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Ocean-color radiometry across the Southern Atlantic and Southeastern Pacific: Accuracy and remote sensing implications

Natália de Moraes Rudorff [a,*], Robert Frouin [b], Milton Kampel [a], Clemence Goyens [c], Xavier Meriaux [c], Brian Schieber [b], B. Greg Mitchell [b]

[a] Instituto Nacional de Pesquisas Espaciais, Avenida dos Astronautas, 1758 São José dos Campos, São Paulo, Brazil
[b] Scripps Institution of Oceanography, University of California San Diego, La Jolla Shores Drive, La Jolla, CA 92037, USA
[c] Laboratoire d'Océanologie et de Géosciences, Université du Littoral-Côte d'Opale, 32 Avenue Foch, 62930 Wimereux, France

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ABSTRACT

Ocean color radiometry (OCR) provides valuable data for biogeochemical oceanography. In situ OCR measurements are used in the development and validation of bio-optical models and vicarious calibration of satellite ocean-color sensors. It is thus crucial to obtain accurate in situ OCR measurements, which is a challenge, especially in regions subjected to adverse environmental conditions and where waters are optically complex. In the present work, the accuracy of in situ OCR is analyzed with data acquired in a wide range of bio-geographic provinces across the Southern Atlantic and Southeastern Pacific during the R/V Melville MV1102 cruise. Varied techniques employed to measure above-water remote sensing reflectance (R_{rs}) are inter-compared. Measured R_{rs} is also compared with modeled R_{rs} in a closure experiment. The impact of R_{rs} uncertainties on the retrieval of chlorophyll a concentration (Chl*a*) and inherent optical properties (IOPs) is evaluated using operational bio-optical algorithms. The relative percent difference (RPD) between R_{rs} measured by the various techniques ranged from 12 to 26% for the ocean-color bands (412–555 nm), and 3–12% for the ratios (412–510/555). A merged R_{rs} obtained by averaging the different types of measurements, INS, is recommended to reduce uncertainties. The coefficient of variation of INS and reflectance ratios was 11–13% and 3–5%, respectively. The RPD between INS and modeled R_{rs} and the corresponding ratios ranged from 18 to 34% and from 13 to 17%, respectively. Complete closure could not be obtained due to both measurement and modeling uncertainties. The impact of INS uncertainties on retrieved Chl*a* and IOPs was generally smaller than the intrinsic errors of the inversion schemes. The results suggest that even though more accurate ocean-color radiometry is desirable, improving retrieval algorithms is essential to properly describing and furthering our understanding of bio-optical variability in the world's oceans.

1. Introduction

Ocean color radiometry (OCR) has developed rapidly since the launch of the first ocean color satellite sensor, the *Coastal Zone Color Scanner* (CZCS), in the late 1970s. With more sophisticated sensors onboard the subsequent satellites, generating an enormous volume of data across the global ocean, the impetus has been strong to develop and provide high quality ocean-color products for applications in various fields of biogeochemistry, oceanography, and atmospheric sciences (McClain, 2009). The indirect measurements obtained by the satellite sensors are however highly influenced by various sources of noise and uncertainty associated primarily to atmospheric interference (IOCCG, 2010). Hence, the development and maintenance of OCR satellite programs rely heavily on in situ radiometric measurements, which are used for the development and validation of bio-optical models, validation of satellite products, and vicarious calibration of satellite sensors (Bailey & Werdell, 2006; Hooker, Lazin, Zibordi, & McLean, 2002).

To obtain accurate in situ radiometry however, is as well, not a trivial task. The difficulties have been reported in several works with in situ experiments and radiative transfer modeling (Antoine et al., 2008; Hooker & Morel, 2003; Hooker, Zibordi, Berthon, & Brown, 2004; Hooker et al., 2002; Mobley, 1999; Piskozub, Stramski, Terrill, & Melville, 2009; Stramski & Tegowski, 2001; Toole, Siegel, Menzies, Neumann, & Smith, 2000; Zibordi, Berthon, & D'Alimonte, 2009). According to the SeaWiFS protocol the above-water remote sensing reflectance, hereafter R_{rs}, should be accurate to ±5% to meet the goals of satellite vicarious calibration and bio-optical modeling (McClain, Feldman, & Hooker, 2004). This accuracy may result in a 35% error in the retrieved Chl*a* (Bailey & Werdell, 2006; Werdell et al., 2009).

