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EVALUATION OF OCEAN COLOR AND ITS EFFECT ON THE POLARIZATION OF WATERLEAVING RADIANCES DURING THE CHESAPEAKE LIGHTHOUSE AND AIRCRAFT MEASUREMENTS FOR SATELLITES (CLAMS) EXPERIMENT

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1. INTRODUCTION

The linear polarization of light observed over the ocean from an aircraft or spacecraft contains a wealth of information that is not readily available from total radiance data. At near infrared wavelengths, one can ignore the contribution of waterleaving radiances and use such information to retrieve aerosol properties such as size distribution and real refractive index with accuracies far exceeding those of photometric retrievals as demonstrated by *Breon and Goloub* (1998) and *Chowdhary et al.* (2001). The situation becomes more complex for visible wavelengths, where one has to account for light emerging from the ocean. The water leaving radiance contributes less than 20% to the total radiance observed from space, but its absolute magnitude varies substantially with the amount of phytoplankton concentration (*Morel*, 1988). Commonly, one incorporates the infrared retrievals to constrain the amount of atmospheric scattering in the visible (*Gordon*, 1997), but such extrapolations still require assumptions on the spectral behavior of aerosol properties.

In a recent article (*Chowdhary et al.*, 2002*a*) we explored inverting visible polarized radiances obtained over the ocean by the Research Scanning Polarimeter (RSP) instrument (*Cairns et al.*, 1999), an airborne remote sensor that is functionally similar to the Earth Observing Scanning Polarimeter (EOSP, *Travis*, 1993). Using for the underwater light a hydrosol model whose scattering function resembled the ones measured by *Petzold* (1977) for turbid waters, we showed that the polarized contribution of this light to our data set was negligibly small near the backscattering direction. This important observation enabled us to expand the range of wavelengths used for aerosol retrieval and to obtain additional valuable information on aerosol refractive indices in the visible part of the spectrum. However, it has been known in the ocean color community that using Petzold's (1977) data in underwater light computations can lead to waterleaving radiances whose albedos are inconsistent with ocean color observations (*Morel and Maritonera*, 2001). This does not affect the conclusions for aerosol retrieval drawn by *Chowdhary et al.* (2002*a*), who avoided the use of total reflectances in the visible for this retrieval. But it interferes with their retrieval of ocean color, which depends strongly on these reflectances. Complicating the matter further is the presence of aerosol absorption which can lead to a reduction in the internal atmospheric radiation field by an amount that is comparable to the contribution of waterleaving radiances. Moreover the magnitude of aerosol absorption is difficult to estimate from remote sensing data (e.g., *Mishchenko and Travis*, 1997). In this study, we combine a new hydrosol model with *in-situ* measurements of the ocean to estimate the ocean color contribution to RSP data obtained during the CLAMS experiment, and use this estimate to constrain the imaginary part of aerosol refractive index which determines aerosol absorption.

2. OCEAN MODEL

To obtain the contribution of waterleaving radiances to RSP-type remote sensing data, we perform rigorous multiple scattering computations for the underwater light using a phase matrix and single scattering albedo that result from a mixture of three components: pure sea water, phytoplankton, and detritus particles. For the pure sea water component we adopt Rayleigh scattering with a depolarization factor of 0.09

(*Morel*, 1974) and the scattering and absorption coefficients given by *Pope and Fry* (1997). To constrain the size distribution and real refractive index of phytoplankton and detritus particles, we use typical *in-situ* measurements (e.g., *Spinrad and Brown*, 1986; *Jonasz*, 1983, and references therein) and underwater light polarization signatures (e.g., *Voss and Fry*, 1984). For the mixing of these two hydrosol components we require the resulting backscattering ratio to follow the values given by bio-optical models for case I waters as a function of phytoplankton pigment concentration [Chl] (*Morel and Maritonera*, 2001). The scattering and absorption coefficients for this mixture as a function of wavelength λ and [Chl] are also taken directly from the bio-optical models. Hence, the advantage of this ocean model is that the microphysical properties of its components are consistent with in-situ measurements, that it leads to realistic variations of total and polarized waterleaving radiances with λ and [Chl], and that the albedos of these radiances are consistent with ocean color observations (Fig. 1). For a more detailed discussion on this ocean model, we refer to *Chowdhary et al.* (2002*b*).

