ticularly intense self-irradiation. It would seem prudent to investigate these and related problems fully before we embark on the irr versible step of large-scale storage of nuclear waste in vitreous materials.

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Long-Range Atmospheric Transport of Soil Dust from Asia to the Tropical North Pacific: Temporal Variability

Abstract. *The concentration of airborne soil dust at Enewetak Atoll (11°N, 162°E) in April 1979 was 2.3 micrograms per cubic meter but decreased steadily to 0.02 microgram per cubic meter over the next 5 months. The spring dust is probably derived from China; its deposition rate (~ 0.3 millimeter per 1000 years) suggests that it may be a significant contributor to the deep-sea sediments of the North Pacific.*

The areal distribution of certain mineral components such as quartz and illite in the sediments of the North Pacific suggests that wind may be the primary transport mechanism for these materials from the continents. The greatest concentrations of these minerals are found in Pacific sediments at mid-latitudes (30°N to 40°N) beneath the prevailing westerly winds. A continental origin for the quartz fraction of both North Pacific sediments and Hawaiian soils is also inferred from oxygen isotope studies (*1*). The source for this eolian (wind-borne) material has been assumed to be the arid regions of central and eastern Asia—the Takla Makan, Gobi, and Ordos deserts and the regions where loess is deposited south of the Gobi and Ordos deserts.

There are few data on dust in the atmosphere over the North Pacific. High concentrations (up to 60 μg m^{-3}) of dust have been measured over Japan (*2*). This material, generally yellowish, light brown, or red in color, and called Kosa in Japan, is observed most frequently in the spring, when large-scale dust storms occur in northern China and Mongolia. A mean atmospheric dust concentration of 0.16 μg m^{-3} was reported for the equatorial mid-Pacific from filter samples collected aboard the D.V. *Glomar Challenger* in November and December 1973 (*3*). In another ship-sampling program, a mean dust concentration of 2.1 μg m^{-3} was measured in the South China and Philippine seas in April 1975, and a concentration of 1.2 μg m^{-3} was observed in the eastern and central North Pacific between 26°N and 28°N in April and May 1975 (*3*). Rahn *et al.* have concluded that long-range transport of Asian desert dust may contribute to the formation of haze layers commonly found in the North American arctic (*4*).

No earlier study of dust over the Pacific that we know of has extended over a sufficiently long time to permit the determination of the seasonal variability of dust transport and how it might be related to meteorological and climatological factors. We present here the results of a mineral dust investigation that extended over a period of 5 months, from April through August 1979, on Bokandretok Island, Enewetak Atoll, Marshall Islands, as a part of the SEAREX (Sea/Air Exchange) program. This site, at 11°20′N, 162° 20′E, is located in the northeast trade-wind regime and is approximately 5000 km southeast of Asia and 8000 km west-southwest of North America. Samples of atmospheric particulate matter were collected from a tower 20 m high erected on the windward shore of the island. We used double Whatman 41 filters (20 by 25 cm), each of which has a collection efficiency of ≥ 90 percent for particles with radii ≥ 0.2 μm at the flow rate used. Filters were mounted in plastic holders within a plastic rain shelter. We collected size-separated particle samples by using a Sierra high-volume cascade impactor operating at ~ 68 m^{-3} hour^{-1}. Particles were deposited on Whatman 41 filters mounted on the five stages of the cascade impactor, and then the airstream was passed through a final Whatman 41 filter. Collection was stopped automatically when the surface wind direction was not from the open sea, when the wind speed dropped below 5 knots (9.3 km hour^{-1}), or when the count of condensation nuclei was above 750 particles per cubic centimeter. The sampling duration was generally 1 week for each filter pair or cascade impactor sample.

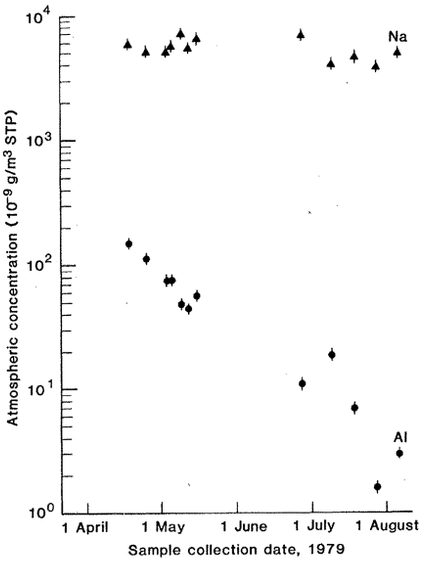

Fig. 1. Atmospheric concentrations of Na and Al at Enewetak Atoll. *STP*, standard temperature and pressure.

