April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 279

Aerosol Optical Characteristics in the Yellow Sand Events

Observed in May, 1982 at Nagasaki-Part II Models

By Teruyuki Nakajima, Masayuki Tanaka, Maki Yamanol

and

Masataka Shiobara2

Upper Atmosphere Research Laboratory, Tohoku University, Sendai 980, Japan

Kimio Arao

Faculty of Education, Nagasaki University, Nagasaki 852, Japan

and

Yuji Nakanishi3

EKO Instruments Co., 1-21-8, Hatagaya, Shibuya-ku, Tokyo 151, Japan (Manuscript received 2 November 1988, in revised form 14 February 1989)

Abstract

Phase functions of yellow sand particles were measured by a polar nephelometer during 24 April-11 May, 1982 at Nagasaki, Japan. They suggested a strong nonsphericity of the particles, which can be reconstructed by the semi-empirical theory of Pollack and Cuzzi or by Mie particles with large fictitious absorption. Spectral extinction cross section, single scattering albedo, asymmetry factor and backscattering phase function were estimated using the volume spectra retrieved from data of several instruments including the polar nephelometer data. Volume loading of yellow sand particles
at the observation site was estimated as 666l/km2 at the maximum stage of the yellow sand event of
4-6 May and 183l/km2 for the secondary maximum of 8 May. Using two estimates of the absorption
index (0.01 and a model variable with wavelengths), these values show that solar radiative heating
from 0.08 to 0.4*/day can be expected in the atmosphere over considerably wide area in one yellow
sand event.

1. Introduction

Studies of the radiative effect of aerosols have

rested on the Mie scattering theory assuming ho-
mogeneous spherical dielectrics (Mie particles). As
for a strong perturbation of the radiation regime by dust storms, however, such an assumption seems to be too simplified, because dust particles have ir-regular shapes (Tanaka et al., 1987; Okada et al., 1987) and are large enough to affect the light scat-

1 Present address: 2 -9-10, Nagao, Tama-ku, Kawasaki 214,
Japan.
2 Present affiliation: Meteorological Research Institute
,

Tsukuba 305, Japan.

3 Present affiliation: Stabilizer Co. Ltd., 2-22-23,
Nishioizumi, Nerima-ku, Tokyo 177, Japan.
* 1989, Meteorological Society of Japan

tering property. Welch et al. (1981) showed that
it is possible to overestimate the particle concen-tration by several tens of percent if we neglect the nonsphericity in the analysis of flux measurements. Otterman et al. (1982) suggested that their satel-lite remote sensing method overestimates the single scattering albedo if the nonsphericity of dust par-ticles is neglected. In spite of such observations, we prefer to use the Mie scattering theory because of its simplicity and uncertainty in how to describe the nonsphericity. Although there are many theo-ries for calculating the light scattering properties of nonspherical particles (e.g., Asano and Sato, 1980; Mugnai and Wiscombe, 1986), we must assign the exact shape of particles before applying those the-ories. Since we see almost infinite kinds of particle

280 Journal of the Meteorological Society of Japan Vol. 67, No. 2

shape in a microscope image, it is not an easy task
to determine reasonable statistics for the particle
shape. Therefore, it will be very useful to accu-
mulate measurement data of phase functions in real
conditions of dust storms. There has been little work

in this direction. Especially there are no investiga-tions of the phase function of yellow sand particles in the North-Eastern Asia to our knowledge . The scattering property of each nonspherical par-ticle depends on its shape as shown by a number of measurements of light scattering by nonspheri-cal particles in laboratory conditions (e.g., Holland and Gagne, 1970; Pinnick et al., 1976; Chylek et al., 1977; Zerull, 1976; Schuerman et al., 1981; Co-letti, 1984). For example, the asymmetry factor can increase or decrease as compared with the equal-volume sphere, depending on the particle shape and size (Mugnai and Wiscombe, 1986). In spite of the variety of the scattering patterns for a variety of the particle shapes, there may be some possibility of de-scribing its general features using a semi-empirical fitting as in Pollack and Cuzzi (1980). Basically the phase functions of nonspherical particles are less de-pendent on the scattering angle than that of Mie particles (Coletti, 1984). The degree of linear po-larization also tends to become smaller than that of

Mie particles.
In this paper we study in sun measurements of the phase function of yellow sand particles using a po-lar nephelometer for the yellow sand events of 1982 (Tanaka et al., 1989). We describe some general fea-tures common in observed phase functions and try to fit the function using the semi-empirical theory of Pollack and Cuzzi (1980) or introducing a ficti-tious absorption into Mie particles. As the result of such study and the volume spectra retrieved from several instruments, we will calculate the spectra of the extinction cross section, moments of the phase function and the backscattering phase function.

