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Long-range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the southeastern United States

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ABSTRACT **Soil dust is a major constituent of airborne particles in the global atmosphere. Dust plumes frequently cover huge areas of the earth; they are one of the most prominent and commonly visible features in satellite imagery. Dust is believed to play a role in many biogeochemical processes, but the importance of dust in these processes is not well understood because of the dearth of information about the global distribution of dust and its physical, chemical, and mineralogical properties. This paper describes some features of the large-scale distribution of dust and identifies some of the geological characteristics of important source areas. The transport of dust from North Africa is presented as an example of possible long-range dust effects, and the impact of African dust on environmental processes in the western North Atlantic and the southeastern United States is assessed. Dust transported over long distances usually has a mass median diameter <10 μm. Small wind-borne soil particles show signs of extensive weathering; consequently, the physical and chemical properties of the particles will greatly depend on the weathering history in the source region and on the subsequent modifications that occur during transit in the atmosphere (typically a period of a week or more). To fully understand the role of dust in the environment and in human health, mineralogists will have to work closely with scientists in other disciplines to characterize the properties of mineral particles as an ensemble and as individual particles especially with regard to surface characteristics.**

There is increased interest in the properties of small airborne particles (aerosols) because of the role that they play in many environmental processes. Much of this interest stems from the possible impact of aerosols on climate-related processes that involve radiation and clouds. For this reason, aerosol studies have focused on the chemical and physical properties of aerosols that relate to radiation and to hygroscopic behavior. For many years, research efforts have mainly focused on anthropogenic aerosols, especially sulfate aerosols. Sulfate receives most attention because humans have massively affected the global cycle of atmospheric sulfur mainly through emissions from combustion sources (the burning of fossil fuels, oil and coal) and because the physical and chemical properties of sulfate particles make them especially efficient for affecting radiation propagation in the atmosphere and cloud nucleation (1).

Humans have lived with pollutant aerosols for a relatively short time in their history, since the beginning of the industrial age. In contrast, humans have lived with wind-borne mineral dust over the entire course of their history on earth. This long history can be clearly read from the record retained in ice and snow cores and in deep sea sediments. These show that the concentration of dust has varied over an extremely wide range through time and that dust activity can change very abruptly. Here, I focus on the present-day transport of mineral dust to better understand the processes that affect transport and the possible environmental effects.

Soil dust transport has a number of implications for humans. At the most fundamental level, the history of human agriculture has been closely tied to loess deposits. Most loess soils are comprised of mineral particles that are largely derived from till and outwash at the front of glaciers (2). Winds generate dust clouds; the larger-sized particles (tens of micrometers in diameter) because of their high settling velocity are deposited relatively rapidly (generally within hundreds to a thousand kilometers of the source) to form deep blankets of soil. Such soils can be extremely fertile and easily tilled. They lie predominantly in the mid-latitudes, where weather tends to be favorable for agricultural pursuits (relatively mild temperatures, a long growing season, adequate rainfall). Massive loess deposits are found throughout Europe and Asia in regions that saw the development of many of the early civilizations. In the new world, the loess deposits of the Midwestern United States and in southern South America supported a highly productive agriculture that facilitated colonization and rapid economic development.

The generation and transport of dust are processes that continue to this day, playing an important role in geochemical and geophysical processes, including the addition of nutrients to soils and to the oceans (1).

More recently, there is a new focus on the effects of aerosols on human health. The Environmental Protection Agency (EPA) is required by the Clean Air Act to set standards for air quality at levels that protect public health. To this end, the EPA has established a new standard that focuses on particles <2.5 μm in diameter; only these small particles can efficiently penetrate into the lungs. It has long been known that, in certain industrial environments (e.g., mines, factories), there were clearly identifiable health effects associated with specific minerals (e.g., silica, asbestos). However, a substantial fraction of wind-borne soil dust is found in this "respirable" size range. Thus, we must consider the possible impact of ambient mineral dust on human health.

Because the most effective particles from the standpoint of radiation, nucleation, and health are those with diameters of a few micrometers or less, they will have a relatively long lifetime in the atmosphere with respect to gravitational settling—in the absence of precipitation removal, on the order of

Abbreviations: EPA, Environmental Protection Agency; AOT, aerosol optical thickness; AVHRR, Advanced Very High Resolution Radiometer; TOMS, Total Ozone Mapping Spectrometer; AI, aerosol index.

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several weeks. During this time, they can be transported thousands of kilometers by winds. To assess the impact of such particles on climate, biogeochemical process, and health, we must have a good understanding of the sources of the particles, the processes that affect dust mobilization and transport, and the consequent global distribution.

I review various aspects of dust transport and show that mineral particles can have a clearly discernable impact on atmospheric properties at great distances from the source. I discuss the global scale distribution of dust and the factors that affect its mobilization and long-range transport, including geological and geomorphological factors. Then, I focus on dust transport over the North Atlantic, showing how dust transport varies on a temporal and spatial scale. As an example, I present data from South Florida that show that African dust comprises an important part of the ambient aerosol, that it plays an important role in air quality, and that it has implications regarding geochemical processes and human health. Finally, I summarize those aspects of long-range dust transport that are poorly characterized and warrant further study.

