Polarimetric Investigation of the Aerosols Over the Ocean for the Atmospheric Correction

Kazuhiko Masuda[1], Masayuki Sasaki[1],
Tsutomu Takashima[2], and Hiroshi Ishida[3]

1) Meteorological Research Institute
1-1, Nagamine, Tsukuba, Ibaraki 305
2) National Space Development Agency of Japan
1-9-9, Roppongi, Minato, Tokyo, 106
3) Maritime University of Kobe
5-1-1, Fukae-minami, Higashi-naga, Kobe, 658

ABSTRACT

Measurements of the sky radiation at a scattering angle of 90° were made by a multichannel polarimeter as well as the direct solar radiation at wavelengths of 443nm, 490nm, 565nm, 670nm, 765nm, and 865nm over the Pacific Ocean in August 1997, and over the Inland Sea of Japan in September 1997. To investigate the feasibility of the use of the degree of polarization to retrieve the optical properties of atmospheric aerosols over the ocean, radiative transfer calculations were performed using the doubling-adding method for a realistic atmosphere-ocean model. Aerosols were assumed to be composed of "water soluble" and "oceanic" models where these components are externally mixed. Particles are assumed to be spherical, and the size distributions are also assumed to be expressed by the log-normal functions. A look-up table of the degree of polarization at a scattering angle of 90° (p_{90}) was created with parameters of the solar zenith angle, the aerosols optical thickness at λ=550nm ($\tau_{a,550}$), and the Ångström coefficient (α). $\tau_{a,550}$ and α were simultaneously retrieved using the look-up table. Most of the differences between the $\tau_{a,550}$ retrieved from p_{90} and those derived from the direct solar radiation were within 0.03.

1. Introduction

Since radiation detected at satellite sensors over the ocean is significantly influenced by the radiation from atmospheric scatterers such as aerosols and molecules, it is essential to correct their effects to quantitatively derive the oceanic information. The atmospheric correction requires precise information of atmospheric aerosols. Atmospheric correction techniques first estimate the aerosol model and its optical thickness from the longer wavelength bands of a ocean color sensor then derive oceanic information from the shorter wavelength bands (for example, Gordon, 1997; Fraser *et al.*, 1997). For this purpose, it is necessary to prepare appropriate aerosol models. However, there are not so many measurements of the solar and sky radiation over the ocean from vessels (Hoppel *et al.*, 1990; Takayama *et al.*, 1991; Korotaev *et al.*, 1993; Villevalde *et al.*, 1994). The purpose of this paper is to investigate the feasibility of using the degree of polarization to retrieve the optical properties of aerosols over the ocean and to find a candidate aerosol model for the atmospheric correction.

2. Atmosphere-Ocean System Model

Downward radiation just above the ocean surface was computed by the doubling-adding method for wavelengths (λ) of 443nm, 490nm, 565nm, 670nm, 765nm, and 865nm. The computational method is the same as used by Masuda and Takashima (1988) where multiple scattering and polarization are taken into account. A plane-parallel and vertically inhomogeneous atmosphere is simulated by four homogeneous sub-layers (0-2km, 2-5km, 5-13km, 13-100km). The optical thickness of molecular scattering and absorbent constituents such as ozone were obtained by LOWTRAN7 (Kneizys *et al.* 1988) for the mid-latitude summer model. The depolarization factor of atmospheric molecules is 0.0295 according to Kneizys *et al.* (1980). The basic components of the maritime aerosol model are generally the "oceanic" model (OC) for the particles generated at the sea surface and the "water soluble" model (WS) for aerosols soluble in water and

consisting of a mixture of sulfate, nitrate, and organic components (WCP-112, 1986). These two types of aerosol component models are considered in this study where they are assumed to be externally mixed. The size distribution for each aerosol model is expressed by the log-normal function,

$$\frac{dn(r)}{d\ln r} = \frac{1}{\sqrt{2\pi}\ln\sigma}\exp\left(-\frac{\left(\ln r - \ln r_m\right)^2}{2\ln^2\sigma}\right), \qquad (1)$$

