Arid regions as sources of mineral aerosols in the marine atmosphere

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ABSTRACT

Measurements show that in many ocean regions the major aerosol constituent is mineral matter derived from the continents. The greatest concentrations of soil aerosol particles are found over marine areas "downwind" from arid regions and deserts. Because of the transport of soil material out of North Africa, the Arabian Peninsula, and India, the geometric mean mineral aerosol concentrations over the tropical North Atlantic, the Indian Ocean, and the Mediterranean were at least an order of magnitude greater than those over the Pacific Ocean and the North and South Atlantic. The concentration of soil aerosols in these regions produces highly turbid sky conditions. The relationship between the concentration distribution of soil aerosols over the oceans and that of haze suggests that climatological records of the frequency of occurrence of haze at sea may be useful for delineating those oceanic regions where soil aerosol transport might be most significant.

ZUSAMMENFASSUNG


RÉSUMÉ

Des mesures montrent que, dans de nombreuses régions océaniques, le constituent principal en suspension dans l'air est de la matière minérale dérivée des continents. Les plus grandes concentrations de particules du sol en suspension furent trouvées sur les aires maritimes placées sous le vent des régions arides et des déserts. A cause du transport des matériaux depuis l'Afrique du Nord, la Péninsule Arabique et l'Inde, des concentrations de poussière minérale calculées, en moyenne géométrique, sur l'Atlantique Nord Tropical, l'Océan Indien et la Mediterranée furent d'un ordre de grandeur plus élevé que sur l'Océan Pacifique et l'Atlantique Nord Sud. La concentration des poussières dans ces régions produit une forte turbidité dans le ciel. Le rapport entre la distribution de cette concentration des poussières sur les océans et la brume suggère que les enregistrements climatologiques de la fréquence des brumes sur la mer pourraient être utiles pour délimiter les zones océaniques où les transports des poussières peuvent être les plus significatifs.

РЕЗЮМЕ

Показывают размерения, что в многих океанских районах, более важная аэрозольная часть—минеральный материал континентально-го происхождения. Находят большие концен-трации почвенных аэрозольных частиц над морскими районами "по ветру" от засушливых районов и пустынь. Из-за перевозки почвен-ного материала из Северной Африки, из араб-
provide a basis for planning future studies. The last portion of this paper is directed toward this end.

MEASUREMENTS OF MINERAL AEROSOLS OVER THE OCEANS

Tropical North Atlantic Ocean

Meteorological Setting. During the summer months, the properties of the atmosphere over the tropical North Atlantic are strongly affected by large-scale outbreaks of Saharan air (Carlson and Prospero, 1972). The meteorological parameters that characterize these air parcels are markedly different from those generally regarded as "normal" for the tropics. In addition, these air parcels contain extremely high concentrations of mineral aerosol (Prospero and Carlson, 1972) that profoundly alter many properties of the atmosphere. The air parcel characteristics are established by processes occurring over the Sahara Desert and the arid and semiarid regions to the south. Because of the intense heating of the land surface, a very deep isentropic mixing layer develops; high-velocity, gusty winds generate dust that is carried to the top of the mixing layer at about 500 mb. The hot (45 °C), dry (mixing ratio 2 to 4 g/kg), dust-laden air emerges from the coast of Africa in mesosynoptic-scale outbreaks that usually follow the passage of the trough of an easterly wave. As these outbreaks emerge, they are undercut by the cool, moist, northerly coastal winds, thereby generating a sharp inversion at about 850 mb in which the temperature may increase in the vertical by 5 to 10 °C over a few tens of millibars. The outbreak process is depicted schematically in Figure 1. The westward dust transport takes place primarily within the nominal isentropic layer known as the Saharan Air Layer (SAL); dust is transferred downward to the moist layer by convective erosion of the base of the SAL and by the settling out of large particles through the inversion. The sharp gradients of temperature and the water-vapor mixing ratio in the vertical are clearly evident in soundings taken along the west coast of Africa north of about 10°N to about 25°N (Carlson and Prospero, 1972). However, large gradients also appear in the horizontal across the boundaries of Saharan air outbreaks. Between 900 mb and 700 mb, latitudinal temperature differentials of 3 to 5°C often occur over 8° to 9° of latitude. The temperature anomaly appears to be associated with an easterly jet of 20 to 25 ms−1, which is a persistent feature within and along the southern boundary of the outbreaks (Carlson and Prospero, 1972).