The Global Scale Distribution of Mineral Dust

Studies performed over the past few decades have clearly established that large amounts of soil dust are mobilized by winds, mostly in arid regions, and that substantial quantities can be carried great distances (reviewed in refs. 2–7). Many aspects of global scale mineral dust mobilization and transport are summarized in an excellent review by Duce (8). I (9) review dust transport to the global ocean. Guerzoni and Chester (10) present papers focusing on African dust transport with emphasis on the Mediterranean. The volume by Leinen and Sarnthein (11) contains papers on dust studies relevant to paleoclimatic interpretations.

Satellites can give an excellent picture of the transport of dust and other aerosols on a global scale: e.g., Fig. 1 shows the global distribution of aerosol optical thickness (AOT) as estimated from the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (AVHRR) (12). AOT is estimated from backscatter radiation measurements made at an effective wavelength of 0.63 μm; high values of AOT usually indicate high concentrations of suspended particles. Because the AOT algorithm requires that the underlying surface has a low and constant albedo, AOT measurements can only be made over oceans. Fig. 1 shows the mean AOT distributions for July. The most prominent features in the figure are the very large ''plumes'' of high values of AOT that extend westward from the coast of Africa and eastward from the Middle East. The plume emerging from the west coast of North Africa is unambiguously attributable to dust whereas that off the west coast of South Africa is attributed to biomass burning. The high values of AOT over the Arabian Sea are due to dust transported from the Middle East.

There are examples of other types of plumes that show somewhat elevated values of AOT but are not nearly so prominent, coherent, or persistent as the plumes attributed to dust and smoke. In particular, in July, pollutant aerosols over the North Atlantic appear as a plume that emerges from the east coast of North America and the west coast of Europe and also along the east coast of Asia. Nonetheless, the effects of pollutant aerosols (as interpreted from AVHRR) are modest in comparison to the dust and biomass burning aerosols.

Unfortunately, AVHRR (and other satellites operating in the visible spectrum) cannot be readily used to obtain information about specific source areas because of the restriction of the algorithm to ocean surface retrievals. Recently, the Total Ozone Mapping Spectrometer (TOMS) instrument has been used for detecting absorbing aerosols based on the spectral contrast at 340 and 380 nm in the upwelling ultraviolet spectrum (13). TOMS is sensitive to UV-absorbing aerosols such as mineral dust, volcanic ash, and soot aerosol from fossil fuel combustion sources and biomass burning. Because the UV surface reflectivity is typically low and nearly constant over both land and water (14), TOMS can detect aerosols over continents as well as oceans (15). The UV spectral contrast can be used in a nonquantitative way as an aerosol index (AI). The

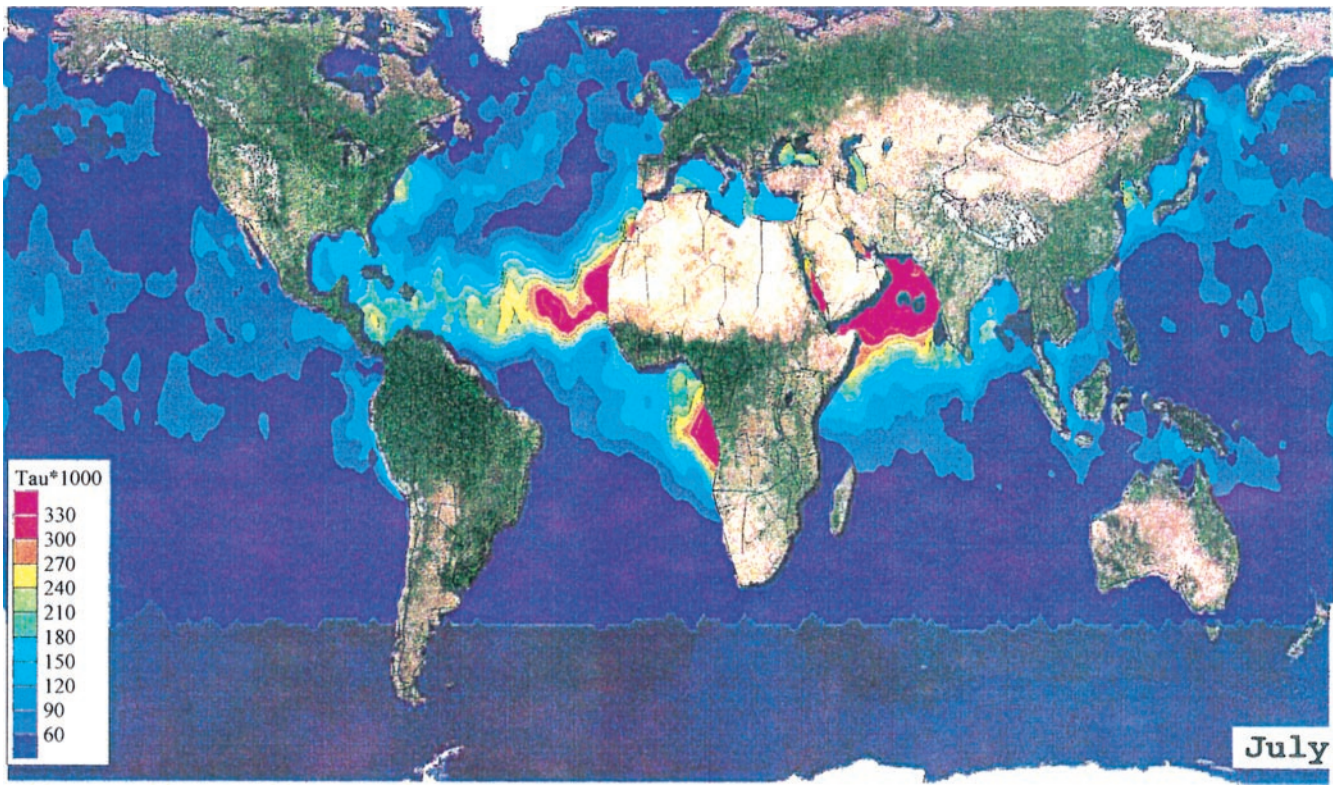

FIG. 1. AVHRR aerosol optical depth, mean for July, 1988 through July, 1989. (R. Husar, personal communication; see also ref. 12.)

