

Retrieval of Aerosol Scattering and Absorption Properties from Photopolarimetric Observations over the Ocean during the CLAMS Experiment

JACEK CHOWDHARY,* BRIAN CAIRNS,* MICHAEL I. MISHCHENKO,⁺ PETER V. HOBBS,[#] GLENN F. COTA,[@] JENS REDEMANN,& KEN RUTLEDGE,** BRENT N. HOLBEN,⁺⁺ AND ED RUSSELL^{##}

**Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York*

⁺NASA Goddard Institute for Space Studies, New York, New York

[#]Department of Atmospheric Sciences, University of Washington, Seattle, Washington

[@]Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, Virginia

& Bay Area Environmental Research Institute, Sonoma, California

***Analytical Services and Materials, Inc., Hampton, Virginia*

⁺⁺NASA Goddard Space Flight Center, Greenbelt, Maryland

^{##}SpecTIR Corp., Santa Barbara, California

(Manuscript received 27 April 2003, in final form 18 June 2004)

ABSTRACT

The extensive set of measurements performed during the Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) experiment provides a unique opportunity to evaluate aerosol retrievals over the ocean from multiangle, multispectral photometric, and polarimetric remote sensing observations by the airborne Research Scanning Polarimeter (RSP) instrument.

Previous studies have shown the feasibility of retrieving particle size distributions and real refractive indices from such observations for visible wavelengths without prior knowledge of the ocean color. This work evaluates the fidelity of the aerosol retrievals using RSP measurements during the CLAMS experiment against aerosol properties derived from in situ measurements, sky radiance observations, and sun-photometer measurements, and further extends the scope of the RSP retrievals by using a priori information about the ocean color to constrain the aerosol absorption and vertical distribution.

It is shown that the fine component of the aerosol observed on 17 July 2001 consisted predominantly of dirty sulfatelike particles with an extinction optical thickness of several tenths in the visible, an effective radius of $0.15 \pm 0.025 \mu\text{m}$ and a single scattering albedo of 0.91 ± 0.03 at 550 nm. Analyses of the ocean color and sky radiance observations favor the lower boundary of aerosol single scattering albedo, while in situ measurements favor its upper boundary. Both analyses support the polarimetric retrievals of fine-aerosol effective radius and the consequent spectral variation in extinction optical depth. The estimated vertical distribution of this aerosol component depends on assumptions regarding the water-leaving radiances and is consistent with the top of the aerosol layer being close to the aircraft height (3500 m), with the bottom of the layer being between 2.7 km and the surface. The aerosol observed on 17 July 2001 also contained coarse-mode particles. Comparison of RSP data with sky radiance and in situ measurements suggests that this component consists of nonspherical particles with an effective radius in excess of $1 \mu\text{m}$, and with the extinction optical depth being much less than one-tenth at 550 nm.

1. Introduction

Aerosols can change the radiative budget of the atmosphere by scattering or absorbing sunlight (“direct climate forcing”) and by modifying the formation and life cycle of clouds (“indirect climate forcing”). There is significant uncertainty in our knowledge of how large these climate forcings are, with the magnitude of absorption by aerosols being a major source of uncertainty in the direct climate forcing. This is because both the amount and the vertical distribution of absorption by aerosols are poorly known, which can affect not just the magnitude of the radiative forcing by aerosols but also its sign. In order to determine the direct radiative forcing and diagnose the indirect radiative forcing caused by aerosols accurate retrievals of the size, complex refractive index, and number of these particles are required (Hansen et al. 1995) together with some estimate of the vertical extent of the aerosols. In a recent

article (Chowdhary et al. 2002) we explored the estimation of aerosol properties from visible polarized reflectances 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; see Travis 1993). We demonstrated that the polarized reflectance near the backscattering direction is essentially insensitive to light emerging from the ocean body, which enabled us to expand the spectral range of measurements that can be used for aerosol retrievals over the ocean. The RSP polarized reflectance measurements could therefore be used to retrieve the aerosol particle size distribution, the real part of the refractive index, and extinction optical depth. In this paper we extend our analysis to include an evaluation of how well the aerosol single scattering albedo and vertical distribution of the aerosol can be estimated from the full set of RSP measurements.

The Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) experiment, which took place during the period of 10 July to 2 August 2001, offers a unique opportunity to explore how well remote

Corresponding author address: Dr. Brian Cairns, NASA GISS, 2880 Broadway, New York, NY 10025.
E-mail: bc25@columbia.edu

