3 The Atmospheric Transport of Particles to the Ocean

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3.1 INTRODUCTION

The atmosphere is an important pathway for the transport of materials from the continents to the oceans. Although the magnitude of these wind-borne fluxes is not accurately known, there is evidence that some could be large enough to have a significant impact on chemical and biological processes in the oceans. The concentration, composition and physical properties of particles in the marine atmosphere can vary greatly, depending on the distribution of sources, the controlling meteorological processes in the source regions, the large scale circulation systems that subsequently control long-range transport and, finally, the various removal processes that act on the particles and cause them to be deposited in the ocean. In order to assess the transport of continental materials to the oceans, we must have a good understanding of all these processes.

The emphasis in this chapter is on mineral aerosol transport. Mineral dust is a substantial, at times major, component in the marine aerosol over many ocean regions. The principal sources of mineral dust are found in the arid and semi-arid regions of the world, especially those in North Africa, eastern Asia and the Middle East. These sources have a major impact on the mineral flux to the North Atlantic, the North Pacific and the northern Indian Ocean. This result is evident in the mineral assemblage distributions in the ocean sediments and it should also be reflected in the suspended particle distributions in these waters.

In this chapter I will characterize the distributions of mineral dust over the oceans and discuss some of the factors that affect the transport and deposition of dust to the oceans. An important consideration is the short-term (i.e., days to weeks) temporal and spatial variability of dust deposition; because of the highly episodic character of dust events, the concentration of dust (and associated materials) in sea water can be highly variable. Dust fluxes also appear to be highly variable on longer time scales (i.e., decades and longer); some of the climatic factors that might affect this variability will be discussed.

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3.2 AEROSOL DISTRIBUTIONS OVER THE OCEANS

Our knowledge of aerosol transport over the oceans rests on a variety of sources. The quantitative understanding of this transport is based on actual measurements of aerosol concentrations; some of these measurements will be discussed in later sections. However, there are relatively few data for most ocean regions because of the difficulties in sampling on the spatial scale of the ocean; also much of the data are derived from short time-scale field studies that provide little information about seasonal variability which can be very large. Furthermore, the vast majority of such measurements are made at the surface, either at island stations or on ships. There are relatively few data from the free troposphere because such measurements must be made from aircraft and, as a result, are very expensive.

As a result of the dearth of *in situ* measurements, much of our understanding of the large scale features of aerosol transport over the oceans is derived from satellite imagery. Dust events are readily observable in visible spectrum satellite imagery such as GOES and METEOSAT. For example, individual dust storms can be tracked across the Atlantic from the time they emerge from the west coast of Africa until they reach the western Atlantic and the east coast of the United States (Ott et al., 1991). Similar events have been observed off the coast of Asia (Iwasaka et al., 1983; Takayama and Takashima, 1986). Over land surfaces, dust can best be tracked in the infrared bands (Tanre and Legrand, 1991; Jankowiak and Tanre, 1992).

NOAA issues a routine operational satellite product (Advanced Very High Resolution Radiometer (AVHRR)) that provides mapped distributions of aerosol optical depth (AOD) over the oceans on a weekly and monthly basis (National Climatic Data Center, Asheville, NC). The AOD provides a semi-quantitative indication of the geographical distribution of the vertically integrated loading of aerosols (Rao et al., 1988) over the oceans on a weekly basis. Plate 3.1 shows a color composite of the mean AVHRR AOD for four seasons (R. Husar and L. Stowe, personal communication). The AOD distributions in Plate 3.1 clearly show that areas of increased AOD are associated with continental sources. The continents are often fringed by regions of high AOD and in some regions the continents appear, in effect, to emit long "plumes" of enhanced AOD. The following paragraphs present an overview of the major features in Plate 3.1; later sections present a more detailed examination in terms of actual aerosol measurements.

The most prominent areas of high AOD values (red, indicating an optical depth greater than 0.5) are found in the tropical North Atlantic Ocean (NAO) and Indian Ocean (IO), especially the Arabian Sea. The plume in the low-latitude NAO is associated with mineral dust that is transported out of North Africa. The African AOD plume is by far the largest, the most persistent, and the most dense to be found over any ocean region. Plate 3.1 shows large seasonal changes in the location and density of the AOD plumes over the NAO. These patterns are due to seasonal changes in the distribution of dust storm activity (which is related in part to seasonal rainfall patterns) and also to the seasonal shift of the large scale circulation. For example, the relatively steep gradient of the southern dust boundary of the NAO dust plume roughly corresponds to the seasonal climatological position of the northern boundary of the intertropical convergence zone (ITCZ). Large seasonal changes are also found in the Arabian Sea (and, to a lesser extent, the Bay of Bengal). The extremely high AOD values (greater than 0.5) are attributable to dust transport from the Arabian peninsula and from sources in the Middle East and northern India. The seasonal progression of the monsoon circulation system exerts a strong control over dust distributions, especially over the Arabian Sea.

Pollution plumes are also evident over the mid-latitude NAO. During the spring and summer, a large AOD plume emerges from the east coast of the U.S.A. and extends to the central NAO. There is also a substantial transport of pollutants out of Europe, to the west. During the summer, the North American plume merges with that from Europe, effectively bridging the NAO. The large area of relatively low AOD values in the central NAO coincides with the mean position of the Bermuda-Azores high pressure center. While the pollution plumes are obviously major features, both their areal extent and the magnitude of the AOD values are considerably less than those associated with dust transport region to the south.

In the North Pacific, a large plume emerges from the east coast of Asia in the spring. This plume is associated with the transport of mineral dust and pollution aerosols from sources in Asia. While the areal extent of this plume is quite large, the AOD values are considerably lower than those observed in the tropical NAO and the Arabian Sea. Although there is considerable evidence of a substantial continental influence in the coastal regions of Asia in the other seasons, there is no indication of a major plume comparable to that in the spring.

There are many other interesting AOD features in Plate 3.1, but the ones described above are the most obvious cases. It should be noted that these large-scale plumes are all located in the northern hemisphere. Prominent areas of enhanced AOD are visible in the southern hemisphere, but they are small. Plumes off the west coast of South Africa could be associated with arid regions in Angola and South Africa (e.g., the Kalahari desert); these plumes could also be related to biomass burning in these latitudes (Crutzen and Andreae, 1990). One of the most interesting features of the southern ocean AOD distributions is that there is no evidence of major dust plumes emerging from Australia despite the fact that it is the largest expanse of arid and desert land in the southern hemisphere (Pye, 1987).

There are other interesting features in Plate 3.1 which cannot be readily explained. A particularly striking one appears in the March-May composite, the large band of increased AOD that extends from Central America westward, almost reaching the Philippines. There are no known major sources of aerosol in

Central America and, even if there were, it is difficult to understand how substantial amounts of material could be carried over such great distances (10000–12000 km).

Satellite imagery makes a persuasive case for the prominence of mineral dust aerosols over the oceans and the presence of pollutant aerosols. In the following sections, I will discuss the quantitative measurements of aerosols and use the satellite imagery to generalize to the larger ocean.

3.3 MINERAL DUST

3.3.1 INTRODUCTION

The importance of aeolian transport to oceanic processes was first suggested by studies of the mineral distributions in pelagic ocean sediments. The concentration patterns of certain minerals (e.g., quartz, kaolinite, illite) in sediments off the coasts of some continents (e.g., the west coast of North Africa and North America, the east coast of Asia) were not related to fluvial sources but rather to the pattern of large scale wind fields (Prospero, 1981a). Various aspects of dust transport and effects have been extensively studied during the past two decades (for reviews, see for example: Andreae, 1995; Chester, 1986; Buat-Menard, 1986; Chester and Murphy, 1990; Prospero, 1981a; Prospero 1981b; Prospero, 1990; Pye, 1987; Middleton, 1990; Duce et al., 1991; Duce, 1995; Goudie and Middleton, 1992; Pèwè, 1981; Leinen and Sarnthein, 1982; Schütz et al., 1990; Morales, 1985; Golytsin and Gillette, 1993).

The following sections focus largely on dust transport out of Africa and Asia, the two regions that have been most extensively studied. Table 3.1 summarizes the annual mean concentrations of mineral dust at selected stations in the Atlantic and Pacific. These data are from samples collected with identical systems in continuous sampling programs that extend over a period of about one year or more. In Table 3.1 (Savoie et al., 1995), the aluminum values are converted to equivalent mineral dust concentrations based on the average concentration of Al in crustal materials (6–8%, Taylor and McLennan, 1985). Duce (1995) presents a much more extensive compilation of mineral aerosol measurements over the oceans although many of the measurements are for relatively limited time spans and some were made using semiquantitative techniques; Duce also provides an excellent review of aerosol physical properties.

3.3.2 NORTH AFRICA AND THE NORTH ATLANTIC

3.3.2.1 Concentrations and seasonal trends

Large quantities of mineral dust are transported from sources in North Africa across large areas of the tropical Atlantic during much of the year. The most extensive long term record of African dust transport are the measurements that have been made almost continuously at Barbados since 1965 (Delany et al., 1967; Prospero and Nees, 1986). These data show that the dust transport in the trade winds in this region is extremely variable on time scales of hours to decades. The short term variability is shown in the daily dust concentrations for 1989–1992 (Figure 3.1, Arimoto et al., 1995a). Although it is not readily seen in Figure 3.1, the dust concentrations at Barbados typically rise and fall in a coherent manner over the period of several days; this pattern can usually be associated with identifiable weather phenomena such as the passage of easterly waves that emerge from Africa in the summer months and move across the Atlantic (Carlson and Prospero, 1972; Prospero and Carlson, 1972; Karyampudi and Carlson, 1988). The time required for a specific dust-laden air mass to be carried past Barbados by the trade winds is usually several days; this suggests that the dimensions of the dust clouds along the transport trajectory range from hundreds of km to over a thousand km. This is substantiated by satellite imagery (principally GOES and AVHRR) which also show that it takes about one week for dust outbreaks to cross the tropical NAO from the coast of Africa to the Caribbean (Ott et al., 1991).

Although dust transport takes place during much of the year in the tropical North Atlantic, the maximum at Barbados occurs in the summer when monthly mean concentrations typically fall in the range of about 10–30 $\mu g\, m^{-3}$. The African dust transport affects a very large area of the NAO, producing a similar seasonal pattern of aerosol Al concentrations at Barbados, Bermuda and Izaña (Tenerife) - a summer maximum and a winter minimum (Figure 3.1). Saharan dust is also carried into the Miami area, at times producing dense hazes; in Miami, dust concentrations follow the same seasonal cycle as that at Barbados (Prospero et al., 1987) although mean concentrations are only about half those at Barbados (Prospero et al., 1993). Bermuda Al concentrations are only about a third of those in Barbados (Table 3.1). It is significant that major dust events in Bermuda are always associated with the advection of dust from African sources (which are at least 4500 km distant) whereas dust sources in North America (1000 km distant) appear to have relatively little effect.