temporal and spatial variability of TOMS AI has been matched to specific types of absorbing aerosols and with known sources: for example, specific volcanic eruptions, forest fires, and large dust events (15–17). Fig. 2 *a* and *b* shows global distributions of the frequency of occurrence of relatively high TOMS AI values for the months of January and July, 1984 (15).

A comparison of Fig. 2 with Fig. 1 shows that there is a good conformity between the plumes located over the oceans. An exact match is not expected because the data in Fig. 1 are mean values of AOT, whereas Fig. 2 shows the frequency of occurrence of elevated values of TOMS AI. Also, the AI is not a quantitative measure of aerosol concentration. TOMS is sensitive to a number of aerosol physical properties and, of most importance, to the altitude of the aerosols layer (13).

Dust Sources and Regional Characteristics

Fig. 2 also provides information about the distribution of dust (and smoke) over land, and, of most importance, it yields clues about the location of dust sources. The most striking feature is that the greatest number of sources and the most active ones are distributed across a band of arid regions that extends from the west coast of North Africa, across the Middle East, and into central Asia. [Because most dust sources have a strong seasonal activity pattern, they will not necessarily be visible in the two examples shown in Fig. 2. Many of the patterns discussed here are visible in the figures presented in Herman *et al*. (15), where they show maps identical to those in Fig. 2 for each month of 1984 and 1988.] In contrast, there are many arid regions, including deserts, that do not show any significant dust activity. It is notable that there are no prominent dust plumes associated with any of the southern hemisphere arid regions, including the deserts in Australia, the Kalahari and Namib deserts in southern Africa, and the Atacama and Patagonian deserts in South America. (Note also the absence of any evidence of persistent absorbing aerosol production and transport over the heavily industrialized and developed regions of North America and Europe.) This is not to say that there is no dust mobilization in these regions. Indeed, the daily TOMS AI product shows relatively large-scale dust episodes in regions where one might expect to see them—for example, in the southwestern United States (15)—but the frequency is relatively low and the AI values tend to be small.

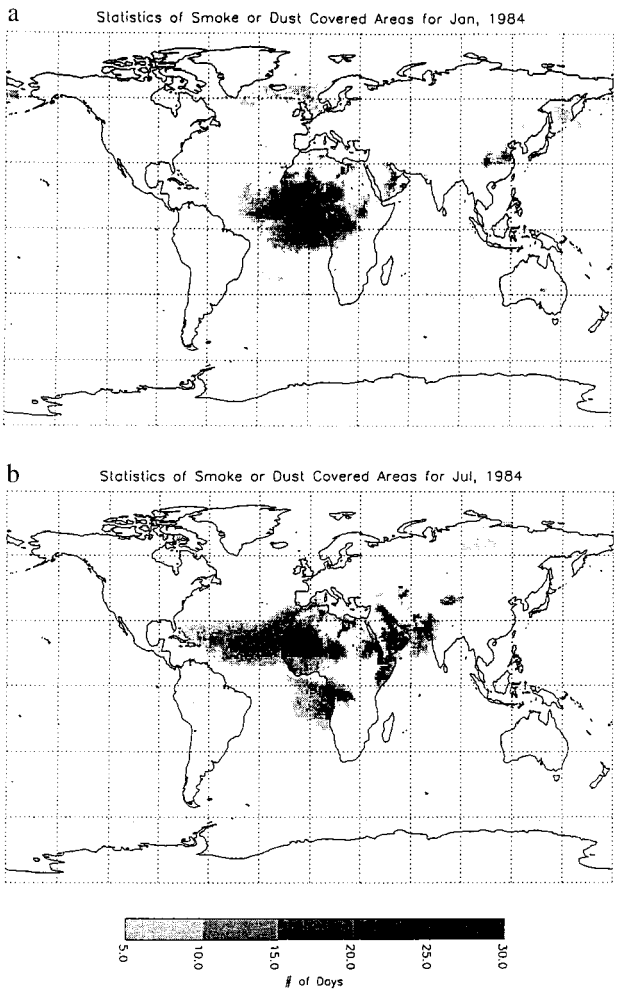

FIG. 2. Statistics on the occurrence of high values of TOMS aerosol index. The shaded area shows the number of days (lightest shading, 5–10 days; heaviest shading, 25–30 days) when moderate-to-high concentrations of absorbing aerosol were detected by the TOMS/NIMBUS-7 satellite. (*a*) January, 1984. (*b*) July, 1984. (Figures adapted from ref. 15, figure 4.)

