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Satellite retrieval of aerosol properties over the ocean using measurements of reflected sunlight: Effect of instrumental errors and aerosol absorption

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Abstract. A major task of several currently existing and planned satellite instruments is to provide accurate global monitoring of the distribution and properties of tropospheric aerosols using radiance and/or polarization measurements of the reflected sunlight. We use advanced computer simulations of radiative transfer in a realistic atmosphere-ocean model at a wavelength of 865 nm to examine the sensitivity of several widely used and recently developed retrieval techniques to aerosol absorption and instrumental errors. We assume that nonabsorbing (e.g., sulfate) and strongly absorbing (e.g., soot) aerosol components are mixed externally and that the scattering matrix of the mixture is that of the nonabsorbing component, while the only effect of the absorbing component is to reduce the single-scattering albedo. We show that neither algorithms using multiple-viewing-angle radiance measurements nor analogous polarization measurements or their combination can retrieve the aerosol single-scattering albedo with sufficient accuracy. However, accurate retrievals of the aerosol optical thickness, refractive index, and effective radius using polarization measurements do not require a precise knowledge of the aerosol single-scattering albedo, whereas potential uncertainties in the single-scattering albedo can strongly influence the accuracy of aerosol retrievals based on intensity measurements alone. Another important conclusion is that the accuracy of aerosol retrievals based on intensity and/or polarization measurements of the reflected sunlight is strongly corrupted by instrumental errors. We show that nonzero measurement errors can result in the best fit of model computations to measurement data being obtained with aerosol parameters far different from the actual ones. Our results emphasize the importance of accurate and stable instrumental calibration and suggest that the absolute radiometric uncertainty should be constrained to about ±4% or better and the absolute polarization accuracy should be kept to within ±0.2%. However, less accurate polarization measurements can still be used to estimate the aerosol refractive index and effective radius with reasonable accuracy. The results of our previous paper [*Mishchenko and Travis*, 1997] and this one demonstrate the limited capabilities of aerosol retrieval techniques based on intensity measurements alone and suggest that high-precision spaceborne polarimetry may potentially be the only way of retrieving aerosol characteristics with accuracy needed for long-term monitoring of global climate forcings and feedbacks.

1. Introduction

Owing to the important role of tropospheric aerosols in direct and indirect effect on climate [*Charlson and Heintzenberg*, 1995], there has been an increasing effort in monitoring the global distribution of aerosols and their properties through the use of passive instruments onboard Earth-orbiting satellites. These instruments are the advanced very high resolution radiometer (AVHRR) [*Rao et al.*, 1989], moderate resolution imaging spectrometer (MODIS) [*King et al.*, 1992], multiangle imaging spectroradiometer (MISR) [*Diner et al.*, 1991], sea-viewing wide field-of-view sensor (SeaWiFS) [*Hooker et al.*, 1992], polarization and directionality of the Earth's reflectances instrument (POLDER) [*Deschamps et al.*, 1994], Earth observing scanning polarimeter (EOSP) [*Travis*, 1992, 1993], global

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ozone monitoring experiment instrument (GOME), and scanning imaging absorption spectrometer for atmospheric cartography (SCIAMACHY).

It is well known that the accuracy of aerosol retrievals from satellite measurements of the reflected sunlight can be strongly influenced by many factors such as the availability of multiple-viewing-angle measurements for the same location, availability of polarimetric as well as photometric data, completeness of polarimetric measurements (only the degree of linear polarization versus measurements of the third as well as the second Stokes parameters), availability of multiwavelength measurements, adequacy of the atmosphere-ocean model, adequacy of modeling aerosol scattering and absorption properties, and instrumental accuracy [e.g., *Wang and Gordon*, 1994; *Diner et al.*, 1996; *Kaufman and Tanré*, 1996]. In a previous paper [*Mishchenko and Travis*, 1997] (hereinafter referred to as paper 1) we described the results of a systematic analysis of the effect of several of these factors on the quality of satellite aerosol retrievals. Specifically, we used exact numerical solutions of the vector radiative transfer equation for a realistic atmosphere-ocean model to theoretically simulate several types of satellite aerosol retrievals over the ocean utilizing radiance measurements alone, polarization measurements alone, and radiance and polarization measurements combined. We restricted all simulations to a single near-infrared wavelength of 0.865 μm and assumed that aerosols are spherical, monomodal, and nonabsorbing. Two types of passive satellite measurements were considered, namely, what we called the AVHRR type (reflectance and/or polarization measurements of a scene are acquired at only one viewing angle) and the MISR type (assuming quasi-simultaneous multiple-viewing-angle measurements of a scene). The reasonable simplicity of the atmosphere-ocean model allowed us to perform a detailed comparison of different retrieval algorithms under exactly the same conditions, thus clearly demonstrating their relative capabilities. Not surprisingly, we found that the MISR-type radiance-only algorithm performs far better than that based on single-viewing-angle radiance measurements (the AVHRR-type algorithm). However, even multiple-viewing-angle radiance measurements taken at a single wavelength are not always sufficient to determine the aerosol optical thickness, effective radius, and refractive index with high enough accuracy. In contrast, high-accuracy, single-wavelength, multiple-viewing-angle polarimetry alone was found to be capable of uniquely retrieving all three aerosol characteristics with very high accuracy.

In the analysis of paper 1 we assumed that the instrumental accuracy is 4% for reflectance and 0.2% for the normalized Stokes parameters q and u, thus corresponding to the anticipated accuracy of EOSP measurements for typical aerosol optical thicknesses over the relatively dark ocean surface [*Travis*, 1992, 1993]. However, these accuracies are at the edge of the current instrumental capabilities and can be unattainable with other instruments and/or difficult to maintain. For example, the polarimetric accuracy of the POLDER instrument is expected to be (much) worse than 0.2%. Also, it is well known that providing accurate postlaunch radiometric calibration is an extremely difficult problem [e.g., *Brest and Rossow*, 1992, and references therein]. Therefore it appears important to analyze the effect of nonzero and potentially varying instrumental errors on the accuracy of satellite aerosol retrievals.

Another factor which was ignored in paper 1 is aerosol absorption. Specifically, we considered only nonabsorbing aerosols, whereas a significant fraction of tropospheric aerosols can be rather strongly absorbing [e.g., *Lacis and Mishchenko*, 1995; *Penner*, 1995; *Hobbs et al.*, 1997; *Hegg et al.*, 1997]. It is well known that the direct radiative forcing of climate by aerosols strongly depends on the aerosol single-scattering albedo [*Lacis et al.*, 1992; *Toon*, 1995; *Hansen et al.*, 1997]. Furthermore, applying a nonabsorbing model to absorbing aerosols and vise versa can potentially result in significant errors in the retrieved values of the aerosol optical thickness, size, and refractive index. Therefore it is important to examine the ability of photometric and/or polarimetric remote sensing techniques to retrieve the aerosol single-scattering albedo and also to analyze the effect of absorption on the accuracy of retrieving other aerosol parameters.

