircraft geometric mean is obtained from the daily arithmetic means of all samples taken in the mixed layer. The Barbados concentrations were calculated by using the regression equation in Fig. 1.

Sampling location	*N*	Mean aerosol concentration ± S.D. ($\times 10^{-6}$ g m^{-3})	
		Arithmetic	Geometric
Aircraft	21	12.74 ± 10.92	8.76 ± 2.54
Barbados	82	11.90 ± 11.60	7.75 ± 2.69

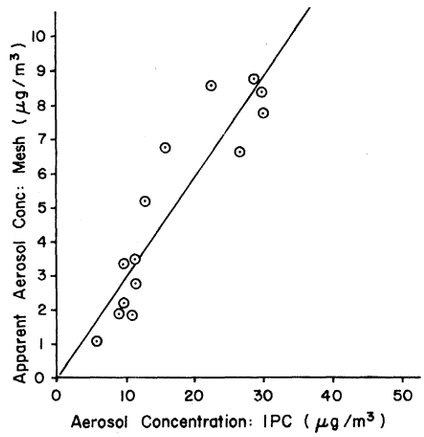

Fig. 1. Determination of mesh collection efficiency. The aerosol was sampled simultaneously with nylon monofilament meshes and IPC 1478 filters during 14 days in July 1971. The apparent aerosol concentration as determined by the meshes is simply the total weight of the collected mineral aerosol divided by the total volume of air flowing through the dimensional area of the mesh panel (1 m^2). The cross-sectional area of the monofilament (that is, the cross-sectional collection surface) is 50 percent of the dimensional area. The regression equation is $Y = -0.06 + 0.296X$, and the correlation coefficient, r, is .91.

to have begun with the deficit of 1968. Recent reports indicate that rainfall rates returned to normal in 1974 and apparently have remained so through 1975. The mean aerosol concentrations at Barbados during 1972 to 1974 were about three times those for the years before the drought (that is, before 1968). The aerosol data for 1975 and a preliminary analysis of samples from 1976 suggest that the aerosol concentrations are returning to predrought levels. (See note added in proof.)

The increase in aerosol concentration at Barbados does not in itself prove that an increase had occurred in the aerosol output of Africa. It can be argued that the trend at Barbados is simply a consequence of large-scale changes in atmospheric circulation over the Atlantic, which could affect transport patterns (*10–12*). However, there is evidence that the increase at Barbados is indicative of a general trend over the equatorial North Atlantic. In the summer of 1974, we deployed a network of aerosol and atmospheric turbidity stations across this region as a part of the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) (*13*). One such station was situated in the Cape Verde Islands (16°45′N, 22°55′W) 600 km off the coast of Africa. Turbidity was measured with Volz-type sun photometers (*14*) manufactured by F. E. Volz and calibrated against Environmental Protection Agency standards (*15*). The arithmetic mean Volz turbidity at 500 nm was 0.325 for July (number of days $N = 24$) and 0.291 for August ($N = 22$). Our 1974 values are equal to the maximum mean monthly values for a large, heavily industrialized urban area such as Baltimore, Maryland (*14*). Volz (*16*) has presented turbidity data from the same region for July and August 1964; he obtained means of 0.171 ($N = 24$) and 0.146 ($N = 26$), respectively—approximately half our values.

Table 2. Mean mineral aerosol concentrations for the months of June, July, and August at Barbados, and rainfall in the Sahel expressed as a percentage of the 1931–1960 mean (*8*) and the 1941–1970 mean (*9*). Geometric means were calculated using samples grouped on a bidaily basis except for 1972 and 1973 and part of 1971 when samples were processed on a weekly basis; consequently, both the 1972 and 1973 geometric means will be somewhat higher than bidaily values, but the difference should be less than 15 percent. The geometric mean for 1971, given in parentheses, was calculated only from July samples on a bidaily basis; the August samples were processed on a weekly basis and could not be meaningfully incorporated into the mean.

Year	N	Aerosol concentration ($\times 10^{-6}$ g m^{-3})		Rainfall (%)	
		Arithmetic mean	Geometric mean ± S.D.	Data of (*8*)	Data of (*9*)
1965*	18	6.2	4.3 ± 2.8	101	106
1966	88	7.5	4.5 ± 3.2	85	94
1967	83	13.8	11.0 ± 2.0	107	92
1968	90	6.0	3.9 ± 2.9	72	79
1969	77	11.9	8.0 ± 2.5	98	92
1970†	29	16.2	7.8 ± 3.6	97	82
1971‡	60	14.4	(17.3) ± 1.6	74	84
1972§	74	14.4	12.5	69	62
1973§	98	26.5	24.4	65	
1974	88	24.4	19.1 ± 2.1		
1975	90	14.2	11.1 ± 2.1		

*August only. †July only. ‡July and August only. §Means were calculated on a weekly basis.

