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The transport and spacial scale of Asian dust-storm clouds: a case study of the dust-storm event of April 1979

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ABSTRACT

A dust storm which originated in the China desert area covered the Japan Islands on April 14–15, 1979. Simultaneous measurement by lidar and geosynchronous meteorological satellite enabled the spacial structure and transport path of the dust storm cloud to be characterized. The horizontal scale of the dust cloud was about 1.36×10^6 km^2, and the total dust particle mass load was at least $\sim 1.63 \times 10^6$ ton/1.36×10^6 km^2. The lidar measurements indicated that the dust cloud consisted of 2 distinct layers, one at 6 km height and the other at 2 km. The trajectory analysis of air mass suggests that the particulate matter contained in the upper layer is probably transported from the Takla-Makan desert and that in the lower layer from the Gobi desert and the Huang-Ho basin.

1. Introduction

The soil particles which are derived from the deserts of the Asian continent are frequently transported over the Eastern China Sea and/or the Yellow Sea to the Japan Islands during the spring season. These Asian dust clouds which are a common atmospheric phenomena in Japan, are referred to as "KOSA" which literally means yellow sands in Japanese.

The wind-blown dust particles lifted into the atmosphere are of obvious importance in the study of local climate and the atmospheric environment because of their rôle in cloud physics and in radiative transfer processes. In addition, the long-range transport of particulate matter has recently become a center of interest in the fields of chemical oceanography and geochemistry because the particulate matter can be carried over large areas and contribute significantly to the flux of material to the deep-sea sediments. Therefore the understanding of the transportation of wind-blown dust particles in the atmosphere is essential in these research fields (e.g., Duce et al., 1980; Atlas and Giam, 1981).

Saharan dust transport has been systematically investigated (Carlson and Prospero, 1972; Fraser, 1976; Carlson and Caverly, 1977; Gringel and Muhleisen, 1977; Jaenicke and Schütz, 1978; Yaalon and Ganor, 1979; Prodi and Fea, 1979). However, there has been only very limited research on Asian dust storms.

A typical "KOSA" event was seen over the Japan Islands on April 14–15, 1979. Coverage from the Japanese Geosynchronous Meteorological Satellite, HIMAWARI, enabled the behavior of the dust storm cloud to be observed from beginning to the end. Fortunately, we could also observe the vertical structure of the dust cloud using laser radar located at Nagoya (35° N, 137° E) on the night of April 14. In this paper we describe our measurements of this dust event and compare our results with other investigators' observations.

2. Dust storm of April 1979 measured by laser radar and by satellite

The wind-blown dust cloud moved directly over the Japan Islands on April 14–15, 1979, and many meteorological observatories in Japan reported various atmospheric phenomena attributable to the dust cloud, for example, the fall of sand particles, the decrease of visibility, the yellow sky, and so on.