The other striking feature in Fig. 2 is that some regions stand out as persistent dust sources. Although many source regions are obscured by dense dust plumes (for example, in West Africa, where high concentrations of dust are present almost continuously), many areas are clearly visible as well defined geometric patterns that persist from year to year. These features can often be linked to specific geographical locations. For example, in Fig. 2 *a* and *b*, a large circular pattern is located at the eastern end of the North African dust plume. This area coincides with the Chad basin. Between 5,000 and 10,000 yr ago, when the climate was more humid, Lake Chad was much larger (Mega-Chad); its surface was 320 m above sea level compared with 200 m today (18). The floor of the former lake now forms a monotonous desert plain with dunes, shallow wadis, and salt flats (18). The soils in this region are readily deflated and dust storms are quite frequent throughout the region (19). In addition to anecdotal evidence, visibility reports (20) confirm the extremely high frequency of dust storms and low visibility in this region, and they show the same seasonal pattern that is seen in TOMS. The dense Harmattan dust clouds that affect the coastal regions of the Gulf of Guinea during the winter have long been attributed to dust transported largely from the Chad basin, especially in the northern region, in the Bodele Depression (19). The TOMS AI product does indeed show that this region is persistently active and is the source of the consistently high AI values; furthermore, an inspection of daily TOMS AI images shows that, within the Chad basin, the highest AI values are obtained in the region of the Bodele depression.

Other active areas are visible in Fig. 2 *a* and *b*. In northwest North Africa, there is an active spot in Tunisia and northern Algeria, on the south side of the Sahara Atlas mountains. Two large chotts (salt lakes) are located in this region, which is part of a large depression that was formerly an arm of the sea and that extends 400 km westward from the Gulf of Gabes. The chotts, which receive runoff from the mountains, are covered with water only in the lowest areas, except after periods of heavy rains. Thus, large areas of chott sediments are frequently exposed and subject to deflation. The dust sources observed by TOMS are most likely associated with these features. There is a persistently active region in northeastern Libya and western Egypt.

In West Africa, persistent dust features appear on the western flanks of the Ahaggar mountains. In Fig. 2*b*, there is a prominent area in northeastern Sudan between 30°E and the Red Sea and flanked to the southwest by the Ethiopian Highlands. Other well defined source patterns are visible on the Arabian Peninsula extending up the Tigris-Euphrates region. A persistent feature is seen in the Aral Sea region. Finally, there is a well defined feature in western China, north of the Indian subcontinent; this is located in the Tarim Basin between the Tibetan Plateau and the Tian Shan Mountains.

Many of the dust sources visible in TOMS have a sharply defined geometry that appears to be determined by characteristics of the topography. There has been considerable discussion and debate for many years about the types of terrains and environments that can serve as a source of fine-grained dust. Pye (ref. 2, pp. 65–73) identifies (among others) wadi sediments, lake and playa sediments, alluvial fans, and alluvial floodplain sediments. Although field investigations have validated these source types at specific sites, it has been difficult to extrapolate to larger scales. For example, Herrmann *et al*. (19) summarize the reported locations of dust activity in North Africa; these would appear to suggest that, in effect, almost all of North Africa is a source of dust. This observation may be literally true at ground level. But TOMS suggests that, from the standpoint of large-scale dust events and long-range transport, some sources are much more active and effective than others.

The source terrains identified by the TOMS satellite appear to be generally consistent with those listed in Pye (2). These implied source areas have a number of features in common. They are located in arid regions. Many prominent sources are found in well known ancient sedimentary basins (e.g., Mega-Chad, Tigris-Euphrates) (18). A common characteristic of the TOMS sources is that they generally lie in topographical lows that currently receive runoff from surrounding highlands. The association of the TOMS-identified dust sources with such topographical features suggests a mechanism that could explain the activity of these sources. Precipitation in the highlands weathers rocks and soils. Fine particles are carried downstream to the basin and are deposited in river channels and wadis; in the dry season, the deposits become exposed, dry out, crack, and flake. When the wind velocity increases, the disrupted soil surface is easily deflated, and clouds of fine-grained dust are carried away (21).

Although many sources can be identified in TOMS, there are large regions where the sources are obscured by persistent dust clouds during much of the year—in West Africa and the Arabian Peninsula, for example. In some cases, TOMS shows active sources that cannot be readily associated with topographical lows nor with readily identifiable sources of runoff. Nonetheless, it is reasonable to assume that the dominant dust sources in such regions will most likely have the same environmental attributes as the visible sources cited above and those listed in Pye (2).

On the other hand, other types of hypothesized sources are not validated. For example, Pye (2) specifically mentions stony deserts and uses the Gobi as an example. TOMS does not show the Gobi as a major dust source (see below). Furthermore, Fig. 2 shows that many regions that would seem to provide favorable conditions for dust activity are, in fact, free of significant sources. This suggests that there are other factors involved. In Australia, for example, the absence of significant dust activity might be attributable to character of the soil particles. Kiefert *et al*. (22) compare Saharan and Australian dusts. Australian suspended dusts display particle size modes between 8 and 12 μm that are surprisingly uniform in time and space. In contrast (and in agreement with the discussion above) dusts collected in Mali (West Africa) were much finer, with a mode at 2–3 μm. Australian soils and sediments tend to be highly aggregated, with large quantities of clay pellets. On the basis of the TOMS product, we conclude that aridity is a necessary, but not sufficient, characteristic of dust sources.