The aim of the present paper is to extend the analysis of paper 1 by allowing the aerosol single-scattering albedo w to deviate from unity and by varying the assumed instrumental accuracy. As in paper 1, we will use a reasonably simple single-component aerosol model consisting of polydisperse spherical particles, restrict our discussion to the single near-infrared wavelength 0.865 μm, and consider only retrievals over the ocean surface with surface roughness corresponding to the global average of the long-term annual mean wind speed (7 m/s). We refer the reader to paper 1 for a detailed description of the model and the computational technique used. Since the performance of a single-wavelength AVHRR-type retrieval algorithm is always (much) poorer than that of its MISR-type counterpart, we will discuss here only the latter and will assume that the derived retrieval capabilities of the MISR-type algorithm provide an overstated upper limit for those of the AVHRR-type algorithm.

2. Effect of Absorption

Bohren and Huffman [1983] note that for most solids in the visible, the imaginary part of the refractive index Im(m) is either very small (e.g., 10^{-6} or less) or is of order unity. Therefore the modest deviation of the single-scattering albedo from unity for real aerosols almost always results from the presence of strongly absorbing impurities like soot or iron rather than from aerosols being homogeneous dielectrics with a moderately large (10^{-3} - 10^{-2}) imaginary part of the refractive index. Nonabsorbing and strongly absorbing components can be mixed both internally (strongly absorbing impurities are inside nonabsorbing particles) and externally (strongly absorbing and nonabsorbing particles are separated), thus suggesting two different ways of modeling optical properties of moderately absorbing tropospheric aerosols. In this paper we will assume that the nonabsorbing (e.g., sulfates) and strongly absorbing (soot) components are mixed externally. Furthermore, we will assume that the typical size of soot particles is very small so that because of the large imaginary part of the soot refractive index [*d'Almeida et al.*, 1991], their scattering cross section is much smaller than their absorption cross section [*Bohren and Huffman*, 1983]. Therefore, the phase function and the Stokes scattering matrix of the aerosol mixture are those of the nonabsorbing component, while the only effect of the soot component is to make the total single-scattering albedo smaller than 1. The

more complicated case of internal mixing will be examined in a separate paper.

To theoretically model satellite aerosol retrievals over the ocean, we have followed the approach developed in paper 1 and used precomputed quantities I (intensity) and q and u (normalized second and third Stokes parameters) for a large set of "candidate" aerosol models assuming a monomodal nonabsorbing aerosol component with effective radius r_{eff} varying from 0.01 to 0.8 μm in steps of 0.01 μm, real refractive index m varying from 1.3 to 1.7 in steps of 0.01, total aerosol optical thickness τ_0 ranging from 0 to 0.4 in steps of 0.01, and total single-scattering albedo w varying from 0.78 to 1 in steps of 0.02. The latter represents the range of typical single-scattering albedos retrieved by *Hegg et al.* [1997] during the tropospheric aerosol radiative forcing observational experiment (TARFOX). The nonabsorbing aerosol particles were assumed to be homogeneous spheres with radii obeying the standard gamma distribution [*Hansen and Travis*, 1974] with effective variance fixed at $v_{\mathrm{eff}} = 0.2$. All computations have been performed at the relatively long wavelength $\lambda = 0.865$ μm at which the contributions of light scattering in the ocean body and Rayleigh scattering in the atmosphere are negligible [*Gordon and Wang*, 1994]. We have used the Cox and Munk model of the ocean surface [*Cox and Munk*, 1954] with the mean square surface slope value corresponding to a median wind speed of $W = 7$ m/s [*Hsiung*, 1986]. For this wind speed the reflectance contribution due to oceanic whitecaps is negligibly small [*Koepke*, 1984].

The MISR type of satellite measurements has been modeled by assuming that the cosine of the Sun zenith angle is fixed at $\mu_0 = 0.8$ and the cosine of the satellite zenith angles varies from $\mu = 0.2$ to 1 in steps of 0.2 in the satellite orbit plane given by the relative satellite-Sun azimuth angles $\varphi - \varphi_0 = 60°$ and $-120°$ so that there are nine different viewing directions covering the range of scattering angles from about 82° to 148° (as described in paper 1, the azimuth angle is measured in the clockwise direction when looking upward). We first assumed that the effective radius of the nonabsorbing component was known beforehand and was equal to $r_{\mathrm{eff},0} = 0.4$ μm so that only the total aerosol optical thickness τ_a, the real refractive index m, and the total single-scattering albedo w must be retrieved from the measurements. As computer-simulated measurement data, we chose the theoretically computed quantities I, q, and u for a "standard" model with $\tau_0 = 0.2$, $m_0 = 1.45$, and $w_0 = 0.94$. We then attempted to reconstruct the "unknown" optical thickness, refractive index, and single-scattering albedo by comparing the reflectivity and/or polarization computed for the standard model with those for each of the candidate models from the large precomputed set. We have used three acceptance criteria which were designed to model retrievals using radiance only, polarization only, and radiance and polarization combined, respectively. The first two criteria, (A) and (B), are given by

$$\frac{1}{9}\sum_{j=1}^{9}\frac{|I_c^j - I_s^j|}{I_s^j} \le \Delta_I, \tag{1}$$

$$\frac{1}{9}\sum_{j=1}^{9}\frac{1}{2}\left[|q_c^j - q_s^j| + |u_c^j - u_s^j|\right] \le \Delta_P, \tag{2}$$

respectively, where the superscript j numbers the viewing directions, the subscripts s and c label quantities pertaining to the standard and candidate models, respectively, and Δ_I and Δ_P are the photometric and polarization instrumental accuracies, respectively. The third criterion, (C), is a superposition of criteria (A) and (B):

$$(\mathrm{C}) = (\mathrm{A}) \wedge (\mathrm{B}). \tag{3}$$

In other words, (C) is fulfilled if and only if both (A) and (B) are fulfilled. These criteria specify the maximum allowable relative reflectance (criterion A) and absolute polarization (criterion B) differences between the standard and acceptable candidate models averaged over the nine measurements. All candidate models passing these criteria are equally acceptable retrievals so that none of them can be considered a unique solution.

Plate 1 demonstrates the use of criteria (A), (B), and (C) assuming the expected EOSP photometric and polarization instrumental accuracies $\Delta_I = 4\%$ and $\Delta_P = 0.2\%$. The horizontal and vertical dotted lines in the panels of Plate 1 show the actual values of the optical thickness ($\tau_0 = 0.2$) and refractive index ($m_0 = 1.45$) for the standard model, while the green color marks the panel corresponding to the correct single-scattering albedo ($w_0 = 0.94$) so that the intersection of the dotted lines in this marked panel indicates the correct solution. The blue areas in the 12 panels corresponding to candidate single-scattering albedos varying from 0.78 to 1 in steps of 0.02 show the acceptable candidate models that passed the radiance-only criterion (A), whereas the red areas show the result of passing the polarization-only criterion (B) and the intersections of the blue and red areas show the result of applying criterion (C) based on simultaneous use of reflectance and polarization measurements.

