Transport of Mineral Aerosol From Asia Over the North Pacific Ocean

Mitsuo Uematsu,1 Robert A. Ducê,3 Joseph M. Prospero,1 Lizhi Chen,3,4 John T. Merrill,3 and Ray L. McDonald3

Concentrations of atmospheric aluminum—a good indicator of mineral aerosol—have been measured weekly, between January 1981 and March 1982, at the seven stations of the SEAREX Asian Dust Network in the North Pacific. A sea- and land-based transport pattern was found at most of the sites, with high AI concentrations from February to June and low concentrations from July to January. There was a latitudinal gradient in the mean annual atmospheric dust concentration, with the greatest concentrations occurring in the mid-latitudes. When coupled with statistics of dust storms in Asia and of Kusa (dense dust hazes traced to Chinese origins) in Japan, the data suggest that the dust collected in the network was transported by the westerlies from and regions in Asia. It is estimated that 6–12 × 10^10 tons of Asian dust are transported annually to the central Pacific; larger quantities are probably deposited over the western North Pacific, closer to the Asian sources. This annually transported mineral aerosol is a significant source of sedimentary material for the North Pacific.

INTRODUCTION

The mineralogy of atmospheric dust over the North Pacific is similar to that of the underlying deep sea sediments [Prospero, 1981]. It has been suggested that the primary source for the clay minerals in these sediments is windblown (eolian) soil material transported from arid regions bordering the Pacific [Rez and Goldberg, 1958; Griffin and Goldberg, 1966; Windom, 1969; Prospero, 1981]. Individual atmospheric mineral dust events have been observed during short-term experiments at various locations in the Pacific, including Alaska [Hsiao et al., 1971; Rahn et al., 1980], Hawaii [Hsiao, 1980; Darzi and Winchester, 1982], and at 30°N, 160°E [Tang and Kondo, 1982]. Extensive measurements of soil aerosols in the North Pacific were also made at Enewetak Atoll in the Marshall Islands (11°20'N, 162°20'E) during a 5-month atmospheric chemistry field experiment [Duce et al., 1980]. Mineral dust concentrations were relatively large (2.3 µg/m³) at the start of the experiment in April 1979, but they decreased gradually and regularly to 0.02 µg/m³ during the next 5 months. Recently, Parrington et al. [1983] also observed a seasonal variation of dust concentration in upper-level winds at Hawaii over a 4-year period.

In order to characterize the temporal and areal distributions of mineral aerosol in the marine boundary layer and its deposition to the North Pacific, it is necessary to make measurements over an extended time and space scale. To this end, as part of the Sea/Air Exchange (SEAREX) Program [Duce, 1983], we began the SEAREX Asian Dust Study (SADS) in January 1981. The SADS network consists of seven island stations: Shemya, Midway, Oahu, Enewetak, Fanning, Guam, and Belau (see Figure 1). At these sites, aerosol and total deposition samples are being collected for at least two consecutive years. In this paper we present the results of the analysis of aerosol samples collected during the first year, along with statistical data for dust storms in Asia and Kusa events in Japan.

METHODS

Atmospheric Sampling

Aerosol samples were collected continuously for one-week periods by using high-volume air-sampling systems (~1.1 m³/min) and Whatman 41 filters (20 × 25 cm). The sampling system at each site was located on the windward coast and as close to the ocean as possible. The air sampler was controlled by a wind monitoring system in order to minimize the possibility of contamination from local sources. The acceptance angle of each wind direction monitor was set to a sector facing the ocean (see Table 1) so that the pumping system only operated when the wind came from the sea. The aerosol sample filter was usually changed on the same day at all stations (Thursday, east of the dateline; Friday, west of it) so that synoptic comparisons could be made.

