Transport of Asian Desert Aerosol to the Hawaiian Islands

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ABSTRACT

A cloud of aerosol with optical thickness $\tau \approx 0.18$ (500 nm wavelength), passed over the Hawaiian Islands from late April to early May 1979. Vertical profiles, taken by evaluating the optical extinction coefficient by sun photometry, showed that 80–90% of the aerosol was confined to a 1 km thick layer centered at 3.5–4 km altitude. Trajectory analysis at the 500 mb pressure level (~5 km) indicated that the aerosol probably had its origin in sandstorms in the eastern deserts of Asia nine days before the event. The dust cloud was first observed passing over Japan where sand particles fell out at Nagasaki on 21 April. By the time dust from the sandstone reached Hawaii, it has spread out to ~1500 km and contained an estimated 10^{11} g of sand material, mainly in the $0.5 < r < 5.0$ μm size range. This episode clearly indicates that substantial quantities of primary aerosol are being transported on global distance scales. The episode is used to obtain a desert aerosol surface particle flux which agrees to an order of magnitude with that suggested by Junge.

1. Introduction

The sky over the Hawaiian Islands was charged with thick clouds of dust which emanated halfway across the Pacific Ocean in the great deserts of Asia during the time period from late April to early May 1979. The Hawaiian event was strong enough to create obvious visual effects, for instance, distinct bands stood out against the horizon (Fig. 1) and a remarkably bright glow of scattered sunlight, ~20–40° in diameter (Fig. 2) and tinted slightly reddish, surrounded the sun. The sky appeared little different at sea level than at 3.6 km altitude, the only contrast being that smaller, roughly 10° diameter aureole (probably caused by marine sea salt) was superimposed on the overall aureole near sea level. The evidence indicates that the aerosol cloud had its origin in dust storms over the eastern deserts of Asia and it illustrates an example of long-range transport of tropospheric primary particulates over distances nearly half-way around the world. The discussion of the event which follows is believed to be of some relevancy since knowledge can be drawn from it about the evolution of particulate material during long-range transport.

2. Temporal variations of the haze

The Hawaiian dust event lasted several days, peaking on 30 April 1979. Fig. 3 illustrates the time sequence of the optical thickness above 3.6 km (the altitude of Mauna Loa Observatory) at 500 nm wavelength, τ_{500}, and the diffuse monochromatic sky intensity at 1 and 6° from the sun's limb and at 850 nm wavelength. There is an obvious correlation between the sky brightness in the solar aureole at 1 and 6° from the sun and optical thickness.

The background (dust-free) optical thickness at Mauna Loa Observatory is very small throughout the year, though it does have a seasonal variation that peaks in spring (Mendonca *et al.*, 1978) about the time this event occurred. Normally, when Gobi dust is not present, the optical thickness is $\tau_{500} = 0.015$–0.020 (Shaw, 1979a), while the maximum τ_{500} observed during this particular dust episode was $\tau_{500} = 0.18$, or an *order of magnitude* higher than average for that time of year.

3. Vertical profile of the haze

The vertical profile of the dust optical extinction coefficient, and hence the dust concentration, was determined by performing measurements of optical thickness of the overlying aerosol at different elevations along the roadway up Mauna Loa Volcano, from sea level to a maximum elevation of 3.6 km.

In Fig. 4, vertical profiles of the aerosol optical extinction coefficient, β (km^{-1}), defined by

$$\beta(\lambda,h) = \frac{1}{\mu_0 I(\lambda,h)} \frac{dI(\lambda,h)}{dh}, \qquad (1)$$

is shown for four illustratory periods. In the equation above, I is the direct solar intensity at height h and wavelength λ and $\mu_0 = \cos z_0$, where z_0 is the sun's zenith angle. Fig. 4 also shows the vertical plot of relative humidity (RH), air temperature and