Dust concentrations are high in the eastern tropical NAO. Note, however, that the concentrations at Tenerife are only about 50% greater than at Barbados despite the fact that Tenerife is only 300 km from the coast of Africa. While major dust events are often observed in this region (Bergametti et al., 1989a), the relatively low values at Tenerife are due to the fact that much of the dust transport takes place in the latitudes south of the Canary Islands (see Plate 3.1). As a result of the large north-south gradient in the dust concentration in this region, small shifts in the large scale wind systems or in the dust sources in Africa could result in very large changes in dust transport and in the related deposition to the oceans. The factors affecting the Tenerife dust record can be generalized to dust transport over the oceans in general: because of the large gradients in the plumes, small

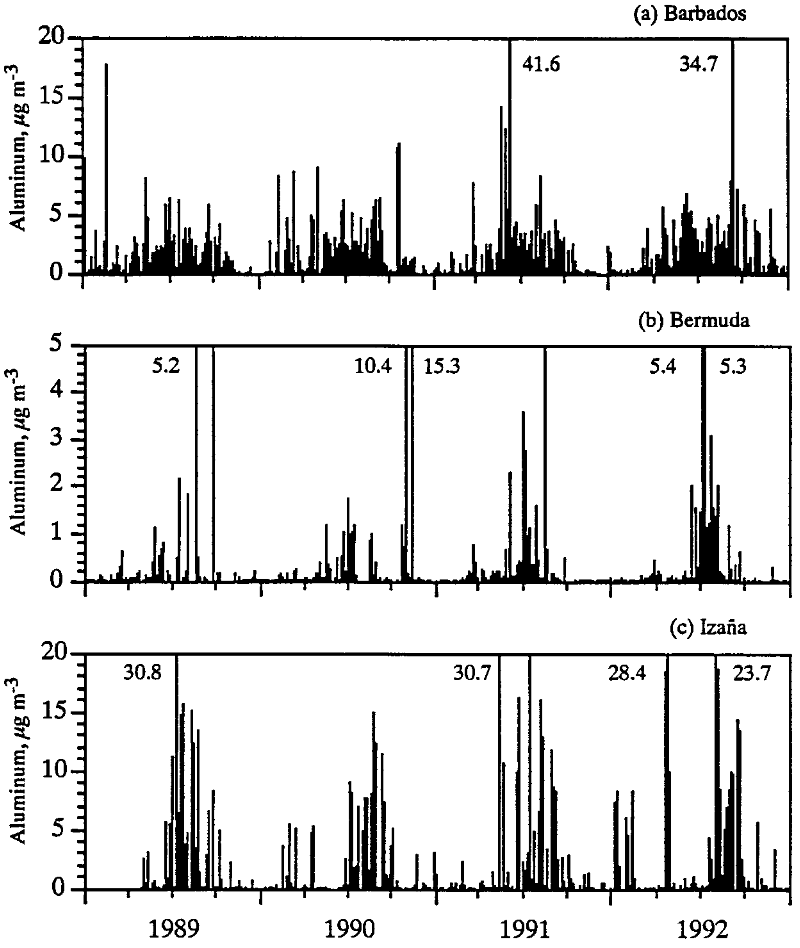

Figure 3.1 Aluminum concentrations at Barbados, Bermuda and Izaña (Tenerife, Canary Islands) from 1989 to 1992 (Arimoto et al., 1995a; reproduced by permission of the authors). Each bar represents a one-day sample. Note that the ordinate for the Bermuda graph is only 25% of those for Barbados and Izaña. The numbers in the Figure represent off-scale values. To convert the aluminum concen-tration to an equivalent mineral dust concentration, multiply by 12.5, a value that assumes an average Al crustal abundance of 8% (Taylor and McLennan, 1985).

changes in sources distributions and transport conditions can result in very large changes in concentrations at specific locations. This applies to the day-to-day changes in dust concentrations (which are subject to the winds associated with the controlling large-scale meteorological situation) and also to longer term concentrations (which are related to climatological factors and the associated long-term changes in meteorology).

During the northern hemisphere winter the large scale circulation systems shift southward; consequently, dust concentrations at Barbados and the other NAO stations are at a seasonal low. Large amounts of dust continue to be transported out of North Africa but the trajectories lie further to the south, including the Gulf of Guinea. Much dust is transported across the Atlantic in the low latitudes and into South America (Prospero et al., 1981; Talbot et al., 1986) and over the Amazon basin where they are believed to serve as a significant and important source of nutrients for the soils (Swap et al., 1992).

Large quantities of dust are carried over the Mediterranean and into Europe (Bergametti et al., 1989b, Bergametti et al., 1989c). Studies of dust accumulation in Alpine snows have provided an excellent quantitative record of Saharan dust transport over the past few decades (De Angelis and Gaudichet, 1991; Dessens and Van Dinh, 1990). These studies show that dust transport to Europe increased markedly during the past two decades, in agreement with the observations in the trade winds. Whatever the cause of the increased emissions of dust from Africa, they have had a widespread effect.

The seasonal pattern of dust concentrations measured at the various stations in the NAO are consistent with the AVHRR satellite observations shown in Plate 3.1. The dust distributions and satellite imagery are also consistent with records of haze distributions at sea prior to the 1930's as recorded from ships observations (McDonald, 1938; see also, Prospero, 1981a). All evidence suggests that the North African dust outbreaks are large, synoptic scale events that fill much of the lower troposphere, and that they are frequent occurrences. Historical records show that they have been taking place for at least hundreds of years (Prospero, 1981a).

3.3.2.2 Aerosol chemical properties

In addition to carrying large quantities of dust, the winds over the NAO often bring high concentrations of pollutants. The pulses of increased dust concentrations are accompanied by sharply increased concentrations of nss-$SO_4^=$ and NO_3^- which are largely attributed to pollutant sources (Table 3.1). At Barbados, the pollutants appear to be derived mostly from Europe (Savoie et al, 1989a; Savoie et al., 1992), a conclusion that is supported by the lead isotope ratios in Barbados aerosols (Hamelin et al., 1989). Similarly, the aerosols collected at Bermuda are strongly affected by North American pollution sources (Arimoto et al., 1992; Arimoto et al., 1995a; Ellis et al., 1993). A recent study used tracers to quantitatively assess the relative impact of natural and anthropogenic sources of sulfate aerosol over the NAO (Savoie et al., 1995); the annual mean anthropogenic component of aerosol nss-$SO_4^=$ was 50% at Barbados, 70% at Bermuda and 80–90% at Mace Head, Ireland. A number of studies suggest that many aspects of the particle and elemental distributions in ocean waters can be interpreted in terms of atmospheric transport (see, for example: Helmers and Rutgers van der Loeff, 1993; Duce and Tindale, 1991; Donaghay et al., 1991; Fanning, 1989; Owens et al., 1992; Kremling and Streu, 1993; Veron et al., 1992; Veron et al., 1993; Carder et al., 1986).

These studies show the pervasive effects of the long range transport of natural and pollutant materials over the NAO. Nonetheless, on a mass basis, dust is the major component. Indeed, at Barbados during the past decade, the mean concentration of mineral dust is almost an order of magnitude greater than that of the other major non-sea-salt aerosol components (i.e., NO_3^-, nss-$SO_4^=$, and NH_4^+); even at Bermuda, the mean mineral dust mass is about 50% greater than other components despite the fact that dust concentrations are lower and pollutant concentrations higher than at Barbados.

3.3.2.3 Relationship of dust transport to rainfall in Africa

The long-term record of dust concentrations at Barbados (Figure 3.2; Prospero and Nees, 1986; Prospero et al., 1993) shows the long-term consistency of the pattern of annual dust transport in the trade winds. Dust concentrations increased sharply beginning in 1970 when a persistent drought began in the sub-Saharan (Sahel) regions of Africa. Prior to 1970, the annual average dust concentration was 3.9 µg m^{-3} (range 3.2–4.5 µg m^{-3}); from 1970 to 1992, the average was 11.0 µg m^{-3} (5.4–18.7 µg m^{-3}). The highest dust concentrations at Barbados occurred in the mid 1980’s when the drought was especially severe; during 1983–87 (excepting 1986), the June to August average dust concentrations exceeded 25 µg m^{-3}; the maximum June-August mean concentration for the entire 27 year record occurred in 1984, 37.8 µg m^{-3}.

The Barbados dust concentrations for 1965–1992 are inversely related to the prior year rainfall in sub-Saharan (Sahel) Africa (Lamb and Peppler, 1991; Figure 3.2). A similar relationship is obtained using rainfall data (Gray et al., 1992) from West Africa that incorporates more stations closer to the coast (Prospero et al., 1993). Mean summer dust concentrations at Barbados increase by about 10 µg m^{-3} for every standard deviation of rainfall deficit. The relationship between dust concentrations and rainfall is less evident during the winter when the transport of dust to Barbados is more sporadic. While the dust and drought data can be interpreted as supporting a direct drought-related cause for increased dust, there are other mechanisms that could effect the same result (see below, 3.4.4, Long Range Dust Transport and Climate).

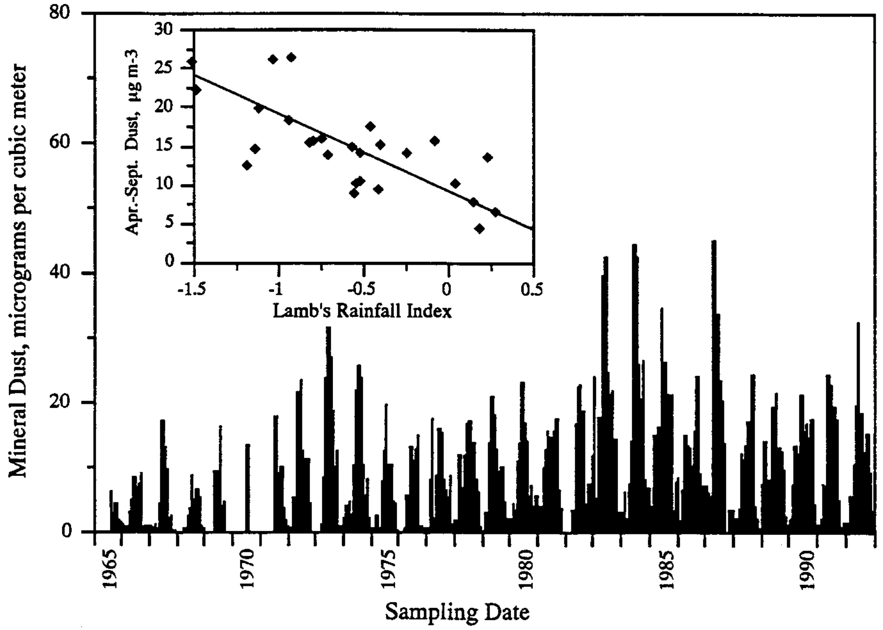

Figure 3.2 Long-term (1965–1992) record of monthly average atmospheric dust concentrations at Barbados (Prospero and Nees, 1986. The inset shows the relationship of Barbados dust concentrations to rainfall deficits in the Sahel as expressed by the Lamb rainfall index (Lamb and Peppler, 1991) which is a measure of rainfall departures (in standard deviations) from the mean. The rainfall data are from 20 sub-Saharan stations. The index uses as a reference base rainfall from 1941 to 1982. Lower index numbers correspond to drier conditions.