Chemical Analysis

The samples were analyzed for AI by instrumental neutron activation analysis. A sample was cut from a folded quartz filter with a titanium punch 2.2 cm in diameter, and the two pieces were then placed in a polyethylene vial. The sample vial and a neutron flux monitor were irradiated for 60 s in the Rhode Island Nuclear Science Center swimming pool reactor at a flux of 4 × 10¹¹ n/cm² s⁻¹. The irradiated sample was transferred to an unirradiated vial and, after a 24-h cooling period, was counted for 500 s on a 25 Ge(Li) detector (resolution of 2.5 keV for the 1332-keV gamma ray of ⁹⁵Zr) coupled to a multichannel analyzer. The aluminum concentration was calculated by using the program computer program PIDAQ [Money et al., 1977].

The aerosol particles were distributed quite uniformly over the filter surface. Table 2 presents the results of the analysis of one filter sample collected at a coastal site in Miami, Florida, using one of the SADS systems. Twenty punches were cut from the filter in a uniform pattern. Twelve were equivalent cuts spaced along the four edges of the filter and centered within 2 cm of the edge. Eight were cut in a...
uniform pattern from the remaining center portion of the filter. There was no significant difference in concentration between the edge and center samples for either the mineral aerosol (Al) or the sea salt aerosol (Na). The overall uncertainty in the measured atmospheric concentration of aluminum was estimated to be less than 15% including both the analytical and air volume uncertainties.

Aluminum as an Indicator of Aluminosilicate Mineral Particles

Atmospheric dust concentrations have been measured directly by gravimetry (Dolcy et al., 1967; Prospero and Bonatti, 1969); dust concentrations measured by this technique have been reported in various ocean regions [e.g.,

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Selected Sector</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheinna</td>
<td>12°44'N</td>
<td>175°W</td>
<td>SSW-W</td>
<td>south side of the island, 2 m aboveground, on the shore.</td>
</tr>
<tr>
<td>Midway</td>
<td>28°13'N</td>
<td>177°21'W</td>
<td>NWW-SSE</td>
<td>east side of the island, 4 m aboveground on the roof of the NOAA tide shack, on the shore.</td>
</tr>
<tr>
<td>Oahu</td>
<td>21°20'N</td>
<td>157°42'W</td>
<td>NWW-SE</td>
<td>northeast side of the island, 20 m aboveground on a tower at Bellows Air Force Base, on the shore.</td>
</tr>
<tr>
<td>Guam</td>
<td>17°29'N</td>
<td>144°48'E</td>
<td>E-SE</td>
<td>south side of the island, 10 m aboveground on the roof of the Marine Laboratory Building, University of Guam, on the shore.</td>
</tr>
<tr>
<td>Eniwetok</td>
<td>11°20'N</td>
<td>162°20'E</td>
<td>NE-SE</td>
<td>north end of the island, 5 m aboveground on the roof of the MicPac Research Laboratory trailer, on the shore.</td>
</tr>
<tr>
<td>Belau</td>
<td>7°20'N</td>
<td>134°29'E</td>
<td>SW-NNW</td>
<td>west side of Marcus Island, 6 m aboveground on the roof of the Marine Education and Research Center, on the shore.</td>
</tr>
<tr>
<td>Fanning</td>
<td>3°55'N</td>
<td>159°20'W</td>
<td>NWW-SW</td>
<td>west side of the island, 25 m aboveground on a tower, on the shore.</td>
</tr>
</tbody>
</table>
TABLE 2. Variation of Aerosol Concentration Over a Fiber Surface

<table>
<thead>
<tr>
<th>Section</th>
<th>Number of Samples</th>
<th>Al, µg</th>
<th>Na, µg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge</td>
<td>12</td>
<td>6.7 ± 0.4</td>
<td>104 ± 7</td>
</tr>
<tr>
<td>Center</td>
<td>8</td>
<td>6.5 ± 0.3</td>
<td>105 ± 7</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>6.6 ± 0.4</td>
<td>105 ± 8</td>
</tr>
</tbody>
</table>

*See text for details.