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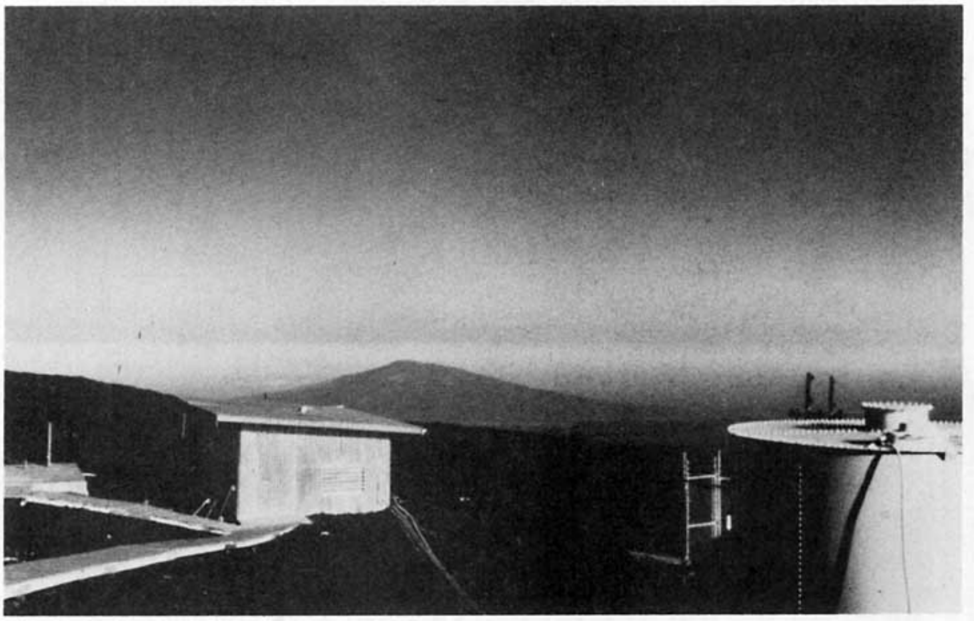

FIG. 1. Haze band over the Hawaiian Islands on 2 May 1979 (0720 HST) looking southwest from the Mauna Loa Observatory.

winds aloft from radiosonde releases at the Hilo Airport.

Several things should be noted in the vertical profile in Fig. 4. First, a considerable fraction of the haze is contained in the altitude range 0–3.6 km. Second, a minor peak, at least on 2 and 5 May, existed below the main layer at or just below the marine trade inversion. We attribute this secondary peak to humidity growth of hygroscopic particles; note that it occurs where the relative humidity takes a large jump downward. Perhaps some of the particles in this sublayer had diffused down from above, but more likely they are particles which had originated locally, possibly in the form of fine sea salt particles which became trapped near the top of the marine boundary layer. The main feature of interest is obviously the thick haze layer at near 4 km altitude. On 4 and 6 May, however, the haze layer is not "topped" by the measurements, but a major fraction of the optical depth lay below 3.6 km.

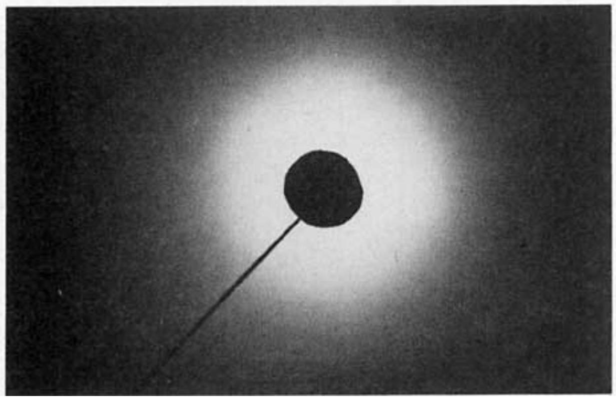

FIG. 2. Photograph of the bright glow around the sun due to forward-scattering of light by particles suspended in the air. The sun is blocked out with an opaque disk.