It is clearly seen that despite the use of multiple-viewing-angle measurements, the radiance-only criterion (A) finds acceptable solutions for all single-scattering albedos from 0.78 to 1 and for optical thicknesses and refractive indices significantly different from the actual values. It has been realized for a long time that the determination of the singe-scattering albedo from satellite radiance measurements is a very difficult problem [e.g., *Wang and Gordon*, 1994]. Plate 1 demonstrates that this problem is hardly solvable at all. Furthermore, since aerosol absorption can be expected to be wavelength-dependent, availability of multiwavelength measurements is unlikely to improve the sensitivity of reflectance to the single-scattering albedo [cf. *Wang and Gordon*, 1994]. Also, comparison of the panel corresponding to $w = 0.94$ with other panels in Plate 1 indicates that inexact knowledge of the actual single-scattering albedo value can significantly worsen the accuracy of the aerosol optical thickness retrieval.

Red areas in Plate 1 (panels corresponding to $w = 1$, 0.98, 0.96, 0.94, 0.92, 0.9, 0.88, and 0.86) show all acceptable solutions produced by the polarization-only algorithm. It is seen that high-precision multiple-viewing-angle polarization measurements also are poorly sensitive to single-scattering albedo and that even the combined use of reflectance and polarization measurements does not improve the accuracy of the single-scattering albedo retrieval significantly. However, a crucial advantage of polarization over radiance measurements is that uncertainties in the single-scattering

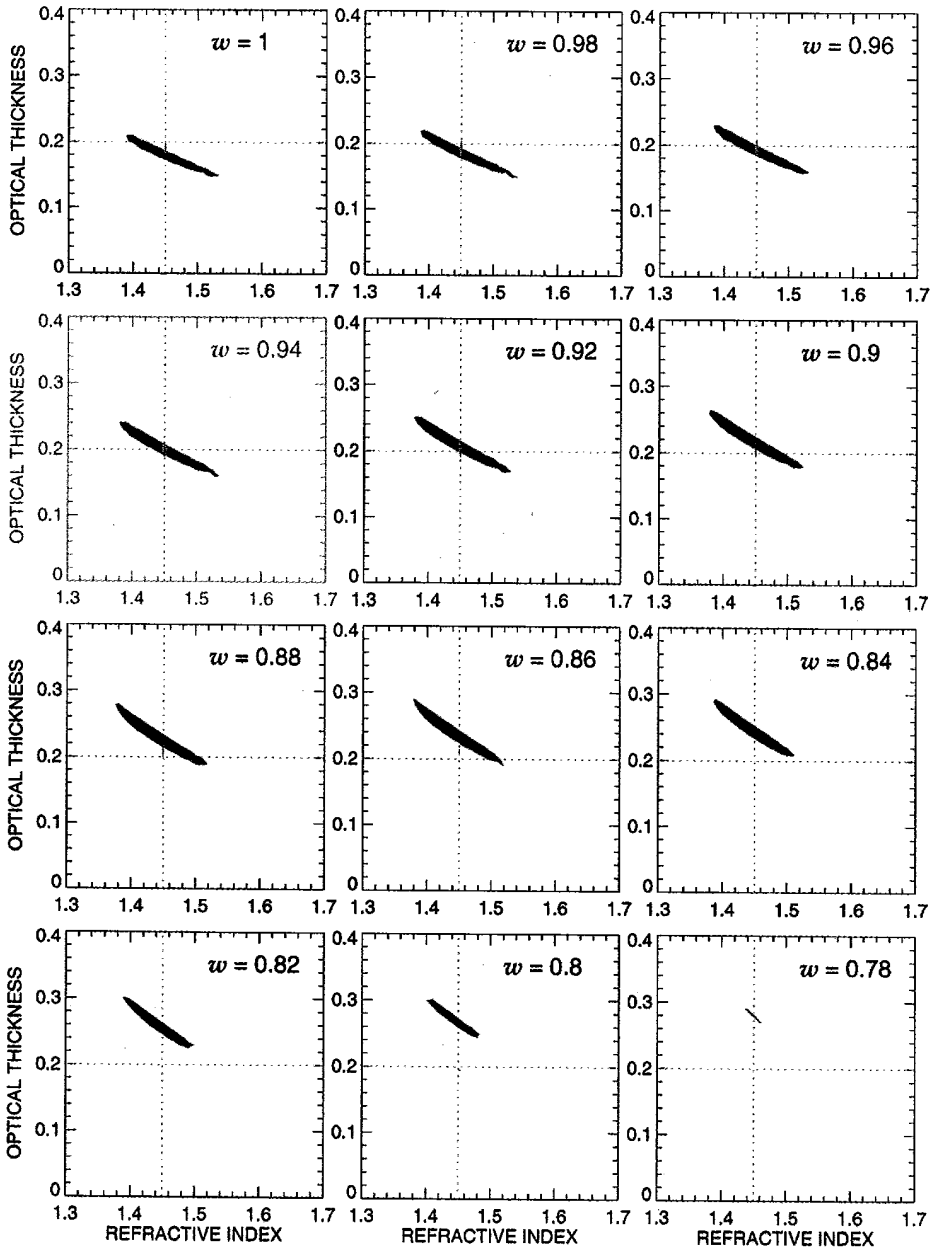

Plate 1. Modeling MISR-type aerosol optical thickness, refractive index, and single-scattering albedo retrievals using the acceptance criteria of equations (1) (blue areas), (2) (red areas), and (3) (intersections of blue and red areas) for a standard model with $\tau_0 = 0.2$, $r_{\mathrm{eff},0} = 0.4$ μm, $m_0 = 1.45$, and $w_0 = 0.94$. All model parameters but $r_{\mathrm{eff},0}$ are assumed to be unknown. The illumination and viewing geometries are specified by the values $\mu_0 = 0.8$, $\mu = 0.2$, 0.4, 0.6, 0.8, and 1 and $\varphi - \varphi_0 = 60°$ and $-120°$. The assumed instrumental accuracies are $\Delta_I = 4\%$ and $\Delta_P = 0.2\%$. The green color marks the panel corresponding to the correct single-scattering albedo $w_0 = 0.94$.

albedo do not worsen the accuracy of polarimetric retrievals of the aerosol optical thickness and refractive index. Whatever the assumed single-scattering albedo is, the aerosol optical thickness and refractive index are retrieved with an extremely high accuracy ($\Delta\tau < 0.02$ and $\Delta m < 0.01$).