2. Measurements

As described in Part I of our papers (Tanaka et al., 1989) we carried out measurements of solar ra-diation and aerosols during the period from 22 April to 12 May, 1982. We had two yellow sand events at Nagasaki, Japan during the period. We have divided the observation period into the maximum stage of the yellow sand event of 4-6 May, the secondary yellow sand event of 8 May, and the normal condi-tion preceding and following the events. The strong enhancement of the forward light scattering was ob-served in the yellow sand events showing dominance of large sand particles of several microns. In the same period, we carried out measurements of the phase function using a polar nephelometer.
The polar nephelometer was newly designed for the purpose of field work as shown in Fig. 1. Lin-early polarized light from a He-Ne laser (NEC/GLG-

Fig. 1. Optical design of the polar nephelometer.

5700, the output light power of 25 mW at the wave-length *=0.6328*m) is guided into a chamber through two mirrors (M1 and M2), Glan-Thompson prism (P1) and a polarizer (P2) which is a sliding
* /2 retardation plate to rotate polarization axis of incident light by 90* . Scattered light is collected by an object lens (P5) of 110 mm in effective diameter through a rectangular prism (P3) and an analyzer (P4) on a horizontal turntable, and photon-counted by a photo-multiplier (P.M.: Hamamatsu Photon-ics, R649). The analyzer consists of two sliding lin-ear polarizers parallel and perpendicular to the scat-tering plane. The field of view of the detector is limited by a shadowing screen (SS) as the rectan-gular prism rotates. By this optical alignment, we can measure scattered radiation at scattering angles from 7 to 170* within the scattering chamber of 1 m length. Changing the polarization state of the inci-dent and scattered radiations by the polarizer and the analyzer, we can get the elements P1, P2, Dl and D2 of the phase matrix of air mass using following equation:

where (I0r, I0l) and (Ir, Il) denote respectively in-cident and scattered radiations polarized perpen-dicularly and parallell to the scattering plane; s and R are the scattering cross section and dis-tance between the scatterer and the detector. We

observed the phase matrix at scattering angles of
* =7,10,15, 20(10)160,165, and 170*. Calibra-tion of the light intensity was done using pure N2 gas (Takamura and Tanaka, 1978). Measured phase functions were analyzed after subtracting the air molecule scattering, to retrieve the size distribution and refractive index of aerosols by the inversion-library method of Tanaka et al. (1982). The po-

April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 281

lar nephelometer was set at the top of a building of
Nagasaki University as well as other instruments de-

scribed in Tanaka et al. (1989). For the nephelome-
ter, the air was sampled with a rate of 70l/min
through an elephant tube of 50 mm diameter and 5
m long.

3. Light scattering property of the yellow sand particles

Figure2 shows typical examples of the observed unnormalized phase functions, i,e., sP1 by circles and sP2 by triangles, for aerosols near the ground surface in the normal condition (left panel) and the yellow sand event (right panel), respectively. We also show the linear polarization ratio and depolar-ization ratios defined as follows:

By lines in Fig. 2 we show unnormalized phase functions reconstructed by the method of Tanaka et al. (1982) assuming Mie scattering. In Fig. 2 we also listed the retrieved values of the refractive in-

dex (m), scattering cross section (s in cm-1), single scattering albedo (*), backscattering phase function (Pb) which is the value of the normalized phase func-tions at *=180*, and relative root mean square deviation (rmsd) between theoretical and measured values (*).
In the normal condition, the shape of the phase function and the associated refractive index were

very similar to those of other measurements (Tanaka et al., 1983). In the yellow sand events, however, we find a significant enhancement of the forward scat-tering caused by large particles, which was also ob-served in the solar aureole measurements (Tanaka et al., 1989). In spite of this large forward peak, we can find no enhanced backward scattering, which is expected for large spherical particles with small ab-sorption index as seen later in Fig.7. The backscat-tering phase function (Pb) took a value of 0.0211 for yellow sand particles as small as 0.0218 for the nor-mal condition. The inversion-library method chose 1.70-0.08i as the optimum value of the refractive index in the case of the yellow sand events. This value of the refractive index is very large for both of its real and imaginary parts as compared with a realistic value around 1.55-0.005i for Saharan dust

particles. It is considered that this unsuccessful esti-mation was caused by nonsphericity of the particles rather than by difference of the chemical composi-tion of yellow sand particles from that of Saharan dust particles. Values of the depolarization ratio (DV and DH) reached 50 % as shown in Fig. 2 sup-porting this expectation. Depression of backscatter-ing and large depolarization of light scattering by nonspherical particles have been reported by many

Fig. 2. Phase functions (* and *), the degree of the linear polarization ratio (DP) and the depolarization ratios (DH, DV) on 25 April and 5 May, 1982. Lines show the reconstructed values using Mie theory with parameters: m=1.55-0.03i, s=9.57*
10-7cm-1, w=0.828, Pb=0.0218 and
* =0.056 for 25 April; m=1.70-0.08i,
* = 2.08*10-6cm-1, w=0.602, Pb=
0.0211and *=0.087 for 5 May.

investigators from measurements and theories. In spite of the evidence of nonsphericity notable in the observed phase functions, the reconstructed phase functions of Mie particles with large fictitious ab-sorption follow remarkably well observed phase func-tions including the linear polarization ratio (DP) as shown by lines in Fig.2. The relative rmsd (*) be-tween the observed and reconstructed phase func-tions was as small as 8.7% in this example. Such similarity between nonsphericity and absorption in the phase function was also pointed out by Grams et al. (1974) and Pinnick et al. (1976).
Figure 3 shows the time series of the moments g1, g2 and g4 of the Legendre expansion of the phase function:

where x=cos*. The ratio of the total depolarized cross section DS to the total scattering cross section s is given by

282 Journal of the Meteorological Society of Japan Vol. 67, No. 2

Fig. 3. Time series of moments of the phase
function (g1, g2, g4) and the total depolar-
ization ratio (Ds/s).

