

Satellite and ground-based study of optical properties of 1997 Indonesian forest fire aerosols

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Abstract. Optical properties of biomass burning aerosols in the event of Indonesian forest fires in 1997 were studied by ground-based sky radiometry and satellite remote sensing with AVHRR and TOMS radiometers. The AVHRR-derived optical thickness distribution agreed with the distribution of TOMS-derived UV-absorbing aerosol index and with the optical thickness measured by sky radiometry and sunphotometry. The single scattering albedo of aerosols was fairly constant as 0.9 in the September-October period. Relationship between Ångström turbidity factor and exponent supported the polydispersion consisted of aged small particles. This observation was consistent with the fact that the retrieved volume size distribution by sky radiometry has a distinct accumulation mode with a peak radius of 0.25 μm . Those optical properties of smoke aerosols seem to reflect the specific chemical structure of Indonesian forest fire aerosols, i. e., a mixture of carbonaceous and sulfate particles.

Introduction

Large scale Indonesian forest fires occurred in the autumn season of 1997, triggered by heavy plantation and dry atmospheric condition associated with the large El Niño event in this year. The magnitude of particle emission in the fire event is estimated as 0.5 to 6 M ton depending on studies [Nichol, 1997; Asiaty *et al.*, 1998; *this study*]. The magnitude of the fire activity is largest among the last four events in the Indonesian region, that were triggered by El Niño events in 1982/83, 1987, 1991 and 1997/98, reaching to 1 to 10 % of the total global emission of biomass burning aerosol particles. Such a large fire event can cause a significant local climate effect and a considerable global environmental effect. On the other hand, simultaneous chemical and radiative measurements of smoke aerosols are extremely lacked in this region for simulating the climate effect of the event, as compared with other two largest areas of biomass burning, i. e., South America and South Africa [e.g., Kaufman *et al.*, 1992; Holben *et al.*, 1996; Maenhaut *et al.*, 1996; Pereira *et al.*, 1996]. Motivated by the above mentioned situation, we have conducted an *INDONESIAN FOREST FIRE STUDY-1997 (INFOS-1997)* collaborating with researchers in Japan, Indonesia and Singapore

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and others. Here we report data analysis of AVHRR and TOMS satellite-borne radiometers [Higurashi and Nakajima, 1999; Nakajima and Higurashi, 1998] in the project. In order to support the satellite remote sensing, we also performed solar radiation measurements by a sky radiometer in Singapore and by a sunphotometer on a commercial vessel between Tokyo and Singapore. This paper studies the optical properties of smoke aerosols obtained from these measurements, which are effective for evaluating the radiative forcing of smoke aerosols.

Satellite remote sensing of fire smokes with AVHRR and TOMS

We have applied the two channel algorithm of Higurashi and Nakajima [1999] to six month global area coverage (GAC) data in red- and near infrared-channels of AVHRR for retrieving Ångström parameters, $\tau_{0.5}$ and α , of the Ångström's law for the spectral optical thicknesses $\tau_{\lambda} = \tau_{0.5}(\lambda/0.5)^{-\alpha}$ [Ångström, 1961]. The inverse of α can be regarded as an aerosol size index. The results over ocean area are shown in Fig. 1. Significant increase in the aerosol optical thickness at wavelength of 500nm, $\tau_{0.5}$, appeared from September to November with a peak enhancement in October. It is found that the region of optical thickness values larger than 0.5 cover a fairly large area, such as $S = 2000 \times 5000 \text{ km}^2$, reaching Indian and Australian coasts. At the same time, large values of the Ångström exponent were found around large optical thickness values, indicating forest fire smokes were rich in small submicron aerosols.

