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Airborne and shipborne polarimetric measurements over open ocean and coastal waters: Intercomparisons and implications for spaceborne observations

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A B S T R A C T

Comprehensive polarimetric closure is demonstrated using observations from two in-situ polarimeters and Vector Radiative Transfer (VRT) modeling. During the Ship-Aircraft Bio-Optical Research (SABOR) campaign, the novel CCNY HyperSAS-POL polarimeter was mounted on the bow of the R/V Endeavor and acquired hyperspectral measurements from just above the surface of the ocean, while the NASA GISS Research Scanning Polarimeter was deployed onboard the NASA LaRC's King Air UC-12B aircraft. State-of-the-art, ancillary measurements were used to characterize the atmospheric and marine contributions in the VRT model, including those of the High Spectral Resolution Lidar (HSRL), the AErosol RObotic NETwork for Ocean Color (AERONET-OC), a profiling WETLabs ac-9 spectrometer and the Multi-spectral Volume Scattering Meter (MVSM). An open-ocean and a coastal scene are analyzed, both affected by complex aerosol conditions. In each of the two cases, it is found that the model is able to accurately reproduce the Stokes components measured simultaneously by each polarimeter at different geometries and viewing altitudes. These results are mostly encouraging, considering the different deployment strategies of RSP and HyperSAS-POL, which imply very different sensitivities to the atmospheric and ocean contributions, and open new opportunities in above-water polarimetric measurements. Furthermore, the signal originating from each scene was propagated to the top of the atmosphere to explore the sensitivity of polarimetric spaceborne observations to changes in the water type. As expected, adding polarization as a measurement capability benefits the detection of such changes, reinforcing the merits of the full-Stokes treatment in modeling the impact of atmospheric and oceanic constituents on remote sensing observations.

1. Introduction

Within the discipline of ocean color, many attempts to obtain the optical and microphysical parameters of submarine particulates often reveal mismatches between data and simulations, deriving from the large variability of the water Inherent Optical Properties (IOPs), especially regarding the scattering properties of the samples (Brown and Gordon, 1973; Jonasz and Prandke, 1986; Loisel and Stramski, 2000; Loisel et al., 2008) and poorly understood spectral behaviors (Kostadinov et al., 2009). This complexity is exacerbated in coastal waters, where the input from freshwater sources usually cause the amount of Color Dissolved Organic Matter (CDOM) to spike, and the

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ocean color is affected by a multitude of additional substances such as minerals and detrital matter originating from rivers and run-offs. In addition, mechanical stressors like waves and tides contribute to turbulent mixing.

Early advances in polarimetric remote sensing (Hansen and Travis, 1974; Cairns et al., 1999) have been demonstrated to provide unique constraints on the determination of the optical and microphysical properties of atmospheric particulates suspended both over ocean (Chowdhary et al., 2012; Ottaviani et al., 2012a) and land (Waquet et al., 2009), such as the parameters defining their size distributions and both real and imaginary parts of their complex refractive index, recognized as a proxy for the chemical composition. Obvious interest now exists in expanding this potential to the detection of characteristics of underwater particulates (Chami et al., 2001; Chami and Platel, 2007; Tonizzo et al., 2009; Lotsberg and Stamnes, 2010; Ibrahim et al., 2016; Zhai et al., 2017). The fundamental issue concerning the application of polarimetry-based techniques to the retrieval of oceanic parameters from space is that the polarization signatures of light emerging from the water body are generally small in magnitude because 1) the relative index of refraction of the particulates is much smaller than for atmospheric particles (1.04–1.06 for organic and 1.15–1.20 for inorganic particles), 2) of multiple scattering effects and 3) the directions of scattered light carrying the maximum degree of polarization are usually outside the Snell's window and are not detectable above the water surface. These signatures also tend to be further washed out as the radiance from the water body travels through the air-water interface (Tonizzo et al., 2011; Mobley, 2015; Foster and Gilerson, 2016), and especially through the highly polarizing atmospheric medium where scattering generates up to 90% of the visible signal at the top of the atmosphere (TOA), in addition to the large impact of surface processes such as the glint caused by the specular reflection of the direct solar beams (Ottaviani et al., 2008a). Starting from the pioneering efforts to understand the submarine polarization light field in the 1950s (Waterman, 1954), progressively better matches between experimental data, theoretical analyses and numerical simulations were achieved in the following decades (Ivanoff et al., 1961; Timofeeva, 1961; Voss and Fry, 1984; Adams et al., 2012; Kattawar, 2013). Organic particles are weak scatterers because of their low refractive indices (Aas, 1996), and therefore modulate the underwater Degree of Linear Polarization (DoLP) primarily via their absorption coefficient. In Case I waters, this leads to a small decrease in the DoLP compared to that of pure seawater, with observed maximum DoLPs of ~ 0.7 (Chami et al., 2001). These maxima occur at around 90° from the direction of propagation of the transmitted beam since, unlike reflection, transmission across the interface does not introduce significant polarization ($< 5\%$ for Solar Zenith angles up to 80°, see e.g. Kattawar and Adams, 1989). Conversely, in Case II waters the higher refractive indices of inorganic particles (Babin et al., 2003) imply more complex scattering patterns (as is the case for atmospheric aerosols), which can be used in principle to distinguish them from organics (Chami, 2007; Lotsberg and Stamnes, 2010). However, the significant amounts of minerals typically found in coastal waters also favor multiple scattering, which suppresses the polarization originating from the single-scattering properties and yields maximum DoLPs of ~ 0.2–0.4 (Tonizzo et al., 2009).