In the normal condition, this ratio took values as
small as 1%, so that Mie particles will be a good
approximation for aerosols in the normal condition. In the yellow sand events, on the other hand, g4 in-creased about 3 times that of the normal condition

and the depolarized cross section reached about 10 % of the total scattering cross section showing non-sphericity of particles. Although the depolarization ratios (DV and DH) differed from each other and depended on scattering angles, the elements D1 and D2 took similar values almost independent of scatte ring angles through the observation period. This means that orientations of aerosols were distributed

randomly through the period regardless of condi-tions.

Mean values of gl and g2 were respectively 0.631
* 0.320 and 0.407*0.218 for the normal condition, 0.713* 0.157 and 0.563*0.128 for the period of 4
- 6 May, and 0.651*0.026 and 0.474*0.027 for 8 May. Small rmsd values of these parameters in the yellow sand events show that the size distribution of yellow sand particles was relatively stable during one or two days as noted from the constancy of * shown in Fig. 7 of Part I. According to Nakajima et al. (1986),values of g1 and g2 in Sendai, Japan were relatively constant in autumn and were 0.615 and 0.391, respectively, indicating the air mass of Nagasaki in the normal condition was characterized by somewhat larger aerosols.

4. Modelling the aerosol optical scattering

Since yellow sand particles showed a strong non-sphericity as studied in the previous section, we must be careful to model the optical characteris-tics of the particles. In this section, we discuss the volume spectrum consistent with the interpretation of several instrumental results including the phase function data and try to obtain spectra of the op-tical characteristics by integrating the volume spec-trum assuming a scattering theory of nonspherical particles.

(a) Model volume spectra
To see the variability of the retrieved volume spec-tra from various instruments, we show the averaged volume spectra in the normal (Fig. 4), the maximum stage of the yellow sand event condition during 4 - 6 May (Fig. 5), and the secondary stage of 8 May (Fig. 6). Since the OPC signal was calibrated us-ing polystyrene particles having the refractive index of 1.60-0i, correction of the refractive index from 1.60-0i to 1.50-0.01i has applied to the data in the normal condition. For transformation of the vertical coordinate of the columnar data (denoted as A+O), the scale height of the aerosol layer was assumed to be 5km, 2.6km and km for these pe-riods, respectively. Since yellow sand particles are sometimes multi-layered as reported by Shaw (1980) and Iwasaka et al. (1982), the scale height necessar-ily does not correspond to the mean height of the layers.
For the normal condition, the volume spectra from various methods agreed well with each other for r*0.8*m. For smaller particles, however, the columnar volume spectrum (A+O) did not show a peak around 0.2*m corresponding to the accumula-tion mode for the surface data. We should note that

the averaged columnar volume spectrum tended to become flat as a result of averaging multi-modal spectra having different peaks as shown in Figs. 9 and 10 of Part I. Peaks at different mode radii will

be associated with aerosols of different origin. For the yellow sand events (Figs. 5 and 6), the volume spectra from various methods agreed well in their general features. Inverted volume spec-tra from the nephelometer data with an abnormally large absorption (1.70-0.08i) also follow other pro-files. For a more realistic refractive index such as m=1.55-0.005i, we had an unrealistic volume spectrum different significantly from other profiles. Such unsuccessful retrievals due to nonsphericity (which would have an effect similar to assuming the wrong refractive index) were also pointed out by others (Shifrmn and Gashko, 1974; Gorchakov et al., 1976; Heintzenberg and Welch, 1982). Similarity between the nephelometer result and other profiles, therefore, show some similarity between effects of nonsphericity and absorption. As already shown in

April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 283

Fig. 4. Averaged volume spectra in the nor-
mal condition obtained by the neph-
elometer (NEPH), optical particle counter
(OPC) and aureolemeter (A+O). The line shows the model NM.

Fig. 6. Same as Fig. 4 but for 8 May. The
solid line shows the model YB.

those of the maximum stage obtained by other in-struments. The Andersen sampler data in Fig.5 is an integral of the volume spectrum during the sam-pling period of 4-6 May, so that large particles be-come less dominant by time averaging. If we fit this volume spectrum by a log-normal function, we have a dispersion smaller than that of other pro-files in Fig.5. It is very difficult, however, to come to a sound conclusion because we could not have a good estimate for volume of submicron particles without sufficient sampling time. Another disagree-ment among the instruments in Figs. 5-6 is that at the maximum stage the amount of submicron par-ticles from the nephelometer agreed well with the columnar spectrum, while the OPC result showed a smaller amount of submicron particles. We will discuss this disagreement later.
To model the observed volume spectra during the observation period, we fit the data to the following log-normal plus power law function:

Fig. 5. Same as Fig. 4 but for 4-6 May. The
result of Andersen sampler is shown by
IMPC. The solid and dashed lines show
the models YA and YC, respectively.