It is interesting to compare the AVHRR results with TOMS UV-absorbing aerosol retrieval results [Herman *et al.*, 1997]. For this purpose we have obtained one month mean values of TOMS aerosol index in the same region, as also shown in Fig. 1. Comparison of the two results indicates that the aerosol signatures in the two methods are very similar to each other in spatial distribution, especially around sources located in Sumatra and Kalimantan Islands. It is worthwhile, however, to find there are some differences in thin aerosol distribution around the Indian Ocean and Malay Peninsula. AVHRR-aerosols look like distributed over areas wider than TOMS-aerosols. Although it is possible to attribute such a difference to detailed technical differences in the two satellite algorithms, it may be possible to find a reason in difference of aerosol transportation range. Indonesian forest fire smokes are considered to have two chemically different constituents, i. e., biogenic carbonaceous aerosols formed from gases emitted from biomass burning, and sulfate aerosols

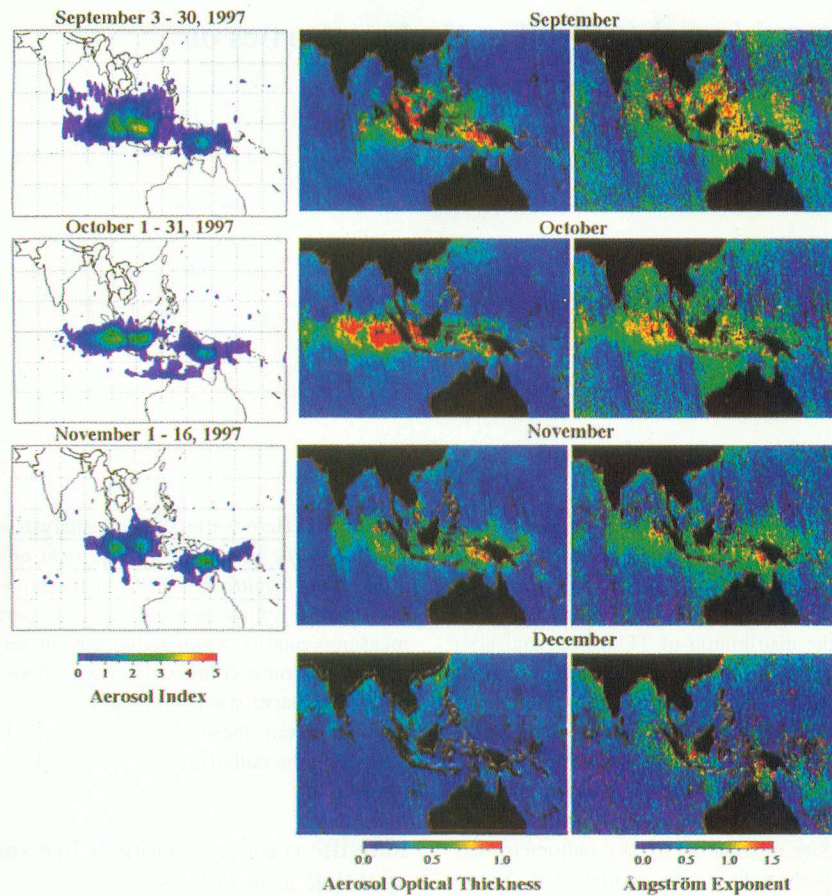


Figure 1. Distribution of TOMS-derived aerosol index, AVHRR-derived Ångström parameters, $\tau_{0.5}$ and α . Monthly mean values in September-December.

formed from sulfuric acid emitted from peat bog burning [Nichol, 1997; Asiati et al., 1998]. The range of transportation strongly depends on the reaction time of gas-to-particle conversion process and size distribution of secondary aerosols, as well as meteorological condition. It is highly possible, therefore, to have different spatial distributions from AVHRR and TOMS algorithms, since the latter is sensitive to carbonaceous aerosols which absorb UV radiation, whereas both carbonaceous and sulfate aerosols are detected by AVHRR. Another possibility is a contribution from local sulfate aerosol emission which can be detected only by AVHRR.