3.3.2.4 Meteorology of long range African dust transport

Large scale dust outbreaks are usually associated with complex meteorological processes; our understanding of them is poor because there has never been a major field experiment that focussed on synoptic-scale dust mobilization processes in the areas where the mobilization of long-range dust transport is greatest (West Africa, Asia and the Middle East). Much of our current understanding about African dust events was obtained incidentally during a large-scale meteorological program off the west coast of North Africa (the GARP Atlantic Tropical Experiment - GATE) during the summer of 1974 (Karyampudi and Carlson, 1988). Large dust outbreaks were associated with strong convective disturbances that developed deep in West Africa at about 15°–20°N and moved to the west. Over the ocean, the dust outbreaks events were usually associated with easterly waves which emerge from the coast of Africa every 3–4 days. Easterly waves have a complex dynamic structure which produces complex distribution patterns for the dust. The areal distributions are plainly visible in satellite imagery as stated earlier. A consistent feature is that the main transport occurs at higher altitudes in a layer that typically reaches to several km and often to 5–6 km (Prospero and Carlson, 1972; Talbot et al., 1986; Karyampudi and Carlson, 1988); concentrations aloft are usually several times greater than in the marine boundary layer. Because of the unusually high temperature and low relative humidity of the dust layer, it can be identified in routine meteorological soundings as far west as the Caribbean, Miami (Carlson and Prospero, 1972; Ott et al., 1991) and over the Amazon basin in eastern Brazil (Swap et al., 1992).

Because of the complexity of the meteorological events associated with African dust transport, it is very difficult to assess dust transport in a comprehensive and quantitative way. Indeed, the fundamental meteorological processes themselves are poorly understood and it has not been possible to understand the evolution of the layered structure even in terms of the dynamics of the systems (Westphal et al., 1987; Westphal et al., 1988).

3.3.3 PACIFIC STUDIES

There are many dust sources in Asia, most notably the large deserts in the People's Republic of China especially the Gobi and the Takla Makan. In addition, China has extremely large loess deposits (Pye, 1987) much of which is used for agriculture; because of their fine texture, these soils are easily deflated by winds. Dust storms are quite frequent in these regions (Littmann, 1991; Middleton, 1989; Middleton, 1991), especially in the spring when there is wide-spread dust which can be carried great distances (Gao et al., 1992a). In Japan and Korea during the spring, they often experience extensive dust hazes that are caused by yellow dust (Kosa) that can be traced to sources in Asia (Gao et al., 1992b; Chung, 1992; Iwasaka et al., 1983; Takayama and Takashima, 1986; Tsunogai et al., 1985).

Dust transport across the North Pacific has been most extensively measured in the Sea/Air Exchange (SEAREX) Program (Prospero et al., 1989). Continuous measurements were begun in the early 1980's when a network of stations was established in the North and South Pacific (Prospero et al., 1989; Uematsu et al., 1983; Uematsu et al., 1985; Uematsu, 1987). Subsequent measurements were made as a part of the NASA Pacific Exploratory Mission (PEM, Arimoto et al., 1995b). The stations in the North Pacific show a well-defined seasonal pattern of dust transport with a maximum in the spring months and a minimum in the summer. The seasonal cycle is best illustrated by the data from Midway (Figure 3.3) where the record is longest. The dust maximum corresponds to the seasonal cycle of dust storm activity in Asia (Duce, 1995). There are often large year-to-year variations in the seasonal cycle; these can be related to changes in dust storm frequencies in Asia and to changes in the large-scale wind systems (Duce, 1995; Merrill, 1989).

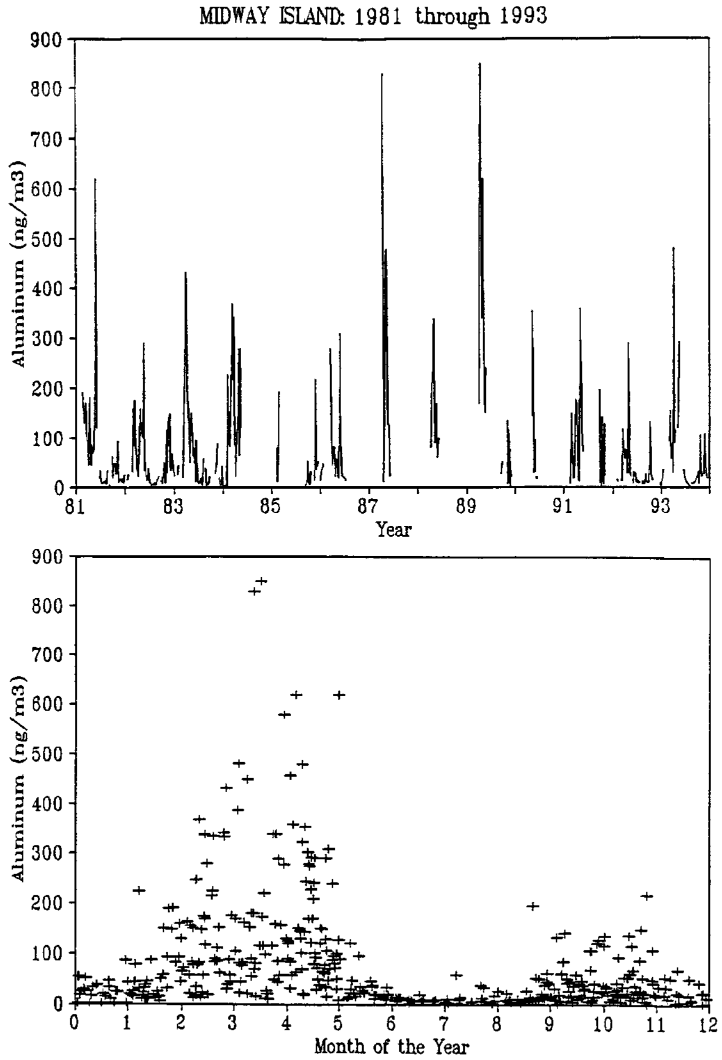

Figure 3.3 Aluminum concentration in aerosols collected in oceanic air at Midway island: 1981 – 1993. Top: 12 year time series. Bottom: same data as in the time series but plotted on an annual basis. (Arimoto et al., 1995b; R. Arimoto, personal communication).

The mineral characteristics of aerosols over the North Pacific Ocean (NPO) reflect many of the characteristics of the underlying sediments (Blank et al., 1985, Leinen et al., 1994). The mineral composition of the aerosols changes with the transport trajectories and can be associated with sources in Asia and North America (Merrill et al., 1994).

Over the North Pacific, continental sources strongly affect the concentration of several other species: aerosol NO_3^- and nss-$SO_4^=$ (Savoie et al., 1989a) and ^{210}Pb (Turekian et. al., 1989). ^{210}Pb is a daughter product of ^{222}Rn that is emitted from soils and, as such, it serves as a tracer for air masses that have recently been in convective contact with soils. All have a seasonal cycle similar to that for dust. The spring-time maximum of nss-$SO_4^=$ and NO_3^- is attributed to the transport of pollutants along with dust; concentrations are substantially higher than would be expected from natural sources (Savoie et al., 1989a).

The monthly mean Al concentrations at all the major NPO stations are shown in Figure 3.4. The highest monthly means are observed at the stations on the western NPO, Okinawa, Cheju (Korea) and Hong Kong (Arimoto et al., 1995b). Okinawa and Cheju show a springtime maximum similar to that at the central Pacific sites (Oahu, Midway and Shemya). The Hong Kong data show a bimodal distribution with a small peak in the spring and a larger, broader one in the winter; the winter peak is associated with transport from the North. Thus, all stations show a consistent picture of large scale dust transport in the spring as depicted in the AVHRR imagery (Plate 3.1).

The effects of continental transport are much greater over the NPO than the SPO. Figure 3.5 shows the annual arithmetic mean mineral aerosol concentrations over the NPO and SPO as measured in the SEAREX network (Prospero et al., 1989). Dust concentrations are highest in the mid-latitude of the NPO and lowest in the equatorial Pacific and central SPO. The relatively high concentrations at Funafuti compared to the other equatorial stations is attributed to Asian dust transport. New Caledonia and Norfolk Island are affected by dust transport from Australia (Prospero et al., 1989). Nonetheless, considering the distance from Australia and comparing concentrations with those at stations off the coast of Asia and Africa, the concentrations of dust and other trace species (Arimoto et al., 1990) are quite low. The low concentrations are consistent with the AVHRR imagery which shows very low AOD in this region in all seasons. Collectively these data suggest that Australia is a poor source of dust. The lowest dust concentrations are observed at American Samoa; the concentrations of other continental sources species (nss-$SO_4^=$, NO_3^- and ^{210}Pb) are also extremely low (Savoie et al., 1989b).

The meteorological setting for long-range dust transport events over the NPO is quite complex. Major dust storms are most frequent in the spring because of the combined effects of low rainfall (and, hence, dry soils), large expanses of soils freshly plowed for spring planting, and the frequent occurrence of high winds that are usually associated with cold fronts that move out of central Asia (see Prospero et al., 1989; Merrill et al., 1985, Merrill et al., 1989); dust is typically lifted to 5–6 km (Merrill et al., 1985; Kotamarthi and Carmichael, 1993). Because of the extremely dynamic character of cold fronts, dust is often lifted from widely diverse

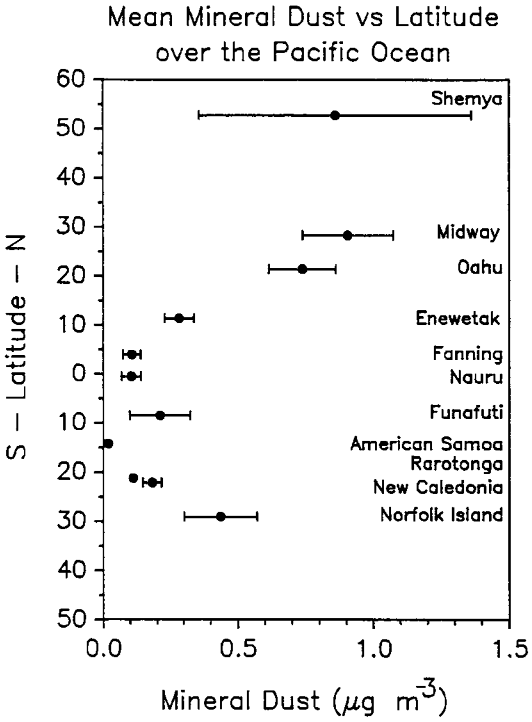

Figure 3.5 Annual arithmetic mean mineral aerosol concentrations over the Pacific Ocean as measured in the SEAREX network (Prospero et al., 1989). This figure contains only the data from relatively remote stations; it does not contain the data from the stations in the western North Pacific which are more heavily impacted by dust transport because of their proximity to sources in Asia. Dust concentrations are based on measurements of Al concentration multiplied by 12.5, assuming an average Al crustal abundance of 8% (Taylor and McLennan, 1985).

regions; plumes from distant sources are lofted and interleaved in the atmosphere, producing a strongly layered structure (Kotamarthi and Carmichael, 1993). The larger-scale meteorological setting will control the trajectories that transport the dust over the ocean (Merrill, 1989). These factors combine to yield the highly episodic dust events that are observed in the NPO.