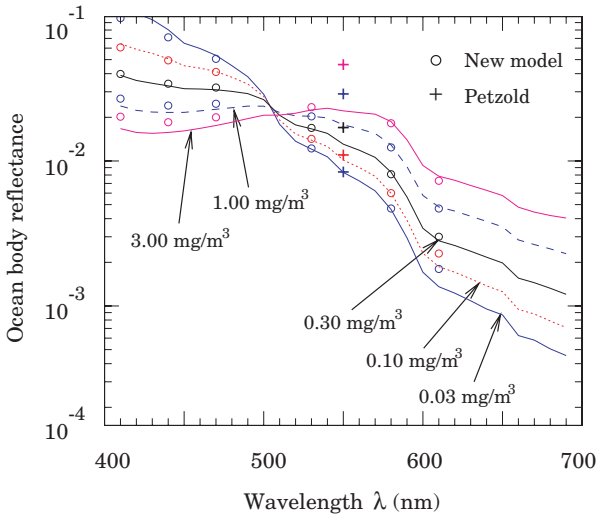

Fig. 1 Semi-empirical predictions (lines, adopted from Morel and Maritonera, 2001) versus radiative transfer computations (symbols) of ocean body reflectance as a function of wavelength and pigment concentration

3. RESULTS AND DISCUSSION

The RSP data used for this study were acquired on July 17th, 2001, at 16.13 UTC from a Cessna 210 flying at a height of 12,000 ft near the Chesapeake Lighthouse platform in the solar plane away from the Sun. Figure 2 shows for $\lambda \leq$ 865 nm the standard deviation of these data (error bars) along with the simulated results of our aerosol retrieval (see Table 1) in which the contribution of waterleaving radiances are excluded (dashed lines) and included (dotted lines).

The left, middle, and right columns are for the total reflectance, linearly polarized reflectance, and degree of linear polarization as a function of the view zenith angle, respectively. The view zenith angle is negative in the direction of the aircraft's flight; hence, the sharp increase in reflectances seen for negative viewing angles corresponds to the sun glint profile.

Table 1. Spectral dependence of real refractive index (m), single scattering albedo (ϖ) and aerosol optical thickness (AOT) for the fine mode (reff=0.15, veff=0.2) and coarse mode (reff=0.6, veff=1.0) aerosol retrieved from RSP data during the CLAMS experiment. Single scattering albedo of coarse mode is 1.0 at all wavelengths.

	Fine Mode			Coarse Mode	
	Re(m)	ϖ	AOT	Re(m)	AOT
410	1.46	0.946	0.543	1.41	0.034
470	1.44	0.941	0.411	1.41	0.034
550	1.43	0.935	0.288	1.41	0.033
670	1.42	0.921	0.187	1.39	0.030
865	1.41	0.898	0.097	1.39	0.027
1590	1.40	0.739	0.018	1.39	0.016
2250	1.39	0.547	0.007	1.39	0.011

We remark first that the retrieved aerosol has a bimodal size distribution, and that the real refractive indices for these two modes are distinctively different from one another. The spectral values of these refractive indices compare well with those retrieved by an AERONET sunphotometer on the Chesapeake Lighthouse platform (Table 2), whose values are close to the ones of the fine mode particles for the shortest wavelengths and close to the ones of the coarse mode particles for the longest wavelengths.

Table 2. AERONET values for the aerosol retrieved in Table 1

λ	Re(m)	ϖ	AOT
441	1.45	0.88	0.613
673	1.41	0.83	0.254
873	1.39	0.78	0.132
1022	1.37	0.75	0.081

Secondly, the retrieved aerosol model is consistent with the aerosol optical thickness (AOT)