With the exceptions of the POLarization and Directionality of the Earth's Reflectances (POLDER) series of instruments (Fougnie et al., 2007), decommissioned in 2013, and the Aerosol Polarimetry Sensor (APS) on board the Glory mission (Mishchenko et al., 2007) which however failed to reach orbit in 2011, no spaceborne polarimeter has yet been deployed. Therefore, several agencies worldwide presently advocate the use of dedicated polarimeters: JAXA's Second-generation GLobal Imager (SGLI) sustained a successful launch on 23 December, 2017, as this paper was in press, while ESA/Eumetsat's Multi-Viewing Multi-Channel Multi-Polarization Imaging (3MI) and NASA's Plankton, Aerosol, Clouds, and ocean Ecosystem (PACE, (PACE Science Definition Team, 2012)) missions, specifically designed to assess the interplay between carbon cycle and climate, are projected to launch in 2021 and 2023, respectively. It is therefore imperative for the success of these forthcoming ocean color spaceborne missions to explore the sensitivity of the polarized signal at the TOA to ocean and atmospheric constituents, in order to establish thresholds for detection. Recently, a few studies have targeted these space-based potential retrievals finding non-negligible polarization contributions at the shortest end of the spectrum over open ocean (Chowdhary et al., 2012; Harmel and Chami, 2008; Chami, 2007; Harmel, 2016) and at near-infrared wavelengths in coastal waters (Loisel et al., 2008), but also some signatures at wavelengths in the green (Ibrahim et al., 2016).

The focus of this paper is to demonstrate comprehensive closure between ship- and airborne measurements of polarized radiance and inherent optical properties for a variety of ocean and aerosol conditions using robust vector radiative transfer (VRT) computations, which should be considered as a critical step toward the application of such measurements in advanced inversion models for atmospheric correction and the retrieval of additional water parameters. A description of the instrumentation is given in Section 2, followed by the description of the modeling approaches (Section 3) and the discussion on the match sought to the RSP and HyperSAS-POL observations (Section 4). To extend the application of the results to spaceborne observations, Section 5 presents the changes in total and polarized reflectance at the TOA caused by variations in the aerosol and oceanic parameters used to model the scenes. Such an excercise helps quantifying the improvements that polarimetry can bring to space-based retrievals of the descriptive parameters.

2. Instruments and method

2.1. SABOR field campaign

The NASA SABOR (Ship-Aircraft Bio-Optical Research) scientific mission took place from 17 July to 7 August, 2014 in the Atlantic ocean off the US East Coast. The research vessel (R/V) Endeavor, operated by the Graduate School of Oceanography at the University of Rhode Island, sailed from Narragansett, RI into the Gulf of Maine. It then proceeded to Bermuda before returning to Narragansett through Norfolk, VA. The effort aimed at state-of-the-art measurements over a large range of water types, acquired through a redundant set of both remote-sensing and in-situ instruments. Particular emphasis was placed on investigating the polarization signatures of ocean constituents, with the intention of improving the knowledge on critical biogeochemical processes and the links between photosynthetic activity and primary production.

In this work a closure study is presented, that exploits in-situ measurements of water optical properties and atmospheric parameters collected from the R/V Endeavor, in order to assemble the input to VRT simulations used to reproduce the spatially and temporally co-located observations from two spectropolarimeters: the HyperSAS-POL (City College of New York (CCNY)), installed on the mast of the ship, and the Research Scanning Polarimeter (RSP, NASA GISS) deployed together with the High-Spectral Resolution Lidar (HSRL) on the NASA Langley Research Center UC-12B aircraft, which overflew the ship at an altitude of ≈ 9 km. The observations analyzed in this work pertain to two very different water types: an open-ocean station near Bermuda (identified as LS6; 27 July, 2014) and a near-coastal station (identified as LS9; 30 July, 2014) located in proximity of the CERES Ocean Validation Experiment (COVE) AErosol RObotic NETwork (AERONET; Holben et al., 1998) station, near the mouth of Cheseapeake Bay, VA. In Fig. 1, near real-time imagery from the MODerate-resolution Imaging Spectrometer (MODIS) on the Terra spacecraft is included for context. The LS6 station was characterized by exceptionally clear waters, as opposed to the shallower, near-coastal waters met at LS9. In both cases, atypical aerosol loads with complex vertical stratification and spatial variability were present. Incidentally, the RSP had encountered a similar scenario