The history of individual dust outbreaks can be followed on satellite photographs. Excellent satellite coverage of dust storm activity was obtained during the Global Atmospheric Research Program (GARP), Atlantic Tropical Experiment (GATE), held in the summer of 1974. For the duration of GATE, the SMS-1 satellite was moved to a more easterly position so that much of West Africa was
visible with a good perspective. Over West Africa, dust storms stand out clearly in the infrared as light-toned (cool) areas against the black (hot) desert surface. Individual storms have dimensions exceeding 1,000 km in length and several hundred km in breadth. The outbreaks seem to have very sharp fronts; on at least one occasion during GATE, the front was associated with a squall line. Generally, dust storms commence in mid or late morning and attain full development in a matter of hours. This suggests the possibility that the storms may be triggered by momentum derived from the middle level jet and brought down to the surface via the dry convective layer. In addition to these major dust storms, a more or less steady flow of dust appears to derive from the Sahel region; this may be related to the intensity of dry convective activity and to the repeated passage of easterly disturbances in this region.

An example of a satellite infrared imagery sequence showing dust storm genesis and subsequent movement is presented in Figure 2. Fifteen major dust storms are observable in the SMS-1 photographic archive for GATE. Many minor dust events are also visible.

Over the oceans, the movement of dust outbreaks is most readily followed in the visible imagery. Convection is greatly suppressed in the outbreak area because of the sharp inversion at the base of the SAL; hence, the predominant cloud is stratocumulus with occasional altocumulus. Satellite imagery shows that individual outbreaks are 10° to 15° wide latitudinally and move in a belt nominally located between 10° N and 25° N. The transit time between the coast of Africa and the Caribbean is five to seven days, and individual outbreaks can extend over most of the Atlantic during that time (Carlson and Prospero, 1972; Savoie and Prospero, 1977).

A sequence of visible spectrum SMS-1 satellite photographs is presented in Figure 3. These show the emergence of a dust storm from the coast of Africa and its subsequent movement into the mid-Atlantic.

Aerosols. (a) Distribution and Turbidity. During GATE, aerosols and direct solar radiation were measured in a network of eight ships and four land stations (Savoie and Prospero, 1977; Prospero and others, 1979). The daily surface level concentrations of mineral aerosol fluctuated by factors of 10 to 100 from day to day in the eastern Atlantic as the outbreaks passed over the stations (Savoie and Prospero, 1977). Fluctuations were less extreme in the western Atlantic; however, the passage of individual outbreaks could still be correlated with the occurrence of peak dust loads at stations. This behavior is evident in Figure 4, which shows daily mineral aerosol concentrations for Sal Island (16°45'N, 22°57'W), Barbados, West Indies (13°10'N, 59°25'W), and Miami, Florida (25°45'N, 80°15'W) (Prospero and others, 1979; Savoie and Prospero, 1977). Even in Miami, the dominant insoluble aerosol constituent in the summer of 1974 was Saharan dust.

However, because the main transport occurs in the SAL, surface-level measurements are not indicative of the local atmospheric loading. The vertically integrated aerosol concentration is best represented by the measurements of atmospheric turbidity made in the aerosol network (Prospero and others, 1979). Atmospheric turbidity is a measure of that part of the extinction of direct solar radiation (as measured in relatively narrow pass-bands) that is attributable to the effects of aerosols. Turbidity measurements were made in the GATE network using Volz sun photometers (Volz, 1970). The mean Volz turbidities at a 500 nm wavelength for GATE are shown in Figure 5. Values off the coast of Africa (B = 0.300) are comparable to the maximum mean monthly turbidity for a heavily industrialized urban area such as Baltimore, Maryland (Carlson, 1979). The decrease in turbidity toward the west
is attributable to aerosol removal and to plume-broadening in transit.