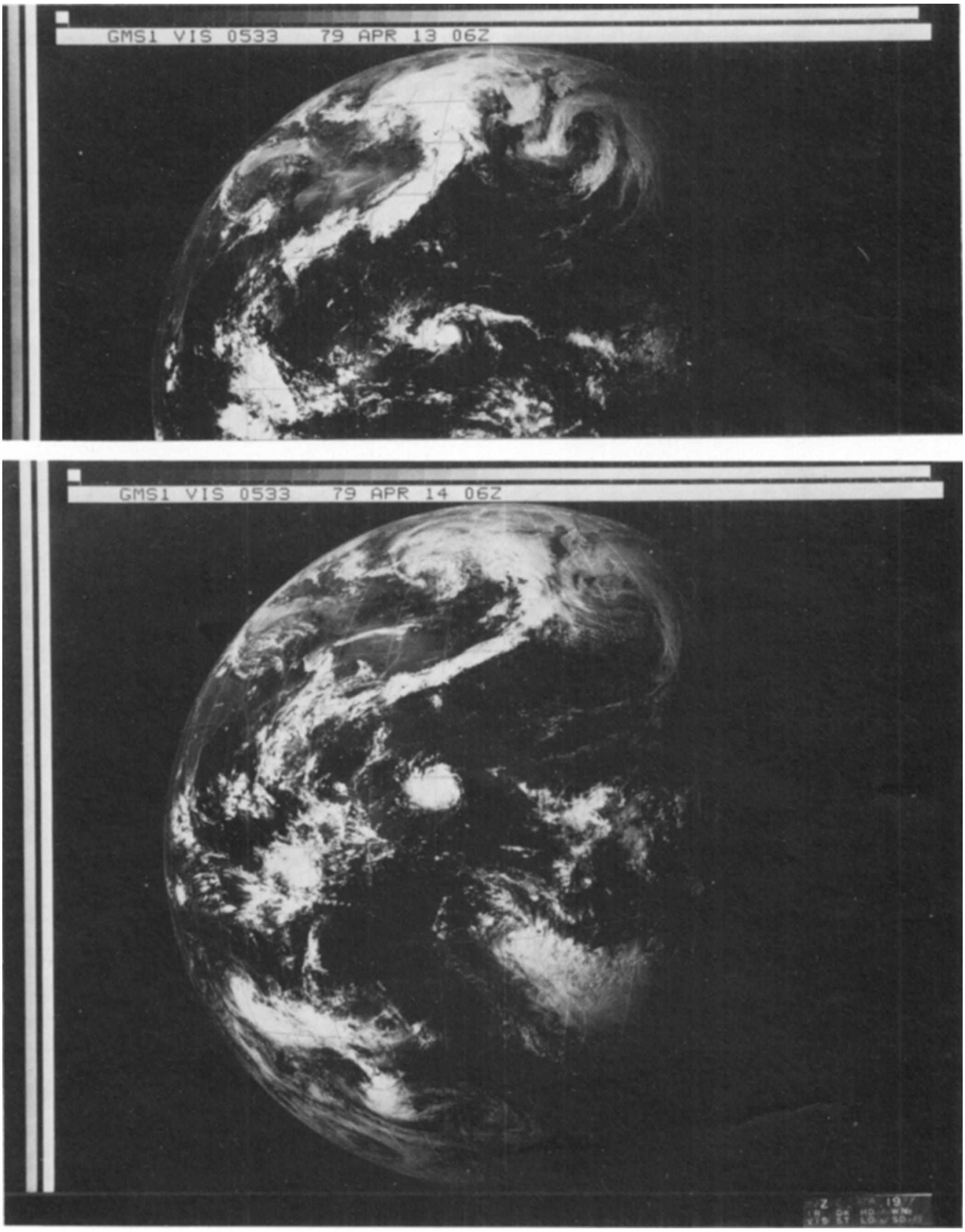

Fig. 1. Meteorological satellite photographs of an Asian dust storm (06.00 GMT, April 13, 1979, and 06.00 GMT, April 14, 1979). The grey region found at the left side (top panel) shows an area covered by the dust storm which is extending from the Huang-Ho basin to the Takla-Makan desert. The picture of April 14 shows that the grey region spread a little and shifted towards the Japan Islands.

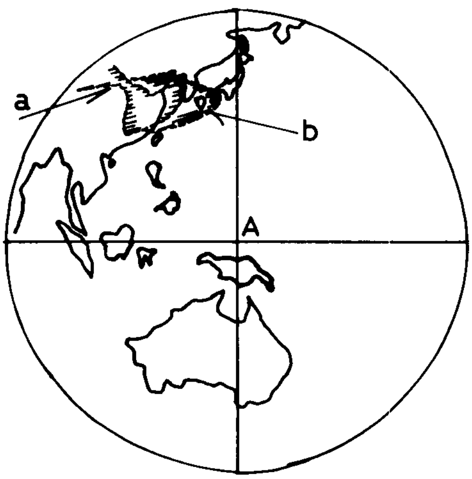

Fig. 2. Projections of the earth seen from a geostationary satellite. Point A is the location of the satellite (longitude 140° E, latitude 0°). The areas a and b are the dust storm regions estimated from the satellite photograph, 06.00 GMT, April 13, 1979, and 06.00 GMT, April 14, 1979, respectively.