Part I, Figs. 4 - 6 show that the volume concentra-tion of submicron particles in the yellow sand events was smaller than that in the normal condition.
In the detail of Figs. 5 and 6 we can see several discrepancies depending on instruments. The An-dersen sampler result has a dispersion smaller than that of other profiles. The Andersen sampler mea-sured less aerosol volume at a radius 4.5 pm than

with p'=p for r>rm and p'=0 for r*rm . Lines in Figs. 4-6 are the fitted volume spectra with pa-rameters shown in Table 1. We set as p=4 and r0
=0.1*m for all models, since this is not so sensitive
to the results. For the yellow sand events we have three models, i,e., models YA and YB for 4-6 May and 8 May to interpret the data of the aureoleme-ter, nephelometer and OPC, and the model YC for the data of Andersen sampler during 4-6 May. The model YC has a smaller dispersion than other two. For comparison, Table 2 lists values of rm and S ob-tained by fitting data from several studies of dust

284 Journal of the Meteorological Society of Japan Vol. 67, No. 2

Table 1. Parameters in Eq. (6) for model volume spectra (cm3/cm3) and the specific volume (cm3/cm3)
in Eq. (13). A notation like 7.5-12 in the columns of CL and CJ means 7.5*10-12.

Table 2. Mode radius (rm) and dispersion (6) of sand particle volume spectra.

storms. These values show that wide variation in

the volume spectrum is possible, depending on the
history of aerosols, with some positive correlation
between rm and *. As an average of the listed val-
ues, (rm, *) are (1.5, 1.5) for moderate dust storms and (3.5, 2.5) for heavy dust storms or at sites near the source.

Figure 7 shows the mean observed and the best fit total phase function, s(P1+P2)/2, at *=0.6328*m for the periods of 4-6 May and 8 May. In the fig-ure we have determined the coefficients CL and CJ

by two linear regressions: one is assuming Mie par-ticles with m=1.70-0.08i (dashed line) and the other is assuming nonspherical particles expressed by the semi-empirical theory of Pollack and Cuzzi (solid line). For the latter, the semi-empirical phase function is described by parameters of x0, G and r defined in the original paper. After many regres-sions for various sets of r, x0 and G, we were able to determine the optimum values of (x0, G) as (7, 10) for the period 4-6 May and (7, 7) for 8 May. Fol-lowing the original paper we assume r=1.1, since the fitting depends weakly on the value of r, which is the ratio of the surface area of the particle to that of the sphere of the equivalent volume. Morphological analysis of scanning electron microscope images of yellow sand particles showed that the distribution of the ratio of the minor radius to the major one had a mode around 0.6, which is equivalent to r=1.03. Okada et al. (1987) also got a similar value. Larger values of x0 and G compared with the cases studied by Pollack and Cuzzi show that the nonsphericity of

Fig. 7. Observed total phase functions of yellow sand particles for 4-6 and 8 May (O); Mie phase functions (m=1.55-0.005i*; 1.70-0.08i----); the semi-empirical phase functions of non-spherical particles (-). The values for
8 May are shifted upward by one loga-rithmic scale.

April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 285

Table 3. Extinction cross section (e), single scattering albedo (*), moments of the phase function (g1, g2)
and backscattering phase function (Pb) in the normal condition (Table 3a) and the yellow sand event
(Table 3b). Letters NM, YA, YB and YC in the model name show the volume spectrum; L and J
indicate the modes of the volume spectrum; and A, T and V show the models of the refractive index
(m). Units are cm-1 for e; 1/1000 for *, g1 and g2; 1/10000 for Pb.

yellow sand particles is more moderate and the size
is larger than that of the cases in Pollack and Cuzzi.
We can see that the value of x0 of around 7 is rea-

sonable as compared with the deviation of the asym-
metry factor and backscattered fraction of Cheby-
shev particles from equal-volume spheres (Mugnai and Wiscombe, 1986).
The coefficients (CL, CJ) are determined as (9.9* 10-11, 0) for 4 - 6 May and (3.3*10-11, 4.0*10-12) for 8 May, while for the absorbing Mie particle model they are determined as (1.1*10-10, 6.7*10-12) and (2.7*10-11, 7.4*10-12). It is found that the values of CL are similar for both methods, while the values of CJ for absorbing Mie particles are much larger than those for nonspherical particles. This fact means that the effect of nonsphericity of yellow sand particles can be replaced by absorbing large Mie particles with an additional scattering by submicron particles (with increasing CJ). However, this analogy is not valid for the single scattering albedo since the absorbing Mie polydispersion has an extinction cross section larger than that of the nonspherical polydispersion for the same scattering cross section. This comparison between absorbing Mie particles and nonspherical particles is very use-ful in understanding the disagreement between the nephelometer and OPC results for submicron parti-cles. If we reduce the volume of submicron particles