Assume now that the aerosol effective radius is unknown as well, so that all four aerosol parameters (optical thickness, real refractive index, single-scattering albedo, and effective radius) must be retrieved simultaneously from reflectance and/or polarization measurements. Figures 1-4 are analogous to Plate 1 but assume wrong values of the effective radius $r_{\mathrm{eff}} = 0.2$ μm (Figure 1), 0.35 μm (Figure 2), 0.45 μm (Figure 3), and 0.7 μm (Figure 4) instead of the correct value $r_{\mathrm{eff},0} = 0.4$ μm. We have found that none of these candidate effective radii generated acceptable solutions when the polarization-only criterion (B) is used. Therefore Figures 1-4 do not use color, and the shadowed areas show the result of applying the intensity-only criterion (A). The fact that criterion (B) produced no acceptable solutions even for the candidate effective radii $r_{\mathrm{eff}} = 0.35$ and 0.45 μm

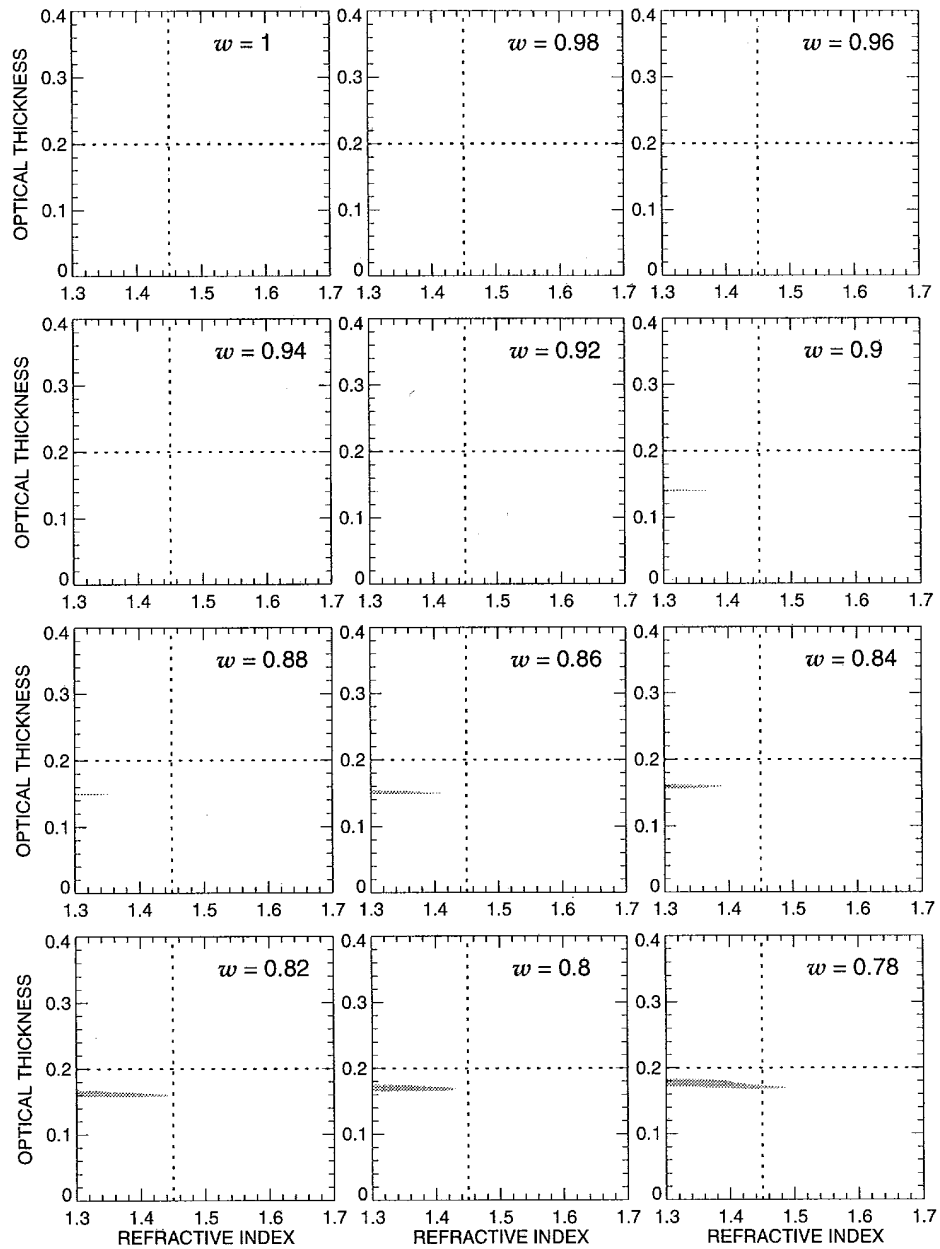

Figure 1. Modeling the MISR type of aerosol retrieval using the intensity-only algorithm for a standard model with $\tau_0 = 0.2$, $r_{\mathrm{eff},0} = 0.4$ μm, $m_0 = 1.45$, and $w_0 = 0.94$ and assuming a wrong effective radius value $r_{\mathrm{eff}} = 0.2$ μm. The shadowed areas show the result of applying the acceptance criterion of equation (1).

demonstrates that the polarization-only retrieval is extremely sensitive to the aerosol effective radius (retrieval accuracy $\Delta r_{\mathrm{eff}} < 0.05$ μm) as well as to the aerosol optical thickness and real refractive index and that this sensitivity is not negatively influenced by an uncertainty in the single-scattering albedo. On the other hand, the intensity-only retrieval generates false solutions with all four aerosol parameters significantly deviating from their actual values.

3. Effect of Measurement Errors

If the aerosol effective radius, real refractive index, and single-scattering albedo were known exactly, then the effect of nonzero measurement errors on the accuracy of the optical thickness retrieval would be relatively weak (see Plate 1, panel corresponding to $w = 0.94$, vertical cross section of the red and blue areas corresponding to Re(m) = 1.45; also *Kaufman and Tanré* [1996]). However, since the aerosol model is never known exactly, calibration uncertainties can result in wrong models producing a better fit to measurements than the true model [*Wang and Gordon*, 1994]. This explains the existence of large areas of acceptable solutions in Plate 1 and Figures 1-4 and emphasizes the importance of a thorough analysis of the effect of measurement errors on the accuracy of aerosol retrievals. A preliminary analysis of this problem has been