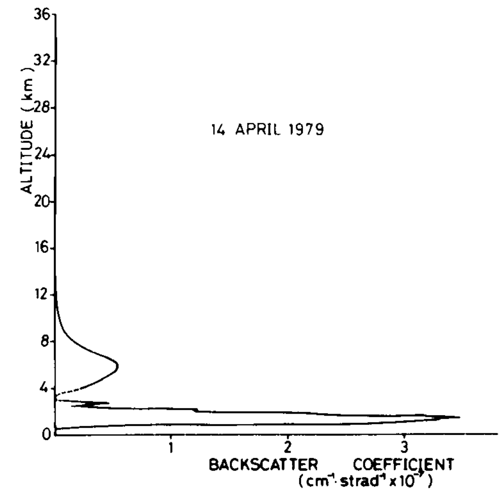

Fig. 3. The back-scatter coefficient of particulate matter at wavelength 0.6943 μm measured by laser radar on the night of April 14, 1979, at Nagoya (35° N, 137° E). The back-scatter coefficient profile has two peaks at 400 mb (potential temperature, $\theta = 316.4$ K) and 850 mb (potential temperature, $\theta = 292.9$ k).

The horizontal scale and track of the dust cloud was estimated on satellite photographs taken in the wavelength band 0.5–0.75 μm (Figs. 1 and 2). The dust storm area was first observed near the Takla-Makan desert area on April 11, 1979, on satellite photographs. The dust storm cloud then proceeded over the Huang-Ho basin, the eastern China Sea and finally the Japan Islands. The laser radar measurements began on the night of April 14, 1979, at Nagoya when the fall-out of sand was greatest. The main characteristics of the laser radar have been described in other papers (e.g., Iwasaka et al., 1976; Iwasaka and Isono, 1977). This laser radar emits a laser pulse of wavelength = 0.6943 μm at a maximum power of 1.0 J and a pulse repetition rate of 0.2 s^{-1}. The back-scattered light from particulate matter and air molecules is detected by a photomultiplier.

The backscattering coefficient of particulate matter, $\beta(z)$, has the following relationship to the size distribution function of particles, $n(z, R)$:

$$\beta(z) = \int \sigma(R)\, n(z, R)\, \mathrm{d}R, \qquad (1)$$

where R is the radius of the particle, $\sigma(R)$ the back-scattering cross section of the particle, and $n(z, R)$ the size distribution function of particulate matter at height $= z$. The number density of particles with the radius range R_1–R_2 per unit volume is given by

$$N(z) = \int_{R_1}^{R_2} n(z, R)\, \mathrm{d}R. \qquad (2)$$

The analytical procedure for evaluating the back-scattering coefficient of particulate matter from the back-scattered signal obtained from an air parcel has been discussed by many investigators (e.g., Russell et al., 1976).

The back-scatter coefficient of particulate matter measured on the night of April 14, 1979, is shown in Fig. 3. Of course, the back-scatter coefficient in Fig. 3 contains both the contribution of dust particles transported into Nagoya and the aerosol particle component which is usually measured in the absence of a dust storm event. According to the routine (non-dust storm) lider observations of Nagoya, the back-scatter coefficient of particles in the lower atmosphere is usually in the range of 10^{-8}–10^{-6} cm^{-1} sr^{-1}. It is reasonable to assume that the large back-scatter coefficient obtained on April 14 was due to the dust storm particles. Moreover, it should be noted that the vertical profile of back-scatter has 2 maxima at heights of 2 km and 6 km. Such a feature has not been found in