The mean surface-level mineral aerosol concentration in the transport belt centered around 15° to 17°N was several times greater than in the region to the south, especially in the intertropical convergence zone (ITCZ). This can be seen in Figure 6, which shows the mean mineral aerosol concentrations for GATE. The aerosol data from GATE are unique in that they are the first to show areal distributions that are clearly related to synoptic-scale phenomena. That is, the mineral aerosol distributions can be understood in terms of a remote source area and subsequent transport conditions.

Sea salt aerosol concentrations were also measured during GATE (Savoie and Prospero, 1979, 1980). These data are not presented here; however, on a daily basis over the eastern Atlantic, the mass of mineral aerosol exceeded that of sea salt aerosol on about 60% of the days. The dominance was greater during the earlier phases of GATE. During Phase I (late June to mid-July) at the research vessel GILLISS (9°N, 25°W), the mean weight ratio of mineral aerosol to sea salt aerosol was 5:1, and the daily ratio exceeded one on all days.

As indicated earlier, the concentration of mineral aerosol increased with altitude; aircraft data from nine flights (Prospero and Savoie, 1976, unpub.; Carlson and Caverly, 1977; Carlson and Benjamin, 1979) show that the
Figure 3. SMS-1 visible imagery of a dust outbreak over the Atlantic. (a) 1600 GMT, July 30, 1974. Dust from the
dust storm of July 29 (shown in Fig. 2) streams across the coast of Africa between 16°N and 25°N. (Some stratus-type
cloud is associated with the dust.) Dust from the storm of July 28 extends west to 35°W and northward out of the
picture. Note the difference in cloud character inside the dust outbreak as compared to that outside. (b) 1630, August 2,
1974. Dust from the July 28-29 outbreaks now extends from the coast of Africa to 55°W. Note the sharp haze boundary
along 30°N. The bright area off the coast of South America is due to sun glint.
ratio of dust concentration in the SAL to that in the mixed layer ranged from 1.4 to 69 (with the exception of one day when it was 0.4). In contrast, sea salt aerosol was completely confined to the mixed layer because of the sharp inversion at the base of the SAL. Thus, for a vertical column through the depth of the atmosphere, the loading of mineral aerosol was much greater than that of sea salt over most of the GATE region on most days. This same dominance was noted during the Barbados Oceanographic and Meteorological Experiment in 1969 in the Atlantic to the east of Barbados, West Indies, (Prospero and Carlson, 1972).

(b) Composition. The elemental and mineralogical composition of Saharan aerosol is similar to that of a highly winnowed soil material and closely resembles that of soil aerosols from other regions, including the midwestern United States. The dominant minerals are clays (Glaccum, 1978; Prospero, 1981; Glaccum and Prospero, 1980). More than 50% (mass basis) are micas, mostly illite, and 6% to 7% are kaolinite. The major nonclay material is quartz, 14% to 20% by weight. A small but significant decrease occurred in the quartz concentration (from 20% to 14%) in transit across the Atlantic. This decrease is attributed to the relatively greater Stokes settling velocity of the quartz, a consequence of its greater mass median diameter relative to the other major minerals.

The elemental composition of the mineral aerosol (25 elements analyzed) resembles that of shales or deep-sea sediments (with a few expected exceptions); the same is true for the mineralogical composition. Only very minor changes in the elemental composition occurred during transit across the Atlantic (Glaccum, 1978; Prospero, 1981). However, the elemental and mineralogical composition was essentially invariant from outbreak to outbreak; thus, the
Figure 5. Volz turbidity at 500 nm (~1000) during GATE. Values in parentheses are means for one phase or less; all others are for two to three phases.