In order to calculate the atmospheric concentration of aerosol and the total loading along the optical path, it is necessary to have detailed knowledge of the radiative properties of the aerosol and the size distribution. However, it appears (*13, 15*) that these characteristics have not changed significantly; thus we can infer from the 1974 turbidity data that the mean aerosol loading was approximately double that of 1964.

We next address ourselves to the question of the basic causes of the increased aerosol transport. The increase could be attributed to meteorological factors other than reduced rainfall associated with the drought—for example, stronger winds, increased gustiness, and altered circulation patterns (*10–12*). However, the causes of the drought in North Africa are the subject of considerable controversy, which cannot be readily resolved because of the very limited data base in this region. In any event, it is our belief that the increased aerosol transport may be principally rainfall-related. We base our conclusion on the fact that there was a lag of several years between the onset of the drought in 1968 and the period of maximum transport, 1972 to 1974. We interpret this delayed response as the time required for the drought-stricken soils to degenerate to the point where they are easily erodible.

What, then, is the source of the drought-related aerosol? There is no question but that much of this aerosol material is normally derived from established deserts. During GATE, in the summer of 1974, SMS-1 satellite coverage was available for West Africa and the equatorial Atlantic; the excellent product from this satellite enabled us to identify the source areas of some of the major dust outbreaks. The most visible sources were those north of about latitude 20°N; this region was generally free of cloud and, in the infrared photographs, dust outbreaks stood out clearly against the deep black of the hot desert surface. The most active source was the

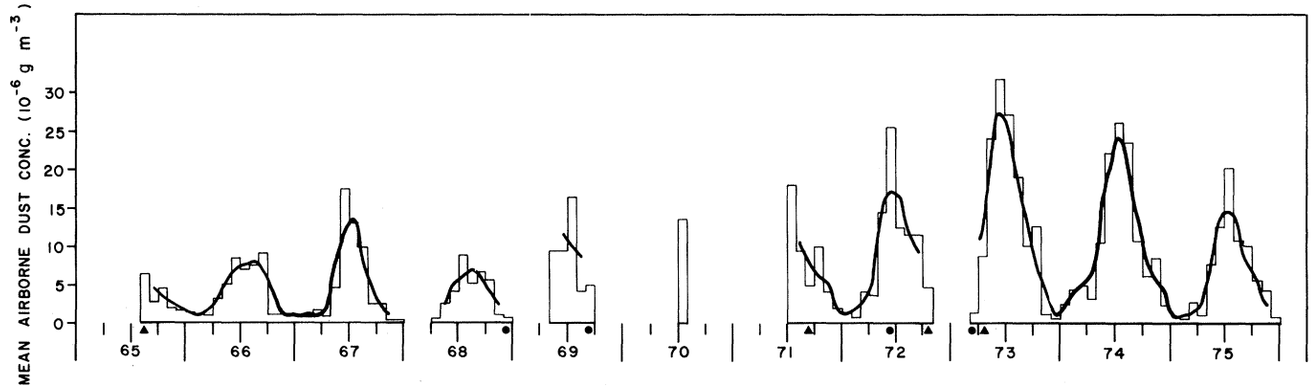

Fig. 2. Arithmetic mean monthly mineral aerosol concentration at Barbados. Each monthly value is based on a minimum of 21 days of continuous sampling except for (▲) 15 to 20 days and (●) 10 to 15 days. Months for which less than 10 days of data are available are not plotted. Dust concentrations for the period August 1965 to April 1966 were calculated from data in (*5*) and those for May to September 1966 from unpublished data supplied by A. C. Delany [see also (*5*)]. The curve depicts the 3-month moving arithmetic average.

vast dune system that extends from south-central Algeria, west of the Ahaggar mountains, to the coast of Mauritania; 15 outbreaks occurred here during GATE. Although these Saharan outbreaks were the most dramatic, the sources to the south, in the frequently clouded Sahel, appeared to be more persistent. The SMS-1 infrared photographs consistently showed large, gray-toned areas, suggestive of dust, between areas of heavy cloud buildup. Indeed, the association of the dust with deep convection suggests a causative relationship.