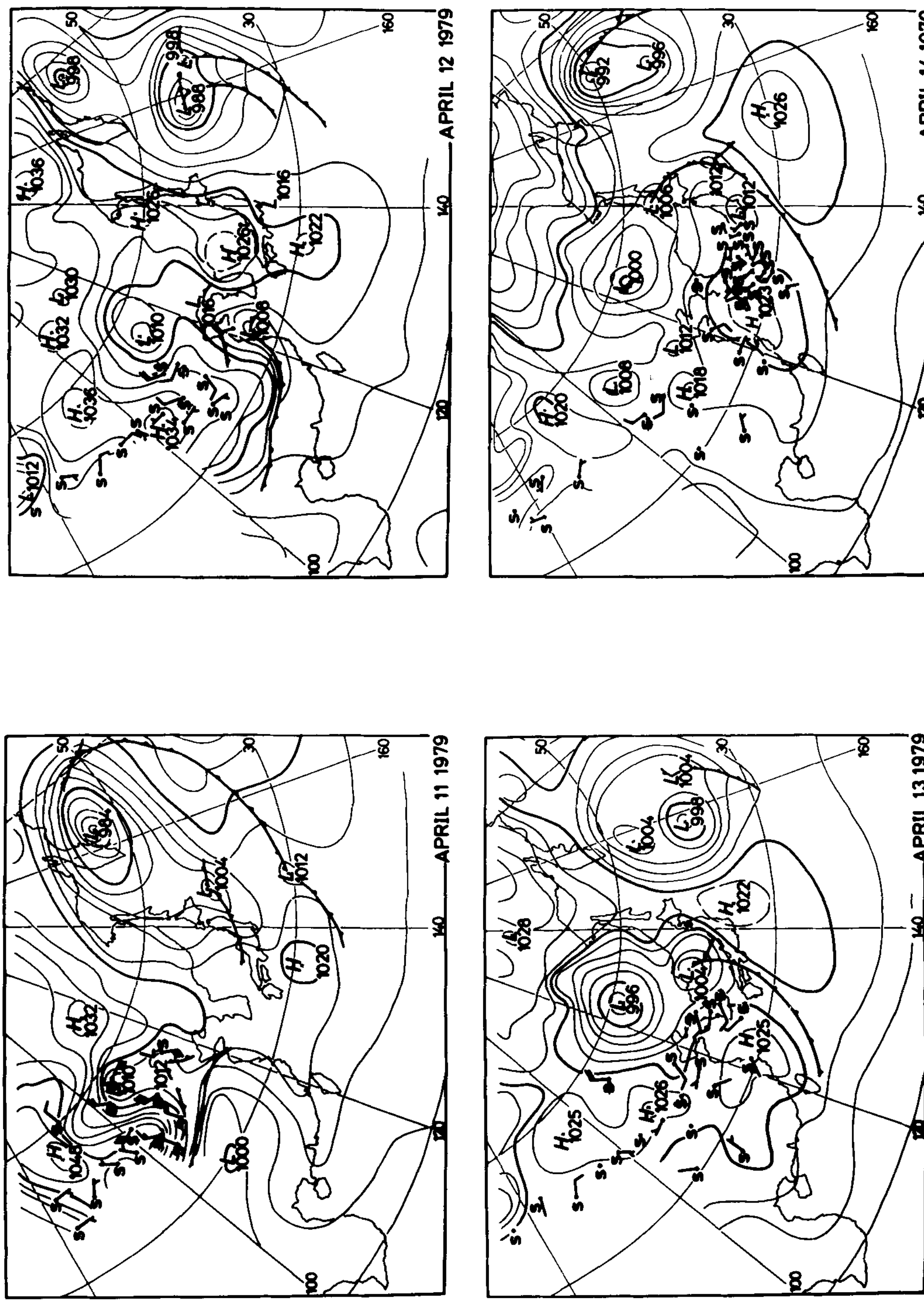

Fig. 4. A series of maps describing the meteorological situation during April 11–14. The symbols "S" and "$" indicate the stations which observed the dust storm.

routine measurements. The small peak at a height of 6 km is not due to cloud particles since we could not see any clouds on the night of April 14. Furthermore, the Nagoya Meteorological Observatory reported the sky to be clear that night.

In Fig. 4, we show the meteorological situations during the period from April 11–14. The symbol S in the maps means a sand storm event. Many observatories near the Takla-Makan desert reported the sand storm on April 11. After that, the sand storm area moved in a south-easterly direction following the high-pressure region.

Air-mass trajectory analyses were performed on surfaces of constant potential temperature, 319.0 K and 292.9 K, which correspond to the height of the back-scatter maxima. The air mass at the 6 km height was traced back to the Takla-Makan desert area on April 12. On the other hand, the air mass at the 2 km altitude was traced back to the Huang-Ho basin on April 12 (Fig. 5). Thus, the material in the 2 back-scatter maxima layers on April 14 arose from different sources.

Ishizaka and Ono (1981) presented interesting results of X-ray analysis of the dust-particles sampled at Nagoya near the surface. The results suggested that the origin of the fall-out particles was not only the desert area of Takla-Makan or Gobi but also the Huang-Ho basin. They found many particles which contained a large amount of Kaolinaite, having a large value of the ratio of Illite to Kaolinite. They concluded that all of the sampled particles were not identified as being desert soil particles. Some of them were pedocal and/or non-calcic soil particles which are found in the area of the Huang-Ho upper stream (see e.g., Hseung and Jackson, 1952). Their measurements suggest that the dust sampled was derived from the main layer at 2–3 km.