3.3.4 INDIAN OCEAN AND THE ARABIAN SEA

There are very few data for the Indian Ocean and most are for short periods during cruises. Nonetheless, these data clearly show that dust concentrations are very large over the Arabian Sea and the NW IO close to Africa; values are comparable to those along the west coast of Africa (Savoie et al., 1987; Prodi et al., 1983). These values and the seasonality of the concentrations are consistent with the dust transport distributions shown in AVHRR (Plate 3.1) and with the monsoon circulation (Ackerman and Cox, 1989). Soils in the Tigris and Euphrates River basin appear to be major source of dust that is transported to the Arabian Sea (Ackerman and Cox, 1989; Prospero, 1981a; Prospero, 1981b); the transport takes place in deep, well-defined layers that extend to 4–7 km, similar to those observed with Saharan dust outbreaks (Ackerman and Cox, 1989).

There is even less quantitative data from the central and southern IO. The few data that exist suggest that concentrations are extremely low. Measurements (a total of 3 samples!) at Amsterdam Island (34°47’S, 77°31’E), yield concentrations in the range of those observed at American Samoa (Table 3.1) (Gaudichet et al., 1989). The dearth of measurements makes it extremely difficult to characterize deposition to this vast region but it would appear that mineral dust concentrations across much of the southern oceans are extremely low.

3.3.5 SUMMARY

Figure 3.6 presents graphically the Al data from Table 3.1. The Al values range over three orders of magnitude. It is not surprising that the highest values are found close to the continents (e.g., the western North Pacific stations; Tenerife). It is notable that the concentrations at Barbados (which is 4500 km from the coast of Africa) are comparable to those in coastal regions. Indeed, the distance from Barbados (and also Bermuda) to the coast of Africa is about the same as that between Midway and the coast of Asia; yet the mean dust concentration at Barbados is about 20 times that at Midway. These data illustrate once again that

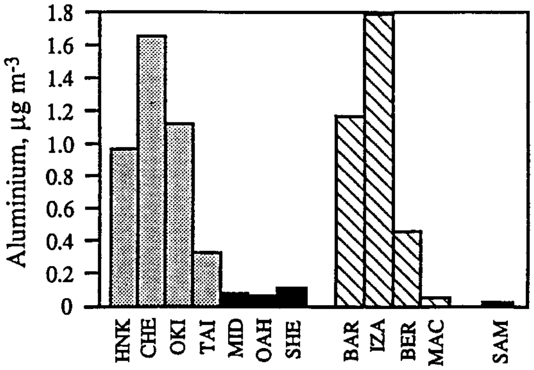

Figure 3.6 Annual mean aluminum concentrations at sites in the Atlantic and Pacific Oceans based on measurements in the PEM-West, SEAREX, and AEROCE networks. HNK: Hong Kong; CHE: Cheju, Korea; OKI: Okinawa; TAI: Taiwan; MID: Midway; OAH:

Oahu; SHE: Shemya; BAR: Barbados; IZA: Izaña, Tenerife, Canary Islands; BER: Bermuda; MAC: Mace Head, Ireland; SAM: American Samoa.

the efficiency with which materials are transported by winds from the continents to the oceans is a function of many factors (Merrill 1989; Whelpdale and Moody, 1990), and that distance alone is not necessarily important. Indeed, the intensity and year-round persistence of the dust transport in the tropical NAO seems to be unique: it appears to be the result of the coupling of the strong dust sources in North Africa with an extremely efficient transport system - the trade wind regime. Finally, the fact that pulses of dust are usually accompanied by increased levels of pollutants must be considered when assessing the effects of dust deposition on ocean processes.

3.4 MINERAL PARTICLE DEPOSITION TO THE OCEANS

3.4.1 SOURCE STRENGTHS

The quantitative estimation of dust transport is extremely difficult for a number of reasons, one of which is the difficulty in defining what is meant by "transport". Vast amounts of soil material are moved by winds each year especially in regions of sand dunes and in eroding agricultural areas (Pye, 1987). However, close to the source regions, much of the transported mass consists of large particles (i.e., diameters of tens of microns; d’Almeida and Schütz, 1983; Duce, 1995) which have a very short residence time in the atmosphere because of their high Stokes settling velocity; therefore, such large particles will not be carried very far by winds. For this reason, flux estimates are usually based on that portion of the mass that is below 10–20 µm diameter. During transport, the size distribution rapidly shifts to smaller particles because of the rapid fallout of large particles (i.e., 5–10 µm diameter and greater); at distances of a few hundreds of kilometers or more from the source, the dust attains a relatively stable size distribution with a mass median diameter of one-to-several µm (e.g., Duce, 1995) although some very large particles can be carried great distances (Betzer et al., 1988; Carder et al., 1986). Thus, the properties of the "long-range" dust will be those of the clay-silt fraction in soils (Gomes et al., 1990). Consequently the physical, mineralogical and chemical properties of this component of soils are relevant to understanding the properties of deflated dust and long range transport.

Because of the uncertainties about sources, dust deflation processes and the subsequent transport and removal dynamics, estimates of the source strength of dust are probably the poorest of any major aerosol species. Duce (1995) has recently reviewed and summarized the dust estimates made over the past 25 years. Early estimates yielded global input rates on the order of several hundreds of Tg y^{-1}. In contrast, estimates made since the mid 1980’s are an order of magnitude higher, ranging from 1000 to 3000 Tg y^{-1}. Some of the recent estimates are based on process studies in North Africa and, consequently, they may be biased by the increased deflation associated with the drought. Nonetheless the agreement of the recent estimates is surprising because, for the most part, they are generated on the basis of different models.

3.4.2 DUST DEPOSITION RATES

Over the open ocean, where the mass median diameter is only a few microns at most, the dominant deposition mechanism is generally removal by precipitation (e.g., "wet" removal). Removal by "dry" processes (principally by sedimentation and impaction) could be important in coastal regions close to sources (such as along the west coast of North Africa) where the dust size distribution is skewed towards large particles. Unfortunately, there have been very few efforts to make direct measurements of dust deposition to the oceans for extended time periods. Consequently, estimates of wet deposition rates must be based on calculations using scavenging ratios (defined as the concentration of a substance in rain divided by the corresponding concentration in air, e.g., Scott, 1981; Galloway et al., 1993). Scavenging ratios are empirically derived from measurements made with co-located precipitation and aerosol samplers. However, because of the dearth of long-term measurements of dust in precipitation and aerosols (Prospero et al., 1987; Uematsu et al., 1985), it has been necessary to extrapolate scavenging ratios to the world ocean. The most recent and most comprehensive estimate of dust deposition to the oceans is presented in Duce et al. (1991). For various reasons, Duce et al. (1991), use a scavenging ratio of 200 for the NAO; for the remainder of the world ocean, they used a ratio of 1000 (which, all other things being equal, will yield a deposition flux that is five times that obtained with the 200 value). The Duce et al. dust deposition rates for various ocean regions are shown in table 3.2. The largest basin rates (per unit area) are, in order, the North Indian Ocean, the NPO and the northern NAO.

The high fluxes in the IO and NAO are consistent with the patterns of dust seen in AVHRR (Plate 3.1). In contrast, the very large values for the NPO seem high in light of the indicated transport from AVHRR. The calculated deposition flux fields in the western NPO are comparable to those in the eastern tropical NAO. Yet the AVHRR data suggest that aerosol concentrations are never as high as those in the tropical NAO and that the transport takes place only during the spring; in contrast dust is carried out of North Africa all year long. It is possible that this discrepancy is due to a sampling bias by AVHRR which only can measure aerosols in cloud-free regions. Consequently, if dust transport in Asia takes place under cloudy conditions (for example, with persistent high stratus), the transport would not be recorded in the AVHRR data base. Nonetheless the previously cited measurements of aluminum (and other) aerosols over the NPO do support the seasonality implied by AVHRR.

Table 3.2 Dust deposition rates to various ocean regions (After Duce et al., 1991).

Ocean	Mean Basin Flux, g m^{-2} y^{-1} *	Total Basin Deposition, Tg y^{-1}	
		Duce et al., 1991*	SR = 200^{+}
North Pacific	5.3	480	96
South Pacific	0.35	39	8
North Atlantic	4.0	220	220
South Atlantic	0.47	24	5
North Indian	7.1	100	20
South Indian	0.82	44	9
Global	2.5	910	358

* Duce et al. (1991) SR = 1000 except for North Atlantic where SR = 200
\+ Duce et al. (1991) Modified using SR = 200 globally

The total estimated deposition to the world ocean is 910 Tg y^{-1} (Table 3.2). Compared to the estimates of dust production (Duce, 1995), the estimated total ocean deposition rate is equal to 100% of the lowest production estimate and about a third of the highest estimate. This suggests that the estimated transport (i.e., 910 Tg y^{-1}) may be too high or that the lower-range estimates of dust source strength might be too low. The mean global ocean accumulation rate is 250 mg cm^{-2} ky^{-1}. Basin means range from 35 to 710 mg cm^{-2} ky^{-1} but there are very large gradients across basins.

In some basins the deposition rates reported in Duce et al. (1991; Table 3.2) are remarkably high and are comparable to those measured on the continents or near major source regions. For example, the mean deposition rate for the entire North Pacific (about 500 mg cm^{-2} ky^{-1} is about half that measured for the deposition of Saharan dust in the Alps (about 1000 mg cm^{-2} ky^{-1}, De Angelis and Gaudichet, 1991) and on Corsica (about 800 mg cm^{-2} ky^{-1}, Bergametti, 1989b; Bergametti, 1989c); these measurements were made in the 1980’s when dust transport from the Sahara was unusually high. The Duce et al. values are even high compared to measured continental deposition rates. The most extensive continental program (Reheis and Kihl, 1995) was a five year study at 55 sites in southern Nevada and California. The average silt-clay deposition rate (both wet and dry) over most of this relatively arid region was in the range of 430–1570 mg cm^{-2} ky^{-1}. Reheis and Kihl summarize dust deposition rates from various continental regions (their

Table 8); the rates are generally consistent with those that they obtained (excluding the values that included sand). At the very least the Reheis and Kihl data emphasize the fact that arid regions are not necessarily good sources of dust compared to the major sources that we see today in North Africa, Asia and the Middle East.

3.4.3 COMPARISON WITH AEOLIAN DEPOSITION RATES

Recently Rea (1994) has reviewed aeolian deposition rates to the oceans based on the analysis of pelagic sediment cores. Rea's measured accumulation rates for aeolian materials in Holocene sediments in the NPO, where he has a relatively high data density, seem to be in reasonable agreement with the estimates by Duce et al. (1991). Data in the Atlantic are quite sparse and concentrated in the eastern equatorial regions; but here too, the agreement seems acceptable. Rea has much less data in the low sedimentation rate regions, especially in the southern oceans but most notably in the IO. Rea states that the Duce et al. deposition rates to the southern oceans are too high by a factor of 5 to 10; however Rea's data density in these regions is very sparse and does not warrant a strong conclusion in this regard.

Recent data (Duce, 1995) seem to suggest that the scavenging ratio of 1000 (which was used in the Duce et al. (1991) estimate for every ocean region except the NAO) may be too high and that a value of 200 (which was used for the NAO) might be appropriate. If true, this would lower the estimated deposition fluxes by a factor of five, all other factors being equal. In Table 3.2, the deposition rates are also shown for this lower rate which yields a global rate of 360 Tg y^{-1}. A scavenging ratio of 200 will yield deposition rates in the southern oceans that are more in line with Rea's (sparse) data; however the resulting values in the NPO would be substantially lower than Rea's.