The precipitation in the region of the active dune system discussed above is extremely variable, a common characteristic of deserts, and the mean annual precipitation is well under 100 mm. Under such conditions, it is difficult to determine quantitatively the occurrence of a drought and even more difficult to ascertain the effects of such an occurence. However, it seems unlikely that the mobility of the dunes would be greatly affected. An alternative source of the drought-related aerosol is the Sahel. It is clear that the desert is spreading to this region. Opinion is essentially unanimous that the present-day spread of desert conditions in Africa, and elsewhere in the world, is due to poor land-use practices in the arid and semiarid regions bordering the deserts (*17, 18*). Because of population growth and economic pressure, there is a tendency to develop these regions during periods of increased rainfall. These activities include increased grazing, plowing, and cultivation of new land, and wood collection around new camps and settlements. This appears to be the case in the Sahel, where there was an extended period of abnormally high rainfall during the 1950's and of normal rainfall during the early 1960's (*8–10*). Over this 20-year period, the way of life in this region changed radically, as did land-use practices (*18, 19*). It appears that, of these practices, the raising of livestock is probably the only anthropogenic activity carried out on a sufficiently large scale to influence aerosol generation significantly.

We believe that our measurements are the first to quantitatively document a major change in atmospheric aerosol concentration that might be related to a variation in climate through its effect on aerosol generation and transport on a macroscopic scale. However, aerosols can, in themselves, affect weather and climate by several mechanisms, one of which is the altering of the radiative properties of the atmosphere. Reynolds *et al.* (*20*) found that, in the Barbados area, the absorption of solar radiation in a cloud-free troposphere could be as much as 100 percent greater in the presence of Saharan aerosols. The reduced net cooling rate may be a significant factor in explaining the persistence of the inversion that defines the base of the SAL, a feature that is still recognizable on meteorological soundings from the Caribbean and at Miami (*3*). This inversion at the SAL base severely inhibits the development of deep convection over large areas of the Atlantic; indeed, it is the relatively cloud-free character of the SAO's that makes it such a simple matter to track the movement of the outbreaks over the ocean by means of satellite photographs (*3, 21*). The inhibition of convection over such a large area has important implications. The equatorial regions receive a disproportionately large fraction of the solar radiation reaching the earth's surface, and much of this energy is transferred to the atmosphere as sensible and latent heat (the latter as water vapor), which are subsequently transported to the higher latitudes. Atmospheric convection, especially the deep convection associated with cumulus cloud, plays a critical role in this transfer process (*22, 23*).

If the increased dust transport is due principally to poor land-use practices and if the dust does modify the radiative properties of the atmosphere to a significant degree, as experiments appear to indicate, then this may be the first relatively clear-cut case study of a possible anthropogenic impact on weather (and perhaps climate) on a macroscopic scale. However, at this time we cannot determine to what degree the observed aerosol increase is attributable to natural physical processes.

Note added in proof: The complete analysis of samples for June, July, and August 1976 yields the following: arithmetic mean, 12.3×10^{-6} g m^{-3}; geometric mean ($\pm$ standard deviation), 10.8 ($\pm$ 1.7) $\times 10^{-6}$ g m^{-3}; $N = 92$.

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6. The mass collection efficiency of the dibutoxyethyl phthalate–impregnated IPC 1478 filters at the filtration velocities employed in our studies is essentially 100 percent for African mineral aerosols. The efficiency was determined in a series of comparison studies with Whatman 41 filters. The mineral aerosol weight on the filter was measured by ashing the filter at 500°C after first extracting the water-soluble materials. The IPC efficiency, measured in this manner, is 0.97 with a standard deviation of 0.19. The IPC filter ash blank is 0.04 mg; generally, the mineral residue sample size is large relative to the ash blank and the analytical uncertainty is less than a few percent.
7. The distribution of mass concentrations for the mineral aerosol is accurately described by the sum of two lognormal distributions (*13*). The dominant mode is attributable to Saharan aerosol associated with major identifiable SAO's; the minor mode may be due to the combined influences of background aerosols from the high latitudes and from Africa.
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23. The dust may also affect cloud growth at the microphysical level. Measurements made within the SAL during the GATE in the summer of 1974 [H. Weickman, in *Preliminary Scientific Results of the GARP Atlantic Tropical Experiment* (GATE Report No. 14, World Meteorological Organization–International Council of Scientific Unions, Geneva, 1975), vol. 2, p. 145] showed that the concentration of ice nuclei active at −20°C was often in the range of 10 to 100 per liter; these values are considerably higher than typical continental values, which are generally less than 1 per liter. Thus the ingestion of dust-laden air into deep cumuli should result in rapid glaciation above the freezing level; this process could explain the very prominent cirrus outflows that were so commonly observed over the eastern Atlantic.
24. We thank C. Shea of Barbados for his services in operating our station and Judge and Mrs. G. L. Taylor and E. S. Manning, all of Barbados, for permitting us to establish our facilities on their properties. We also thank A. C. Delany, A. C. Delany, and D. W. Parkin for providing us with the previously unpublished aerosol data used in Fig. 2 and for their assistance in establishing the aerosol program at Barbados. This work is supported by grant DES70-00289 A03 from the National Science Foundation. Contribution from the Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Fla.

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