Figure 6. Geometric mean mineral aerosol concentration during GATE (Units: 10^1 g m^-3). Values in parentheses are for one phase or less.
main sources of aerosol in West Africa appear to have a very homogeneous composition.

(c) Size Distribution. The aerosol size distribution as measured in the eastern Atlantic aboard the National Oceanic and Atmospheric Administration (NOAA) DC-6, (Prosero and Savoie, 1976, unpub.; Carlson and Caverly, 1977) and at Sal Island (Savoie and Prospero, 1976) was essentially invariant in the range 0.3 μm to 10 μm diameter. This was true for measurements made within the major outbreaks studied but may also be true for outbreaks in general, even though the dust concentration might vary considerably. The short-term temporal, vertical, and areal variability in concentration, but constancy in size, is particularly evident from the DC-6 data. In Figure 7, two composite spectra are shown for July 3— one in the dust layer and one below it. The dust layer spectrum shows a peak at 3.6 μm diameter, which is characteristic for Saharan dust; the low-level spectrum shows a peak at about 1.4 μm, which is characteristic of sea salt aerosol. (The small shoulder on the sea salt spectrum is attributable to the presence of a small amount of dust mixed down from the SAL.) It is typical in this example that the total particle surface area in the SAL is about 20 times that in the mixed layer, where sea salt dominates. The mean values of dust particle concentrations in outbreaks range from about 6 to 40 cm⁻³ for particles of 0.3 μm to 10 μm diameter. The corresponding mean dust loads for outbreaks are 20 to 600 μg m⁻³, with peak values of milligrams per cubic meter.

The size distribution of Saharan dust between 1.3 μm and 10 μm is essentially identical to that of soil aerosols measured in other regions (Patterson and Gillette, 1977).

Although the size distribution was relatively invariant off the coast of Africa, a marked and systematic change occurred in transit across the Atlantic (Savoie and Prospero, 1976; Savoie, 1978). Because of Stokes settling effects, the larger particles fell out at a relatively greater rate; consequently, the peak in the distribution decreased to about one-half its initial value. This is clear in Figure 8 (Savoie, 1978), which shows composite size spectra from three land stations (Sal Island, Barbados, and Miami). However, there was no significant difference in the size distribution at Barbados and Miami; this suggests that the major changes in this distribution occurred relatively soon after the outbreaks emerged from Africa.

(d) Long-Term Trends. Measurements made at Barbados during the last 12 years (Prosero and Nees, 1977) show a

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Figure 7. Aerosol size spectra, NOAA DC-6, July 3, 1974. (a) Composite spectrum between 5 to 7K ft dominated by dust peak. (b) Composite spectrum at 500 ft dominated by sea salt peak. Note change in ordinate scales. The distribution of area under the curve is proportional to the distribution of total particle area as a function of size.
threefold increase in mineral aerosol concentration during the early 1970s, attaining a maximum in 1973 and 1974 (Fig. 9). This increase coincided with the occurrence of severe and widespread drought conditions in West Africa and appears to reflect a real increase in aerosol output from Africa; turbidity measurements made at Sal Island during GATE were about two to three times those made in the predrought mid-1960s by Volz. These turbidity measurements do not preclude the possibility that the main axis of the dust outbreaks shifted further to the south (placing Sal Island in a denser portion of the plume) in response to a major shift in circulation patterns that might have been associated with the drought. However, the occurrence of such a shift has not actually been established. If a major increase in dust output did indeed occur, an argument can be made that land use practices might be responsible for some of this increase (Prospero and Nees, 1977).

The drouth terminated with the rains of 1974 and 1975. Since then, the aerosol concentration at Barbados has dropped to one-half of the peak value (Prospero and others, 1981).