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* Corresponding author. Tel.: +55 12 32086498.
E-mail addresses: nmr@dsr.inpe.br (N. de Moraes Rudorff), rfrouin@ucsd.edu (R. Frouin), clemence.goyens@univ-littoral.fr (C. Goyens), xavier.meriaux@univ-littoral.fr (X. Meriaux), bschieber@spg.ucsd.edu (B. Schieber), gmitchell@ucsd.edu (B.G. Mitchell).
URL: milton@dsr.inpe.br (M. Kampel).

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There are two main approaches to obtain in situ R_{rs}: the above and in-water approaches. Well defined protocols exist for the measurement procedures and data processing for each one (Mueller, Fargion, & McClain, 2003). Nevertheless, further improvements are still needed, as uncertainties may range from a few percent (>5%) to several tens percent (over 50%), with the highest levels generally associated to above-water measurements, optically complex waters and adverse environmental conditions (Hooker & Morel, 2003; Hooker et al., 2002, 2004; Kowalczuk, Durako, Cooper, Wells, & Souza, 2006; Toole et al., 2000).

An advantage of the above-water approach is that the measurements can be obtained with the platform in movement and take advantage of opportunity cruises (Deschamps, Fougnie, Frouin, Lecomte, & Verwaerde, 2004). It is also considered a better approach for turbid waters where the in-water method is usually more biased due to the high attenuation and stratification of the water column (Mueller et al., 2003; Ruddick, De Cauwer, Park, & Moore, 2006). The main constraints and difficulties are the requirement of clear skies for instruments that need aerosol optical thickness e.g., SIMBAD (Deschamps et al., 2004), and the contamination of reflected skylight on the ocean surface (Mobley, 1999; Zibordi, Hooker, Berthon, & D'Alimonte, 2002), e.g., ASD, *Analytical Spectral Devices*.

The in-water approach is considered to provide more accurate radiometric measurements (Hooker & Maritorena, 2000). Nevertheless, there are also some important issues related to the variability of the submersed light field and extrapolation procedures. Besides the vertical stratification of the bio-optical properties, the underwater light field can be affected by diverse sources of noise, which include: focus and defocusing effects of the downwelling solar rays (Gernez & Antoine, 2009; Mueller et al., 2003; Zibordi et al., 2009), effects of wave motion (Stramska & Dickey, 1998), bubble clouds (Flatau, Piskozub, & Zaneveld, 1999; Piskozub et al., 2009; Stramski & Tegowski, 2001), and illumination variation during the cast (Mueller et al., 2003). Hence, this approach may also provide R_{rs} with high uncertainty levels if the above issues are not properly addressed.

Some works have attempted to compare measured R_{rs} with modeled R_{rs} using forward semi-analytical models (Chang, Barnard, & Zaneveld, 2007; Green & Sosik, 2004). Such a closure experiment presents high challenges as there may be significant uncertainties also associated to the modeled R_{rs} due to biases in the inherent optical properties (IOPs) and constants used. Nevertheless, comparing modeled and measured quantities is an interesting approach, since the R_{rs} is obtained in a totally independent way, and the modeled R_{rs} is not affected at all by environmental variability and instrumental effects. Thus, the closure experiment could highlight some of these effects on the different approaches, and indicate least biased retrievals. Other investigations have used radiative transfer modeling (e.g., Hydrolight) to analyze the relations between apparent and inherent optical properties and the environmental influences on the light field (Mobley, 1999). As a result some works have provided look-up-tables (LUTs) with parameterized coefficients that can be used to correct for some effects such as: the sea surface reflectance factor for sky glint (Mobley, 1999) and the environmental and bidirectional f/Q factors (Morel, Antoine, & Gentili, 2002).