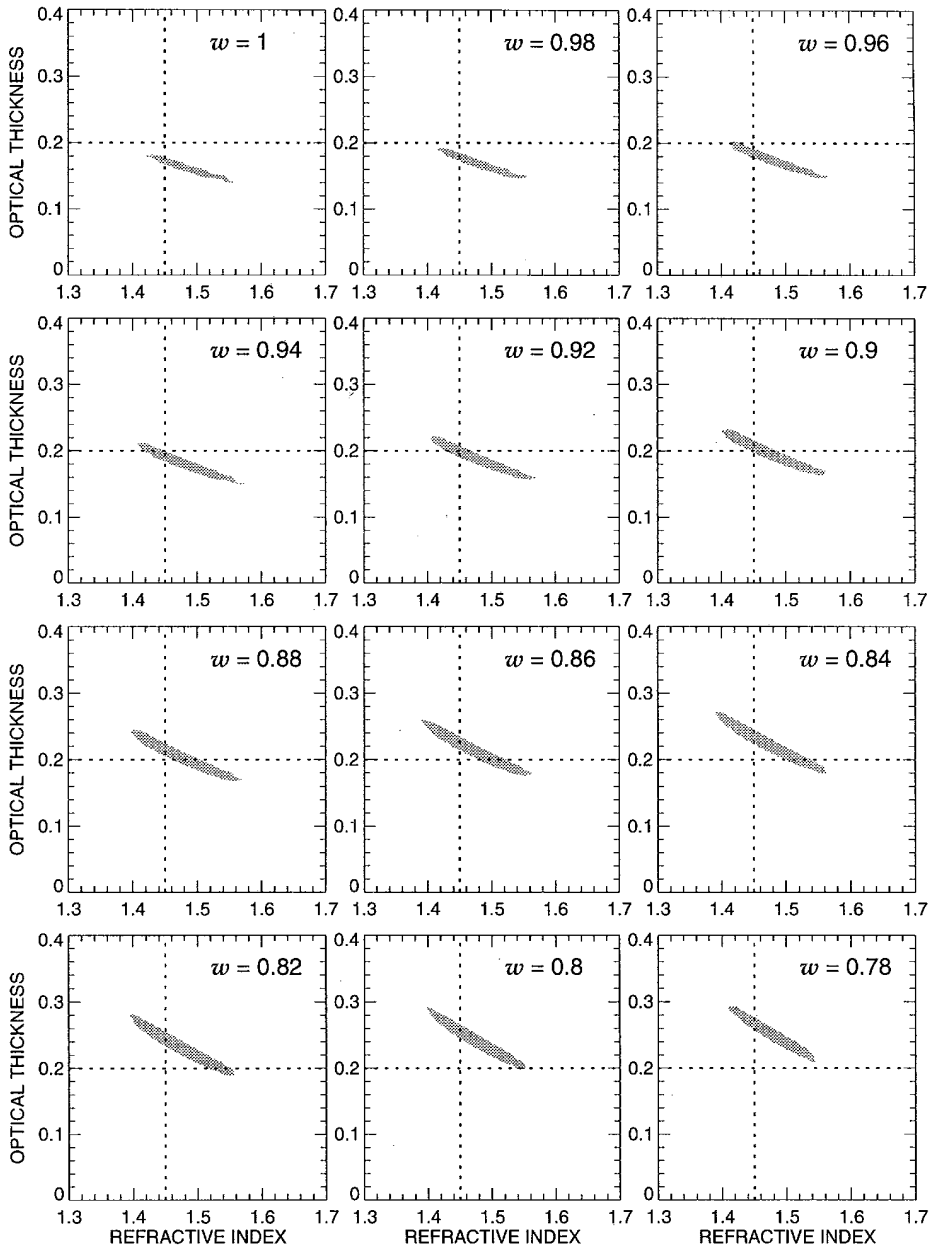

Figure 2. As in Figure 1, but assuming a wrong effective radius value $r_{\mathrm{eff}} = 0.35$ μm.

reported by *Wang and Gordon* [1994]. However, they used only a small number of candidate aerosol models which may not fully expose the problem given the strong time and space variability of tropospheric aerosols.

Plates 2 and 3 are analogous to Plate 1 but assume worse radiometric and polarization instrumental accuracies. It is obvious that increasing instrumental errors results in a significant spread of the blue and red areas, thus indicating much poorer accuracy of aerosol retrievals based on both intensity and/or polarization measurements. Plate 2 and analogous computations for other effective radii show that worsening the radiometric accuracy from 4 to 6% can increase errors in the retrieved aerosol parameters (effective radius, refractive index, single-scattering albedo, and optical thickness) by a factor exceeding 2. A similar deterioration in the accuracy of the polarization-only optical thickness retrieval occurs as the instrumental polarimetric accuracy is degraded from 0.2 to 0.8% (Plate 2).

Plate 3 shows an even more disappointing picture for $\Delta_I = 8\%$ and $\Delta_P = 2\%$. Plates 1-3 are horizontal cross sections of two-dimensional surfaces represented by the left-hand sides of equations (1) and (2) as functions of the optical thickness and refractive index for different values of the single-scattering albedo. Therefore the rapid spread of blue and red areas with increasing Δ_I and Δ_P can be explained by the shallowness of the global minimum in these surfaces. This, in turn, indicates the ill-posed character of the retrieval problem and explains the existence of multiple false solutions when instrumental errors are not identically equal to zero.