It is also informative to compare the distribution of dust sources with the distribution of loess deposits (e.g., ref. 2). In general, the geographical distribution of dust sources is distinctly different from that of loess deposits. This leads to the conclusion that loessal soils do not seem to consistently supply substantial amounts of dust to the atmosphere under present day conditions. There are certainly some loess deposits, especially those in the People's Republic of China, that appear to be the source of major dust events (23). Although these may have a widespread and significant impact on air quality and geochemical processes, they are sporadic events and they are limited to the spring months. Also, dust activity may be aggravated to a large extent by human activity, especially agriculture. As pointed out above, in China, the Tarim Basin is the most persistent feature in the TOMS AI. In contrast, the Gobi Desert, which lies to the northeast of the Tarim Basin, does not appear to be a major source of long-range dust, contrary to common belief. This should not be too surprising because the Gobi is predominantly a stony desert, with only 5% covered with sand dunes; indeed, the name "Gobi" in Chinese means "gravelly, pebbly plain."

Processes in Dust Source Areas

In order for mineral dusts to be carried great distances, it is necessary that a substantial fraction of the deflated dust has a size under $\approx$10 μm in diameter. The limitation of the source dust to this size range has implications regarding the weathering processes by which particles of this size are produced and also about the consequent physical, chemical, and mineralogical properties of "long-range" dust. The association of dust sources with topographical lows is consistent with the abundance of fine-grained soil material. We would expect that the soil particles will be highly weathered; the particle surface can be physically abused, and it may have acquired surface coatings (e.g., iron oxide deposits, adhering flecks of very fine clay particles). In the case of clay minerals, the lattice structure may be distorted through removal or substitution of elements. In short, we should not expect to see fresh mineral entities.

Contrary to general belief, sand dunes are not usually good sources of fine particles. This point is emphasized by the observation made above that the TOMS sources are associated with topographical lows that suggest that wet processes are important. This is not to say that substantial amounts of dust are not (or could not be) generated from sand dunes but, rather, that other types of sources are clearly important.

The size distribution of the deflated dust is a strong function of many factors, including the physical properties of the soil matrix (e.g., the size distribution of soil particles, soil moisture, cohesiveness), the condition of the surface (e.g., whether it has been disturbed, the degree of protection afforded by vegetation), and the characteristics of the wind field above the surface (21). Studies of dust mobilization in soils from arid regions show that particles $<$10 μm in diameter can be released in large numbers. For example, measurements in Mali, West Africa, show a bimodal distribution with one mode at 44 μm in diameter and another at 5 μm; the large particle mode is attributed to relatively localized sources, and the 5-μm mode is attributed to long-distance transport (24). Measurements in dust storms in Tadzhjikistan show a substantial mass mode in the size range $<$10 μm; at a distance of 100 km downwind of a dust source, the dust mass peak was in the range 2–5 μm in diameter (7). In a study of windblown dust from agricultural fields in the Pacific Northwest, Clairborn *et al*. (25) compared size distributions during windy conditions with those during nonwindy conditions. They found that concentrations in the size range of 1–10 μm in diameter increased by as much as a factor of 5.

A substantial fraction of the wind-borne dust particles are in the size range $<$1.0 μm in diameter. These are released from the soil by a "sandblasting" process (26). SEM studies show that the larger (1–10 μm) airborne particles are often coated with clay-like platelets (see also ref. 1). The impaction of wind-driven large particles dislodges the fine particles. Studies in wind tunnels using different types of soils (27) show that the concentration of submicrometer particles increases sharply when the wind velocity attains a threshold value that imparts

enough momentum to impacting particles to effect the dislodgment of the fine particles.

Given the fact that the suspended dust has such a small mass median diameter, we would expect that the composition will be largely determined by the composition of the small particles in the soil and that clay minerals will be strongly represented. Schütz (28–29) reviews the literature on the mineralogical composition of African dusts. He shows that the dominant clay minerals are illite and kaolinite with additional amounts of smectite, montmorillonite and chlorite. Quartz and calcite are also important. As one might expect, there are regional differences in the composition that reflect the regional differences in geology and weathering processes. For example, kaolinite is more prominent in dust from the low latitudes of West Africa, and illite is more prominent in dust from the northern regions, toward the Mediterranean coast; this latitudinal distribution is consistent with the idea that kaolinite is a favored weathering product in warm, humid environments (e.g., the tropics), whereas illite is a product of midlatitude weathering conditions. This latitudinal distribution of illite is observed in dust collected over the world oceans (3). Schütz also shows differences in the composition of eastern North African dusts versus western dusts. Nonetheless, the dusts derived from sources within relatively large regions have a relatively uniform mineralogical composition. Caquineau *et al.* (30) show that, in wind-borne dusts over the eastern tropical Atlantic, the illite/kaolinite ratios fall into consistent patterns; in contrast, the amounts of quartz can vary widely and show no regional pattern. Although some regional mineralogical differences are noted, in general, these differences are not great. As a consequence, it is difficult to identify unique characteristics that would allow for a straightforward and unambiguous attribution to specific source regions (31–32).

The elemental composition of North African dust is also rather homogeneous. If one normalizes composition data to Al or Fe (29), one finds that, for the vast majority of elements, the ratios are quite close to those of average crustal abundances (i.e., generally within a factor of about 0.5 to 2–5). Much higher ratios are found for some elements that are known to have substantial anthropogenic sources (e.g., Zn, As, Sb, etc.); also, the size distribution of these elements is shifted strongly to the submicrometer fraction, as one might expect for pollution sources (33) in contrast to the soil-derived elements, which peak in the supramicrometer size range.