Prospero (1979). Soil aerosol concentrations have also been computed from the Al concentration in samples on the assumption that soil aerosols will have an Al content equal to that of average soils, i.e., 6 to 8% (Rahn, 1979; Duce et al., 1980).

To compare these two techniques, we determined the correlation between Al mass and filter ash residue, which we assume to be mineral matter. A quarter section of the filter samples was washed with distilled water to remove salts, ashed at 500°C, and the residue was weighed. A quarter section of the same filters was analyzed for Al. Figure 2 shows the relationship between ash concentrations and aluminum concentrations in samples from Osaka and Midway. The regression equation indicates that the Al content was 8% of the ash weight. Most of the data points for the Midway samples fall on a regression line similar to that for the Osaka samples. However, three samples from Midway yield a low Al content in the ash. This was due to contamination on the filter by calcium carbonate particles derived from the coral sand beach in the vicinity of the sample. Such contamination was not observed at Osaka because the sample was located on a tower 20 m above beach level. The value of 8% Al agrees well with the mean Al content in the continental crust (2.2%, Taylor 1964) but is on the high end of the values (3.5-8.2%) observed for loess in China (Kudowski, 1979). The small difference could be related to the differences between the particle size distribution of the soil and that of the aerosol particles. Because of the decreasing concentration of silica-rich minerals, such as quartz, with decreasing particle size, the Al concentration will increase with decreasing particle size between 400 and 4-µm radius. The Al concentration is relatively constant in particles with radii less than 4 µm [Schatz and Rahn, 1982]. This trend is seen pronounced in highly weathered dune sands and desertlike soils. The contribution of large soil particles with low Al concentration is probably negligible in aerosol populations far from their source. Indeed, the mass median radius (MMR) of mineral aerosols collected at Osetewat was ~1 µm (Duce et al., 1980), and the MMR of mineral aerosols collected in the western Atlantic was ~4 µm (Prospero, 1981). Thus we conclude that mineral aerosol concentrations can be estimated quite accurately from the Al concentration in the samples from this area.

**Dust Storm Reports and Kosa Events**

There are over 250 surface meteorological stations on the Asian continent. The "present weather" code specified at each reporting time designates the intensity, duration, and apparent source of dust (i.e., either raised locally or advected) during dusty periods. We used these reports to characterize the temporal and geographical distribution of atmospheric dust over Asia. The dust storm frequency statistics (summed to produce weekly values) for 1981-1982 are presented in Figure 3a and are discussed in the following section.

Major dust events ("Kosa") are observed during the spring in Japan. Kosa is yellow or brown airborne dust which is known to be transported to Japan from the Asian continent. During Kosa outbreaks, colorful phenomena are often observed: e.g., red snow, black rain, yellow fog (Tsunoage, et al., 1972). During the past 62 years, 85% of the Kosa events occurred between March and June, based upon visual observations at Nagasaki in southern Japan. Kosa has been
observed at Nagasaki as average of 5.3 days per year, with
an annual range from 0 to 18 days [Arao et al., 1979]. The
seasonal cycle of Kosa events in Japan correlates with the
seasonality of dust storm activity in China.

RESULTS AND DISCUSSION

The atmospheric Al concentrations observed at the SADS
network sites are presented in Figure 3b. Samples for which
the collection pump operated less than 10% of the collection
period are not reported. These samples usually contain
relatively small quantities of mineral dust, which can lead to
unacceptably large analytical uncertainties. In addition, with
short pump operating times, any deposition of local soil on
the filter would produce relatively large artifacts. Unfortu-
nately, half of the filter samples from Belau and Guam were
rejected because of their short pump operating times. Be-
cause of the possibility of local soil dust contamination, data
from the analysis of the remaining Belau and Guam filters
are not discussed in detail, although they are presented in
Figure 3b.