There are a number of possible explanations for discrepancies between the estimated deposition rates and the measured accumulation rates. First, the scavenging ratios used in the estimates could be wrong; it is possible that scavenging could vary regionally or even temporally with changes in climate and that large scale extrapolations of scavenging ratios are not appropriate. There are so few data on the dust scavenging that it is impossible to assess these effects. Second, the accumulation rates in sediments are in effect long-term averages, typically thousands of years, whereas the dust deposition estimates are based on current measurements. Differences could be due to relatively recent changes in climate that could affect dust transport. Third, only recently have humans had the capability to strongly alter the landscape; land-use practices, especially cultivation and intense grazing of livestock, can lead to greatly increased rates of deflation. Fourth, the sediment accumulation rates could be wrong or the material could have been transported by mechanisms other than aeolian. At this time, it is not possible to resolve these issues.

3.4.4 LONG RANGE DUST TRANSPORT AND CLIMATE

3.4.4.1 Wind erosion and climate

Aeolian particles in pelagic sediments can provide a long-term record of the transport of mineral dust to the oceans. On the basis of our knowledge (and assumptions) about the relationship between dust transport, weather and climate, the aeolian sediment component can be interpreted in terms of past climate on the continents. Changes in the accumulation rates and grain-size distributions of aeolian dust in deep-sea sediments have been used as indicators of past aridity and as a measure of the "vigor" of the atmospheric circulation (Rea, 1994). Many studies have suggested that the aeolian dust in sediments might serve as a useful indicator of paleoclimate (Sarnthein et al., 1982; Leinen, 1989; Hovan et al., 1991; Rea, 1994). These studies show that there have been large changes (factors of ten) in the transport of dust to the oceans in the past. Changes have been related in a general way with glacial cycles, suggesting that the major glaciations were associated with greatly increased dust transport and more vigorous wind systems. The association of cold cycles with enhanced dust transport has also been noted in ice core studies, especially in the northern hemisphere.

There is an extensive literature on large scale wind erosion (Middleton, 1985; Middleton, 1990; Goudie, 1983; Goudie and Middleton, 1992; Pye, 1987; Golitsyn and Gillette, 1993). This shows that major sources are associated with arid and semi arid regions. But deserts (and arid lands) are not necessarily good sources; for example, as shown above, Australia is a very weak source of dust despite the fact that it is largely arid and desert. High rates of emission are generally associated with semi-arid regions where marginal lands are used for agriculture and herding (Middleton, 1990; Littmann, 1991); during periods of drought, the denuded and broken soil surface is easily carried away. The periodic creation of "dust bowl" conditions in the midwestern United States is a good example.

It is difficult to relate the sedimentary dust record with climate in an unambiguous way. Indeed, the physical basis for the interpretation of the sedimentary record (Rea, 1994) has never been established by measurements of dust/transport relationships in the present day world (Prospero, 1985; Duce, 1995). For example, the Barbados data (Figures 3.2 and 3.3) certainly appear to suggest that there is a relationship between dust transport and rainfall. Yet, if dust were strictly related to rainfall, then we would expect that the dominant source in North Africa would be the Sahara. We do know that the Sahara is an important source, especially for dust that is transported northward, across the Mediterranean to Europe (De Angelis and Gaudichet, 1991). But if the Sahara is the major source for the trans-Atlantic dust, then why should dust transport from this source be modulated in such a way as to correlate with rainfall in the Sahel and West Africa? Is "drought" occurring in the Sahara as well? One could argue that the meteorological factors that produced the drought in the Sahel were accompanied by other changes (for example, changes in wind speed and gustiness) that could have deflated more dust in the Sahara itself. Because there is a threshold wind velocity for deflating soils (e.g., Gillette et al., 1980; Gillette, 1981; Gillette, 1984), dust generation and transport are linked to the wind speed distribution spectrum.

There is evidence that the variability of rainfall in the Sahel is linked to changes in meteorological features on a hemispheric or even global scale. Consequently, concurrent variations in other meteorological variables over and downwind of North Africa may influence the dust concentrations measured at Barbados as much as, or more than, the variation in the Sahelian rainfall. Indeed, Gray et al. (1992) have developed a predictive model for North Atlantic hurricanes that is based on African rainfall statistics. The frequency and intensity of hurricanes has diminished greatly since the beginning of the African drought (Gray et al., 1992). Both the Hadley circulation and the mid-tropospheric easterly jet are more intense during the Sahelian dry spells (Nicholson, 1986; Newell and Kidson, 1984). The intensification of these two features could cause greater dust generation and transport even in the absence of drought. Moreover, the overall meteorological changes may result in variations in the intensities of dust storms associated with strong winds over the Sahara as well as those associated with squall lines in the Sahel. Episodic disturbances (Nickling and Gillies, 1989) and the seasonality of climate in the source regions (Leinen, 1989) also may influence dust fluxes. The "Sahara vs. Sahel" argument may eventually be resolved by remote sensing. Unfortunately it is not easy to use satellites to identify sources of dust storms in a systematic way; although Saharan storms are relatively easy to identify, squall-line clouds tend to obscure those that occur in the Sahel. Indeed, it may be significant that the season of greatest dust transport in the tropical NAO coincides with the greatest frequency of squalls in the sub-Saharan region.

3.4.4.2 The role of humans

A further complicating factor is the role of humans in augmenting the deflation of soils. The vastly increased dust transport out of North Africa during the past 25 years seems to be associated with marginal lands in the Sahel that were brought into cultivation during a relatively moist climate phase in the 1950’s and 1960’s. Cash crops were introduced into this region and the raising of livestock was greatly increased due to the availability of water at natural sources and also from bore-holes that became widely available as a result of development programs. As a result of these activities, the soil surface was greatly disturbed over wide areas; these soils were highly susceptible to wind erosion once the drought began in the late 1960’s. If the increased dust amounts that we have seen over the North Atlantic in the past few decades are due to the effects of drought augmented by land use practices, then the dust/drought relationship that we observe may not be applicable to "natural" processes. Under such conditions, the dust that we seen in this region could be regarded as an anthropogenic pollutant. The same statement may be applicable to Asian dust sources. Thus, the present-day dust transport may not be representative of the transport over the geological record. This could explain some of the discrepancies between the present day measurements of dust transport and the aeolian record in the sediments.

3.4.4.3 Modeling dust generation and transport

In the preceding sections, we have seen that large scale dust events are associated with intense meteorological events: traveling disturbances in West Africa; severe frontal passages in Asia and monsoon events over the Arabian Sea. In this regard, dust transport is different from that of other "pollutants" which are emitted essentially continuously and transported according to the prevailing meteorological conditions. In contrast dust generation is a highly non-linear process and it occurs under meteorological conditions that are quite complex.

The complexity of the dust deflation processes is reflected in the difficulty that models have in replicating the global distribution of dust sources and the temporal and spatial distribution of dust transport (e.g., Joussaume, 1990; Tegen and Fung, 1994; Genthon, 1992; G. Rau, personal communication). The dust generation algorithms give heavy weight to rainfall and soil moisture conditions; consequently, they tend to show plumes emerging from deserts. For example, the present day dust transport (as indicated by AVHRR AOD) off west Africa is located much further south than the plumes produced in models. Also, in the models, the dust plume emerging from west Africa does not move much from season to season whereas in AVHRR the plume, in addition to being much further south of the model plume, undergoes a very large seasonal north-south migration, tracking the movement of the equatorial circulation and the ITCZ.

These comments are not intended to denigrate modeling in general or any model in particular, but rather to emphasize that it is a much more difficult task to model dust sources than other continental aerosol materials because of the many complex factors that are involved in dust generation. Furthermore, it will be difficult for modelers to incorporate the human factors such as land use in their algorithms. Yet humans may be the chief factor affecting present-day dust emission rates.

3.5 EFFECTS OF AEOLIAN INPUTS TO THE OCEANS

Wind transported dust has a significant impact on a number of sedimentary processes on geological time scales. As stated previously, the distribution of minerals in the oceans is clearly related to aeolian inputs. Saharan dust is also a major contributor to the soils on Barbados (Muhs et al., 1987, Muhs et al., 1990) and possibly the soils on Bermuda (Bricker and McKenzie, 1970) and other islands in the Caribbean and the Bahamas (Muhs et al., 1990). Over the past decade, there has been increased interest in the role of aeolian transport to present-day ocean processes. Much of this interest was stimulated by the possible role of aeolian inputs as nutrients (Duce, 1986), especially the role of Fe (Martin, 1990; DiTullio et al., 1993; Donaghay et al., 1991; Duce and Tindale, 1991; Morel et al., 1991; Young et al, 1991).

The impact of mineral dust nutrient inputs to the oceans will depend on a number of factors including the composition of the particles and the solubility of the species of interest. The gross elemental composition of dust is close to that of average crustal material (see for example, Prospero, 1981a). The dust generation process does result in a fractionation of some elemental species (Schütz and Sebert, 1987; Eltayeb et al., 1993) but for many elements the fractionation factors are relatively minor in the small-particle size range that is important in long-range transport. There is evidence of some significant regional differences in some species such as the rare earths (Sholkovitz et al., 1993). A major consideration is the solubility of the aerosol species in sea water since this will affect the availability to biological processes. Solubility is a complex property that depends on the weathering history of the soil particle in the source environment, the chemical and physical processes that occur during the particle's lifetime in the atmosphere (especially the cycling of the particle through clouds), and subsequent processing in sea water. There are many aspects about particle solubility that are poorly understood (Lim and Jickells, 1990; Kersten et al., 1991; Maring and Duce, 1989; Maring and Duce, 1990; Zhou et al., 1992; Zhu et al., 1992; Zhu et al., 1993; Zhuang et al., 1992; Giusti et al., 1993). Nonetheless, aeolian inputs do seem to have a discernible impact on some particle and elemental distributions in the oceans (Helmers and Rutgers van der Loeff, 1993; Jickells et al., 1990; Kremling and Streu, 1993; Maring et al., 1989; Veron et al., 1993; Veron et al., 1994). Given the large temporal and spatial variability of dust inputs, especially the sensitivity to climate, we might expect the aeolian-related processes in ocean waters to vary accordingly. Also, to the extent that erosional processes are human-induced, the impact of aeolian inputs on surface water processes may have changed dramatically during the past century.

Based on budget estimates for ocean surface waters and estimates of atmospheric deposition, Duce (1986) suggested that atmospheric NO_3^- (principally in aerosols and precipitation) could serve as a nutrient and enhance primary productivity. A number of studies have supported this conclusion although the magnitude and importance of the effect is still debated (Fanning, 1989; Michaels et al., 1993; Owens et al., 1992; Willey and Paerl, 1993). If atmospheric NO_3^- inputs are important, then we must be concerned about anthropogenic impacts. Various estimates indicate that about half or more of the oxidized nitrogen compounds in the atmosphere are derived from anthropogenic emissions (Hameed and Dignon, 1992). Because most of the world's population is located in the northern hemisphere, pollutant effects will be much greater in the northern hemisphere where over 90% of the global anthropogenic emissions of sulfur and nitrogen occur (Hameed and Dignon, 1992); we would expect the effects to be greatest over the NAO because of the density and proximity of sources on the surrounding continents.