The atmospheric concentration of Al was used as an indicator of continental dust in these samples. Atmospheric Al is commonly used as a reference for aerosols produced from soil and crustal weathering processes because of the high aluminosilicate content of these aerosols. Support for the use of Al as a dust indicator in the Enewetak marine aerosol is derived from the Fe/Al, Sc/Al, and Mn/Al ratios in this aerosol, which are very similar to mean crustal ratios. Atmospheric Na at Enewetak is used as a reference for ocean-derived aerosols, which are produced by the bursting of wave-produced bubbles at the sea surface. Samples were analyzed for Al and Na by instrumental neutron activation analysis at the Rhode Island Nuclear Science Center reactor ($\phi_{thermal} = 4 \times 10^{12}$ neutron cm^{-2} sec^{-1}).

Figure 1 presents the results of the analyses of the atmospheric samples for Na and Al. The atmospheric Na concentration remained quite constant during

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the sampling period, as would be expected since its source is the ocean. However, the atmospheric Al concentration decreased quite regularly by a factor of ~ 100 from mid-April to early August. From 5.1 to 8.2 percent of the mass of loess from China is Al (*2*). If the Al content of the Enewetak dust is similar, that is, ~ 6.5 percent, the near-surface Enewetak dust loadings range from as high as ~ 2.3 μg m^{-3} in April down to ~ 0.02 μg m^{-3} in August.

The observed mass median radii (MMR) for the continental dust (Al) in four impactor samples collected at Enewetak ranged from 0.7 to 1.0 μm. The MMR for Al in a sample collected during a Kosa event in Japan was ~ 2 μm (*2*), somewhat higher than that found in Enewetak, which would be expected since Japan is much closer to the source of the Asian dust. At Enewetak, 80 to 85 percent of the mass of the dust was found in particles with radii between ~ 0.2 and 2 μm.

We collected one rain sample during May 1979 at Enewetak. The Al concentration was 14 μg kg^{-1}, which corresponds to ~ 220 μg of dust per kilogram of rain. If this concentration is typical for May, which has a mean rainfall of ~ 12 cm, the wet flux of dust to the ocean surface that month at Enewetak would have been ~ 2.6 μg cm^{-2}. We collected one dry deposition sample over a 30-hour period in late April, using a flat polyethylene plate 60 cm in diameter. The dry deposition rate of Al during this period was 0.06 μg cm^{-2} month^{-1}, yielding a total dust dry deposition rate of ~ 1 μg cm^{-2} month^{-1}. The total (wet plus dry) flux from the atmosphere to the ocean is thus ~ 4 μg cm^{-2} month^{-1}. With an average atmospheric dust concentration of ~ 1.4 μg m^{-3} during this period, the total deposition velocity for the dust is ~ 1 cm sec^{-1}, very similar to the value observed for the total deposition of ^{7}Be to the ocean in the tropics (*5*).

The dramatic decrease (two orders of magnitude) in dust concentration at Enewetak during the 5 months of the experiment can be rationalized on the basis of our knowledge of the seasonality of dust storm activity in China and of the seasonal changes in the large-scale wind fields over the Pacific. The evidence garnered from the literature (*6*) and from knowledgeable observers suggests that in China dust storm activity is greatest in the spring because of the combined effects of low rainfall, the increased occurrence of high surface winds which are associated with cold fronts, and soil freshly plowed for planting. Statistical compilations of meteorological observations

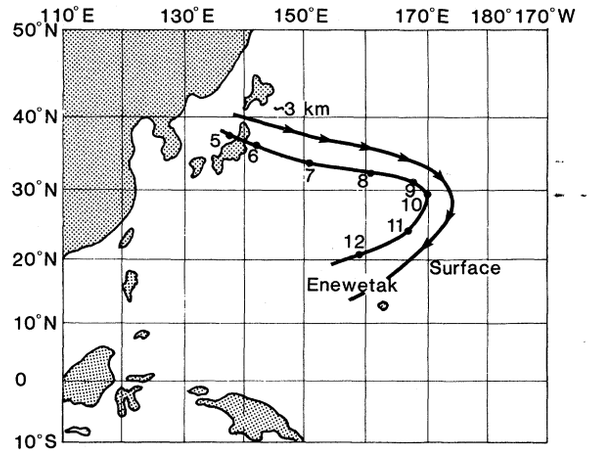

Fig. 2. The idealized trajectory of the air reaching Enewetak about 12 May 1979 is shown by the outer line, progressing from a 3-km elevation to the surface between 5 and 12 May. The center position of the anticyclone is shown by the dot for each day in the period.