The uniformity in dust composition reflects the fact that the mobilized fraction of the soil is a highly weathered product that has been derived from number of sources in the region. Dust-sized particles in soils have gone through repeated cycles of mobilization and deposition, mixing with materials from other regional sources. Thus, dust that travels across the Atlantic is the homogenized product of a long chain of geological, weathering, and meteorological processes.

African Dust Transport to Miami: An Example of Possible Air Quality Issues

General Characteristics of Miami Aerosols. Thus far, I have discussed the general character of dust sources and some of the characteristics of the aerosols generated in those regions. Here, I report on the properties of dust after it has been transported across the North Atlantic, a distance of at least 5,000 km from the sources in North Africa. I focus primarily on measurements made in Miami, Florida, where continuous daily aerosol measurements have been made at a coastal site since 1974 (34). This data set may well be one of the longest records of daily aerosol composition measurements in the U.S. Data for the years 1989–1996 (Fig. 3) show a clear seasonal periodicity, with the maximum dust concentrations in June, July, and August. This temporal pattern is consistent with that

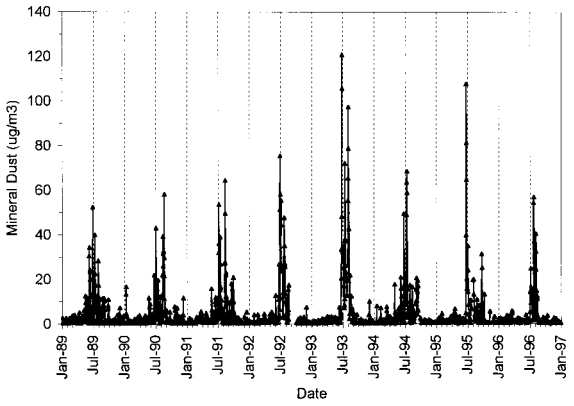

FIG. 3. Daily mineral dust concentrations in Miami, 1989 to 1996. Measurements are made at a coastal site during on-shore wind conditions.

seen in the satellite products, AVHRR (ref. 12; Fig. 1) and TOMS (ref. 15; Fig. 2).

Dust episodes usually extend over several days or more; given the persistence of the trade-wind flow, this suggests that the scale of the dust events is on the order of several hundred to 1,000 km; this scale is consistent with satellite depictions of aerosol distributions over the western North Atlantic and the Caribbean (Figs. 1 and 2) (12, 15). Thus, measurements of aerosol concentration and composition in Miami should be representative of a very large region.

The seasonal pattern of dust concentrations in Miami is similar to that at Barbados, West Indies (13° 15′ N, 59° 30′ W), where the University of Miami aerosol group has carried out a continuous sampling program since 1965 (35–37). Fig. 4 shows the Barbados and Miami dust record for the period 1989 to 1996 (34). The major differences between the records from the two sites are that the dust concentrations are consistently higher at Barbados and that the dust transport season on Barbados is longer than that in Miami, where transport starts later in the year and ends earlier. As a result, the annual mean concentration at Barbados is ≈2.5 times that in Miami (9). The mineralogical composition of dust collected in the western Atlantic is identical to that collected off the coast of Africa (38); the dominant constituents are clay minerals and quartz.

Long-Term Record and Relation to Climate. Summer dust transport has been a persistent feature throughout the 23 years of measurements in Miami, 1974 to 1996, as shown by the monthly mean dust concentrations in Fig. 5 (34). Nonetheless,

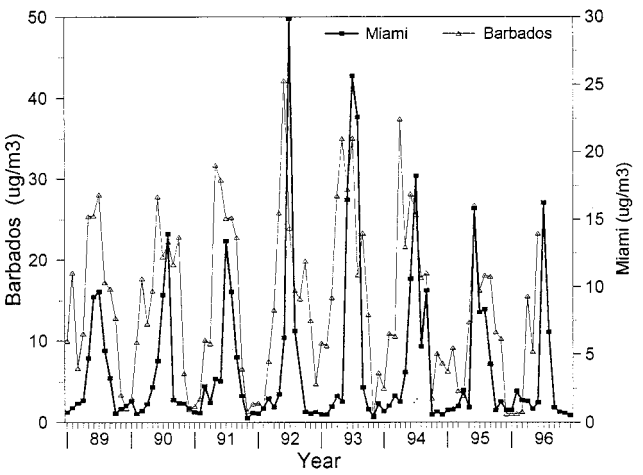

FIG. 4. Monthly mean mineral dust concentrations at Barbados and Miami for the period 1989 to 1996. (Note the difference in the scales for Barbados and Miami.)

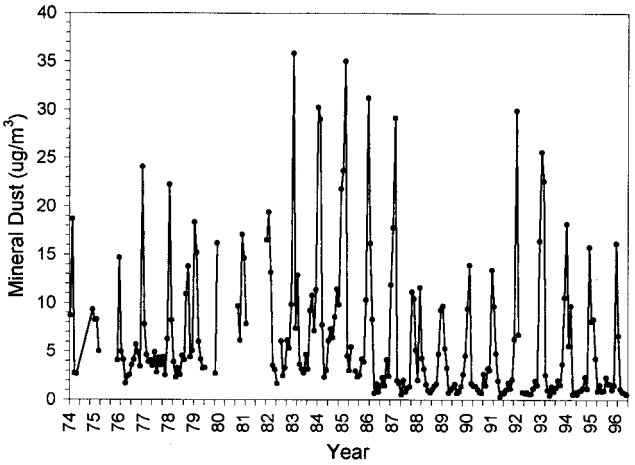

FIG. 5. Monthly mean dust concentrations measured in Miami, Florida, for the period 1974–1996.

there are very substantial variations in dust concentration over this period. Concentrations were consistently high during the period 1983–1987. The early 1980s was a time of severe drought in North Africa. Previous work has shown that summer dust concentrations measured in the trade winds at Barbados are anticorrelated with rainfall in the sub-Saharan (Sahel) region of North Africa (35, 39). In this regard, note that the highest monthly mean dust concentrations in Miami were obtained in 1983, the year after the onset of one of the most intense El Niño events in recent history; a similar sharp increase in dust also was observed on Barbados (35). The longer-term variability of dust transport could be linked in a complex way to other climate variables, such as the North Atlantic Oscillation (40).