On the basis of the satellite photograph (Fig. 1) showing the dust storm over the Takla-Makan, the double peak in laser radar measurements at Nagoya, the trajectory, and mineral analysis, we conclude that there were, indeed, two dust clouds having different origins.

3. Mass load and dust cloud scale

The areal extent of the dust cloud and the mass of particles in it were estimated on the basis of the simultaneous measurements by satellite and laser radar. The dust-particles sampled at ground level at Nagoya from April 14–16, 1979, had the following size distribution function (Ishizaka and Ono, 1981):

$$n(R) = AR^{-3.5}, \quad 0.3\,\mu\text{m} \leqslant R \leqslant 10\,\mu\text{m}. \tag{3}$$

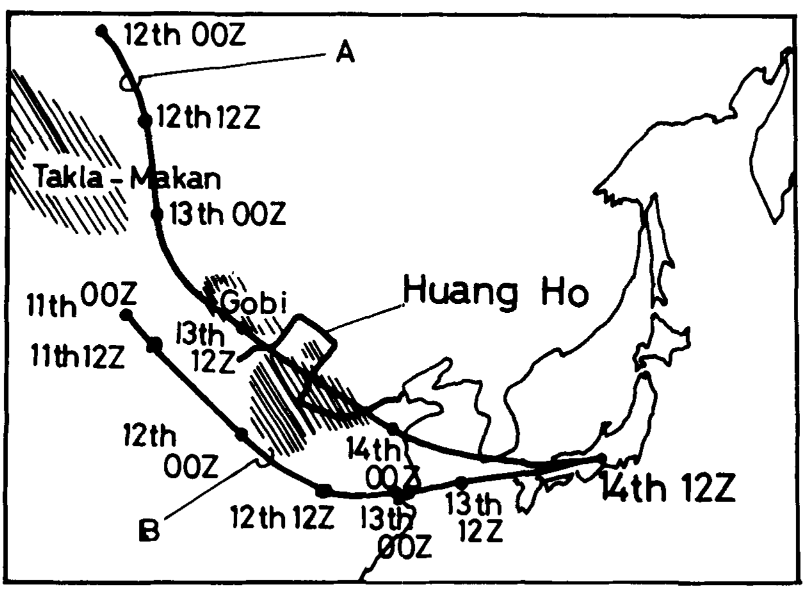

Fig. 5. Trajectories of the air mass. Curve A was computed for $\theta = 316.4$ K and curve B for $\theta = 292.2$ K.

We would like to point out that a very similar size distribution was found in measurements of another "KOSA" event at Nagasaki (33° N, 130° E), $n(R) \propto R^{-3.0} \sim R^{-3.5}$ (private communication by Arao, 1979), and in Sahara dust measurements (Prodi and Fea, 1979). Summarizing those measurements, we assume here the following number size distribution function:

$$n(z, R)\begin{cases} = \text{constant}, & 0.1\ \mu\text{m} \leqslant R \leqslant 0.3\ \mu\text{m}, \\ = A(z)\, R^{-3.5}, & 0.3\ \mu\text{m} \leqslant R \leqslant 10.0\ \mu\text{m}. \end{cases} \quad (4)$$

The constant value and the parameter A of the size distribution function were chosen to satisfy the mesurements of the back-scatter coefficient, assuming the refractive index of dust particles to be $1.5 + 0i$ at wavelength 0.6943 μm.

The mass of dust particles in a vertical column of height range, z_1–z_2 is computed from the following expression:

$$M(z_1, z_2) = \tfrac{4}{3}\pi\rho \int_{z_1}^{z_2} \int_{R_1}^{R_2} R^3\, n(z, R)\, \mathrm{d}R\, \mathrm{d}z, \quad (5)$$

where the average mass density of particulate matter is assumed to be 2.6 g cm^{-3} on the basis of the chemical composition of the dust particles (Ishizaka and Ono, 1981).

The total mass of dust is estimated from the following relation:

$$M_{\text{total}} = SM(z_1, z_2), \quad (6)$$

where S is the area of the dust cloud. According to the satellite photographs, the average horizontal area is estimated to be about 1.36×10^6 km^2. In Table 1, the mass load of the "KOSA" is presented for a layer depth of 2 km for the lower layer and 4 km for the upper layer. This value is compared with those from other investigations.