Seasonal Patterns of Atmospheric Al Over the North
Pacific

As can be seen clearly in Figure 3b, the period from
February to mid-June yielded the highest Al concentration at
Shemya, Midway, Oahu, and Eniwetok. These stations
represent a large portion of the central North Pacific,
extending from 11°N to 52°N and from 162°E to 157°W.
During this period, the surface northeast trade winds were
blowing 70%, 90%, and over 95% of the time at Midway,
Oahu, and Eniwetok, respectively. At these stations the
average dust concentrations during this period were approxi-
mately 1 order of magnitude higher than during the remain-
der of the year at these stations (see Table 3).

This seasonal pattern is comparable to that observed at
Eniwetok from April to August 1979 [Duce et al., 1980] and
at Mauna Loa in Hawaii from 1979 to 1982 [Perrington et al.,
1983]. In spring the westerly winds aloft can carry dust
raised from the surface rapidly out over the Pacific, where it
may be carried to lower latitudes and advected from east to
west by the trade winds. During summer, the weakening of
the westerlies and the northward expansion of the trades
winds make this path ineffective, and less or none of the
dust is carried in the surface northeasterlies. This aspect of
the mean wind field climatology is discussed further in Duce
et al. [1980]. This is consistent with the observed evidence
for the transport of dust in this study. The transition from
the high-dust period to the low-dust period is synchronous
across most of the North Pacific (see Figure 4). Also, the
time of the transition appears to be relatively constant from
year to year. This can be seen by comparing the Eniwetok
dust concentration data for the months of May, June, and
July, as obtained in the 1979 SEAREX field experiment
[Duce et al., 1980] with that obtained at the SADS network
Eniwetok site in 1981 (see Figure 4b). This seasonal pattern
is grossly similar to the frequency of dust storm reports in
Asia for 1981 (Figure 3a). Dust activity in Asia is greatest in
the spring [Wang, 1969] as a result of the combined effects of
low rainfall, increased occurrence of high winds associated
with cold fronts, and freshly ploughed soil for spring planting
[Ing, 1972]. The dust suspended in the cold dry air behind a
front can be raised into the strong westerlies by the approach
of the next front, or deep layers of dust-filled air can be
formed in the strong winds on the periphery of a polar
anticyclone. The seasonal variation is also similar to documented Kosa appearances at Nagasaki in southern Japan, during the past 62 years [Arao et al., 1979] and to the variation of Al and Si concentrations in aerosols at Nagoya from September 1976 to September 1978 [Kadowaki, 1979]. In Figure 3 it can be seen that in the early spring of 1982 the atmospheric Al was increasing again at most of the island sites, as was the frequency of dust storm reports. Thus the seasonal variation of atmospheric Al is consistent with much of the North Pacific, and it appears to be related to dust storm outbreaks in Asia.

The Al concentration measured at Fanning was always low and showed little seasonal variability. Fanning is situated close to the equator, and it lies south of the intertropical convergence zone (ITCZ) much of the year. Thus the low dust loads may be representative of Southern Hemisphere air.

Relationship Among Dust Episodes from the Network, Kosa Events in Japan, and Dust Storms in Asia

Figure 5 shows the dates of the appearance of Kosa over Japan and the periods when atmospheric Al concentrations were high at the SADS network site in 1981. We discuss several of the major dust events. The Al concentration measured at Oahu during the first major episode (February 19-26) was 370 ng/m³, about twice that at Midway (190 ng/m³), and it occurred during the same week, even though Midway is closer to Asia. At Enewetak the maximum Al concentration (150 ng/m³) occurred one week later. There were widespread reports of dust in Asia in the week of February 20, but no corresponding Kosa reports from Japan.