Ground-based solar radiation measurements

We have conducted two kinds of solar radiation measurements, i. e., sky radiometry measurements at the campus of National University of Singapore during 6 June through 12 December 1997, and sunphotometry measurements on a commercial vessel from Japan to Singapore during 13 to 22 October. Direct solar irradiances and diffuse sky radiances were analyzed by *SkyRad.pack* version-3 of The University of Tokyo, which are capable of (1) correction of diffuse radiation within the field of view of a radiometer and (2) retrieval of volume size distribution and complex refractive index by means of an iteration scheme with radiative transfer and inversion algorithms [Nakajima et al., 1996]. Optical thicknesses as large as 4 can be retrieved with this package. Figure 2 shows the results of the analysis as a function of day of the year. The aerosol optical thickness was

very high in October and November and rapidly decreased in early December. Although there was a distinct diurnal variation having a peak optical thickness around noon, satellite retrievals capture the general trend of the ground-based values as indicated by open circles in Fig. 2. Ground-based particle concentration data of von Hoyningen-Huene et al. [1999] show the local pollution effect was one third to one fourth of the surface total aerosol concentration in September - November period of 1997. Consistently Fig. 2 shows $\tau_{0.5}$ in December is less than 0.4, which is one fourth to one fifth of the average value in the October-November period. Therefore we can essentially regard data with $\tau_{0.5} > 1.5$ as those of smoke aerosols.

Figure 2 also shows values of the aerosol single scattering albedo ω , which were derived from sky radiometer data with an assumption of a fixed real part of refractive index as 1.5. It is found that the single scattering albedo was high in the smoke event period in September and October, but became small in late November to December, when the fire events reduced. In order to study more about the behavior of the aerosol optical parameters, scatter plots between $\tau_{0.5}$ vs α and vs ω are made in Fig. 3. The figure shows positive and negative correlations between $\tau_{0.5}$ vs α , as similarly shown by Nakajima and Higurashi [1998] to indicate accumulation process of secondary aerosols and growth process of particles absorbing water vapor. If we regard that data with $\tau_{0.5} > 1.5$ have a significant contribution of smoke aerosols, the figure shows that the Ångström exponent of smoke aerosols reached a peak value close to 1 and existed in the mode of negative correlation between $\tau_{0.5}$ and α . This indicates that those

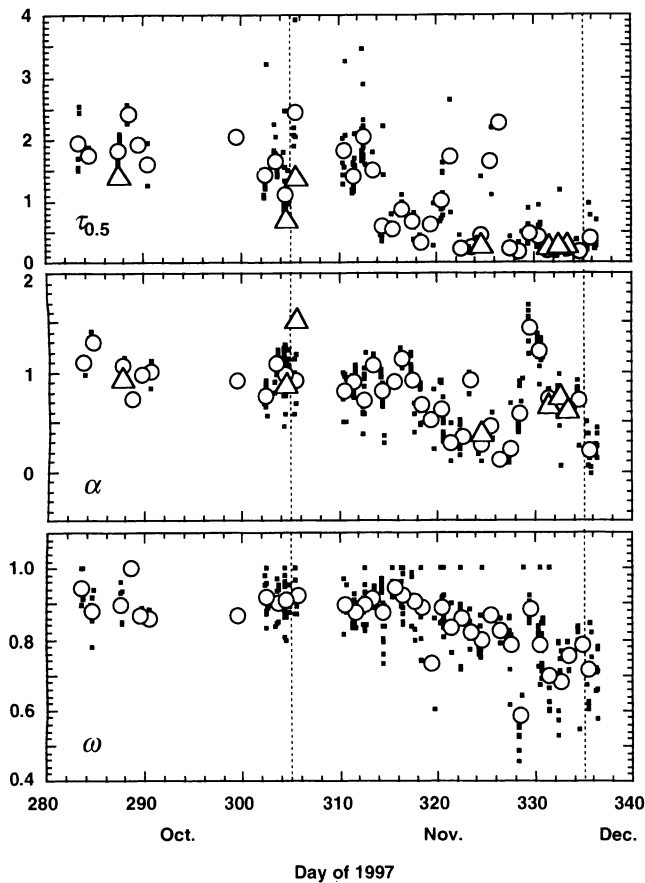


Figure 2. Time series of Ångström parameters, $\tau_{0.5}$ and α , and single scattering albedo of aerosols ω in Singapore. Dots for ground-based sky radiometry, open circles for their daily means, and open triangles for satellite-derived values.

aerosols were well-aged submicron particles absorbing water vapor. Although not shown in a figure, the volume size distribution of the fire event, retrieved from sky radiances, tended to have a submicron peak around $0.25 \mu\text{m}$, which is similar to that of ground-based measurements by *von Hoyningen-Huene et al.* [1999] in Singapore and to the mode radius of accumulation mode aerosols in other areas [*Patterson and Gillette, 1977; Shiobara et al., 1991*].