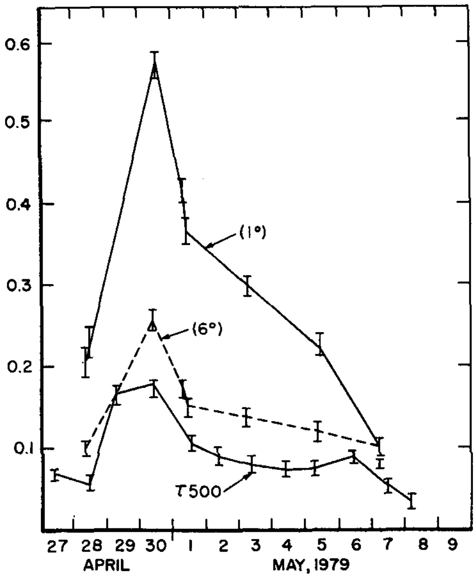

FIG. 3. The temporal variation of (a) τ_{500}, the optical thickness above 3.6 km altitude and at 500 nm wavelength and (b) $\pi I/F$, the sky brightness at 1 and 6° from the sun referred to the vertical direction (I is sky irradiance, F is solar irradiance).

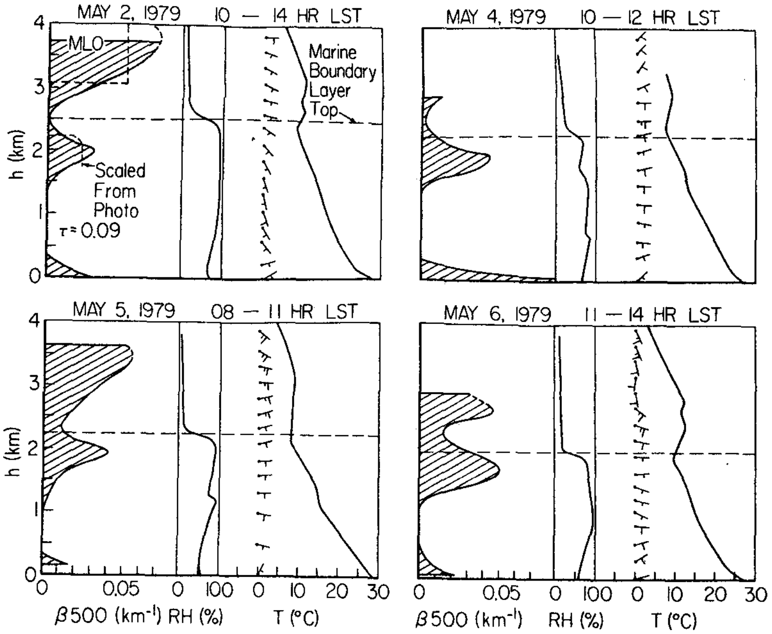

FIG. 4. Vertical profiles of parameters over Hawaii during the haze episode. The curves are from left to right, (a) optical haze extinction coefficient at 500 nm wavelength (km^{-1}), (b) relative humidity (c) wind direction and speed, (d) air temperature (°C). The haze extinction coefficient was obtained by differentiating optical thickness measurements made at different elevations on Mauna Loa Volcano. The dotted line is the optical extinction coefficient scaled from a photograph of the haze bands.

4. Particle size distribution and aerosol mass loading

Measurements of the sky intensity at different angles from the sun (caused by particles scattering light) and optical extinction measurements, expressed in terms of optical depth, at different wavelengths, such as those illustrated in Fig. 5, were used to deduce a rough estimate of the haze particle's size distribution function. A linear constrained inversion method (Shaw, 1979c) was used to obtain the particle size spectrum shown in Fig. 6.

With regard to the accuracy of passive sensing determinations of light intensity and the resultant particle size spectrum, it is estimated that optical thicknesses were uncertain, mainly from systematic errors of calibration, to about ±2%. Simulations