Ideally it would be wise to avoid the influence of the major sources of errors, especially due to agitated seas and variable sky conditions. Nevertheless, during an oceanographic expedition one may not be able to wait for favorable conditions and proper acquisition and data processing are crucial to obtain accurate in situ R_{rs}. In this context the present work aimed to assess the uncertainty of in situ radiometric and bio-optical measurements made during the February–March 2011 R/V Melville cruise (MV1102), across the Southern Atlantic and Southeastern Pacific. An inter-comparison framework was applied using, i.e., the above-water Fieldspec HandHeld ASD (Analytical Spectral Devices Inc.), the two free falling profilers: the HyperOCR PRO II (HOCR, Satlantic Inc.) and Profiling Reflectance Radiometer (PRR, Biospherical Inc.), and the winched profiler TriOS (Optical Sensors Inc.). The uncertainty analysis included (i) an intra-comparison to analyze environmental and instrument uncertainties within each approach, (ii) an inter-comparison between the approaches, (iii) a closure experiment, comparing measured and modeled R_{rs}, and (iv) the implications of the uncertainties for ocean-color products. The uncertainties associated to IOPs and Chl*a* were also analyzed. The rationale was to investigate all possible uncertainties affecting in situ ocean-color radiometry and related bio-optical measurements, in an oceanographic expedition sampling a wide range of bio-geographic provinces and under mostly adverse environmental conditions. The goal was to provide the best R_{rs} and its uncertainty, as well as to recommend procedures for in situ radiometry.

2. Material and methods

2.1. Cruise description and study area

The MV1102 cruise onboard R/V Melville (Scripps Institution of Oceanography, SIO) was conducted from Cape Town, South Africa (02/22/2011) to Valparaiso, Chile (03/14/2011), near the end of the 2011 austral summer. A total of 20 stations with radiometric and bio-optical measurements were made across the Southern Atlantic (33°–53° S and 15°–70° W) and Southeastern Pacific (47–35° S and 74–76° W) (Fig. 1). The region is subjected to predominantly adverse conditions with strong winds, currents, and waves, due to the persistent westerlies. Mid-latitude atmospheric cyclones and fronts also influence surface wind and waves and contribute to persistently high cloudiness (Haynes, Jakob, Rossow, Tselioudis, & Brown, 2011).

In terms of water masses and bio-optical properties, the sampled region is characterized by highly diverse systems. The South African coast is under influence of the Benguela Upwelling System (BENG) that brings to surface cold and nutrient enriched waters from the deep South Atlantic Central Water (SACW), promoting phytoplankton growth (Aiken et al., 2009; Longhurst, 2007). The South Atlantic Subtropical Convergence Zone (STCZ), located at the frontal boundary between the South Atlantic Gyre (SAG) and the Southern Ocean, is also a highly dynamic region marked by a sharp Chl*a* and temperature–salinity gradient (Longhurst, 2007). The Patagonian Shelf Large Marine Ecosystem (PSME) is a highly productive system, due to the intrusion of High Nutrient–Low Chlorophyll (HNLC) Subantarctic waters, carried by the Malvinas Current, onto the shelf, with strong mixing due to eddies and vortices (Longhurst, 2007; Lutz et al., 2010). The Magellan Strait is a narrow and steep channel which connects the South Atlantic and South Pacific oceans, at the southern end of the South American continent, surrounded by fluvial–glacial fjords and regulated by strong tides (Antezana, 1999). The south Chilean coast is influenced by both the Eastern Boundary Upwelling System and intrusions of Subantarctic waters, which periodically enhance phytoplankton growth along the shelf (Romero & Hebbeln, 2003; Romero, Hebbeln, & Wefer, 2001). Despite the relevance of these regions there are only few in situ data sets of bio-optical and radiometric measurements.

The stations were made once a day, around 11–13 h local time to avoid high solar zenith angles (SZAs). For the sake of instrument precaution each deployment was made in subsequent times. The above-water ASD (Fig. 2a), in-water HOCR (Fig. 2d), PRR (Fig. 2c), and TriOS (Fig. 2e) were independently calibrated, and the data processed by the laboratories that provided each instrument with the aim to analyze the bulk uncertainties of in situ ocean color radiometry in a realistic framework of global bases (Bailey & Werdell, 2006).

Water collection was made with a rosette bottle system coupled with a Conductivity–Temperature–Depth (CTD) sensor (Fig. 2f) at four depths in the upper layer, i.e., at 1 m; between 7 and 40 m, at the fluorescence maximum depth (Fl_{max}), and below Fl_{max} (up to 100 m deep). Sub-samples were separated for colored dissolved organic matter (CDOM) absorption (a_s), particle absorption (a_p), and pigment analysis