Figure 3 also shows that the single scattering albedo of smoke particles was almost constant as large as 0.9. This value is similar to the value found by *von Hoyningen-Huene et al.* [1999] in Malaysia for the same Indonesian smoke event. It is interesting to know that a value of 0.9 is also similar to or slightly larger than values found in Amazon and African forest fire smokes [*Kaufman et al., 1992; Kaufman and Nakajima, 1993; Eck et al., 1998*]. A difference in the single scattering albedo value is attributable to differences in species of burning biota and fire temperature in these regions. At the same time, sulfate emission due to peat bog fires was partly contributing to the high single scattering albedo in the Indonesian case. On the other hand, Fig. 3 shows that local pollution aerosols of Singapore may have a lower single scattering albedo as small as 0.8, if we disregard the data points with $\tau_{0.5} < 0.1$ for which the inversion of single scattering albedo tends to include large error. A symptom of ill inversion of w for thin aerosol layers can be seen by growing error bars as large as $\Delta\omega = 0.1$ toward smaller optical thicknesses. The error in our estimation of the single scattering albedo for fire smoke cases will be less than 0.05 because of their large optical thickness.

To have independent estimation of the optical thickness on

large scale, we compared in Fig. 4 $\tau_{0.5}$ values of shipborne sun-photometry with corresponding satellite-retrieved values as a function of latitude. The figure shows there is a good correlation between ship-measured and satellite-retrieved optical thicknesses with slightly smaller values with the satellite. The difference may be caused by difference in observation time, i. e. those of surface measurements and satellite overpass, and in the large sampling area with satellite retrievals (0.5 degrees). Standard deviation bars were added to the satellite data to see this effect. The assumption of only one refractive index, $m = 1.5 - 0.005i$, for satellite analysis will be another cause for the difference. Estimated error is a factor of 2 due to difference in the imaginary index from 0.005 to 0 (or 0.01) at $\tau_{0.5} = 1$ and α values from 0.6 to 0.9 that correspond to the smoke condition shown in Fig. 3. Considering this large expected error, the difference between surface and satellite values is rather small and suggests the assumption of $m = 1.5 - 0.005i$ is not so far from the reality. To investigate this point further, ω was calculated with the Mie theory and α from 0.6 to 0.9. Resulted ω values range from 0.90 to 0.92 indicating the assumption of $m = 1.5 - 0.005i$ is consistent with the single scattering albedo obtained by the surface measurements, i. e. 0.9.

Apart from this slight difference the latitudinal distributions are very close between the two measurements with the principal peak between $0-4^\circ\text{N}$. It is interesting to see that both measurements picked an enhancement of optical thickness off Hong Kong. This supports the large optical thickness and Ångström exponent along the coast of the Asian continent pointed out by *Nakajima and Higurashi* [1998].

Assuming the effective area of $\tau_{0.5} = 0.5$ is $S = 2000 \times 5000 \text{ km}^2$, residence time $T = 10$ days, and emission period $P = 3$ months,