The number of dust storm reports in Asia (Figure 3a), while very variable from day to day, was especially high during the six-week period of April 17 through May 29, exceeding 400 per week every week but one. Kosa events were frequent during this time, as shown in Figure 5. The Al concentrations, particularly at Midway, Oahu, and Shemya but also at Enewetak and Guam, exhibit a broad maximum from the week of April 30 to the week of June 4. The first week of this period was one to two weeks after the Kosa event of April 24, and the last week was about two weeks after the Kosa event of May 22. On the basis of air trajectory analysis we expect it to take about one to two weeks for a dust storm from Asia to spread over the North Pacific [Isono]
et al., 1971). Show, 1980; Duce et al., 1980; Zahn et al., 1980). During this period, the maximum Al concentration (620 ng/m$^3$) was measured at Midway for the sample collected from May 28 to June 4. In this case the Midway concentration was a factor of 3 higher than that of Oahu. In addition, there were two concentration peaks observed during this episode on Oahu; the first peak was measured before the increase was noted at Midway. Thus, despite the large area in plateau sources and the great distance from the sources to the SADS North Pacific stations (5000-40,000 km), the distribution of dust in the North Pacific atmosphere is relatively nonuniform and is obviously governed by specific synoptic situations.

There was also an Al concentration peak of 180 ng/m$^3$ at Midway during the week of April 9-16. The following week an Al concentration peak of 120 ng/m$^3$ was measured on Oahu, and a broad peak of 45 ng/m$^3$ was noted on Eniwetok. The only Kona event prior to these dust concentration peaks occurred on March 25 in Japan; this Kona episode appears to be associated with a major dust outbreak that occurred in Asia during the week of March 20. If this event was responsible for the Al concentration peaks observed at Midway, Oahu, and Eniwetok in mid-April, then the dust would have taken two to three weeks to reach Midway, three to four weeks to reach Oahu, and three to five weeks to reach Eniwetok from Asia. Such long transit times are unlikely.

It is possible that the mid-April dust event over the North Pacific is not related to the March 25 Kona event but rather to an Asian dust outbreak which passed over Japan in the upper troposphere; such upper-level transport has been observed previously. Murayama (1980) observed a dust storm in the Gobi Desert (43$^\circ$N, 117$^\circ$E) by satellite on May 25, 1978. The dust-laden air mass crossed over Japan without any reports of Kona or of ground-level fallout. Thus it is possible that a similar event occurred in Asia in early April (1981). There are other examples of Asian dust outbreaks that passed over Japan at high levels. Lidar measurements in April 1979, at Nagoya, Japan, showed two dust-laden air masses at 0.5-2.5 km altitude and another at 4.8 km [Kawasaki et al., 1982]. Metereological conditions suggest that the dust in the upper layer was transported over the Pacific more extensive than that in the lower layer. Equally interesting is the fact that air mass trajectory analyses showed that the two layers came from distinctly different sources: the lower layer from the Gobi Desert and Yellow River region and the upper layer from the Taklimakan Desert [Ishizaka et al., 1981]. This episode is undoubtedly responsible for the high dust concentrations measured by Duce et al. (1980) during April 1979 at Eniwetok. We will report separately the results of trajectory analyses for such events combined with meteorological analyses of the associated Asian dust storms (G. Merrill, in preparation, 1983).

Another potential source of atmospheric Al during May 1981 was the eruption of Mt. Pagan (18$^\circ$06'N, 145$^\circ$45'E) in the Marianas Islands on May 15. The volcanic plume spread to the southeast and may have affected Guam and Eniwetok in late May. Shemya may have been affected by debris from volcanic activity at Kamchatka and on various Aleutian Islands. Indeed, the Al peak of December 23 to January 6 on Shemya was probably due to the volcanic ash fallout observed by local personnel. The source of the ash probably was the eruption of Klauchevskoi volcano on the Kamchatka Peninsula that occurred 6 km on December 21 through December 28 [SEAN Bulletin, 1981]. The sediments from the Bering Sea show evidence of many volcanic eruptions. The high sediment accumulation rate in this region [Trenary and Yamada, 1979] may be due in part to the input of volcanic ash. It may be possible to distinguish between continental soil and volcanic material in aerosol samples on the basis of the concentration ratios of certain elements, e.g., K/Fe [Durst and Winchester, 1982] or Tl/Td [Parkinson et al., 1983].