sensing measurements, such as those made by the RSP, can constrain the retrieval of aerosol properties. The CLAMS experiment was a shortwave radiative closure experiment that involved measurements obtained from six research aircraft, several land sites, and an ocean platform. Its goal was to validate and improve atmospheric and oceanic products retrieved from observations by the Clouds and Earth's Radiant Energy System (CERES), Multiangle Imaging Spectroradiometer (MISR), and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instruments flown on board the Earth Observing System (EOS) spacecraft *Terra*. The majority of the measurements were centered close to the Chesapeake Lighthouse research platform, which is located 25 km east of Virginia Beach, Virginia, and which functions as the CERES Ocean Validation Experiment (COVE) site where radiation, meteorology, and ocean optics are monitored continuously. One component of the CLAMS field campaign consisted of operating the RSP instrument on board a Cessna 210 aircraft to measure Stokes parameters I , Q , and U of the upwelling radiation as a function of wavelength and viewing angle. Other components of the CLAMS experiment that are of interest in this work are the in situ measurements of aerosol scattering and absorption coefficients (Magi et al. 2005) and aerosol extinction optical depths (Redemann et al. 2005) collected by the instruments aboard the University of Washington Convair 580 (CV-580) research aircraft, the skylight and ocean optics measurements performed from the COVE ocean platform (Jin et al. 2005), and the optical depth measurements made by AERONET (Holben et al. 1998). The CLAMS experiment is therefore ideally suited to study the capability of retrieving aerosol single scattering albedo from RSP observations over oceans.

The measurement of the aerosol single scattering albedo ω , and its variation as a function of wavelength λ , was one of the objectives of the CLAMS field experiment since deviations of its value from that which is assumed in the algorithms used by MODIS and MISR affect their remote sensing retrievals of aerosol properties. Deviations of $\omega(\lambda)$ from unity in the visible part of the spectrum are usually considered to be caused by the presence in aerosol mixtures of strongly absorbing soot impurities. Such impurities can exist either outside nonabsorbing particles, or they can reside inside nonabsorbing particles, as is the case for soot particles scavenged by liquid droplets. Regardless of how these impurities are mixed, one still needs to retrieve both the aerosol scattering and absorption properties in order to determine $\omega(\lambda)$.

Retrievals of $\omega(\lambda)$ based on photometric measurements of the earth's reflectance in visible spectral bands perform best when applied over extremely bright, well-characterized surfaces, while retrievals of aerosol scattering optical depth, size distribution, and real refractive index are most accurate over black surfaces. Both requirements can be satisfied by selecting scenes with strong contrasts such as (near-infrared) images of a desert bordering an ocean (Tanré et al. 2001) or a (near-infrared) view of the ocean containing sun-glint and off-glint areas (Kaufman et al. 2002), but the number of images containing such scenes is typically quite limited over any given satellite orbit. Furthermore, complica-

tions arise if the reflectance of the surface is such that the aerosols have no effect on the observed radiance (Hsu et al. 2004), or if the contrast between bright and dark pixels is blurred by adjacency effects (Santer and Schmechtig 2000).

Aerosol scattering and absorption properties can also be retrieved over dark surfaces if there is sufficient multiple scattering in the atmosphere to enhance the sensitivity of remotely sensed reflectances to the single scattering albedo. This approach avoids some of the complications encountered for scenes with large surface contrasts and has been successfully used in the retrieval of aerosol single scattering albedo and aerosol optical depth in the ultraviolet (UV) from measurements made by the Total Ozone Mapping Spectrometer (TOMS) instruments (Torres et al. 2002). Although these retrievals do not provide any information about the size or real refractive index of the aerosols and must also make assumptions about the vertical extent of the aerosol layer, they can be made over both land and ocean because of the generally low and stable surface reflectance in the UV. However, in order to understand climate forcing by aerosols it is clearly of interest to extend the spectral range of single scattering albedo estimates from remote sensing measurements beyond the UV spectral domain, which is not always indicative of absorption in the visible part of the spectrum.

Over the open ocean, off-glint surface reflectances are usually much smaller and vary much less than the reflectance over land even if one includes the contributions of water-leaving radiances. This makes them an excellent background target for retrieving aerosol properties, primarily aerosol optical depth and particle size distribution (PSD) information, from space (Deuzé et al. 2000; Geogdzhayev et al. 2002; Martonchik et al. 2002; Remer et al. 2002). Typically longer wavelengths in the near-infrared (NIR) have been used in the remote sensing of aerosols over the ocean since water-leaving radiances approach zero (Gordon 1997), which means that the ocean is essentially a blackbody except for the skylight reflected off the surface. However, in order to estimate $\omega(\lambda)$ it is necessary to use shorter wavelengths that are affected by light scattered within the ocean body. Gordon and coworkers (Gordon et al. 1997; Chomko and Gordon 1998) therefore proposed using visible (VIS) reflectance measurements over oceans to constrain both aerosol absorption and the underwater-light contribution simultaneously. The rationale for this approach is that the spectral and angular behavior of light scattered by aerosols is distinctly different from that of underwater-light scattering. The primary difficulty in implementing this method is that the NIR measurements must be used to estimate the aerosol burden and identify an aerosol model. However, if only radiance measurements are available this estimate suffers from serious nonuniqueness problems (Mishchenko and Travis 1997; Chowdhary et al. 2001; Chowdhary et al. 2002). Since the aerosol burden and model are then used in the analysis of the VIS measurements to separate the contributions to the observed VIS radiances from ocean color and aerosol absorption, errors in the selection of aerosol burden and model using the NIR measurements can therefore propagate into erroneous ocean color and $\omega(\lambda)$ estimates (Li et al. 2003; Schollaert et al. 2003).