(*6*, *7*) show that dust storm activity is widespread, especially in central China where there are extensive loess deposits, and in the arid and desert regions of western China. Indeed, the Takla Makan Desert appears to be one of the dustiest places in the world.

Because the mineral dust produces dense hazes, additional information on the transport of Asian dust to the North Pacific can be inferred from data on the frequency of occurrence of haze at sea as presented in marine atlases (*7*). In general, these data suggest that there is a significant transport of continental aerosols out of Asia north of 20°N during the spring and extending into the summer.

The observation of such large amounts of Asian dust during April and May at Enewetak was unexpected, as this site lies well within the easterly (trade) wind regime. Indeed, our wind records show that, during April and May 1979, the surface wind stayed within the sector 040° to 160° over 99.9 percent of the time. However, the transport of dust from Asia to Enewetak and the seasonal variability in this transport can be understood on the basis of the large-scale wind field climatology and of the synoptic conditions during the time of the experiment.

The mean surface wind field (*8*) during the period from March through May shows strong easterlies over the western North Pacific between 30°N and the equator; north of 30°N, the surface winds are weak with a tendency toward westerly winds. However, at 700 mbar (about 3000 m) there is very strong westerly flow north of about 20°N extending from well within Asia to the central North Pacific. Thus, dust raised over China could easily be transported by the mean winds at this level to the region north of Enewetak. During June through August, conditions are not favorable for the transport of dust to the central Pacific. Surface winds are easterly from Enewetak northward to about 40°N. At 700 mbar, the northern boundary of the easterlies is located at about 30°N. Persistent westerlies appear at 700 mbar only north of 40°N, and they are very weak.

The analysis of daily synoptic charts for one period (5 to 18 May) during the experiment illustrates how dust transport might take place during the dry season. A moving anticyclonic circulation traveled from the vicinity of Japan to an area about 600 km north of Enewetak during the period from 5 to 12 May (Fig. 2). The center moved eastward until 10 May and southwestward thereafter. It is known that a generalized sinking motion (subsidence) is associated with circulations of this type. Thus, air that had been at an upper level over Asia would be brought down into the trade winds east of Enewetak. An idealized trajectory was derived from synoptic charts for an air parcel at an altitude of 3 km over Japan on 5 May. The horizontal trajectory shows the air parcel arriving at Enewetak on 11 or 12 May (Fig. 2). The rate of subsidence required to bring the trajectory down to the surface over this period of time is consistent with the synoptic characteristics of the circulation system (that is, with the depth and strength of the anticyclone and the distribution of potential temperature). Such a mode of transport would not appear to be possible during the period from June through August (wet season).

The results of this study suggest that atmospheric deposition of Asian dust can contribute significantly to marine sedimentation rates in the Enewetak area. The Enewetak measurements in late April and May yielded a total dust flux to the ocean surface of about 4 μg cm^{-2} month^{-1}. On the basis of the frequency of occurrence of dust storms in China and of haze over the western North Pacific and in view of the large-scale meteorology of this region, it

would appear that conditions are favorable for the transport of significant amounts of dust to the Enewetak region for 3 or 4 months of the year, beginning perhaps in February or March. If our measured atmospheric deposition rate of 4 μg cm^{-2} month^{-1} applies over a 3- to 4-month period, it would result in an accumulation rate of about 0.3 mm of wet sediment per 1000 years. This assumes an in situ sediment density (the ratio of the dry weight of sediment to the in situ volume occupied by the sediment) of 0.5 g cm^{-3} (*9*). The actual nonbiogenic sedimentation rates to the ocean floor in this region of the North Pacific are not well known but are probably about 1 mm per 1000 years (*9, 10*). We would expect that the atmospheric contribution of dust to Pacific deep-sea sediments would be even greater in the higher latitudes where transport conditions from Asia are more favorable.