Size Distributions. In the discussion of dust properties in North Africa, it was noted that there was a clearly identifiable mode in the mass distribution in the size range below 10 μm. Measurements over the western North Atlantic show that the dominant size in the mass distribution is in the range of several micrometers and that there is very little mass above $\approx$10 μm; thus, the larger particles have been deposited during transit. Studies on Barbados (41) and Miami (42) during African dust events show that about one-third to one-half of the dust mass was less than 2.0–2.5 μm in aerodynamic diameter. In general, the mass median diameter of mineral dust over the oceans is typically 2–3 μm (see ref. 8 for a review of the literature on the size distribution of mineral dust over the oceans).

Distribution of African Dust in the Eastern United States. The temporal and geographical extent of African dust transport to the United States is nicely depicted by Perry *et al.* (43), who studied PM 2.5 soil dust particle concentrations (based on the measured concentration of Al, Ca, Fe, Si, and Ti in twice-weekly daily samples) in a network of approximately 70 sites located in national parks and wilderness areas during the period 1992–1995. They observed that the highest individual PM 2.5 soil concentrations were associated with sites in the eastern United States during the summer, not in the arid southwest, as one might expect. Furthermore, there was a large-scale coherence in the temporal variability of the high PM 2.5 values, suggesting that they were associated with a large-scale forcing process. The elemental composition of the samples in these large-scale PM 2.5 events was distinctly different from other types of soil-dominated samples; furthermore, the composition of the samples at sites in the eastern United States during these events was identical to samples collected in the Virgin Islands. These observations are consistent with the hypothesis that the high PM 2.5 episodes were associated with incursions of African dust. Indeed, the progress of some of these dust incursions could be followed in the data as they moved from the Caribbean and Gulf of Mexico into the southern states and across the northeast United States. Independently, in a retrospective study of data from a field program held in central Illinois in the summer of 1979, Gatz and Prospero (44) noted the occurrence of unusually high concentrations of Si, Al, and other crustal elements carried by winds from the Gulf of Mexico. Concurrent mineral dust measurements at Miami show that there was a strong influx of North African dust at the same time. High concentrations of African dust are also routinely observed on Bermuda during the summer (45–46).

Geological and Geochemical Implications of Dust Deposition. Geologically and geochemically significant amounts of dust are deposited in precipitation. In Miami, rain collected during intense summer dust events can have a turbid appearance. When filtered, some rains yield a "cake" of red-brown mud (47) which, when dried and rubbed with the fingers, produces an extremely fine, rouge-like powder. In contrast, during winter rain events, there is very little sediment, and the sediment is often gray-colored and gritty, characteristics that are associated with particles derived from pollution sources and from local soils that often have a high content of calcium carbonate. Measurements of dust deposition in precipitation in Miami over a 1-yr period (1982–1983) yielded a total Al deposition rate of 0.10 $g \cdot m^{-2} \cdot yr^{-1}$ (47), which is equivalent to a mineral dust deposition rate (8% Al) of $\approx$1.25 $g \cdot m^{-2} \cdot yr^{-1}$. This deposition rate is comparable to the long-term accumulation rate of aeolian minerals in the deep sea sediments of the tropical North Atlantic (47).

When placed in the context of the meteorology and climatology of the region, it is clear that dust events are large-scale phenomena that can affect a very large region. This conclusion is supported by other studies. Landing *et al.* (48) measured the concentration of soil-related species (Al, Fe) in a network of sampling stations in Florida from the panhandle to the Florida Keys. Data show a well defined summer maximum at all sites, a seasonality that is consistent with the summer dust maximum observed at the University of Miami site (47). Concentrations were remarkably uniform during the summer months throughout the state. The deposition rate of Al in precipitation measured by Landing *et al.* (48) at five sites distributed over the length of Florida in 1993–1994 ranged from 0.062 to 0.148 $g \cdot m^{-2} \cdot yr^{-1}$ (equivalent to dust deposition rates of 0.78 to 1.9 $g \cdot m^{-2} \cdot yr^{-1}$). Almost all of the deposition of soil dust takes place during the summer months, which is also the rainy season in Florida.

Dust deposition appears to be high throughout the western North Atlantic (49). Bermuda has an extensive cover of fine-grained red clayey paleosols. Herwitz *et al.* (50) found that the Zr/Y Zr/La ratios of these soils closely resembled that of the $<$2-μm fraction of African dust; contributions from two other hypothesized sources on North America (Great Plains loess and Mississippi River Valley loess) could not be detected. Muhs *et al.* (51) concluded on the basis of elemental composition that the soils on Barbados, Jamaica, the Florida Keys, and the Bahamas that African dust was the most important contributor to the soils on all of the islands.