Plates 1-3 and analogous computations for other values of

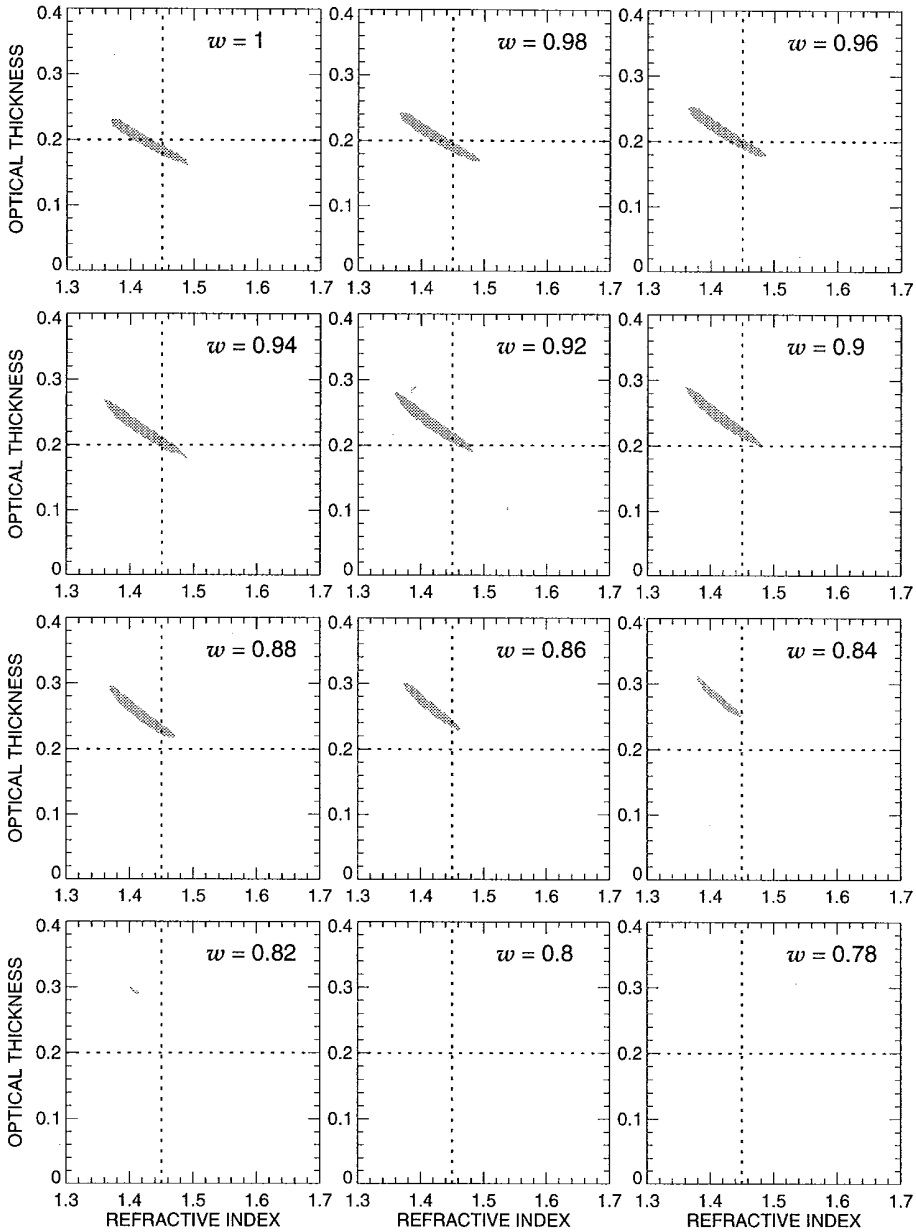

Figure 3. As in Figure 1, but assuming a wrong effective radius value r_{eff} = 0.45 μm.

the effective radius show that there is a fundamental difference between the intensity-only and the polarization-only retrieval algorithms. Specifically, with increasing instrumental errors, the intensity-only algorithm looses its sensitivity to all four aerosol parameters simultaneously, whereas the polarization-only algorithm retains a strong sensitivity to m and r_{eff}. This result suggests that even when the polarization instrumental accuracy is rather poor, satellite polarimetry can still be used to estimate the real refractive index and effective radius of aerosol particles with useful accuracy.

4. Discussion and Conclusions

In this paper we have followed the approach of paper 1 and used numerical radiative transfer simulations for a realistic yet reasonably simple atmosphere-ocean model in order to thoroughly examine the sensitivity of different passive aerosol retrieval algorithms to aerosol absorption and instrumental errors. We have found that neither the intensity-only algorithm nor the polarization-only algorithm nor their combination can be used to retrieve the aerosol single-scattering albedo with accuracy necessary for determining the direct aerosol effect on climate. However, we have shown that accurate retrievals of the aerosol optical thickness, refractive index, and effective radius using the polarization-only algorithm do not require a precise knowledge of the single-scattering albedo, whereas potential uncertainties in the single-scattering albedo can strongly degrade the accuracy of retrievals based on intensity measurements alone. The ability of the polarimetry-based retrieval algorithm to accurately determine the aerosol size

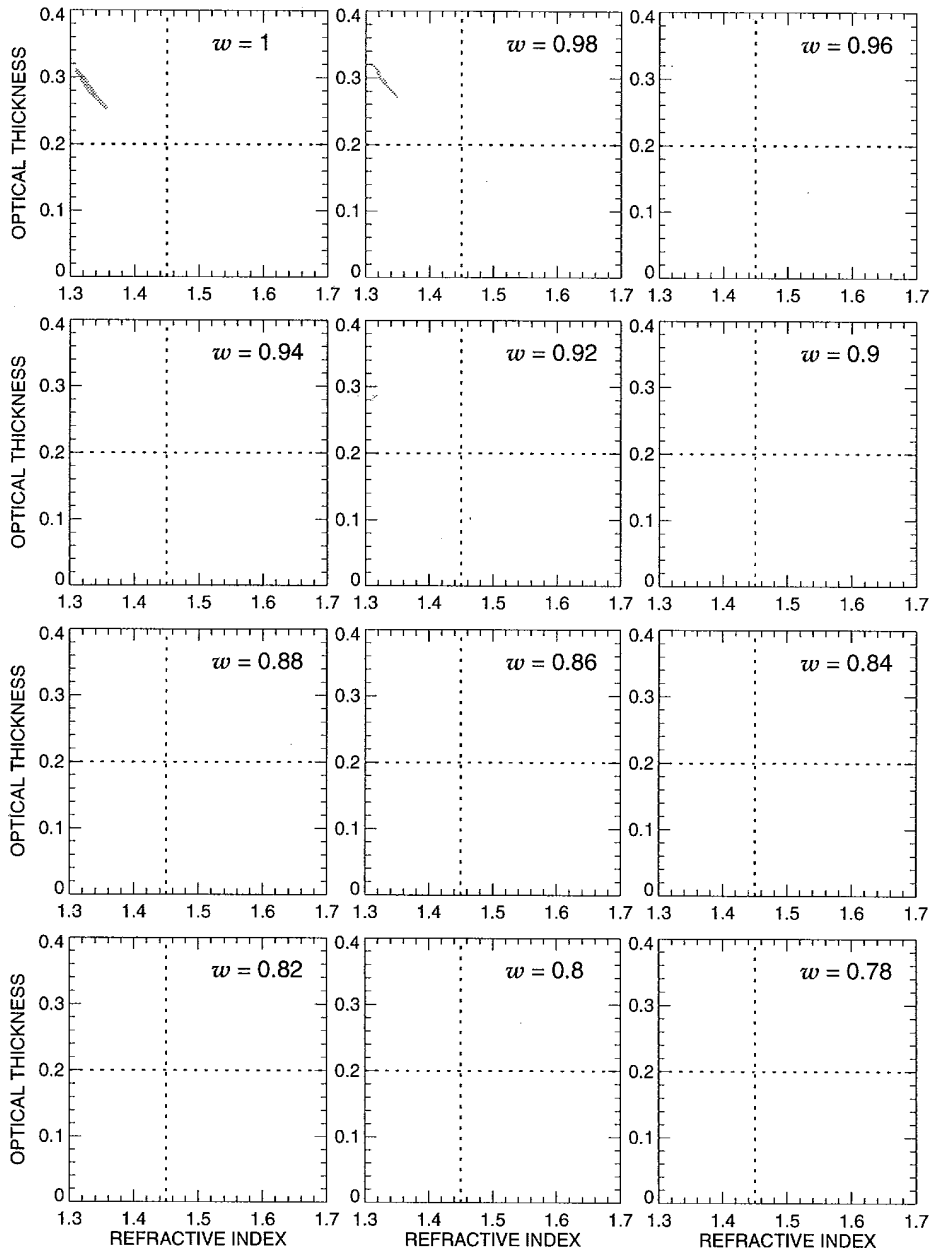

Figure 4. As in Figure 1, but assuming a wrong effective radius value $r_{eff} = 0.7$ μm.

and refractive index combined with an aerosol climatology [*Ogren*, 1995] may potentially be a way of indirectly inferring the aerosol single-scattering albedo.