Mineral Aerosol Concentrations Over the North Pacific

Table 3 summarizes the range and the mean mineral aerosol concentrations, assuming 8% of the dust is Al, from five North Pacific stations of the SADS network. The dust concentrations range over 2 orders of magnitude at most of the stations during an annual cycle. The mean dust concentrations decrease by factors of 2 to 12 from the high dust period (February-June) to the clean period (July-January). There appears to be a systematic geographic distribution
<table>
<thead>
<tr>
<th>Location</th>
<th>Concentration Range, µg/m³</th>
<th>Collection Period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Equatorial Pacific 8°N-17°S</td>
<td>0.04-1.2</td>
<td>February-April</td>
<td>Prosperi and Bonatti [1960]</td>
</tr>
<tr>
<td>North Pacific 32°-45°N</td>
<td>0.5-1.0</td>
<td>April</td>
<td>Ferguson et al. [1970]</td>
</tr>
<tr>
<td>Eastern Mid-Pacific 20°N-20°S</td>
<td>0.44-0.50</td>
<td>November-December</td>
<td>Prosperi [1979]</td>
</tr>
<tr>
<td>Equatorial South Pacific North Pacific 28°-36°N</td>
<td>0.10-0.57</td>
<td>January</td>
<td>Prosperi [1978]</td>
</tr>
<tr>
<td>West and Central North Pacific 28°-40°N</td>
<td>0.73-2.34</td>
<td>May</td>
<td>Prosperi [1979]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May-June</td>
<td>Tsunogai and Kondo [1982]</td>
</tr>
<tr>
<td>Island</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Okinawa</td>
<td>0.02-0.8*</td>
<td>June-February</td>
<td>Hoffman et al. [1972]</td>
</tr>
<tr>
<td>Eniwetak</td>
<td>0.02-2.3</td>
<td>April-August</td>
<td>Duce et al. [1980]</td>
</tr>
</tbody>
</table>

*Minerals aerosol values calculated from atmospheric Fe concentrations.

The atmospheric input rate of mineral particles to the North Pacific Ocean can be estimated by using the mean dust concentrations in the five latitudinal zones represented by data from each station in Table 3. We would expect most of the larger mineral particles (i.e., those with radii greater than ~10 µm) to be deposited relatively close to the coast of Asia because of the high settling velocities of material of such size [Schachts et al., 1980]. As a consequence, the atmospheric concentration will change rapidly during the early stages of transport. At distances greater than a few thousand kilometers the primary mechanism of removal should be precipitation. Thus in our crude model of deposition to the North Pacific we assume the dust concentrations are essentially uniform from 150°E to 130°W longitudinally in the mid-North Pacific region, where most of the SADS stations are located. The estimated deposition rate is calculated by using three different simple models:

**Model 1:** Our primary model uses climatological mean precipitation rates and washout factors (or scavenging ratios). The washout factor is the ratio of the rain concentration of any substance to its concentration in the atmosphere. The wet deposition rate \( F' \) (µg/cm² period) is given by

\[
F' = K F
\]

where

\[
W = K_p C
\]

\( F' \) = precipitation rate in cm²/cm² period,

\( p \) = the air density of 1220 µg/cm³, and

\( C \) = the atmospheric concentration of a substance in µg/cm³.