The World Ocean

Mineral Aerosols. A number of studies have been made of specific mineral aerosol components over other ocean regions (see review articles by Windom, 1969; Chester and Aston, 1976; Windom, 1976; Prospero, 1981). However, the collection techniques generally used were not quantitative; furthermore, the collectors were size selective and therefore yielded a biased aerosol sample. Other studies have been made of the concentration of specific elements in marine aerosols (see review articles by Duce and others, 1976; National Research Council, 1978; Prospero, 1981). A soil aerosol concentration can be inferred on the basis of the concentration of (typically) Fe or Al, assuming that these are representative of a "pure" soil component (that is, no anthropogenic contribution) and that the composition of an "average" soil is applicable.

The most extensive study of mineral aerosol concentrations has been made by Prospero (1979) using filter samples collected aboard two vessels over a three-year period. A total of 246 samples were collected in the Atlantic, Pacific, and Indian Oceans and in various seas. These data are summarized in Table 1. The geometric mean mineral aerosol concentrations over most oceans were low: 0.36 μg m⁻³ in the central and northern North Atlantic; 0.35 μg m⁻³ in the Pacific between 30° N and 40° S; and 0.69 μg m⁻³ in the South Atlantic north of 40° S. Higher mineral aerosol concentrations were obtained in the Mediterranean (4.29 μg m⁻³) and the Indian Ocean (4.76 μg m⁻³). The highest mean concentration in the ship data—14.2 μg m⁻³—was obtained in the tropical North Atlantic; this value is in good agreement with the mean concentration obtained during GATE.

On the basis of this somewhat limited data set, one
TABLE 1. MINERAL AND SEA SALT AEROSOL CONCENTRATIONS FOR MAJOR OCEAN REGIONS
(Units: 10^{-6} g m^{-3})

<table>
<thead>
<tr>
<th></th>
<th>CNNA</th>
<th>TENA</th>
<th>TCSA&amp;C</th>
<th>P</th>
<th>M</th>
<th>I</th>
<th>MS-SC&amp;PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Mineral Aerosol</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Arithmetic Mean</td>
<td>1.30</td>
<td>36.6</td>
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<td>0.58</td>
<td>4.57</td>
<td>7.20</td>
<td>1.51</td>
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<tr>
<td>Geometric Mean</td>
<td>0.36</td>
<td>14.2</td>
<td>0.62</td>
<td>0.35</td>
<td>4.29</td>
<td>4.76</td>
<td>1.09</td>
</tr>
<tr>
<td>b) Sea Salt Aerosol</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>6.71</td>
<td>11.2</td>
<td>11.3</td>
<td>8.44</td>
<td>6.98</td>
<td>3.52</td>
<td>6.47</td>
</tr>
<tr>
<td>Geometric Mean</td>
<td>5.48</td>
<td>8.71</td>
<td>8.26</td>
<td>7.26</td>
<td>6.23</td>
<td>3.34</td>
<td>5.87</td>
</tr>
<tr>
<td>Number Samples</td>
<td>109</td>
<td>22</td>
<td>40</td>
<td>24</td>
<td>13</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

CNNA: central and northern North Atlantic 22° - 28° N to 64° N; TENA: tropical and equatorial North Atlantic 28° - 22° N to 0°; TCSA&C: tropical and central South Atlantic 5° S to 35° S plus Cape of Good Hope; P: Pacific 28° N to 40° S; M: Mediterranean Sea; I: Indian Ocean 15° S to 7° N; MS-SC&PS: Malacca Straits, South China and Phillipine Seas.

would conclude that arid regions and deserts are the principal sources of mineral aerosol over many ocean regions. This conclusion is based primarily on the values for the tropical North Atlantic, the Mediterranean Sea, and the Indian Ocean, all of which are at least an order of magnitude greater than the other ocean regions cited.

ANTICIPATED DISTRIBUTION OF MINERAL AEROSOLS OVER THE OCEANS

Most deserts are concentrated in the low latitudes. In light of the dearth of measurements in these regions either on land or at sea "downwind" of the deserts, it is difficult to assess the magnitude of the mineral aerosol transport to sea. As a consequence, indirect evidence must be used to infer the characteristics of the transport. This will be done in the following sections for each of the ocean regions.