of the nephelometer result as suggested by the pre-ceding discussion, the result becomes rather similar to that of the OPC. This is consistent with an ex-

pectation that estimation of the volume spectrum by the OPC was good for particles smaller than 1 pm because the OPC signal is relatively insensitive to the nonsphericity and the assumed refractive in-dex for submicron particles as explained just below. The OPC, RION KC-01, uses the mean scattering angle of *=70* for light detection.
If we assume Mie particles with m=1.55-0.005i and the volume spectrum obtained by the nonspheri-cal particles, then phase functions are given by dash-dotted lines in Fig. 7. Although these phase func-tions have a notable backscattering glory different from the observed one, the forward part at *70* is similar to other two phase functions. Therefore, it is found that the effect of the nonsphericity of the yellow sand particles is small in the forward part of the phase function, so that the volume spectra estimated from the OPC and the solar aureole data

represent a good estimate for the yellow sand events.

(b) Model optical parameters
Several optical parameters of aerosols important in determining the solar radiative regime of the at-mosphere are calculated as in Table 3 by using the model volume spectra derived in the preceding sub-

286 Journal of the Meteorological Society of Japan Vol. 67, No. 2

section. The table shows values for each mode

(denoted by a letter L or J) of the volume spec-
trum models NM, VA, YB, and YC in Table 1.
Since the listed values of extinction cross section (e)
are for CL=1 and CJ=1, desired values of the
extinction and scattering cross sections (e and s), single scattering albedo (*), moments of the phase function (g1 and g2), and the backscattering phase function (Pb) for arbitrary values of CL and CJ in
Eq. (6) are obtained by following mixing rules:

and

where q=g1, g2, or Pb. For the normal condition (Table 3a) we use the Mie theory with refractive in-dices of 1.55-0.005i (a transparent model labelled T in the model name) and 1.53-0.024i (an absorb-ing model labelled A) which is the average value obtained by the nephelometer. For the yellow sand event (Table 3b) we use the semi-empirical theory of Pollack and Cuzzi (1980) with parameters shown

April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 287

Fig. 8. Spectra of the extinction cross section
(cm-1) for models NMA(*) YAV,
YBV and YCV (- - - -); YAA, YBA and
YCA (-).

in Table 1 with two model spectra of the refractive
index, i,e., an absorbing model (labelled A) with m=1.55-0.01i independent of the wavelength; and a variable model (labelled V) with m of a func-tion of wavelength which is determined after Carlson and Benjamin (1980). Since the results for G= and G=10 are nearly same for the mode J, we only show the models of YAJA (that means the power law mode of the volume spectrum YA with the ab-sorbing model of the refractive index) and YAJV (same as YAJA but with the variable refractive in-dex model) for yellow sand particles.
Using the parameters in Tables 1 and 3, we cal-culated the spectra of the extinction cross section (Fig. 8), single scattering albedo and phase func-tion moments g1 and g2 (Fig. 9), and the backscat-tering phase function Pb (Fig. 10). Figure 8 shows that the extinction cross section is relatively inde-pendent of the refractive index. In the yellow sand events, an enhancement of the extinction in the near infrared region (NIR) is significant, while the extinc-tion for the visible light is comparable with that of the normal condition. In the visible region, the three models of yellow sand particles show a similar wave-length dependence, while the behavior of the model YC in the NIR is different from other two models.

The single scattering albedo of yellow sand parti-cles ranges from 0.82 to 0.93 at *=0.5*m depend-ing on the assumed refractive index. Choice of the volume spectrum is relatively unimportant. Since there is large uncertainty in the reported values of

Fig. 9. Same as Fig. 8 but for the single scat-
tering albedo (*) and moments of the
phase function (g1 and g2).

the refractive index of soil derived particles (Carl-son and Benjamin, 1980), evaluation of the spectral refractive index of yellow sand particles is desired as a future problem. The asymmetry factor (g1) is relatively insensitive to the refractive index and volume spectrum. It is a weakly decreasing func-tion of the wavelength for yellow sand particles and ranges 0.66-0.72 at *=0.5 µm which is slightly larger than that of the normal condition. Existence of the submicron accumulation mode in the normal

condition increases significantly the moments in the visible wavelengths.
The magnitude of the backscattering phase func-tion (Pb) depends strongly on the volume spectrum, refractive index, and wavelength with peaks around
* =1.5-2*m. Especially the model YC has a large backscattering around the peak. This is because of a selective enhancement of the backscattering cross section by the sharp peak of the volume spectrum. The large variety of Pb is serious obstacle to deter-mining the backscattering ratio,

which is necessary for the retrieval of the extinction cross section from the lidar signal. It ranges from 49 to 87 at *=0.5*m and from 32 to 61 at *=

288 Journal of the Meteorological Society of Japan Vol. 67, No. 2

Fig. 10. Same as Fig. 8 but for the backscat-
tering phase function.

Fig. 11. Relationship between * and *0.5 for
various air masses in the observation pe-
riod. Solid lines show the relationship
given in Table 4. The dashed line shows the relationship in Fig. 7 of Kaufman and Fraser (1983).