4. Discussion and summary

The transport of dust storm particles in the atmosphere has attracted many investigators' attention, because such transport processes can be an important source of particulate matter in the ocean. According to Duce et al. (1980), the deposition of Asian dust in the Enewetak area in late April and May 1979 yielded a total flux from the atmosphere to the ocean surface of about 4 μm cm^{-2} month^{-1}. This rate extrapolates to an accumulation rate equal to a third of the measured accumulation rate for deep sea sediments. Shaw (1980) presented a very interesting example showing the long-range transport of a dust cloud that originated in the deserts of China. According to his results, the dust cloud, which was observed in the Hawaiian Islands from late April to early May 1979, probably had its origin in the eastern deserts of Asia. The vertical profiles of haze extinction had a large maximum at about 3 km height which is in the same range as the main peak of the "KOSA" event which we observed.

The investigation of optical scattering and optical extinction in April 1979 at the Hawaiian

Table 1. *Characteristics of dust storms; a comparison*

	Asian dust*	Saharan dust		
	upper layer lower layer	Gringel and Muhleisen (1977)		Prodi and Fea (1979)
Altitude of layer	4–8 km 0.5–2.5 km	1.2–3.7 km	1.7–3.7 km	
Number concentration	50.5 particles cm^{-3} 225 particles cm^{-3}	in the order of 100 particles cm^{-3}		100–500 particles cm^{-3}
Mass concentration†	136 μg m^{-3} 608 μg m^{-3}	160 μg m^{-3}	120 μg m^{-3}	154 μg m^{-3}
Column density†	176 μg cm^{-2}	400 μg cm^{-2}	250 μg cm^{-2}	83.3 μg cm^{-2}
Total mass of dust	1.66×10^6 ton per 1.36×10^6 km^2	3.5–5.0×10^6 ton yr^{-1}		
Distance from source to to observation site	2500–3500 km	1400 km	2200 km	2500 km

* Our results.

† The size range from 0.1 μm to 10.0 mm is assumed here (see text).

Islands indicated that the column particle density was in the range 2–12 μg am^{-2}, and that the mass loading of particles was probably 700 μg m^{-3}, assuming a haze layer depth of 2 km (Shaw, 1980). It is useful to compare both the extinction and laser-radar measurements, even if the dust storm event measured at Nagoya from April 14–15, 1979, was not the same event as described by Shaw (1980). The characteristic scale of a dust storm cloud is roughly estimated by the following equation, assuming that the particles are emitted by a "point source" and that they spread by eddy diffusion as they travel:

$$L_i = \sqrt{DT_i}, \tag{7}$$

where T_i is the traveling time from the source to the ith observation point, D is the effective eddy diffusion coefficient (horizontal direction), and L_i the characteristic horizontal scale of the cloud at the ith observation point.

The travel time from the sand storm source to Nagoya is about a few days and to Hawaii about 10 days, on the basis of the typical air mass tracks at an 800 mb or 850 mb surface. The value of L_1/L_2, $i = 1$ and 2 corresponding to the points Nagoya and Hawaii, is

$$L_1/L_2 = \sqrt{T_1/T_2} = 0.3 \sim 0.5. \tag{8}$$

If sedimentation loss of particles is neglected, and the dust cloud spreads only in the horizontal direction, the vertical column density of dust particles decreases from about 25% to 10% (about 44 μg cm^{-2} to 18 μg cm^{-2}) during the journey from Nagoya to Hawaii. The value measured at the Hawaiian Islands is apparently within this estimation range.

Satellite measurements of dust clouds are very powerful. They make it possible to easily estimate the horizontal scale of the dust storm, its time variation, and the transport path. But there are a few problems to solve if we want to make quantitative measurements, using satellite photographs. We must have a better understanding of radiative transfer processes because the radiance measured by a satellite is certainly affected by various factors: solar zenith angle, the ground surface condition, the vertical structure of clouds, the chemical composition of dust particles, and their size distribution (e.g., Fraser, 1976; Norton et al., 1980). The present estimate of the horizontal scale is probably low because the radiometer mounted on a meteorological satellite cannot detect radiation from the thin part of the dust cloud; the total mass presented here is therefore also underestimated. Fortunately, Murayama (1980) analyzed the same "KOSA" event, also using satellite photographs, and pointed out that the radiation from the dust clouds over the sea is easily detected, but not over the land. Furthermore, his synoptic meteorological analysis showed that the origin of the "KOSA" was probably the area of 40–50° N and 100–110° E and that the dust was transported at a level of about 850 mb. Our trajectory analysis in the lower layer of the dust cloud showed good agreement with his conclusion.