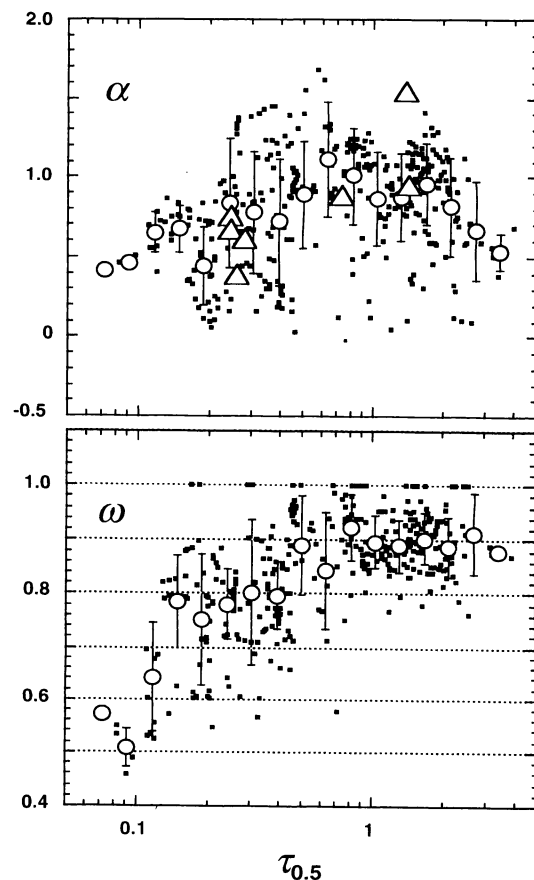


Figure 3. Scatter plots of turbidity factor $\tau_{0.5}$ vs. Ångström exponent α , and vs. single scattering albedo ω . Open circles with error bars for binned averaged values and open triangles for satellite-derived $\tau_{0.5}$.

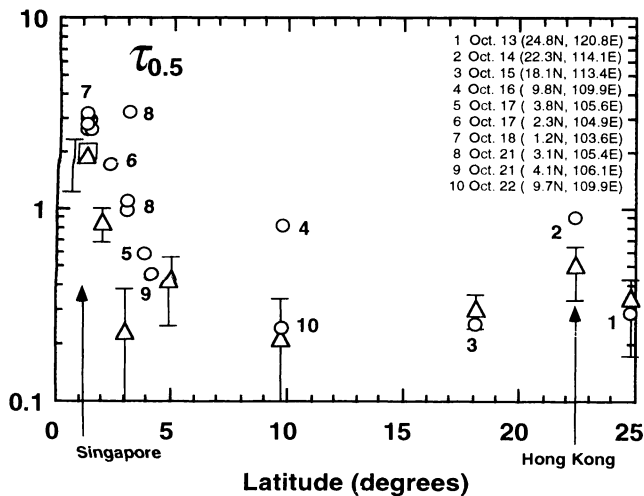


Figure 4. Latitudinal dependence of the aerosol optical thickness measured by sunphotometry (○), sky radiometry (only at Singapore, □) and AVHRR remote sensing (△) along a regular line course from Tokyo to Singapore. Dates and locations of sunphotometer measurements are also indicated. AVHRR remote sensing values are for monthly average of October 1997.

the mass loading of aerosols is roughly estimated as $M = 2\rho r \tau_{0.5} SP / (3Q_c T) = 5.6$ M ton, where we assumed the aerosol density $\rho = 1.5$ g/cm³, typical particle radius $r = 0.25$ μm and extinction efficiency factor $Q_c = 2$. This estimate is significantly larger than that of Asiati et al. [1998], but similar to that of 5.4 M ton by Edwards [private communication, 1997].

Conclusions

An analysis of ground-based solar radiation and satellite data has shown the Indonesian forest fire smokes in 1997 had a characteristic spatial distribution and optical properties depending on its specific generation mechanism, i. e., burning of biomass and peat bog surface layers. A resulting mixture of sulfate and carbonaceous aerosols seems to cause some difference in the spatial distributions of AVHRR-derived and TOMS-derived aerosols. This issue should be investigated in detail with validation effort in order to establish a technique of aerosol type detection from space.

The single scattering albedo of smoke aerosols was found to be close to 0.9, which is similar to or slightly higher than those of Amazon and African biomass burning aerosols. The mode radius of the accumulation mode of volume size distribution was retrieved as 0.25 μm. Such knowledge shows that the Indonesian forest fire smokes are very similar to that of urban type aerosols in their optical properties. The smoke aerosol production was estimated roughly as 5.6 M ton from the present satellite retrievals.

The environmental effects of Asian human activities are expected to increase in the next century. It is, therefore, necessary to make effort for studying biomass and fossil-fuel burning aerosols in this region more thoroughly, in order to increase our ability of modeling the climate effects of anthropogenic aerosols in this region.

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