1*m. Being left with this large uncertainty, it is very interesting to measure the backward portion of the phase function at wavelengths from 1.5 to 2*m. Also it is important to compile data of the volume spectrum, especially to know the typical dispersion of the volume spectrum for the yellow sand events.

5. Discussion

Using the results in the preceding sections, we can investigate furthermore the atmospheric turbid-ity condition during the observation period. Figure 11 shows the same plot as in Fig. 7 of Part I with model values of * and *0.5 calculated by the mixing rules listed in Table 4 for two homogeneous polydis-persions having the extinction cross sections (e1 and e2) and scale heights (Hl and H2):

In Table 4, we distinguish the volume spectra (NM and YA) and its mode (log-normal mode as L and power law mode as J) attaching to quantities in Eq. (12).
In the normal condition, an increase of the mode L (line 2) causes an increase of *, while an increase of the mode J (line 3) causes a decrease of *. For the stage preceding the yellow sand events, the line 3 fits the trend of the observed data showing that the lognormal mode L was unchanged in the course of modification of the mode J. In this case the log-

normal mode L would correspond to aerosols origi-nating from surrounding urban type aerosol sources, while the power law mode J would correspond to the background aerosols. By a dashed line we show a re-lation for growing summer time aerosols absorbing water vapor with increasing humidity by Kaufman

and Fraser (1983). The similarity of their line to the line 3 shows that the general trend between a and *0.5 in the normal condition is caused by the humidity effect as already expected in Part I.
In the yellow sand event, an increase of the mode L causes a decreasing tendency of *. In the max-imum stage of the yellow sand event, the observed data were more similar to the line 4, showing that the background mode J also changed correlating with the concentration of the sand particles. Lines 6 and 7 show a mixing process of two airmass of the normal condition and the yellow sand events with a mixing ratio k. The mixing lines follow well the ob-served data with slight overestimation of the optical thickness of 11 May. Some abrupt cleaning rather than the homogeneous mixing is expected in the de-cay stage of the yellow sand event.
From Eqs. (6), (7), and (12), we have the conver-sion factor from the optical thickness to the colum-nar total volume of aerosols as

with

April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 289

Table 4. Mixing rules for two homogeneous air masses as characterized by the extinction cross section (e)
and the scale height (H). The volume spectrum models and their modes are shown by labels attached
to these quantities.

and the specific volumes VL and VJ for the modes
L and J listed in Table 1 which are the aerosol vol-

umes for CL=1 and CJ=1, respectively. Equation
(13) and Table 1 lead to Vc/*=284, 634, 405, and
849l/km2 for the models NM, YA, YB, and YC, respectively, at *=0.5*m for HL=*HJ . In this estimation, it is important to note that considerable extinction is caused by the mode J and the neglect of this mode of the volume spectrum leads to over-estimation of yellow sand particles. In other words it is important to measure the concentration of sub-micron aerosols associated with the continental air

mass along with that of large particles.
Values of the conversion factor show that yellow sand particles are large and not effective for scat-tering the solar radiation compared with the contri-bution of aerosols in the normal condition. Using the above conversion factor, we can evaluate the to-tal columnar volume as 666l/km2 when the optical thickness of aerosols reaches 1.05 at the maximum stage, and as 183l/km2 when the optical thickness reaches 0.45 on 8 May . From these values it is found that the event of 4-6 May was more significant than the cases investigated by Arao and Ishizaka (1986) and Tomasi et al. (1979) where they reported val-ues around 100 to 400l/km2, while these values are smaller than the value of 1000l/km2 for the aver-

age of Saharan dust of July 1974 at Sal (Carison and Caverly, 1977). Since the corresponding aver-age optical thickness at Sal was 0.74 at *=0.5*m, the conversion factor for the Saharan dust was even

larger than those of the present study due to the large size of the Saharan dust particles at Sal. Since the single scattering albedo ranges from 0.85 to 0.97 at wavelengths around 1 m, energy conver-gence into the atmosphere due to aerosols in the yellow sand events was about (1-*)*S=3 to 15 cal/day/cm2, where S cal/day/cm2 is a daily total of the effective solar insolation. This corresponds to a heating rate of about 0.04 to 0.2*/day depend-ing on the value of the single scattering albedo if

the scale height of the aerosol layer is 3 km with the optical thickness of 0.1. These values are con-sistent with the detailed calculations of Carlson and

Benjamin (1980). According to Arao and Ishizaka (1986), yellow sand particles of about 100l/km2 cov-ered over Japan during about one day. The mean of the reported mass loading of Saharan dust at Italy is also about 100l/km2. These facts suggest that a heating rate about 0.08 to 0.4*/day is expected over a considerably wide area in one yellow sand event. Since the aerosol loading reaches about ten times 100l/km2 at the maximum stage of the severe event, solar heating of several degrees is expected. Kondratyev et al. (1981) observed a heating rate as large as 9.6*/day for a Saharan dust storm.