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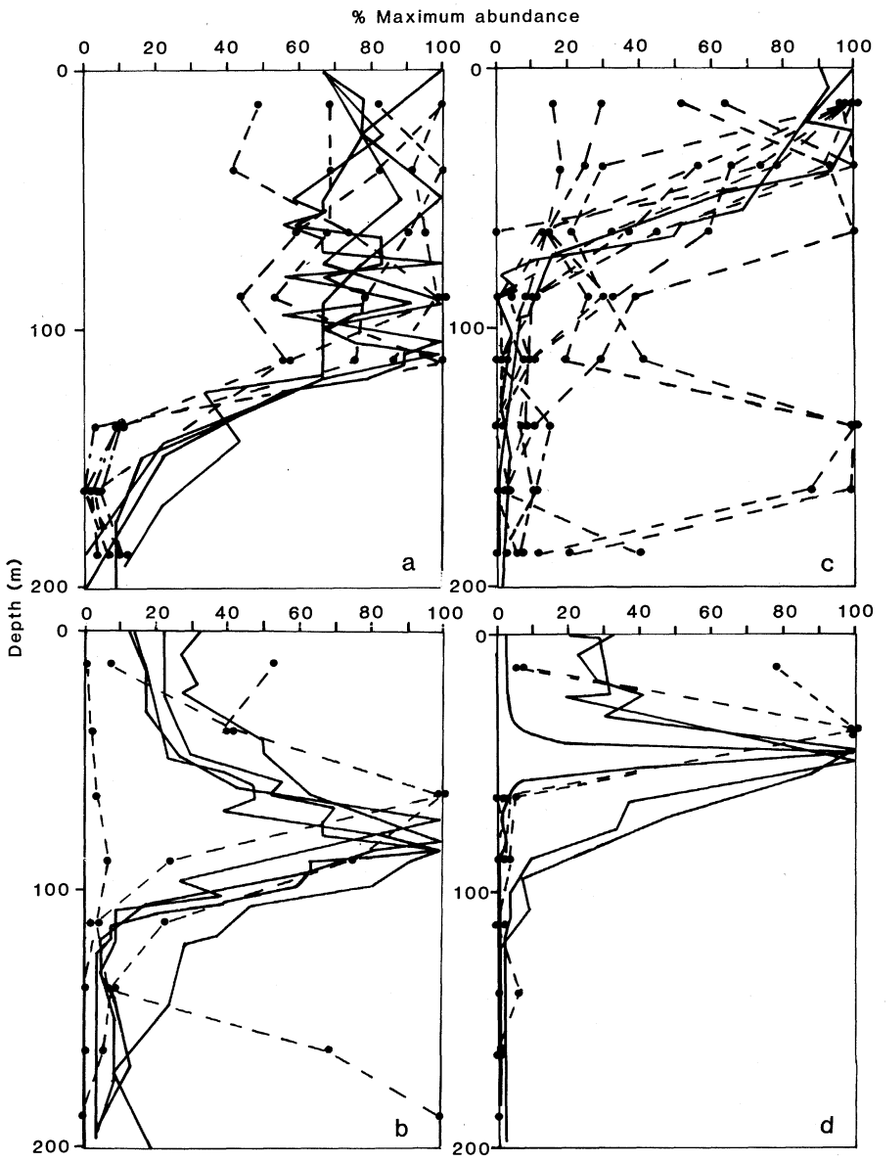
Foraminifera and Chlorophyll Maximum: Vertical Distribution, Seasonal Succession, and Paleoceanographic Significance

Abstract. *Many planktonic foraminiferal species deposit their shells at the chlorophyll maximum zone, and it is the temperature range here that is relevant to oceanographic models which use ratios of oxygen-18 to oxygen-16 in fossil foraminifera and foraminiferal fossil assemblages to ascertain past climates. During periods of stratification of the upper water column, the temperature at the chlorophyll maximum may differ from the sea surface temperature by 10°C in the western North Atlantic.*

Culture experiments on planktonic foraminifera (*1*) show that shell growth rate, size, and productivity are positively correlated with feeding frequency. The first step in assessing the possible significance of this relationship in nature is to examine the association of planktonic foraminifera and phytoplankton in the water column. During the months in which the upper water column remains well stratified in slope water, Sargasso Sea, and Gulf Stream cold core rings in the North Atlantic, plant chlorophyll develops a maximum at the bottom of the euphotic zone. This feature is known as the deep chlorophyll maximum (DCM) (*2*). Numerous investigators have suggested that particular zooplankton species are associated with the DCM (*3-7*).

Ortner and Wiebe (*5*) obtained vertically stratified samples of macrozooplankton and microzooplankton at DCM depths in these regions. Based upon results from cruises *Chain* 125 and *Knorr*



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