From studies of trace elements at Eniwetak in 1979, the washout factor for crustal elements (e.g., Al, Mn, Fe) was found to be 500 ± 300 for both the local wet and dry seasons [Duce, 1982]. Equation (3), of course, only yields wet removal rates. Duce et al. [1980] made direct measurements of wet and dry deposition rates of soil dust at Eniwetak and found that approximately 75% of the total deposition was by wet removal processes. This value will be applied to the entire North Pacific. Thus the total (wet plus dry) deposition rate \( F \) is given by

\[
F = 1.3 F' = 1.3 K_p W C
\]

The average monthly precipitation for each latitude band is taken from Taylor [1973] and Dorman and Bauze [1979], and these values are summed for the high-dust (February-June) and the low (July-January) periods. **Model 2:** This model uses the mean total deposition velocities for aerosol particles in the 10 µm diameter bands over the North Pacific given by Young and Silker [1980]. The


**TABLE 5. Estimates of the Minor Dust Flux Into the North Pacific Ocean**

<table>
<thead>
<tr>
<th>Latitude, °N</th>
<th>High-Dust Period, µg/cm² pd.</th>
<th>Ocean Period, µg/cm² pd.</th>
<th>Both Periods, µg/cm² yr</th>
<th>Both Periods, 10¹⁵ tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-50</td>
<td>16-20</td>
<td>5.9-13</td>
<td>22-33</td>
<td>1.6-2.2</td>
</tr>
<tr>
<td>25-40</td>
<td>16-34</td>
<td>2.7-11</td>
<td>19-43</td>
<td>2.5-4.2</td>
</tr>
<tr>
<td>15-25</td>
<td>12-19</td>
<td>1.7-4</td>
<td>14-23</td>
<td>1.2-2.1</td>
</tr>
<tr>
<td>5-15</td>
<td>5-12</td>
<td>1.5-4.3</td>
<td>6-15</td>
<td>0.5-1.1</td>
</tr>
<tr>
<td>0-5</td>
<td>0.75-4.8</td>
<td>0.51-1.9</td>
<td>1.3-6.7</td>
<td>0.07-0.33</td>
</tr>
</tbody>
</table>

Total

5.8-12

*where V = the total deposition velocity of 14C in cm/yr for each longitudinal band. The flux in each longitudinal band is calculated from the total deposition velocity of 14C for each band, which varies from 0.69 to 1.0 cm/yr.*

*Model 3:* This model assumes that the atmospheric particles are distributed relatively uniformly to a height of 5 km [Braithwaite et al., 1974] and that the residence times of the atmospheric particles range from 5 to 10 days [Prospero et al., 1982]. The particle flux is then given by:

\[
F = CV
\]

*where F = the height of the air column in cm and R = the residence time of the atmospheric particles in seconds; H/R is, of course, the total deposition velocity, which is 1.2 cm/yr in this model, using a residence period of 7 days.*

The ranges of the estimated dust deposition to the mid-North Pacific in the five latitude bands calculated by using these three models are combined and summarized in Table 5. Although some of the parameters used in these model calculations probably have a factor of 2 to 3 uncertainty, the estimated rates agree rather well. Since the flux calculations are primarily controlled by the atmospheric concentrations, the flux increases with increasing latitude.

There are very few direct measurements of Asian dust deposition rates with which we can compare our results. Tsunogai et al. [1972] measured the dust deposition rate in a "red" snow in February 1966 and obtained a flux of 1.5 µg/ cm² for this one event in Japan. In contrast, a single dust storm in Asia in April 1980 produced a dust fall of 2.4 mg/cm² in Beijing, which is located some 1500 km from the source area [Sheng et al., 1981].

The annual atmospheric flux of crustal material to the surface of the North Pacific is comparable to the present-day downward flux of aluminosilicate materials in the water column in the North Pacific as measured by seaweed traps: 50 µg/cm² yr east of Hawaii [Honjo et al., 1985] and 100–200 µg/cm² yr near the Aleutian Islands [Tsunogai et al., 1982]. The atmospheric fluxes are also similar to the distribution of the nonbiogenic sediment accumulation rates over the past 5000 to 15,000 years in the North Pacific, 50–200 µg/cm² yr [M. Leinen, personal communication, 1982].