where r_m is the mode radius and $\ln\sigma$ is the standard deviation. The aerosol particles are assumed to be spherical. The scattering matrices are computed by the Mie scattering theory for the radius ranging from 0.001μm to 10.0μm. The OC model is adopted from the Radiation Commission report (WCP-112, 1986) where (r_m, σ) are (0.3μm, 2.51μm). The refractive indices at λ=443nm and 865nm are 1.384-i8.01×10^{-9}, 1.372-i1.21×10^{-6}. The WS models is adopted from the WCP-55 report (WCP-55, 1983) with (r_m, σ) of (0.0285μm, 2.015μm) where σ is decreased by 10% from the original value. The refractive indices λ=443nm and 865nm are 1.53-i0.005, 1.52-i0.012. The Ångström coefficients (α) of the OC-WS mixed aerosol model is shown in Fig. 1 as a functions of a ratio of the WS component (f_w) to the optical thickness (WS+OC) at λ=550nm ($\tau_{a,550}$).

The ocean surface is simulated by multiple facets whose slopes vary according to the wind speed over the ocean (Cox and Munk, 1954). Wind speed is assumed to be 5m/sec. The effect of the white caps is not taken into account.

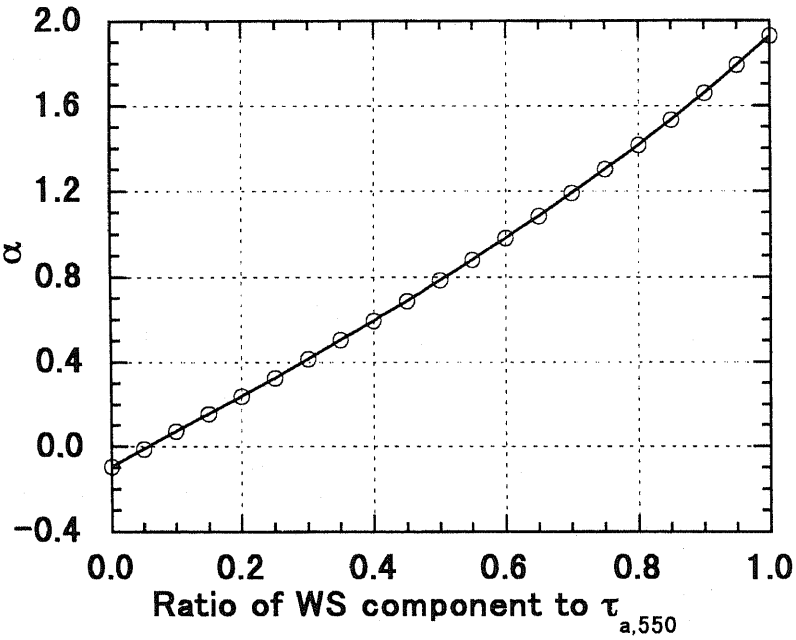

Fig. 1 Ångström coefficient (α) as a function of a ratio of water-soluble component to the aerosol optical thickness at λ=550nm.

3. Instruments and Measurements

FPR1000 (Opto Research Corporation) is a portable multichannel polarimeter to measure the diffused sky radiation as well as the direct solar radiation. The specification and calibration of FPR1000 is described in Masuda and Sasaki (1997). A brief description is given here. FPR1000 has six interference filters whose central wavelengths (half transmission bandwidth) in nm are 443 (20), 490 (20), 565 (20), 670 (20), 765 (40), and 865 (40). These wavelength regions correspond to those of POLDER and the Ocean Color and Temperature Scanner (OCTS) sensors on board ADEOS. A Glan-Thompson prism is installed in front of the interference filters. The field of view is 2°. The detector is a silicon photodiode. The accuracy of polarization measurements is estimated to be about 1% in polarization units (Masuda and Sasaki, 1997). Calibration constants for the direct solar radiation measurements were determined by the modified Langley plot at Mauna Loa Observatory (Masuda and Sasaki, 1997) in December 1996 and in December 1997. FPR5000 is similar to the FPR1000 except that the rotation of the polarizer is controlled by a step

motor which makes it easier to measure the sky radiation.