6. Conclusion

We measured the phase matrix for yellow sand particles in yellow sand events during 4-8 May at Nagasaki, Japan. Measured total phase functions can be fitted by the semi-empirical theory of Pollack and Cuzzi (1980) or by Mie particles with large fic-titious absorption, showing some similarity between the light scattering by nonspherical particles and absorbing spheres. Large size and nonsphericity of yellow sand particles cause a distinct enhancement of forward scattering, suppression o backscattering, small linear polarization, and large depolarization as compared with the light scattering by aerosols in the normal condition. The asymmetry factor increased in the events as compared that in the normal condi-tion.

We set model volume spectra for the normal con-dition and for the yellow sand events as in Table
1. Using the optical parameters tabulated in Table 3, which are calculated by the Mie theory and the semi-empirical theory of Pollack and Cuzzi, we es-timated the spectra of the extinction cross section, single scattering, moments of total phase function, and the backscattering phase function as in Figs. 8 -
10. These figures show that uncertainty in the com-plex refractive index brings large uncertainty in the value of the single scattering albedo; the backscat-

290 Journal of the Meteorological Society of Japan Vol. 67, No. 2

tering phase function in the NIR region depends sig-
nificantly on the dispersion of the volume spectrum
of yellow sand particles.
Volume loading of the yellow sand particles at the
observation site was estimated to be 666l/km2 at

the maximum stage of the yellow sand event and 183l/km2 for the secondary maximum on 8 May. Solar radiative heating of the atmosphere from 0.08 to 0.4*C/day is expected over a considerably wide area in one yellow sand event. Since large uncer-tainties of the volume spectrum, refractive index and backscattering phase function exist, additional mea-surements of the phase function and refractive index should be carried out in the future.

Acknowledgements.

Drs. R.S. Fraser and Y.J. Kaufman of Goddard

Space Flight Center are gratefully acknowledged for valuable discussion.

References

Arao, K. and Y. Ishizaka, 1986: Volume and mass of

yellow sand dust in the air over Japan as estimated from atmospheric turbidity. J. Meteor. Soc. Japan, 64, 79-94.
Asano, S. and M. Sato, 1980: Light scattering by ran-domly oriented spheroidal particles. Appl. Opt., 19, 962-974.
Carlson, T.N. and S.G. Benjamin, 1980: Radiative heating rates for Saharan dust. J. Atmos. Sci., 37, 193-213.
Carlson and R.S. Caverly, 1977: Radiative characteris-tics of Saharan dust at solar wavelengths. J. Geo-phys. Res., 82, 3141-3152.
Coletti, A., 1984: Light scattering by nonspherical par-ticles: A laboratory study. Aerosol Sci. and Tech., 3, 39-52.
Chylek, P., G.W. Grams and R.G. Pinnick, 1977: Light scattering by nonspherical particles. Radiation in the atmosphere. Ed. H.-J. Bolle, Science Press, Princeton, 82-84.
Gorchakov, G.I., I.A. Gorchakova, Ye.A. Lykosov, V.G. Tolstobrov and L.S. Turovtseva, 1976: Deter-mination of the refractive index and microstructure

of foggy haze. Izv., Atmos. Ocean. Phys., 12, 371-375.
Grams, G.W., I.H. Blifford, Jr., D.A. Gillette and P.B. Russell, 1974: Complex index of refraction of airborne soil particles. J. Appl. Meteor., 13, 459-471.

Heintzenberg, J. and R.M. Welch, 1982: Retrieval of aerosol size distribution from angular scattering function: effects of particle composition and shape. Appl. Opt., 21, 822-830.
Holland, A.C. and G. Gagne, 1970: The scattering of polarized light by polydisperse systems of irregular particles. Appl. Opt., 9, 1113-1121.
Iwasaka, Y., H. Minoura, K. Nagoya and A. Ono, 1982: The transportation and spatial scale of dust storm, KOSA. - A case study on the dust storm of April

1979 measured by lidar. Tenki, 29, 231-235 (in Japanese).
Kaufman, Y.J. and R.S. Fraser, 1983: Light extinction by aerosols during summer air pollution. J. Clim. Appl. Meteor., 22, 1694-1706.
Kondratyev, K.Ya, R.M. Welch, S.K. Cox, V.S. Grishechkin, V.A. Ivanov, M.A. Prokofyev, V.F. Zhvalev and O.B. Vasilyev, 1981: Determina-tion of vertical profiles of aerosol size spectra from aircraft radiative flux measurements. 1. Retrieval

of spherical particle size distribution. J. Geophys. Res., 86, 9783-9793.
Mugnai, A. and W.J. Wiscombe, 1986: Scattering from nonspherical Chebyshev particles. I: cross sec-tions, single-scattering albedo, asymmetry factor, and backscattered fraction. Appl. Opt., 25, 1235-1244.

Nakajima, T., T. Takamura, M. Yamano, M. Shiobara, T. Yamauchi, R. Goto and K. Murai, 1986: Con-sistency of aerosol size distributions inferred from measurements of solar radiation and aerosols. J.