The total annual atmospheric input of crustal materials to this area of the North Pacific is estimated to be from 6 to 12 × 10¹⁵ tons/yr. An area of 4.3 × 10¹⁵ km² between the equator and 50°N and between 150°E and 140°W was used for this calculation. The input rate of continental dust to Asian coastal waters is undoubtedly quite large but is not included in our computations. Thus the total input of dust to the entire North Pacific may be considerably greater than the value presented here. Our estimate of 6–12 × 10¹⁵ tons/yr is approximately 4 to 8% of the total quantity of mineral dust, excluding the Saharan region, estimated to be injected into the Northern Hemisphere atmosphere each year (150 × 10¹⁵ tons/yr, Junge 1979). The total mass of the dust for one Kosa event passing over Japan to the North Pacific in April 1979 was estimated to be 1.6 × 10¹⁵ tons [Sakata et al., 1982]. This value supports our estimated total dust flux over the mid-North Pacific, if, as observed, the same scale of dust storms occur in Asia a few times each spring. Compared to the Saharan dust input to the North Atlantic, estimated to be 60–200 × 10¹⁵ tons/yr [Schütz et al., 1980; Prospero, 1981], the dust flux to the North Pacific is rather small, but the long-range transport of the Pacific dust and its seasonal variability can have a significant effect on the North Pacific ocean environment. The significance derives in part from the fact that the nonbiogenic sedimentation rates there are, in general, lower than those for the Atlantic.

**CONCLUSIONS**

Our measurement of atmospheric Al in the samples collected from the network of North Pacific islands lead to the following conclusions:

1. There is a substantial transport of mineral aerosol from Asia to wide areas of the North Pacific. This transport displays a clear seasonal variation, with a strong maximum in the spring.

2. The atmospheric transport patterns of the dust are complex, and the relative impact of individual dust outbreaks on the stations in the network varies from episode to episode.

3. A systematic geographic variation is apparent in the averaged dust values, with higher concentrations being observed at stations located at higher latitudes.

4. The total annual input of dust to the central North Pacific is estimated to be from 6 to 12 × 10¹⁵ tons/yr. This atmospheric transport of dust is a significant source of sedimentary material for the North Pacific.
Efforts are being made in the SADS network to measure directly the fluxes of mineral particles to the ocean by using total deposition collectors. These measurements will yield more accurate estimates of the annual input of the mineral aerosol to the North Pacific. In cooperation with the SADS network, six stations closer to the Asian continent, operated by Dr. Tsogtom of Hokkaido University, Japan, are collecting similar samples synchronously. Eventually, the data from 13 stations will be available for making a more complete estimate of mineral dust transport to the North Pacific Ocean. In addition, 10 new island stations will begin operation in the South Pacific at the spring of 1983.

Acknowledgments. The SADS network would not be possible without the generous cooperation and support in setting up and operating the sites and collecting the samples from the following personnel: K. Lehman, P. Kristensen and M. Thomas at Shemya; C. Cronin and S. Knuth at the Naval Geophysical Command Detachment at Midway; P. Colin and J. Harlin at the Mid-Pacific Research Laboratory at Eniwetok; M. Vitrescu from the University of Hawaii and Tusan at Fatumaf Island; C. Birkeland, F. Cushing, R. Sakamoto, T. Shigida, and A. Krilak from the Marine Laboratory, University of Guam; B. Madronich at the Micronesian Marine Laboratory Center in Koror; Felczak, J. Williams for aid in setting up the samples; T. Snowden for the faxing operation on the sailing system; L. Roba for aid in compiling the Asian dust reports; and the staff of the Idaho Rock Institute Science Center for providing irradiation and counting facilities. We thank all of these people for their help. Supported by NSF grants OCE 77-10873, OCE 77-12106 as part of the SEAREX Program.

References


Doer, A. C., Sea salt and trace element transport across the open ocean, interior surface, paper presented at the Joint Oceanographic Assemblage, Halifax, Nova Scotia, Canada, August, 1982.


(Received November 12, 1982; revised February 3, 1983; accepted February 17, 1983.)