3.6 CONCLUSIONS

Aerosol studies, coupled with satellite imagery, have established that mineral dust is a major aerosol component over many ocean areas; they show that the concentration of the dust is highly variable with time and with geographical location. Unfortunately, there have been very few studies of dust deposition processes to the ocean. Consequently, the estimates of input rates to the oceans are highly uncertain. In order to improve these estimates, it will be necessary to carry out an extensive program of deposition studies in many ocean regions. This will be difficult because of the highly sporadic nature of the dust deposition fluxes; a large fraction of the annual deposition takes place in a very small fraction of the precipitation events. In a one-year study of Saharan dust deposition in Miami (Prospero et al., 1987), 22% of the annual deposition occurred in one day and 68% in rain events that occurred during two dust episodes spread over a total of four days. In a study at Midway Island (Uematsu et al., 1985), about half of the annual deposition of dust occurred during a two week period. Because of the highly sporadic nature of these events, the concentration of mineral dust (or any other atmospheric component that is principally removed by precipitation) in ocean surface waters will be highly variable in time and space. Thus, in ocean regions where there is active dust transport, the mean concentration of dust in the underlying ocean could be relatively high but the concentration distribution could be highly non-uniform. To the extent that atmospheric deposition provides nutrients such as NO_3^- or iron, these inputs will occur as brief and infrequent pulses.

In the absence of actual deposition measurements, we must rely on estimates based on aerosol data; such estimates are crude because of the dearth of aerosol data from many ocean regions. This problem is especially severe for the southern oceans where there are huge regions for which there are essentially no measurements. Nonetheless, we would expect that the concentrations of mineral dust and other pollution-related species in these regions (and the associated deposition to the ocean) would be quite low.

While the measurement of dust deposition rates in precipitation is relatively easy (aside from the logistical problems of making the measurements in remote sites), the measurement of dry deposition rates is fundamentally difficult (Slinn, 1983; Hicks, 1986; Holsen and Noll, 1992; Nicholson, 1988). At present there is no generally accepted method for making quantitative estimates of the dry deposition of dust to water surfaces under ambient conditions. This is a severe problem close to sources where the dust-laden air contains a relatively high concentration of large particles that have a high settling rate. At greater distances, as stated earlier, the dry deposition rate is believed to be a relatively small compared to wet deposition. However, this statement is based on the extrapolation of data from other types of aerosols and it has never been satisfactorily substantiated.

Studies of aeolian components in pelagic sediment cores have provided interesting and provocative results concerning the paleoclimate of the earth. However these interpretations are handicapped by a lack of physical substantiation for the underlying hypothesis. There is a critical need to study the physical processes involved in present day dust transport so that we can more accurately assess the paleoclimatic record in the sediments. In particular there is a major concern about the relationship of modern day dust transport conditions to those that obtained in the past. There is evidence that soil dust deflation has been greatly increased in modern times due to agriculture and poor land use practices. Consequently, if we wish to interpret the past climatic record in the ocean sediments, we must study soil deflation for conditions where soils are in an undisturbed state. In addition, if we are to assess the future trend in dust emissions and the possible impact on climate, it will be necessary to assess the deflation processes that apply to disturbed soils.

If the present-day deflation rates of soils are strongly impacted by human activities, then they must be regarded as a pollutant. There is evidence that dust can play a significant role in climate (Andreae, 1995; Duce, 1995) In order to assess the climate affects of dust, it will be necessary to model the dust distribution and properties. Further, if we are to anticipate future trends, it will be necessary to model the changes in dust transport that we might expect as a consequence of different climate, population and land use scenarios. As pointed out earlier, dust generation is a highly nonlinear process that is very sensitive to the energetics of meteorological processes and to site-specific soil properties. Consequently this modeling task will be much more difficult than for other atmospheric pollutants.

Finally, if dust, pollutants and other continental emissions are having an impact on processes in the oceans, then the effects should be most readily observable over the northern hemisphere oceans, especially the North Atlantic.

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3.8 REFERENCES

Ackerman, S. A. and S. K. Cox (1989) "Surface weather observations of atmospheric dust over the southeast summer monsoon region", *Meteorol. Atmos. Phys.*, **41**, 19–34.

Andreae, M. O. (1995) "Climatic effects of changing atmospheric aerosol levels", in A. Henderson-Sellers (ed) *World Survey of Climatology, Vol. 16, Future Climates of the World*, Elsevier, Amsterdam, (in press).

Arimoto, R., R. A. Duce, D. L. Savoie and J. M. Prospero (1992) "Trace elements in aerosol particles from Bermuda and Barbados: Concentrations, sources, and relationships to aerosol sulfate", *J. Atmos. Chem.*, **14**, 439–457.

Arimoto, R., B. J. Ray, R. A. Duce, A. D. Hewitt, R. Boldi and A. Hudson (1990) "Concentrations, sources, and fluxes of trace elements in the atmosphere of New Zealand", *J. Geophys. Res.*, **95**, 22,389–22,405.

Arimoto, R., R. A. Duce, B. J. Ray, J. D. Cullen, J. T. Merrill and W. G. Ellis Jr. (1995a) "Trace elements in the atmosphere over the North Atlantic", *J. Geophys. Res.*, **100**, 1199–1213.

Arimoto, R., R. A. Duce, D. L. Savoie, J. M. Prospero, R. Talbot, J. D. Cullen, U. Tomza, N. F. Lewis and B. J. Ray (1995b) "Relationship among aerosol constituents from Asia and the North Pacific during PEM-West (A)", *J. Geophys. Res.*, (accepted).

Bergametti, G., L. Gomes, G. Coude-Gaussen, P. Rognon and M. Le Coustumer (1989a) "African dust observed over Canary Islands: Source-regions identification and transport pattern for some summer situations", *J. Geophys. Res.*, **94**, 14,855–14,864.

Bergametti, G., A.-L. Dutot, P. Buat-Menard, R. Losno and E. Remoudaki (1989b) "Seasonal variability of the elemental composition of atmospheric aerosol particles over the northwestern Mediterranean", *Tellus*, **41B**, 353–361.

Bergametti, G., L. Gomes, E. Remoudaki, M. Desbois, D. Martin and P. Buat-Menard (1989c) "Present transport and deposition patterns of African dusts to the North Western Mediterranean", in M. Leinen and M. Sarnthein (eds) *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, Kluwer Acad. Publ., Dordrecht, 227–252.

Betzer, P. R., K. L. Carder, R. A. Duce, J. T. Merrill, N. W. Tindale, M. Uematsu, D. K. Costello, R. W. Young, R. A. Feely, J. A. Breland, R. E. Bernstein and A. M. Greco (1988) "Long-range transport of giant mineral aerosol particles", *Nature*, **336**, 568–571.

Blank, M., M. Leinen and J. M. Prospero (1985) "Major Asian aeolian inputs indicated by the mineralogy of aerosols and sediments in the western North Pacific", *Nature*, **314**, 84–86.

Bricker, O. P. and F. T. Mackenzie (1970) "Limestones and red soils of Bermuda: Discussion", *Geol. Soc. Am. Bull.*, **81**, 2523–2524.

Buat-Menard, P. (1986) "The ocean as a sink for atmospheric particles", in P. Buat-Menard (ed) *The Role of Air-Sea Exchange in Geochemical Cycling*, D. Reidel, Norwell, MA., 165–183.

Carder, K. L., R. G. Steward, P. R. Betzer, D. L. Johnson and J. M. Prospero (1986) "Dynamics and composition of particles from an aeolian input event to the Sargasso Sea", *J. Geophys. Res.*, **D91**, 1055–1066.

Carlson, T. N. and J. M. Prospero (1972) "The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic", *J. Appl. Meteorol.*, **11**, 283–297.

Chester, R. (1986) "The marine mineral aerosol", in P. Buat-Menard (ed) *The Role of Air-Sea Exchange in Geochemical Cycling*, Reidel, 443–476.

Chester, R. and K. J. T. Murphy (1990) "Metals in the marine atmosphere", in R. W. Furness and P. S. Rainbow (eds) *Heavy Metals in the Marine Environment*, CRC Press, Boca Raton, 27–49.

Chung, Y.-S. (1992) "On the observation of yellow sand (dust storms) in Korea", *Atmos. Environ.*, **26A**, 2743–2749.

Crutzen, P. J. and M. O. Andreae (1990) "Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles", *Science*, **250**, 1669–1678.

d'Almeida, G. A. and L. Schütz (1983) "Number, mass and volume distributions of mineral aerosols and soils of the Sahara", *J. Clim. Appl. Meteorol.*, **22**, 233–243.

De Angelis, M. D. and A. Gaudichet (1991) "Saharan dust deposition over Mont Blanc (French Alps) during the last 30 years", *Tellus*, **43B**, 61–75.

Delany, A. C., A. C. Delany, D. W. Parkin, J. J. Griffin, E. D. Goldberg and B. E. F. Reimann (1967) "Airborne dust collected at Barbados", *Geochim. Cosmochim. Acta*, **31**, 885–909.

Dessens, J. and P. Van Dinh (1990) "Frequent Saharan dust outbreaks north of the Pyrenees: A sign of climatic change?", *Weather,* **45**, 327–333.

DiTullio, G. R., D. A. Hutchins and K. W. Bruland (1993) "Interaction of iron and major nutrients controls phytoplankton growth and species composition in the tropical North Pacific Ocean", *Limnol. Oceanogr.*, **38**, 495–508.

Donaghay, P. L., P. S. Liss, R. A. Duce, D. R. Kester, A. K. Hanson, T. Villareal, N. W. Tindale and D. J. Gifford (1991) "The role of episodic atmospheric nutrient inputs in the chemical and biological dynamics of oceanic ecosystems", *Oceanography,* **4**, 62–70.

Duce, R. A. (1986) "The impact of atmospheric nitrogen, phosphorus, and iron species on marine biological productivity", in P. Buat-Manard (ed) *The Role of Air-Sea Exchange in Geochemical Cycling*, Reidel, Dordrecht, 497–528.

Duce, R. A. (1995) "Sources, distributions, and fluxes of mineral aerosols and their relationship to climate", in R. J. Charlson and J. Heintzenberg (eds) *Dahlem Workshop on Aerosol Forcing of Climate*, May, 1994, Berlin, 43–72.

Duce, R. A. and N. W. Tindale (1991) "Atmospheric transport of iron and its deposition in the ocean", *Limnol. Oceanogr.*, **36**, 1715–1726.

Duce, R. A., P. S. Liss, J. T. Merrill, E. L. Atlas, P. Buat-Menard, B. B. Hicks, J. M. Miller, J. M. Prospero, R. Arimoto, T. M. Church, W. Ellis, J. N. Galloway, L. Hansen, T. D. Jickells, A. H. Knap, K. H. Reinhardt, B. Schneider, A. Soudine, J. J. Tokos, S. Tsunogai, R. Wollast and M. Zhou (1991) "The atmospheric input of trace species to the world ocean", *Glob. Biogeochem. Cycles*, **5**, 193–259.

Ellis, W. G., Jr., R. Arimoto, D. L. Savoie, J. T. Merrill, R. A. Duce and J. M. Prospero (1993) "Aerosol selenium at Bermuda and Barbados", *J. Geophys. Res.*, **98**, 12,673–12,685.

Eltayeb, M. A. H., R. E. Van Grieken, W. Maenhaut and H. J. Annegarn (1993) "Aerosol-soil fractionation for Namib Desert samples", *Atmos. Environ.*, **27A**, 669–678.

Fanning, K. A. (1989) "Influence of atmospheric pollution on nutrient limitation in the ocean", *Nature*, **339**, 460–463.