The sky radiation was measured over the Pacific Ocean from Kobe, Japan to Honolulu, Hawaii by the training ship (Seiun-maru) of the Institute for Sea-Training, Ministry of Transport of Japan in August 1997. Similar measurements were made over the Inland Sea of Japan by the training ship (Fukae-maru) of the Maritime University of Kobe in September 1997. We refer to these cruises as the PO and the IS cruises, respectively. The degree of polarization (p_{90}) were measured by the FPR5000 at a 90° angle from the solar direction in the principal plane, where the degree of polarization is generally maximum. This enables us to get stable values despite ship motions. The direct solar radiation was also measured by the FPR1000. Figure 2 shows the observational areas presented in this paper. The solar zenith angles (SZA) were from 27.6° to 57.9° (PO) and from 38.8° to 57.2° (IS).

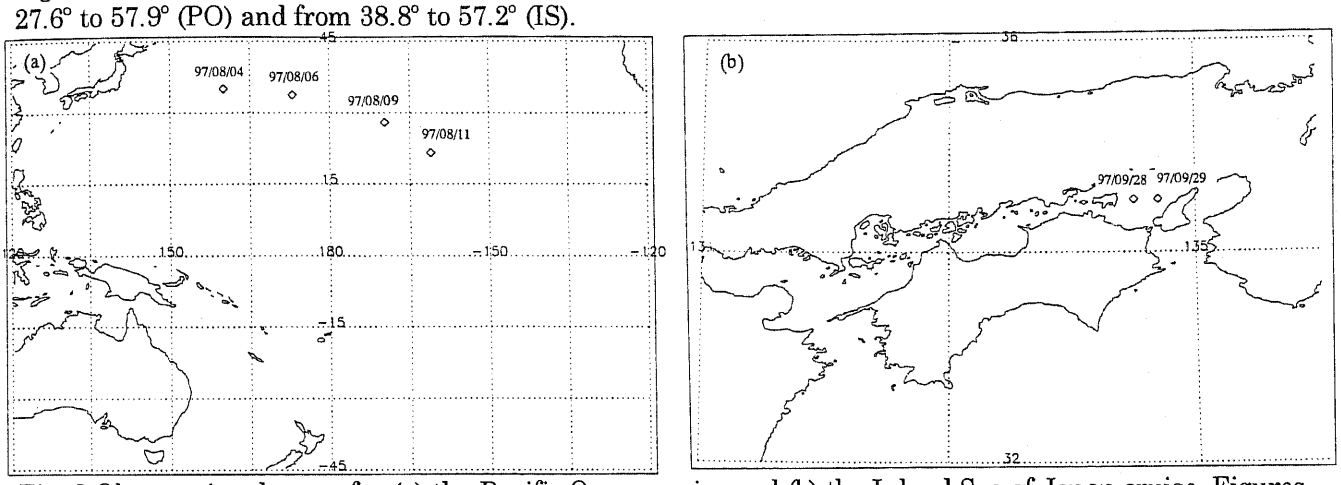

Fig. 2 Observational areas for (a) the Pacific Ocean cruise and (b) the Inland Sea of Japan cruise. Figures denote year/month/day.

4. Results

The relationship of p_{90} between λ=443nm and 865nm is shown in Fig. 3 as a function of $\tau_{a,550}$ and f_w. The SZA is fixed to 45.8°, but p_{90} is not significantly influenced by SZA. In our calculations, p_{90} differs less than 1% in polarization units for 22.5°<SZA<60° from p_{90} at SZA=45.8°. The measurements are also plotted in the figures where circles denote measurements in the PO cruise, and crosses the IS cruise.

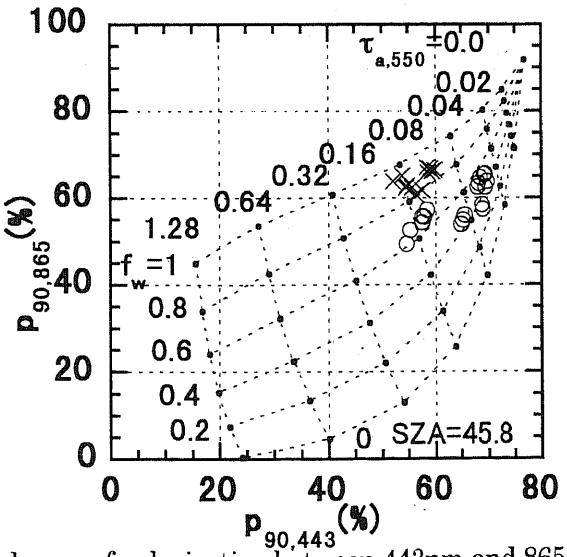

Fig. 3 Relationship of the degree of polarization between 443nm and 865nm as a function of $\tau_{a,550}$ and a ratio of the water-soluble component to $\tau_{a,550}$ for SZA=45.8°.Dotted lines denote the calculations, whereas circles (crosses) denote measurements in the Pacific Ocean cruise (the Inland Sea of Japan cruise).