Mineral Dust and the EPA PM 2.5 Standard for Suspended Particles. There is renewed interest in aerosol properties because of evidence that the exposure of humans to high concentrations of airborne particulate matter can have a detrimental effect on health (52). Much evidence is based on epidemiological studies of death rates and respiratory-related hospital admissions (e.g., aggravated asthma, severe respiratory symptoms, and chronic bronchitis). Regions that have relatively high mean concentrations of particles tend to have higher rates of admissions than those with lower mean levels. Short-term exposures also appear to have an impact, as reflected in sharply increased admissions during severe pollution episodes. Until recently, the EPA standard for sus-

pended particulate matter focused on particles having a diameter of 10 μm or smaller. In July, 1997, the EPA established a new standard for particles 2.5 μm in diameter or smaller (henceforth, the PM 2.5 standard) (52). EPA's new PM 2.5 standard specifies an annual mean of 15 $\mu g \cdot m^{-3}$ and a 24-hour mean of 65 $\mu g \cdot m^{-3}$.

However, as shown above, African dust is the dominant aerosol constituent in south Florida during the summer. African air masses would, in effect, bring into the region very high PM 2.5 "background" aerosol concentrations. During dust events, the concentration of dust, coupled with particles from local emissions, could conceivably yield aerosol concentrations that exceed the EPA's recently implemented PM 2.5 standard. Thus, to account for the impact dust on air quality, it will be necessary to develop a set of diagnostic indicators for African dust, such as the mineral composition of the dust (38), its elemental composition (43–46, 50, 54), or its morphological characteristics (1). As previously stated, African dust has a remarkably uniform mineralogical and elemental composition. In contrast, locally or regionally derived dusts in the eastern United States appear to have distinctly different characteristics and a much more variable composition, as suggested by the studies of elemental composition (9, 43–44, 48).

Mineral Particles and Health. The EPA standards for airborne particulate materials are largely based on epidemiological studies of specific at-risk communities in regions that experience relatively high concentrations of anthropogenic particles and other airborne pollutants. Although these studies suggest that increased illness and morbidity are associated with increased concentrations of airborne particles, it has not been possible to unambiguously identify specific cause–effect relationships with specific components in aerosols nor to validate mechanisms by which low concentrations of particles could cause cardiopulmonary toxicity (55). Amdur (56) and Utell and Samet (55) review various hypotheses regarding mechanisms; they present evidence that suggests that aerosols coated with first row transition metals are especially efficient in producing an inflammatory response in the lungs. In particular, they suggest that surface-complexed iron can generate hydroxyl radicals in lung tissue and that these radicals have acute lung toxicity. In this regard, it should be noted that African dust particles collected on Barbados have a total Fe content of 3.4% (57). The dust particles are heavily coated with iron, which accounts for the characteristic red-brown color of filters collected during dust events. Under acid conditions, 6.2% of the total Fe content of the aerosol was readily soluble (57); thus, it might be expected that a substantial fraction of the Fe on dust could be readily mobilized in the lung once the particles are deposited on lung tissue.

The ease with which trace species are desorbed or extracted from mineral particles will strongly depend on the specific properties of the mineral particles and their weathering history. Consequently, we might expect that the health effects of dust particles could vary greatly from region to region. Thus, any strategy to address the health issues of mineral dust particles will have to incorporate studies of the properties of the mineral particles themselves.

Conclusions

The presence of high concentrations of mineral dust over such large areas of the Earth has implications in many areas of science: meteorology, climate, and biogeochemical processes. To properly assess the role of dust in these processes, we must have a better understanding of the properties of the airborne soil particles. The mass median diameter of long-range dust is generally <10 μm, typically about several micrometers. The soil particles in this size fraction usually show signs of severe chemical and physical weathering. The particle surface may be coated with oxides or salts, other particles (e.g., clays) could be attached to the surface, or the particle itself might be made up of an agglomeration of smaller particles. Consequently, particles will have very complex physical and chemical properties that cannot be elucidated by simply studying the bulk properties of the dust; individual particle analysis will be required.

Dust generation is a highly nonlinear process that is very sensitive to climate change. Indeed, the geological record shows that dust mobilization has varied tremendously through time. Recent research suggests that mineral dust also plays a significant role in climate forcing (see, for example, refs. 59–63). Thus, there could be feedback between the climate–dust generation processes and the climate-forcing effects of mobilized dust. To understand the role of dust in climate, it will be necessary to develop models that can both characterize the radiative effects of dust and predict the location and output rates of dust sources as a function of climate. The modeling of dust sources (58–61) is perhaps the most difficult task facing climate modelers. To accomplish this goal, it will be necessary for geologists and mineralogists to work closely together to study the processes that affect dust mobilization and also to relate the mineral properties of dust to the source terrains.

Finally, there is a renewed interest in the health effects of fine particles as reflected in the new EPA regulations regarding suspended particles <2.5 μm in diameter. In many regions of the world, mineral dust is the dominant aerosol constituent, and, consequently, dust could constitute a widespread health threat. Although some types of mineral particles (e.g., asbestos, silica dust) are unambiguously linked to health issues, the health effects of ambient soil dust are unknown. A number of hypotheses focus on the chemical and physical properties of the particle surface, but these remain unproven. Nonetheless, it is clear that the investigation of health effects will require the participation of mineralogists who can characterize the surface properties of individual particles.

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