Galloway, J. N., D. L. Savoie, W. C. Keene, and J. M. Prospero (1993) "The temporal and spatial variability of scavenging ratios for nss sulfate, nitrate, methanesulfonate and sodium in the atmosphere over the North Atlantic Ocean", *Atmos. Environ.*, **27A**, 235–250.

Gao, Y., R. Arimoto, M. Y. Zhou, J. T. Merrill and R. A. Duce (1992a) "Relationships between the dust concentrations over Eastern Asia and the remote North Pacific", *J. Geophys. Res.*, **97**, 9867–9872.

Gao, Y., R. Arimoto, R. A. Duce, D. S. Lee and M. Y. Zhou (1992b) "Input of atmospheric trace elements and mineral matter to the Yellow Sea during the spring of a low-dust year", *J. Geophys. Res.*, **97**, 3767–3777.

Gaudichet, A., R. Lefevre, A. Gaudry, B. Ardouin, G. Lambert and J. M. Miller (1989) "Mineralogical composition of aerosols at Amsterdam Island", *Tellus*, **41B**, 344–352.

Genthon, C. (1992) "Simulations of the long range transport of desert dust and sea-salt in a general circulation model", in S. E. Schwartz and W. G. N. Slinn (eds) *Precipitation Scavenging and Atmospheric-Surface Exchange, Vol. 3, Hemisphere*, Washington, 1783–1794.

Giusti, L., Y.-L. Yang, C. N. Hewitt, J. Hamilton-Taylor and W. Davison (1993) "The solubility an partitioning of atmospherically derived trace metals in artificial and natural waters: A review", *Atmos. Environ.*, **27A**, 1567–1578.

Golitsyn, G. and D. A. Gillette (1993) "Introduction: A joint Soviet-American experiment for the study of Asian desert dust and its impact on local meteorological conditions and climate", *Atmos. Environ.*, **27A**, 2467–2470.

Gomes, L., G. Bergametti, G. Coude-Gaussen and P. Rognon (1990) "Submicron desert dusts: A sandblasting process", *J. Geophys. Res.*, **95**, 13,927–13,935.

Goudie, A. S. (1983) "Dust storms in space and time", *Prog. Phys. Geog.*, **7**, 502–530.

Goudie, A. S. and N. J. Middleton (1992) "The changing frequency of dust storms through time", *Climatic Change*, **20**, 197–225.

Gray, W. M., C. W. Landsea, P. W. Mielke Jr. and K. J. Berry (1992) "Predicting Atlantic seasonal hurricane activity 6–11 months in advance", *Weather and Forecasting*, **7**, 440–455.

Hameed, S. and J. Dignon (1992) "Global emissions of nitrogen and sulfur oxides in fossil fuel combustion 1970–1986", *J. Air Waste Manage. Assoc.*, **42**, 159–163.

Hamelin, B., F. E. Grousett, P. E. Biscaye, A. Zindler and J. M. Prospero (1989) "Lead isotopes in trade wind aerosols at Barbados: The influence of European emissions", *J. Geophys. Res.*, **94**, 16,243–16,250.

Helmers, E. and M. M. Rutgers van der Loeff (1993) "Lead and aluminium in Atlantic surface waters (50°N to 50°S) reflecting anthropogenic and natural sources in aeolian transport", *J. Geophys. Res.*, **98**, 20,261–20,273.

Hicks, B. B. (1986) "Measuring dry deposition: A re-assessment of the state of the art", *Water Air Soil Pollut.*, **30**, 75–90.

Holsen, T. M. and K. E. Noll (1992) "Dry deposition of atmospheric Particles: Application of current models to ambient data", *Environ. Sci. Tech.*, **26**, 1807–1815.

Iwasaka, Y., H. Minoura and K. Nagaya (1983) "The transport and spacial scale of Asian dust-storm cloud: A case study of the dust-storm event of April 1979", *Tellus*, **35B**, 189–196.

Jankowiak, I. and D. Tanre (1992) "Satellite climatology of Saharan dust outbreaks: Method and preliminary results", *J. Climate*, **5**, 646–656.

Jickells, T. D., W. G. Deuser, A. Fleer and C. Hemleben (1990) "Variability of some elemental fluxes in the western tropical Atlantic Ocean", *Oceanologica Acta*, **13**, 291–298.

Joussaume, S. (1990) "Three-dimensional simulations of the atmospheric cycle of desert dust particles using a general circulation model", *J. Geophys. Res.*, **95**, 1909–1941.

Karyampudi, V. M. and T. N. Carlson (1988) "Analysis and numerical simulations of the Saharan air layer and its effects on easterly wave disturbances", *J. Atmos. Sci.*, **45**, 3102–3136.

Kersten, M., M. Kriews and U. Förstner (1991) "Partitioning of trace metals released from polluted marine aerosols in coastal seawater", *Mar. Chem.*, **36**, 165–182.

Kotamarthi, V. R. and G. R. Carmichael (1993) "A modelling study of the long range transport of Kosa using particle trajectory methods", *Tellus*, **45B**, 426–441.

Kremling, K. and P. Streu (1993) "Saharan dust influenced trace element fluxes in deep North Atlantic subtropical waters", *Deep Sea Res.*, **40**, 1155–1168.

Lamb, P. J. and R. A. Peppler (1991) "West Africa", Chapter 5 in M. Glantz, R. W. Katz and N. Nicholls (eds) *Teleconnections Linking Worldwide Climate Anomalies*, Cambridge Univ. Press, London, 121–189.

Leinen, M. (1989) "The late Quaternary record of atmospheric transport to the northwest Pacific from Asia", in M. Leinen and M. Sarnthein (eds) *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, Kluwer Acad. Publ., Dordrecht, 693–732.

Leinen, M. and M. Sarnthein (eds) (1989) *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, Kluwer Acad. Publ., Dordrecht, 909 pp.

Leinen, M., J. M. Prospero, E. Arnold and M. Blank (1994) "Mineralogy of aeolian dust reaching the North Pacific Ocean, I. Sampling and Analysis", *J. Geophys. Res.*, **99**, 21,017–21,024.

Lim, B. and T. D. Jickells (1990) "Dissolved, particulate and acid-leachable trace metal concentrations in North Atlantic precipitation collected on the global change expedition", *Glob. Biogeochem. Cycles*, **4**, 445–458.

Littmann, T. (1991) "Dust storm frequency in Asia: Climatic control and variability", *Int. J. Climatology*, **11**, 393–412.

McDonald, W. F. (1938) *Atlas of Climatic Charts of the Oceans*, Weather Bureau, Department of Agriculture, Washington, DC., 60 pp.

Maring, H. B. and R. A. Duce (1989) "The impact of atmospheric aerosols on trace metal chemistry in open ocean surface waters, II, Copper", *J. Geophys. Res.*, **C94**, 1039–1045.

Maring, H. B. and R. A. Duce (1990) "The impact of atmospheric aerosols on trace metal chemistry in open ocean surface waters, III, Lead", *J. Geophys. Res.*, **C95**, 5341–5347.

Maring, H., C. Patterson and D. Settle (1989) "Atmospheric input fluxes of industrial and natural Pb from the westerlies to the mid-North Pacific", in J. P. Riley, R. Chester and R. A. Duce (eds) *Chemical Oceanography, Vol. 10*, Academic Press., London, 84–105.

Martin, J. H. (1990) "Glacial-interglacial CO_2 change: The iron hypothesis", *Paleoceanography*, **5**, 1–13.

Merrill, J. T. (1989) "Atmospheric long-range transport to the Pacific Ocean", in J. P. Riley, R. Chester and R. A. Duce (eds) *Chemical Oceanography*, Vol. 10, Academic Press, London, 15–50.

Merrill, J. T., R. Bleck and L. Avila (1985) "Modeling atmospheric transport to the Marshall Islands", *J. Geophys. Res.*, **90**, 12,927–12,936.

Merrill, J. T., M. Uematsu and R. Bleck (1980) "Meteorological analyses of long range transport of mineral aerosol over the North Pacific", *J. Geophys. Res.*, **94**, 8584–8598.

Merrill, J. T., E. Arnold, M. Leinen and C. J. Weaver (1994) "Mineralogy of aeolian dust reaching the North Pacific, II: Relationship of mineral assemblages to atmospheric transport patterns", *J. Geophys. Res.*, **99**, 21,025–21,032.

Michaels, A. F., D. A. Siegel, R. J. Johnson, A. H. Knap and J. N. Galloway (1993) "Episodic inputs of atmospheric nitrogen to the Sargasso Sea: Contributions to new production and phytoplankton blooms", *Glob. Biogeochem. Cycles*, **7**, 339–351.

Middleton, J. J. (1985) "Effect of drought on dust production in the Sahel", *Nature*, **316**, 431–434.

Middleton, N. J. (1989) "Desert dust", in D. S. G. Thomas (ed) *Arid-Zone Geomorphology*, Belhaven Press, London, 262–283.

Middleton, N. J. (1990) "Wind erosion and dust-storm control", in A. S. Goudie (ed) *Techniques for Desert Reclamation*, John Wiley & Sons, New York, 87–108.

Middleton, N. J. (1991) "Dust storms in the Mongolian People's Republic", *J. Arid Environ.*, **20**, 287–297.

Morales, C. (1985) "The airborne transport of Saharan dust: A review", *Climate Change*, **9**, 219–241.

Morel, F. M. M., J. G. Reuter and N. M. Price (1991) "Iron nutrition of phytoplankton and its possible importance in the ecology of ocean regions with high nutrient and low biomass", *Oceanography*, **4**, 56–61.

Muhs, D. R., C. A. Bush, K. C. Stewart, T. R. Rowland and R. C. Crittenden (1990) "Geochemical evidence of Saharan dust parent material for soils developed on quaternary limestones of Caribbean and western Atlantic islands", *Quaternary Res.*, **33**, 157–177.

Muhs, D. R., R. C. Crittenden, J. H. Rosholt, C. A. Bush and K. C. Stewart (1987) "Genesis of marine terrace soils, Barbados, West Indies: evidence from mineralogy and geochemistry", *Earth Surface Processes and Landform*, **12**, 605–618.

Newell, R. E. and J. W. Kidson (1984) "African mean wind changes between Sahelian wet and dry periods", *J. Climatol.*, **4**, 27–33.

Nicholson, K. W. (1988) "The dry deposition of small particles: a review of experimental measurements", *Atmos. Environ.*, **22**, 2653–266.

Nicholson, S. E. (1985) "The spatial coherence of African rainfall anomalies: Interhemispheric teleconnections", *J. Clim. Appl. Meteorol.*, **25**, 1365–1381.

Ott, S.-T., A. Ott, D. W. Martin and J. A. Young (1991) "Analysis of a trans-Atlantic Saharan dust outbreak based on satellite and GATE data", *Mon. Weather Rev.*, 1832–1850.

Owens, N. J. P., J. N. Galloway and R. A. Duce (1992) "Episodic atmospheric nitrogen deposition to oligotrophic oceans", *Nature*, **357**, 397–399.

Pèwè, T. L. (ed) (1981) "Desert dust: Origin, characteristics and effect on man", *Spec. Pap. Geol. Soc. Am.*, **186**, 303 pp.