$\tau_{a,550}$ and α were retrieved from the p_{90} at six wavelengths. First, the calculated p_{90} was interpolated with respect to the cosine of the SZA at the time of measurement. A two-dimensional table of p_{90} was then created for $\tau_{a,550}$=0.0 to 1.28 (step=0.01), and f_w=0.0 to 1.0 (step=0.05) by interpolating the calculations for eight $\tau_{a,550}$ (0.0, 0.02, 0.04, 0.08, 0.16, 0.32, 0.64, and 1.28) and six f_w (0.0, 0.2, 0.4, 0.6, 0.8, and 1.0), using the cubic spline interpolation method. We selected ($\tau_{a,550}$, f_w) pair which minimizes the following equation as the most probable aerosol model.

$$\sum_{i=1}^{6}\left(p_{90,calc}\left(\lambda_i, \tau_{a,550}, f_w\right) - p_{90,meas}\left(\lambda_i\right)\right)^2 . \qquad (2)$$

Figures 4 (a) and (b) show, respectively, the comparison of $\tau_{a,550}$ and α from p_{90} with those determined from the direct solar radiation. Note that α is obtained from f_w (Fig. 1). Figure 4 (c) shows the retrieved f_w (crosses) and the root mean difference (rms_{90}) of p_{90} between the calculations and measurements for six channels. rms_{90} may be considered as a measure of reliability of the retrieval of $\tau_{a,550}$, α, and f_w. Most of the retrieved $\tau_{a,550}$ differ by <0.03 from those determined by the direct solar radiation. The retrieved α values ($\alpha_{(p90)}$) are similar to those from the direct solar radiation ($\alpha_{(dir)}$) for α>1.0 which correspond to the cases of $\tau_{a,550\,(dir)}$>0.1. For the cases of $\tau_{a,\,550,\,dir}$<0.1, however, the $\alpha_{(p90)}$ are larger than $\alpha_{(dir)}$ by about 0.5, especially for $\alpha_{(dir)} \fallingdotseq 0$. The α values for the IS cruise are larger than those for the PO cruise by about > 0.5 because a large WS component is included in the aerosol for the IS cruise. This is reasonable because the measurements in the IS cruise were made near industrial areas, whereas the measurements in the PO cruise were made on the open sea.

5. Conclusion

Sky radiation as well as direct solar radiation were measured with portable multichannel polarimeters over the Pacific Ocean in August 1997, and over the Inland Sea of Japan in September 1997. The degree of polarization was measured at a 90° angle from the solar direction in the principal plane. We calculated the radiative transfer using the doubling-adding method to create a look-up table with three parameters (SZA, $\tau_{a,550}$, and α). $\tau_{a,550}$ and α were retrieved from p_{90} using the look-up table. Differences between $\tau_{a,550}$ retrieved from p_{90} and those determined from the direct solar radiation were mostly within 0.03. Since α values are directly related to a ratio of the WS component to $\tau_{a,550}$, the size distribution of the aerosol model is constructed, which may be a candidate aerosol model for the atmospheric correction in the regions without very absorptive aerosols.

From an observational point of view, it should be emphasized that it is easier to measure the degree of polarization than the radiance or transmittance because it is a relative value for which critical calibration is not required. Further, p_{90}, which generally is maximum with respect to the observation direction, can easily be measured from ships because it is not influenced very much by ship motions. The method described in this paper may be used for the satellite polarization measurements for some geometrical conditions in which the observed radiation is not significantly influenced by the sun glint.