The behavior of Saharan dust has been actively investigated. However, there is very limited information on Asian dust-storms. The various parameters summarized in Table 1 suggest that the Asian dust storm has characteristics similar to those of Saharan dust storms. However, further investigations on Asian dust storms are necessary.

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REFERENCES

Atlas, E. and Giam, C. S. 1981. Global transport of organic pollutants: ambient concentrations in the remote marine atmosphere. *Science 221*, 163–165.

Carlson, T. N. 1979. Atmospheric turbidity in Saharan dust outbreaks as determined by analysis of satellite brightness data. *Mon. Wea. Rev. 107*, 322–335.

Carlson, T. N. and Caverly, R. S. 1977. Radiative characteristics of Sahara dust at solar wavelengths. *J. Geophys. Res. 82*, 3141–3152.

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

Carlson, T. N. and Wendling, P. 1977. Reflected radiance measured by NOAA 3 VHRR as a function of optical depth for Sahara dust. *J. Appl. Meteorol. 16*, 1368–1371.

Duce, R. A., Unni, C. K., Ray, B. J., Prospero, J. M. and Merrill, J. T. 1980. Long-range atmospheric transport of soil dust from Asia to the tropical north Pacific: temporal variability. *Science 209*, 1522–1524.

Fraser, R. S. 1976. Satellite measurement of mass of Sahara dust in the atmosphere. *Appl. Opt. 15*, 2471–2479.

Gringel, W. and Muhleisen, R. 1977. Sahara dust concentration in the troposphere over the north Atlantic derived from measurements of air conductivity. *Beitr. Phys. Atmos. 51*, 121–128.

Ishizaka, Y. and Ono, A. 1981. Mass size distributions of principal minerals yellow sand dust in the air over Japan. Paper presented at Intern. Conf. Condensation and Ice Nuclei of Third Scientific Assembly IAMAP, Homburg, 26–28 August, 1981.

Iwasaka, Y., Mita, A. and Isono, K. 1976. Measurements of the stratospheric aerosols by two-color lidar. *Rep. Ionos. Space Res. Japan 30*, 51–55.

Iwasaka, Y. and Isono, K. 1977. Lidar observation of the stratospheric aerosols at two different wavelengths, 0.6943 μm and 1.06 μm. *J. Atmos. Terr. Phys. 39*, 117–120.

Jaenicke, R. and Shütz, L. 1978. A comprehensive study of physical and chemical properties of surface aerosols in the Cape Verde Island region. *J. Geophys. Res. 83*, 3585–3599.

Murayama, N. 1980. The duststorms over the sea as revealed by the GMS satellite (in Japanese). *Umi to Sora 55*, 149–168.

Norton, C. C., Mosher, F. R., Hinton, B., Martin, D. W., Santec, D. and Kuhlow, W. 1980. A model for calculating desert aerosol turbidity over the oceans from geostationary satellite data. *J. Appl. Meteorol. 19*, 663–664.

Prodi, F. and Fea, G. 1979. A case of transport and deposition of Sahara dust over the Italian Peninsula and southern Europe. *J. Geophys. Res. 84*, 6951–6960.

Russell, P. S., Viezee, W., Hake, Jr., R. and Collins, T. H. 1976. Lidar observations of the stratospheric aerosol: California, October 1972–March 1974. *Q. J. R. Meteorol. 102*, 619–639.

Shaw, G. E. 1980. Transport of Asian desert aerosol to the Hawaiian islands. *J. Appl. Meteorol. 19*, 1254–1259.

Yaalon, D. H. and Ganor, E. 1979. Eastern Mediterranean trajectories of dust-carrying storms from the Sahara and Sinai. In *SCOPE 14*, *Sahara dust* (ed. C. Morales). New York: John Wiley.