Prodi, F., G. Santachiara and F. Olioski (1983) "Characterization of aerosols in marine environments (Mediterranean, Red Sea, and Indian Ocean)", *J. Geophys. Res.*, **88**, 10,957–10,968.

Prospero, J. M. (1981a) "Aeolian transport to the World Ocean", in C. Emiliani (ed) *The Sea, Vol. 7, The Oceanic Lithosphere*, Wiley Interscience, New York, 801–974.

Prospero, J. M. (1981b) "Arid regions as sources of mineral aerosols in the marine atmosphere", in T. L. Pewe (ed) *Geological Society of America Special Paper 186*, Boulder, Colorado, 11–26.

Prospero, J. M. (1985) "Records of past climates in deep sea sediments", *Nature*, **315**, 279–280.

Prospero, J. M. (1990) "Mineral aerosol transport to the North Atlantic and North Pacific: the impact of African and Asian sources", in A. H. Knap (ed) *The Long-Range Atmospheric Transport of Natural and Contaminant Substances*, Kluwer Acad. Publ., Dordrecht, 59–86.

Prospero, J. M. and T. N. Carlson (1972) "Vertical and areal distribution of Saharan dust over the western equatorial North Atlantic Ocean", *J. Geophys. Res.*, **77**, 5255–5265.

Prospero, J. M. and R. T. Nees (1986) "Impact of the North African drought and El Niño on mineral dust in the Barbados trade wind", *Nature*, **320**, 735–738.

Prospero, J. M., R. A. Glaccum and R. T. Nees (1981) "Atmospheric transport of soil dust from Africa to South America", *Nature*, **289**, 570–572.

Prospero, J. M., R. T. Nees and M. Uematsu (1987) "Deposition rate of particulate and dissolved aluminum derived from Saharan dust in precipitation at Miami, Florida", *J. Geophys. Res.*, **92**, 14,723–14,731.

Prospero, J. M., M. Uematsu and D. L. Savoie (1989) "Mineral aerosol transport to the Pacific Ocean", in J. P. Riley, R. Chester, and R. A. Duce (eds) *Chemical Oceanography, Vol. 10*, Academic Press, London, 187–218.

Prospero, J. M., D. L. Savoie, R. Arimoto and F. Huang (1993) "Long-term trends in African mineral dust concentrations over the western North Atlantic: Relationship to North African rainfall", *Eos Trans. AGU*, 74(43), 146. Fall Meeting of the American Geophysical Union, San Francisco, CA, December 6–10, 1993.

Pye, K. (1987) *Aeolian Dust and Dust Deposits*, Academic Press, London, 334 pp.

Rao, C. R. N., L. L. Stowe, E. P. McClain and J. Sapper (1988) "Development and application of aerosol remote sensing with AVHRR data from the NOAA Satellites", in P. V Hobbs and M. P. McCormick (eds) *Aerosols and Climate*, A. Deepak Publishing, Hampton, Virginia, 69–79.

Rea, D. K. (1994) "The paleoclimatic record provided by aeolian deposition in the deep sea - The geologic history of wind", *Rev. Geophysics*, **32**, 159–195.

Reheis, M. C. and R. Kihl (1995) "Dust deposition in southern Nevada and California 1984–1989: Relations to climate, source area and source lithology", *J. Geophys. Res.*, **100**, 8893–8918.

Sarnthein, M., J. Thiede, U. Pflaumann, H. Erkenkeuser, D. Fütterer, B. Koopmann, H. Lange and E. Seibold (1982) "Atmospheric and oceanic patterns off Northwest Africa during the past 25 million years", in U. Von Rad, K. Linz, M. Sarnthein and E. Seibold (eds) *Geology of the Northwest African Continental Margin*, 545–604.

Savoie, D. L., J. M. Prospero and R. T. Nees (1987) "Nitrate, non-sea-salt sulfate, and mineral aerosol over the northwestern Indian Ocean", *J. Geophys. Res.*, **92**, 933–942.

Savoie, D. L., J. M. Prospero and E. S. Saltzman (1989a) "Non-sea-salt sulfate and nitrate in trade wind aerosols at Barbados: Evidence for long-range transport", *J. Geophys. Res.*, **94**, 5069–5080.

Savoie, D. L., J. M. Prospero and E. S. Saltzman (1989b) "Nitrate, non-sea-salt sulfate and methanesulfonate over the Pacific Ocean", in J. P. Riley, R. Chester and R. A. Duce (eds) *Chemical Oceanography, Vol. 10*, Academic Press, London, 219–250

Savoie, D. L., J. M. Prospero, S. J. Oltmans, W. C. Graustein, K. K. Turekian, J. T. Merrill and H. Levy II (1992) "Sources of nitrate and ozone in the marine boundary layer of the tropical North Atlantic", *J. Geophys. Res.*, **97**, 11,575–11,589.

Savoie, D. L., R. Arimoto, J. M. Prospero, R. A. Duce, W. C. Graustein, K. K. Turekian, J. N. Galloway and W. C. Keene (1995) "Marine biogenic and anthropogenic contributions to non-sea-salt sulfate in the marine boundary layer over the North Atlantic Ocean, *J. Geophys. Res.*, (in review).

Schütz, L. and M. Sebert (1987) "Mineral aerosols and source identification", *J. Aerosol Sci.*, **18**, 1–10.

Schütz, L. W., J. M. Prospero, P. Buat-Menard, R. A. C. Carvalho, A. Cruzado, R. Harriss, N. Z. Heidam and R. Jaenicke (1990) "The long-range transport of mineral aerosols: Group report", in A. H. Knap (ed) *The Large-Scale Atmospheric Transport of Natural and Contaminant Substances*, Chapter 10, Kluwer Acad. Publ., Dordrecht, 197–229.

Scott, B. C. (1981) "Modeling of atmospheric wet deposition", in S. J. Eisenreich (ed) *Atmospheric Pollutants in Natural Waters*, Butterworth, Stoneham, MA., 3–22.

Sholkovitz, E. R., T. M. Church and R. Arimoto (1993) "Rare earth element composition of precipitation, precipitation particles, and aerosols", *J. Geophys. Res.*, **98**, 20,587–20,599.

Slinn, W. G. N. (1983) "Air-to-sea transfer of particles", in P. S. Liss and W. G. N. Slinn (eds) *Air-Sea Exchange of Gases and Particles*, D. Reidel, Hingham, Mass., 299–405.

Swap, R., M. Garstang, S. Graco, R. Talbot and P. Kallberg (1992) "Sahara dust in the Amazon basin", *Tellus*, **44B**, 133–149.

Takayama, Y. and T. Takashima (1986) "Aerosol optical thickness of yellow sand over the Yellow Sea derived from NOAA satellite data", *Atmos. Environ.*, **20**, 631–638.

Talbot, R. W., R. C. Harriss, V. Browell, G. L. Gregory, D. I. Sebacher and S. M. Beck (1986) "Distribution and geochemistry of aerosols in the tropical North Atlantic troposphere: Relationship to Saharan dust", *J. Geophys. Res.*, **91**, 5173–5182.

Tanre, D. and M. Legrand (1991) "On the satellite retrieval of Saharan dust optical thickness over land: Two different approaches", *J. Geophys. Res.*, **96**, 5221–5227.

Taylor, S. R. and S. M. McLennan (1985) *The Continental Crust: Its Composition and Evolution*, Blackwells, Oxford, England, 312 pp.

Tegen, I. and I. Fung (1994) "Modeling of mineral dust in the atmosphere: Sources, transport, and optical thickness", *J. Geophys. Res.*, **99**, 22,897–22,914.

Tsunogai, S., T. Suzuki, T. Kurata and M. Uematsu (1985) "Seasonal and areal variation of continental aerosol in the surface air over the western North Pacific region", *J. Oceanogr. Soc. Japan*, **41**, 427–434.

Uematsu, M. (1987) "Study of the continental material transported through the atmosphere to the ocean", *J. Oceanogr. Soc. Japan*, **43**, 395–401.

Uematsu, M., R. A. Duce and J. M. Prospero (1985) "Deposition of atmospheric mineral particles to the North Pacific", *J. Atmos. Chem.*, **3**, 123–138.

Uematsu, M., R. A. Duce, J. M. Prospero, L. Chen, J. T. Merrill and R. L. McDonald (1983) "Transport of mineral aerosol from Asia over the North Pacific Ocean", *J. Geophys. Res.*, **88**, 5343–5352.

Veron, A., T. M. Church, C. C. Patterson and A. R. Flegal (1994) "Distribution and use of stable lead isotopes to characterize the sources and circulation of lead in North Atlantic surface waters", *Geochim. Cosmochim. Acta*, **58**, 3199–3206.

Veron, A., T. M. Church, C. C. Patterson, Y. Erel and J. T. Merrill (1992) "Continental origin and industrial sources of trace metals in the northwest Atlantic troposphere", *J. Atmos. Chem.*, **14**, 339–351

Veron, A. J., T. M. Church, A. R. Flegal, C. C. Patterson and Y. Erel (1993) "Response of lead cycling in the surface Sargasso Sea to changes in tropospheric input", *J. Geophys. Res.*, **98**, 18,269–18,276.

Westphal, D. L., O. B. Toon and T. N. Carlson (1987) "A two-dimensional numerical investigation of the dynamics and microphysics of Saharan dust storms", *J. Geophys. Res.*, **92**, 3027–3049.

Westphal, D. L., O. B. Toon and T. N. Carlson (1988) "A case study of mobilization and transport of Saharan dust", *J. Atmos. Sci.*, **45**, 2145–2175.

Whelpdale, D. M. and J. L. Moody (1990) "Large-scale meteorological regimes and transport process", in A. H. Knap and M. S. Marston (eds) *The Large-Scale Atmospheric Transport of Natural and Contaminant Substances*, D. Reidel, Dordrecht, Holland, 3–36.

Willey, J. D. and H. W. Paerl (1993) "Enhancement of chlorophyll a production in Gulf Stream surface seawater by synthetic versus natural rain", *Mar. Biol.*, **116**, 329–334.

Young, R. W., K. L. Carder, P. R. Betzer, D. K. Costello, R. A. Duce, G. R. DiTullio, N. W. Tindale, E. A. Laws, M. Uematsu, J. T. Merrill and R. A. Feely (1991) "Atmospheric iron inputs and primary productivity: Phytoplankton responses in the North Pacific", *Glob. Biogeochem. Cycles*, **5**, 119–134.

Zhou, M., N. Lu, J. Miller, F. Parungo, C. Nagamoto and S. Yang (1992) "Characterization of atmospheric aerosols and of suspended particles in seawater in the western Pacific Ocean, *J. Geophys. Res.*, **97**, 7553–7567.

Zhu, X. R., J. M. Prospero, F. J. Millero, D. L. Savoie and G. W. Brass (1992) "The solubility of ferric ion in marine mineral aerosol solutions at ambient relative humidities", *Mar. Chem.*, **38**, 91–107.

Zhu, X., J. M. Prospero, D. L. Savoie, F. J. Millero, R. G. Zika and E. S. Saltzman (1993) "Photoreduction of Fe(III) in marine mineral aerosol solutions", *J. Geophys. Res.*, **98**, 9039–9046.

Zhuang, G., Z. Yi, R. A. Duce and P. R. Brown (1992) "Link between iron and sulfur cycles suggested by detection of Fe(II) in remote marine aerosols", *Nature*, **355**, 537–539.