Tropical and Equatorial Atlantic

The tropical North Atlantic has been by far the most thoroughly studied region as a consequence of the GATE program. However, this effort was confined to the summer months. Evidence indicates that an equally impressive transport of dust out of Africa occurs during the winter months. The most graphic evidence is the distribution pattern of the frequency of occurrence of haze at sea (Fig. 10; McDonald, 1938). In most cases, the occurrence of haze at sea can be attributed to the presence of particulate matter of continental origin; Figure 10 shows that most of the continental shorelines are bounded by a margin of increased haze frequency. The continental origin of this material is further corroborated by the fact that the haze distribution is similar to that for the concentration of Aitken particles (particles with a diameter of 0.2 \( \mu m \)) at sea, with the 5% isopleth for haze corresponding closely to the 500 cm\(^{-3}\) isopleth for Aitken particles (Prospero, 1975) based on data taken from Hogan and others (1973) and Elliott and others (1974). The distribution of the Aitken particles clearly shows the continents to be the controlling source for the ocean margins and implies that the haze is similarly controlled. (However, while the distributions of haze and Aitken particles are similar on the margins, one would not necessarily expect the correlation to persist over greater distances; the great difference in particle size will result in large differences in the effectiveness of the various removal mechanisms.)

Accepting that haze is suggestive of a continental source of particles in the optically effective size range (about 0.2 \( \mu m \) to 2 \( \mu m \) diameter), the distribution of haze and its seasonal variation can tell something of the sources and the controlling transport phenomena. In the case of the tropical North Atlantic, the June-July-August distribution agrees with the findings during GATE, that is, that most transport takes place between 10°N to 25°N with the intertropical convergence zone (ITCZ) serving as a sharp cutoff. In contrast, during the winter months, the haze distribution suggests that a major transport continues but that the focus of activity is situated between 5°N to 15°N along the coast of Africa. This is consistent with data from 12 years of essentially continuous aerosol studies at Barbados (see Fig. 9; Prospero and Nees, 1977), which show a maximum in dust concentration during the summer and a minimum during the winter. More impressive is the fact that during the winter, the haze isopleths extend much further out to sea. The 5% isopleth touches South America in the region of French Guiana, while during the summer it extends only to
ORIGIN AND TRANSPORTATION

about 45°W and covers a much smaller area. Again, in the winter, the southern border of the transport seems to be defined by the ITCZ.

There is considerable winter dust activity in the arid and semiarid regions of Chad and Niger. The dust storms seem to be generated as a consequence of conditions associated with the Mediterranean polar front and/or with strong upper tropospheric troughs (Hamilton and Archbold, 1945; Bertrand and others, 1974; Dubief, 1977). The material raised by the winds is transported to the west and southwest; the surface movement of these dust storms over West Africa has been well documented by mapping the day-to-day variations of visibility (Bertrand and others, 1974).

The top of the dust clouds varies from event to event and is reported to be at altitudes ranging from 1.5 to 7 km, although 3 to 4 km is probably more typical (Hamilton and Archbold, 1945; Bertrand and others, 1974; Dubief, 1979). However, as the dust clouds approach the region about 8°N to 10°N—the region of the intertropical front (ITF; in French, FIT)—they are undercut by the southwesterly monsoon wind regime. This situation is depicted schematically (for one incident) in Figure 11 (from Bertrand and others, 1974), the vertical distribution being deduced from aircraft reports. Note that the dust is shown penetrating well into the ITCZ at higher altitudes but not at the surface. The concentration of mineral aerosol over the coastal regions during dust outbreaks is high. At Abidjan, Ivory Coast, daily values are in the range of 150 to 800 µg m⁻³; the mean for one 20-day period in January 1977 was about 400 µg m⁻³ (Bertrand and others, 1974). These values are greater than those obtained at Sal Island during GATE.