Meteor. Soc. Japan, 64, 765-776.
Okada, K., A. Kobayashi, Y. Iwasaka, H. Naruse, T. Tanaka and O. Nemoto, 1987: Features of in-dividual Asian dust-storm particles collected at Nagoya, Japan. J. Meteor. Soc. Japan, 65, 515-521.
Otterman, J., R.S. Fraser and O.P. Bahethi, 1982: Characterization of tropospheric desert aerosols at solar wavelengths by multispectral radiometry from Landsat. J. Geophys. Res., 87, 1270-1278.
Pinnick, R.G., D.E. Carroll and D.J. Hofmann, 1976: Polarized light scattered from monodisperse ran-domly oriented nonspherical aerosols: measure-ments. Appl. Opt., 15, 384-393.
Pollack, J.B. and J.N. Cuzzi, 1980: Scattering by non-spherical particles of size comparable to a wave-length: A new semi-empirical theory and its appli-cation to tropospheric aerosols. J. Atmos. Sci., 37, 868-881.

Schuerman, D.W., R.T. Wang, B.A.S. Gustafson and R.W. Schaefer, 1981: Systematic studies of light scattering. 1: Particle shape. Appl. Opt., 20, 4039-4050.
Shaw, G.E., 1980: Transport of Asian desert aerosol to the Hawaiian Islands. J. Appl. Meteor., 19, 1254-1259.
Shifrin, KS. and V.A. Gashko,1974: Determination of the microstructure of a scattering medium consist-ing of a mixture of particles with different indices of refraction. Izv., Atmos. Ocean. Phys., 10, 943-949.
Takamura, T. and M, Tanaka, 1978: Measurements of intensity and degree of polarization of light scat-tered by aerosols. Sci. Rep. of Tohoku Univ., ser. 5, 25, 169-196.
Tanaka, M., T. Nakajima and T. Takamura, 1982: Si-multaneous determination of complex refractive in-dex and size distribution of airborne and water-

suspended particles from light scattering measure-ments. J. Meteor. Soc. Japan, 60, 1259-1272. Tanaka, M., T. Nakajima, M. Shiobara, M. Yamano, T. Takamura and K. Arao, 1987: Optical proper-

April 1989 T. Nakajima, M. Tanaka, M. Yamano, M. Shiobara, K. Arao and Y. Nakanishi 291
 ties of the turbid atmosphere in the yellow sand
 event over Japan. Atmospheric Radiation, Progress
 and Prospects. Proceedings of the Beijing Interna-
 tional Radiation Symposium., Eds. K.-N. Liou and
 Z. Xiuji, 596-601, Science Press.
Tanaka, M., M. Shiobara, T. Nakajima, M. Yamano
 and K. Arao, 1989: Aerosol optical characteristics
 in the yellow sand events observed in May, 1982 at
 Nagasaki - Part I Observations. Submitted to J.
 Meteor. Soc. Japan., 67, 267-278.
Tanaka, M., T. Takamura and T. Nakajima, 1983: Re-
 fractive index and size distribution of aerosols as
 estimated from light scattering measurements. J.
 Clim. Appl. Meteor., 22, 1254-1261.
Tomasi, C., F. Prodi and F. Tampieri, 1979: Atmo-
 spheric turbidity variations caused by layers of Sa-
 hara dust particles. Contr. Atmos. Phys., 52,
 215-228.
Welch, R.M., S.K. Cox and K.Ya Kondratyev, 1981:
 Determination of vertical profiles of aerosol size
 spectra from aircraft radiative flux measurements,
 2. The effect of particle non-sphericity. J. Geophys.
 Res., 86, 9795-9800.
Zerull, R.H., 1976: Scattering measurements of dielec-
 tric and absorbing nonspherical particles. Contr.
 Atmos. Phys., 49, 168-188.
 長崎における1982年5月の黄砂の光学特性
 第2部　モデル
 中島映至・田中正之・山野牧1・塩原匡貴2
 (東北大学理学部超高層物理学研究施設)
 荒生公雄
 (長崎大学教育学部地学教室)
 中西裕治3
 (英弘精機株式会社)
 長崎において1982年4月24日から5月11日までポーラーネフロメータによる黄砂粒子の散乱位相関
数の測定を行った。Pollack and Cuzzi　の半経験的理論によるモデルや、Mie 散乱粒子に仮想的な吸収を導
入したモデルは、黄砂粒子の強い非球形性を示唆した。また、ポーラーネフロメータを含む数種の測器の
観測データから得られた黄砂粒子の体積スペクトルを用いて、波長別消散断面積、単一散乱アルベド、非
対称因子、後方散乱関数を求めた。
 観測地での黄砂粒子の体積濃度は、黄砂現象の最も強かった5月4～6日には666l/km2、続く5月8日
には183l/km2と推定された。複素屈折率の虚数部として0.01および波長依存するモデル値を用いると、
これらの値から計算される太陽放射加熱率は0.08～0.40*/dayに達し、1回の黄砂到来により広い範囲に
わたって大きな放射効果を及ぼすことが予想された。
1現在所属:川崎市多摩区長尾2-9-10
2現在所属:気象研究所、茨城県つくば市長峰1-13現在所属:スタビライザー株式会社、東京都練馬区西大泉2-22-23