We have assumed in this paper that nonabsorbing and strongly absorbing aerosol components are mixed externally and that the scattering matrix of the mixture is that of the nonabsorbing component, while the only effect of the absorbing component is to reduce the single-scattering albedo. However, if the nonabsorbing and absorbing components are mixed internally (as, e.g., in dust-like particles), then the presence of absorbing impurities will change not only the single-scattering albedo, but also the elements of the scattering matrix (including the phase function). In this case one can expect a stronger sensitivity of the radiance and polarization algorithms to absorption (B. Cairns, personal communication, 1997).

Another important result of our paper is that the accuracy of aerosol retrievals based on intensity and/or polarization measurements of reflected sunlight is strongly affected by instrumental errors. We have shown that owing to nonzero measurement errors, the best fit of model computations to measurement data can be obtained with aerosol parameters far different from the actual ones. This result stresses the importance of an accurate and stable instrumental calibration and suggests that the absolute radiometric uncertainty should be constrained to about 4% or better and the absolute polarization accuracy should be kept to within ±0.2%. However, our computations show that less accurate polarization measurements can still be used to estimate the aerosol refractive index and effective radius with reasonable accuracy.

The approach often adopted in sensitivity studies is to

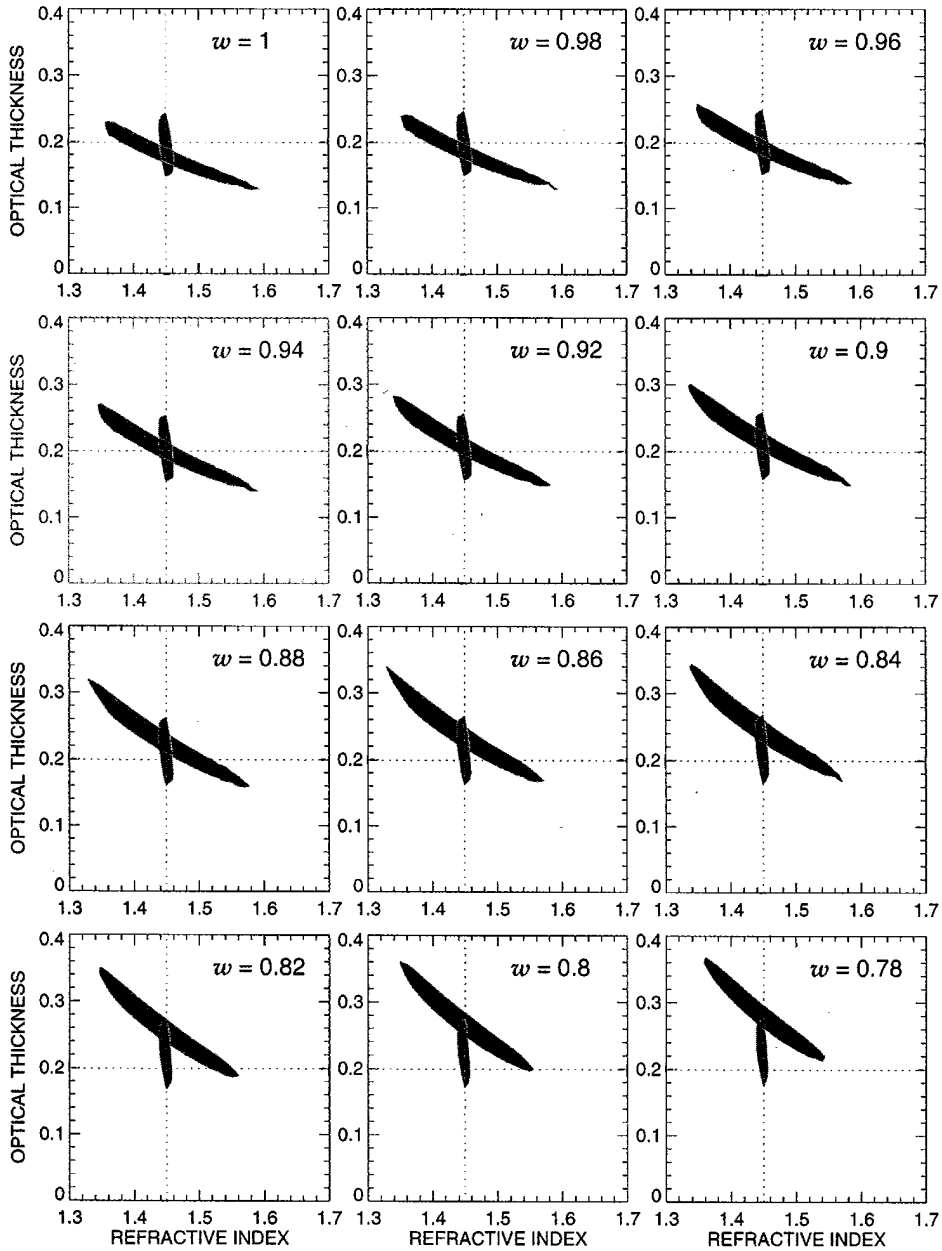

Plate 2. As in Plate 1, but for Δ_I = 6% and Δ_P = 0.8%.

assume that all model parameters but one are known a priori and to examine the effect of measurement errors on the accuracy of retrieving the single unknown model parameter. A similar approach is to neglect instrumental errors, assume that all model parameters but two are a priori known, and examine the effect of uncertainty in one unknown parameter on the accuracy of retrieving the other unknown parameter [e.g., *Kaufman and Tanré*, 1996]. Our analysis clearly shows that this approach can grossly overstate the accuracy and sensitivity of a retrieval technique. For example, if we assume that the aerosol refractive index, effective radius, and single-scattering albedo are known exactly, so that the only unknown model parameter is the aerosol optical thickness, and that the only source of retrieval errors is the 4% instrumental inaccuracy of radiance measurements, then we can conclude that the accuracy of retrieving the aerosol optical thickness is better than ±0.02 (see the vertical cross section at Re(m) = 1.45 of the red area in the green panel of Plate 1). However, when all four aerosol parameters are assumed to be unknown, which is usually the case, the errors in the retrieved optical thickness increase by a factor exceeding 5 (Figures 3 and 4).