It should be noted, however, that dust (haze) conditions are not associated solely with unusual meteorological events such as fronts. Rather, a general haziness exists that is due to dust generated by gusty winds that are a consequence, in part, of the strong, turbulent mixing produced by the high surface insolation in the relatively barren arid regions. In northern Nigeria, the frequency of occurrence of haze accompanied with visibility less than 6 miles (9.7 km) is 30% to 40% in the winter months.

In order to characterize the nature of the winter dust transport across the Atlantic, Prospero and others (1981) established an aerosol sampling program at a coastal station in Cayenne, French Guiana (4°50′N, 52°22′W) in December 1979. The greatest mineral aerosol concentration was observed early in the year with the maximum usually occurring in March. The peak monthly mean concentrations were 29 µg m⁻³ and 23 µg m⁻³ in 1978 and 1979, respectively; these values are markedly higher than the Barbados summer maxima, which were in the range of 15 to 18 µg m⁻³ in the late seventies. The mineralogical composition of the Cayenne winter dust was identical to that of dusts collected in the summer in Barbados or in the tropical North Atlantic off the coast of Africa. In contrast, the summer dusts collected at Cayenne had a composition which was entirely different and which is typical of material that would be derived from lateritic soils.

Thus, broadly speaking, the winter transport of dust out of Africa is similar in many respects to the summer transport, the major difference being a southward shift in transport by about 10°. Consequently, one would expect to see some of the same meteorological features previously noted in GATE, that is, a strong north-south temperature and mixing ratio gradient and strong vertical gradient in the same parameters.

The similarities between the gross characteristics of the summer and winter dust outbreaks suggest that the dynamical impacts might also be similar.

In the equatorial and tropical South Atlantic, one would expect the mineral aerosol concentration to be considerably smaller than in the North Atlantic. However, the arid regions of South Africa do appear to be active to a significant degree, especially in the summer and fall months (Figs. 10c, d).

Indian Ocean

The frequency of distribution of haze during the summer months (Fig. 10) over the Arabian Sea suggests that huge amounts of mineral aerosol are being transported out of the Arabian Peninsula and North Africa; indeed, observations by experienced travelers in this region suggest that the dust concentrations may be greater than off the coast of West Africa.

The distribution of haze as shown in Figure 10 for June, July, and August is very closely related to the major features of the flow that are characteristic of the established summer monsoon. This can be seen clearly by comparing the haze distribution with the mean monthly airflow at 1 km in June as presented by Findlater (1971).

Again, the situation is somewhat analogous to that off West Africa in the summer months during Saharan air outbreaks: hot, dry continental air adjacent to relatively cool maritime air and lying over relatively cool water. As in the case off West Africa, the layer extends up to at least 3 km and perhaps as high as 7 km. Some of the meteorological implications of this feature are discussed in MONEX (1977).

The dust-laden air travels across the Arabian Sea to India. Indeed, a dense pall of dust persists over northern and central India throughout the year, but it occurs more often and most intensely during the premonsoon months when the visibility is reduced by haze and occasionally diminishes to 2 km or less (Lal, 1977). The southern edge of the haze is located at about 8°N all the way across the Bay of Bengal to the coast of Malaya.

However, periods of significant dust transport over Southeast Asia are not confined to the summer months. Exten-
Figure 10. Frequency of occurrence of haze at sea by season. Numbers indicate the percentage of meteorological observations from ships that report the presence of haze at the time of observation (after McDonald, 1938). (a) December, January, February; (b) March, April, May; (c) June, July, August; (d) September, October, November.
sive dust layers have been regularly reported by pilots. These observations were made during operational flights—no research has been done on the subject, and no documentation exists except as routine postflight reports. H. Riehl (oral commun.) states that pilots repeatedly observed dust layers near 15° N over the South China Sea on flights during the winter. These layers are located in the upper westerlies; it is unlikely that they could come from local sources, because the low-level winds are northerly at this time of year. The potential temperatures at the top of the layers coincide with the mean surface maximum temperatures in the Sahara during the winter. Also, personal observations indicate that India appears to be relatively dust-free at this time of year. Thus, it is speculated that the dust is transported from North Africa or Arabia.