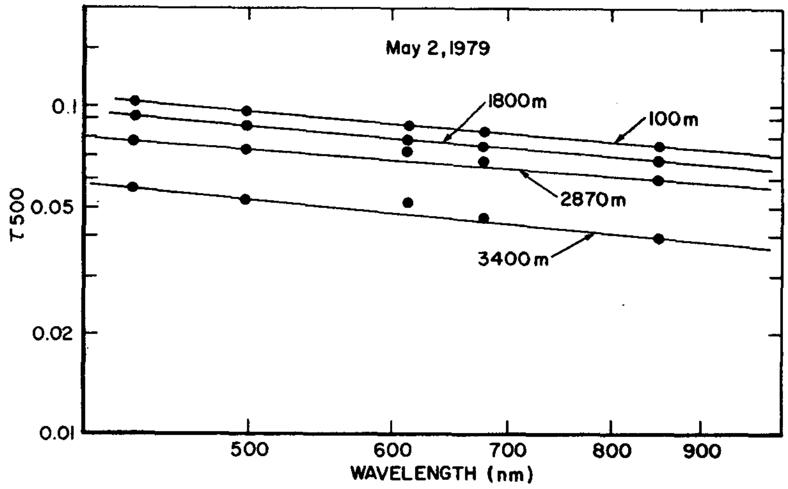

FIG. 5. Wavelength dependence of aerosol optical thickness on 30 April 1979 at altitudes of 100, 1800, 2870 and 3600 m.

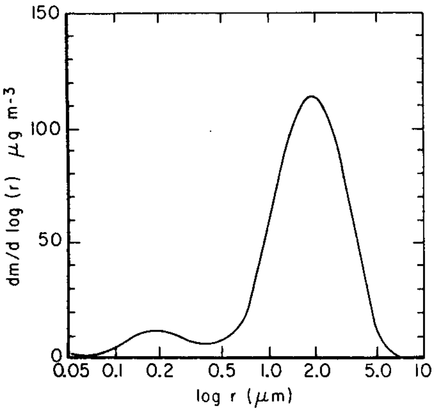

FIG. 6. Particle size distribution function obtained by inverting optical scattering and optical extinction measurements. The ordinate is the mass of particles in the main haze band per increment of log*r*. The particles are assumed to be composed of desert sand material with refractive index of 1.50 and with mass density of 2.5 g cm^{-3}.

conducted on noise-degraded optical data indicated that the uncertainty in the derived spectrum in Fig. 6 are ±50% for $r \approx 0.05$, ±5% in the particle radius range $0.1 < r < 5.0$ μm, and ±25% for the particle size range $r \gtrsim 5$ μm. The inferred depletion of particles in the size range $r > 5$ μm can therefore be considered real; however, a note of caution should be raised with regard to the inferred depletion of particles in the Aitken ($r < 0.1$ μm) size range since these particles interact weakly with incoming optical radiation. Though the inverted size distribution function shows a tendency to decrease for particles having $r \lesssim 0.1$ μm, it is still possible that an Aitken mode may have existed due to gas-particle nucleation; however, the Aitken count record at Mauna Loa was only several hundred per cubic centimeter so we infer from this that no small-particle mode existed. Both the large ($r > \sim 5$ μm) and small ($r < 0.1$ μm) particles were presumably depleted by inertial and diffusive mechanisms, respectively, and the shape of the distribution function suggests that the particles are aged, though one cannot quantify this very exactly without knowing the injected particle's size distribution. Particles with $r \gtrsim 5$ μm have fallen out by gravitational sedimentation during the estimated 9-day travel time of the cloud.

The inversion results for the particle size distribution in Fig. 6 indicates that the aerosol mass loading on 30 April, when all the systematic errors are accounted for, was in the range $2-12 \times 10^{-6}$ g cm^{-2}. Since the main haze layer was ~1 km thick, the mass loading of aerosol material in the band was therefore in the range 40–240 μg m^{-3} (for $\rho = 2.5$ g cm^{-3}), with a most probable value of ~70 μg m^{-3}. This is a substantial aerosol mass loading, usually associated with pollution conditions in urban areas.

5. Source of the haze

The discussion above admits several deductions to be made about the Hawaiian haze: 1) it shows evidence of being crustal-derived material that had aged in the atmosphere for ~1 week, 2) it was contained almost entirely in the lower troposphere at a mean altitude of 3–4 km, and in a layer ~1 km thick, and 3) the mass loading per volume of air at the peak episode was substantial. In fact, it was comparable to polluted air in large or medium-sized cities.

Figure 7 shows an example of the isobaric day-to-day air trajectory from 30 April going back to 21 April at the 500 mb pressure level. The trajectory was calculated from the published Japanese and American weather maps, using half-day steps; it appears that a likely candidate for the haze cloud is the desert region in eastern Asia.