Since the analysis of this paper as well as paper 1 is restricted to a single near-infrared wavelength of 865 nm, one may expect that the retrieval performance of instruments like MODIS, MISR, POLDER, and EOSP can in fact be better because of the use of several widely separated spectral channels. However, this still remains to be demonstrated because addition of new spectral channels provides truly independent information only if the aerosol refractive index and single-scattering albedo do not change with wavelength. For example, the sensitivity study of the MODIS aerosol

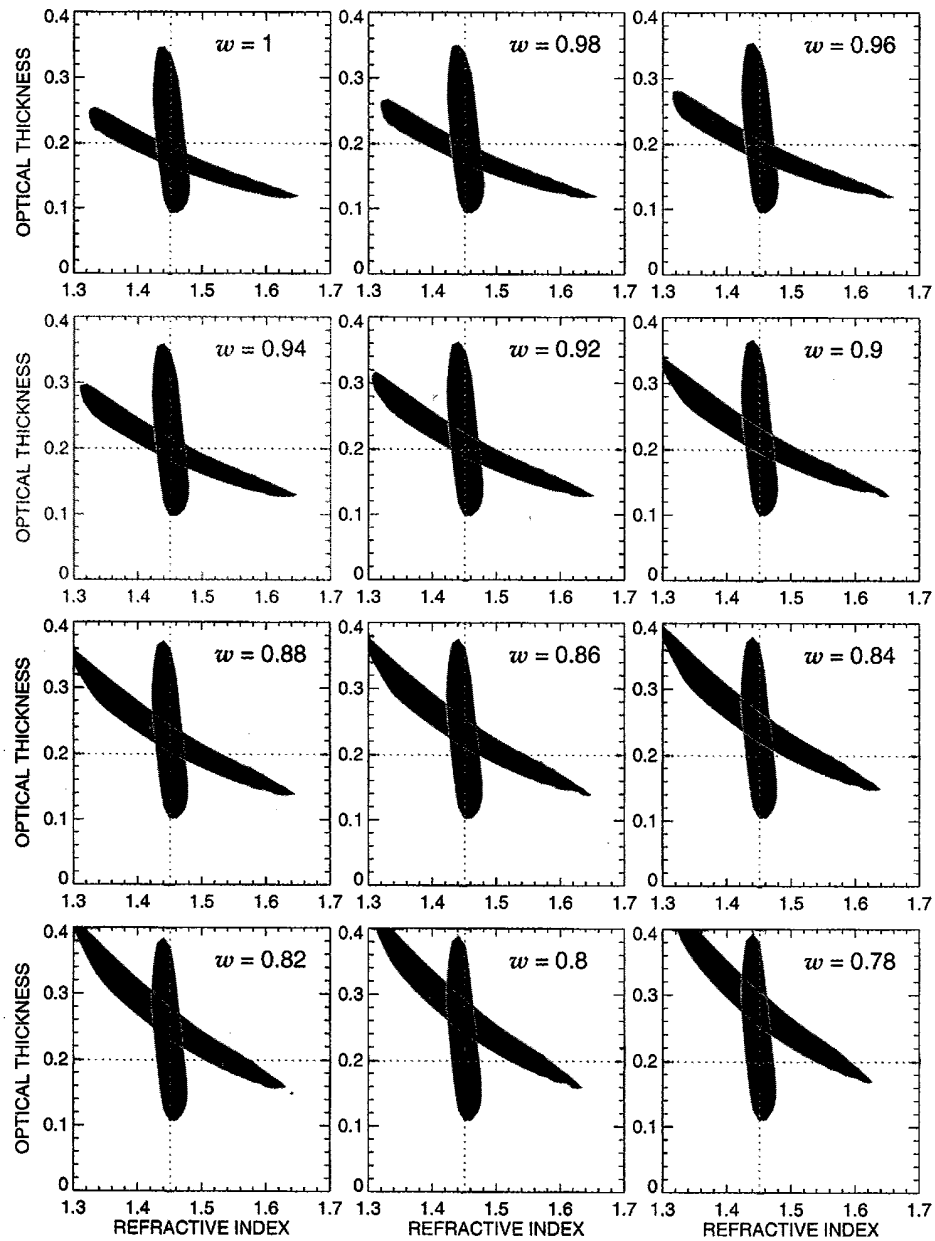

Plate 3. As in Plate 1, but for Δ_I = 8% and Δ_P = 2%.

retrieval algorithm by *Tanré et al.* [1996] assumes that both the real and the imaginary parts of the aerosol refractive index are constant over the spectral range from 470 to 2130 nm. Therefore an additional examination of the effect of spectral variability of the refractive index of real substances on the retrieval accuracy may prove to be necessary.

Two additional restrictions of our analysis are the neglect of Rayleigh scattering in the atmosphere (justified at λ = 865 nm) and the use of a fixed ocean surface roughness. Computations at shorter wavelengths, at which the Rayleigh scattering contribution cannot be neglected, and for other surface roughnesses as well as for other surface types (Lambertian surfaces with varying reflectivity) show that our conclusions remain unchanged as long as the Rayleigh optical thickness and the surface bidirectional reflectance are assumed to be known beforehand. This is always the case with the Rayleigh optical thickness. However, the surface reflectance should, in general, be considered a free model parameter and determined simultaneously with aerosol parameters.

Finally, we emphasize again that the approach adopted in paper 1 and in this paper is based on numerical simulations rather than on real measurement data. A clear disadvantage of this approach is that it can neglect the effect of one or more unknown factors (e.g., aerosol nonsphericity, vertical and/or horizontal inhomogeneity of the aerosol layer, etc.) which can complicate the retrieval problem. As a result, this approach is prone to overstate the capabilities of a retrieval technique. On the other hand, a definite advantage of this approach is that the real solution of the inverse problem is known exactly and provides a complete closure almost never available with real remote sensing measurements. Therefore the numerical modeling approach is most suitable for establishing the nonuniqueness character of an inverse remote

sensing problem, clearly indicates the existence of cases when best fit solutions are not the actual solutions, and always demonstrates the upper limit of capabilities of a remote sensing technique. In other words, if this approach suggests that a remote sensing technique is capable of retrieving aerosol parameters with only a limited accuracy, this means that the technique may or may not be able to actually achieve this accuracy but definitely cannot exceed it, unless some (if not most) of the parameters are narrowly constrained using a priori information. Therefore the results of paper 1 and this paper unequivocally demonstrate the limited capabilities of aerosol retrieval techniques based on intensity measurements alone and strongly suggest that high-precision spaceborne polarimetry may potentially be the only way of retrieving aerosol characteristics with accuracy needed for long-term monitoring of global climate forcings and feedbacks [*DelGenio*, 1993; *Hansen et al.*, 1995].

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