The major dust source for the Indian Ocean proper (that is, below the equator) is Australia, with its immense expanse of arid and desert regions. Haze patterns suggest that significant transport into the low latitudes northwest of Australia occurs during the periods of September through October and December through February. This is supported by observations of pilots in this region during World War II (R. Fairbridge, oral commun.). Fairbridge reports that meteorological observers in Java frequently note widespread haze conditions which they attribute to aerosol material transported by winds from Australia.

Pacific Ocean

In the eastern Pacific, the major source of mineral dust in the low latitudes appears to be the arid regions of Mexico and the coastal desert of South America. This is deduced from haze distribution data in Figure 10, which show these regions to be most active in March, April, May, and, to a lesser extent, in December, January, and February. The only extensive aerosol study in this region was conducted by Prospero and Bonatti (1969); using semiquantitative techniques, they verified that a substantial soil transport apparently does take place in this region in the Northern Hemisphere winter.

In general, high concentrations of mineral aerosol in the low latitudes of the central Pacific would not be expected. However, a significant transport may be taking place from sources in the east. Evidence indicates that a significant fraction of the soils in the Hawaiian Islands is of colonial origin. The micas on the islands have K-Ar apparent ages that are 100 times the age of volcanism on the island; also, the 87Sr/86Sr values for mica-bearing soils are much greater than those for the Hawaiian lavas (Jackson and others, 1973). Furthermore, the soils on the islands frequently contain quartz in spite of the fact that the mineral has not been detected in unaltered rocks; also, the quartz size is much smaller than that normally found in soils, and the greatest concentrations are found at higher elevations where the rainfall is increased because of orographic effects. The conclusion is that the quartz (and micas) are wind transported and are removed principally by precipitation. Danielsen suggested (Jackson and others, 1973) that mineral dust generated from the deserts and arid regions in China is transported in ascending trajectories into the upper troposphere to the east; these parcels of dust-laden air eventually return to the surface to become, once again, a part of the boundary layer. One would certainly expect the arid regions of China to be an abundant source—red snows and rains are often observed in Japan because of this material. This is also consistent with the haze distribution, especially for March, April, and May.

The impact of dust from Asian sources was apparent in a recent atmospheric chemistry field program held in Enewetak Atoll (11° N, 162° E) in 1979 (Duce and others, 1980). In April, the concentration of mineral aerosol was 2.3 μg m⁻³. The concentration steadily decreased during the experiment to 0.02 μg m⁻³ by the end of August. The measured deposition rate for dust is equivalent to a sediment rate of 0.3 mm per thousand years, a rate which approaches that of deep sea sediments in the region. Higher dust concentrations would be expected in the westerlies in the middle latitudes.

In the Southern Hemisphere, Australia is an abundant source. However, the mean flow is to the southeast, and it is questionable if a significant input could be made to the low latitudes.

CONCLUSIONS

Interest is growing in the subject of marine aerosols because of the concern over the possible impact of anthropogenic emissions on the marine atmosphere (see, for example, National Research Council, 1978). Nonetheless, it is clear that in many ocean regions the primary constituent of the marine aerosol is soil material derived from arid and desert regions on the continents. This soil-derived aerosol
material has many unknown aspects: its physical characteristics; its chemical and mineralogical composition; the conditions of transport; the source regions of the soil aerosol and its characteristics relative to those of the parent soil; and the effect of land use and of changes in weather and climate on the generation and transport of soil aerosol.

Many of these questions will only be answered through the coordinated efforts of scientists from many different disciplines: chemists, mineralogists, geologists, soil scientists, geographers, climatologists, and meteorologists. Furthermore, the scope of these studies is such that any efforts will require the cooperation of scientists from many nations. The time for such cooperation has come.

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REFERENCES CITED


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