The suspicion of a dust storm source occurring in the Asian eastern deserts about a week before the passage of the aerosol cloud over the Hawaiian Islands was confirmed by the Japanese surface weather maps, which showed blowing dust at numerous locations in Mongolia during the period from 19 to 24 April 1979. The dust storms were associated with the intrusion of a series of cyclonic storm systems which traveled from northeast to southwest and passed directly over the central Gobi desert. These storms did not seem to have strongly developed frontal systems, though it is

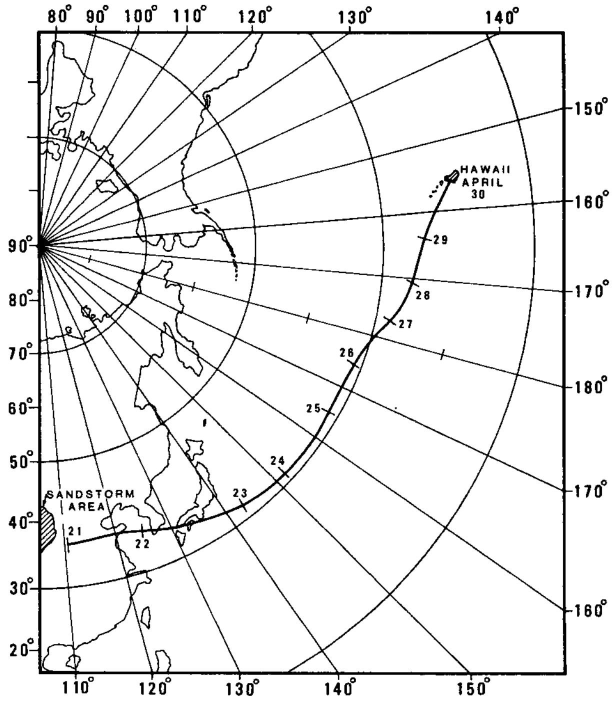

FIG. 7. Back isobaric air trajectory at the 500 mb level.

difficult to confirm this absolutely because of the sparsity of stations in the Gobi. Once injected into the rising cyclonic air the particles were carried out across the sea of Japan just southward of the subpolar jet stream. Strong sand fallouts occurred over the Nagasaki area on 21 April (T. Ohtake, personal communication). Presumably the *low-level* particles at altitudes below the trade inversion were scavenged by rain and clouds during passage across the Pacific.

Although at this point Gobi dust is seen to be the important candidate for creating this dust episode, it is not the only candidate. Other possibilities include 1) desert dust from the Middle East area, 2) Japanese air pollution, and 3) volcanic debris from the explosive eruption of La Soufriere volcano in the Virgin Islands on 13 April 1979—16 days before the peak dust loading occurred (West, 1979).

Construction of back trajectories at the 500 mb level back further in distance than eastern Asia did not pass over the area of the middle eastern deserts or the Sahara, so these deserts can be eliminated as the source of the aerosol. It is difficult, also, to see how Japanese air pollution carried across the Pacific could explain the event. The most important negative evidence, which will be discussed more later, is the identification by Duce *et al.* (1980) of a strong crustal component for the aerosol. Second, urban pollution transported over large distances normally contains particles in the approximate size range $0.1 < r < 0.3$ μm and it can be seen in Fig. 6 that this size range was actually depleted in particles.