times series obtained at about the time (Fig. 3) by

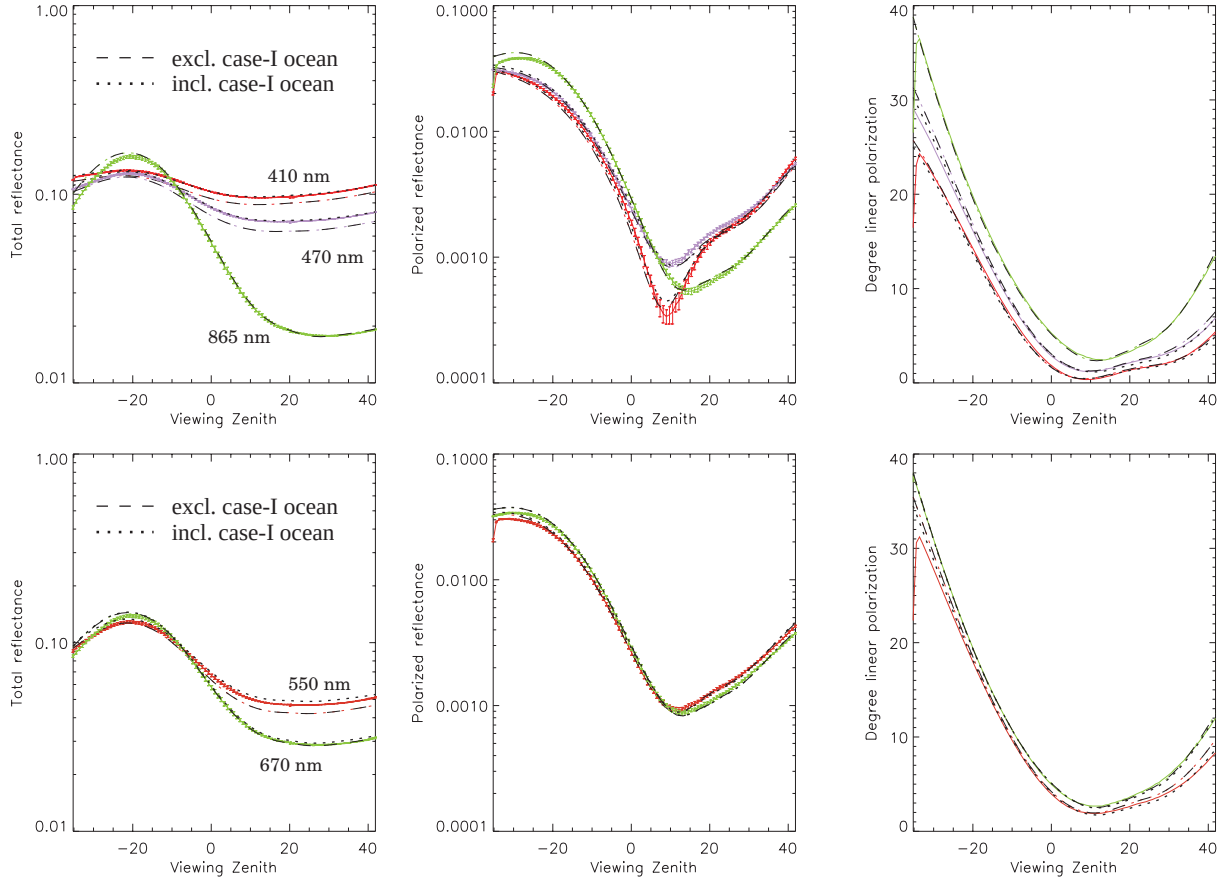

Fig. 2 RSP measurements (color bars) of the total and polarized reflectance as well as of the degree of linear polarization. Dashed and dotted lines denote simulation results for the retrieved aerosol (Table 1) in which the contribution of waterleaving radiances is ignored and accounted for, respectively.

the NASA Ames 14 channel Automated Airborne Tracking Sunphotometer (AATS-14) instrument onboard a CV-580 aircraft (*Redemann et al*., 2002). Note from this figure that the AOT exhibited strong spatial and temporal variability for this day, which may well account for the discrepancies in AOT between our retrieval and the AERONET values. Thirdly, the single scattering albedos corresponding to the retrieved imaginary part of the refractive index of the fine mode particles lies in-between those reported by AERONET (Table 2) and the value of 0.95 reported for that day from *in-situ* measurements (Vanderlei Martins, personal communication). The phytoplankton pigment concentration used for this retrieval is 1 mg/m^3, which is the average *in-situ* value obtained nearby for that day (Glenn Cota, personal communication).

Our retrieval of aerosol size distribution and real refractive index was performed for solar plane observations using for $\lambda \le 670$ nm only the polarized reflectances and for $\lambda \ge 865$ nm both the total and polarized reflectances, i.e., where the contributions of waterleaving radiances can be neglected (*Chowdhary et al*., 2002*a*). Hence, we anticipated the agreement listed above for these two aerosol products. However, the result for the aerosol single scattering albedo is new and encouraging, especially since the bio-optical equations used for our hydrosol model are based on observations for the open ocean only. Our next step is to validate these equations for the CLAMS site using *in-situ* measurements of the underwater light absorption and scattering coefficients. We expect that minor adjustments to our hydrosol model may be necessary for the coastal water observed in this study and this will lead to slightly larger contributions of waterleaving radiances. If this proves to be the case this will in turn reduce the retrieved aerosol single scattering albedos, bringing them closer to the AERONET estimates.

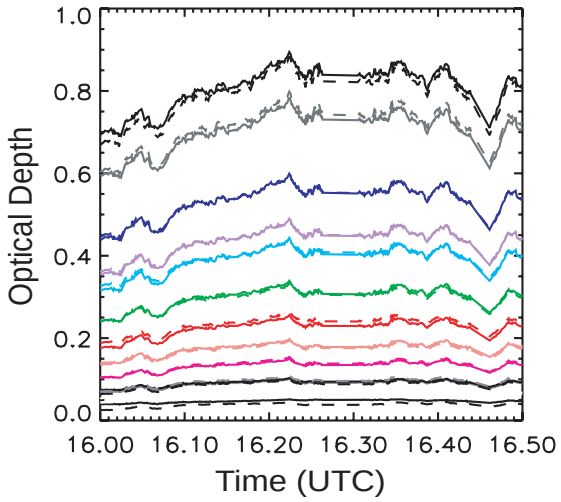

Fig. 3 Times series of the spectral dependence of AOT measured by the AATS-14 (solid lines) and reproduced from the bimodal aerosol in Table 1 (dashed lines).

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