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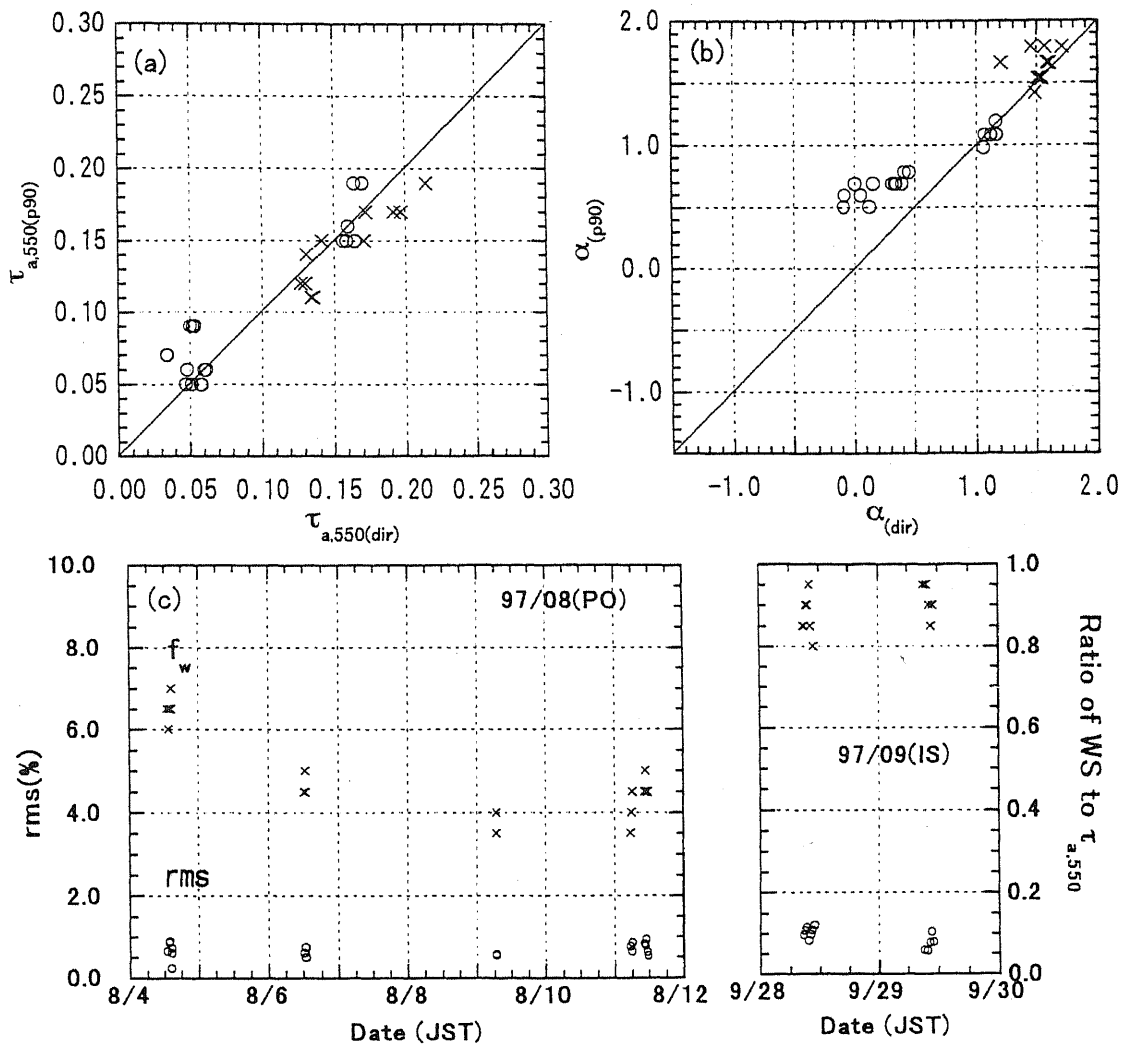

Fig. 4 (a) Comparison of the optical thickness of aerosols at λ=550nm ($\tau_{a,550}$) derived from p_{90} at at six channels with $\tau_{a,550}$ determined from the direct solar radiation. (b) The same as (a) but for the Ångström coefficient (α). Circles (crosses) denote the PO cruise (the IS cruise).
(c) Root mean square difference of p_{90} between measurements and calculations in polarization units (circles) and the retrieved ratio of water-soluble component to $\tau_{a,550}$ (crosses).

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