Finally, the La Soufriere eruption can also be discounted as a source for the haze. No stratospheric layers were detected by lidar (R. Fegley, personal communication) at Mauna Loa Observatory and none were detectable in twilight color ratio measurements made at Hawaii. By comparing records of twilight red-to-green color ratios with those calculated for a model stratosphere contaminated with particulates (Shaw, 1979b), it was possible to deduce that the total optical thickness of the stratosphere at the time of observation was $\tau_{500} < 0.010$. During the dust episode the twilights were nearly colorless. This is strong evidence that from 25 April–10 May 1979 the stratosphere was in a nonperturbed state. It is still conceivable that the dust may have been a residual tropospheric component from the La Soufriere eruption, but the timing is wrong and heavy ash fallouts were not reported anywhere else along the path westward of the Gobi desert. The obvious inquiry to make in order to confirm the hypothesis of an eastern Asian source is to ask what was the composition of the particles? As far as the composition of the haze is concerned, no direct measurements were carried out from Mauna Loa but, fortunately, particles were sampled at Bokandretok Island, Enewetak Atoll and Marshall Island by Duce *et al.* (1980) as part of the Sea/Air Exchange Program studies. The collected particles showed significant increases of crustal material in April 1979. These authors reported a generally decreasing Al concentration from mid-April to early August, with surface concentrations in April as high as 2.3 μg m^{-3}. According to Duce *et al.* 80% of the mass of the dust deposited at Enewetak was in the size range $0.2 < r < 2$ μm, whereas most of the dust mass at Mauna Loa was in the size range 0.5–5.0 μm; the geometric means between these differs by a factor of 2.5. The particle size spectra probably differ at the two locations because of diffusive size fractionation in the cloud. According to the trajectory analysis, the Hawaiian Islands were on a more direct route of a major injection episode across the Pacific, whereas Enewetak Atoll apparently experienced smaller particles that had diffused laterally outward from the main cloud. Indeed, inertially controlled removal mechanisms (slippage of particles in moving air streams and direct impaction on hydrometeors, etc.) start to become important for particles with sizes $r \gtrsim 0.5$ μm; thus it isn't too surprising, in fact, it is to be expected, that as one moves away from the central core of a transported aerosol-laden air mass, the evolving particle size spectrum, initially rich in giant particles ($r > 1$ μm), will continually move to smaller size ranges as giant particles are progressively depleted. Duce *et al.* (1980) point out that the higher dust concentrations found in spring can be understood by evoking an eastern desert source for the particles and by realizing that meteorological conditions in the China deserts favor frequent occurrence of dust storms in spring. They claim that the Takla Maklan Desert in spring "appears to be one of the dustiest places in the world." Further discussions on the synoptic patterns associated with eastern desert dust transport can be found in the paper by Duce *et al.* In summary, the only hypothesis that seems to be in agreement with the observation is that the haze can be attributed to the deserts of eastern Asia.

6. Concluding remarks

Particles emitted by a "point" source spread as they travel by turbulent eddies and would be expected to have very roughly a characteristic dimension l, where

$$l = \sqrt{Dt}, \qquad (2)$$

after traveling for time t, where D is a turbulent diffusion coefficient. Using representative values for the horizontal eddy diffusion coefficient $D = 3 \times 10^{10}$ cm^2 s^{-1} (Czeplak and Junge, 1974) and $t = 9$ days (the travel time from Asia to Hawaii) leads one to expect that the cloud would have a horizontal cross sectional dimension of $l_H = 1500$ km. Thus, a cloud spread out horizontally on the order of 1000–2000 km in size would occur over the Hawaiian Islands from a high concentration source in or near the Gobi Desert. Several days would be required for such a cloud to pass over the islands with the light (10–15 kt) winds aloft at 500 mb; this time of passage is consistent with the observation (See Fig. 3).

It is interesting to note that the total mass of particles contained in the cloud of dimension just stated is 10^{11} g, which would correspond to an emission flux for a day-long sandstorm over the Gobi desert (10^6 km^2) of 10^{-10} g cm^{-2} s^{-1}. But this is a minimum estimate, as a major proportion of the mass of particles initially emitted would have fallen out or would have been removed by precipitation scavenging.

The averaged Northern Hemispheric source strength of desert dust, fine enough to have a residence of one week, has been estimated by Junge (1979) to be 5×10^6 g s^{-1}. Since the Gobi is 10% of the Northern Hemisphere's desert area, the expected long-term mean desert fine-particle source strength would be $\sim 5 \times 10^5$ g s^{-1}. This can be compared with the fine-particle source strength inferred from the Hawaiian cloud of 15×10^5 g s^{-1} (it was assumed the dust storms lasted for about one day). This would imply, if long-term averages were taken, that dust storm episodes occur over the Asian eastern deserts about a third of the time. A review of the synoptic Pacific-Orient surface weather maps indicates, though very roughly, that heavy sandstorms do indeed occur at about this frequency. It leads one to believe that Junge's estimated sandstorm flux is of the correct order of magnitude.

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