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A multi-sensor approach for the on-orbit validation of ocean color satellite data products

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Abstract

The validation of satellite ocean color data products is a critical component in establishing their measurement uncertainties, assessing their scientific utility, and identifying conditions for which their reliability is suspect. Such efforts require a considerable amount of high quality in situ data, preferably consistently processed and spanning the satellite mission lifetime. This paper outlines the NASA Ocean Biology Processing Group's (OBPG) method for validating satellite data products using in situ measurements as ground truth. Currently, the OBPG uses the described method for validating several historical and operational ocean color missions. By way of a case study, results for the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) are shown. These results indicate that for the majority of the global ocean, SeaWiFS data approach the target uncertainties of ±5% for clear water radiances as defined prior to launch. Our results add confidence in the use of these data for global climate studies, where a consistent, high quality data set covering a multi-year time span is essential.

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1. Introduction

Estimating the rates and magnitudes of ocean primary productivity on regional and global scales is key to understanding the role of the ocean in the Earth's carbon cycles (Behrenfeld & Falkowski, 1997b; Longhurst et al., 1995; Kuring et al., 1990; Prasad & Haedrich, 1994). The synoptic views of the marine biosphere captured by satellite-based ocean color instruments provide valuable data at spatial and temporal scales unattainable with shipboard or moored instrumentation. This was aptly demonstrated by the proof-of-concept Coastal Zone Color Scanner (CZCS) (Gordon et al., 1983; Hovis et al., 1980). Drawing on its successful legacy, a number of advanced ocean color satellite instruments were launched in the past decade [e.g., the Ocean Color and Temperature Scanner–OCTS (Iwasaki et al., 1992), the Sea-viewing Wide Field-of-view Sensor–SeaWiFS (Hooker et al., 1992), the Moderate Resolution Imaging Spectroradiometer–MODIS (Salomonson et al., 1989), and the Medium Resolution Imaging Spectrometer–MERIS (Rast & Bezy, 1999)]. More are scheduled for launch in the near future [e.g., the Visible Infrared Imager/Radiometer Suite–VIIRS (Welsch et al., 2001)–on board the National Polar-orbiting Operational Environmental Satellite System].

Space-borne ocean color instruments measure the spectrum of sunlight reflected from ocean waters at selected visible and near-infrared wavebands. These radiance spectra are used to estimate geophysical parameters, such as the surface concentration of the phytoplankton pigment chlorophyll *a*, C_a, via the application of bio-optical algorithms (O'Reilly et al., 1998). These derived data products are subsequently input into secondary (i.e., higher order) geophysical algorithms, as is the case for marine primary production, PP (e.g., Behrenfeld and Falkowski, 1997a). The uncertainties in global estimates of C_a and PP are contingent on the uncertainties of their model input parameters (e.g., spectral reflectance and C_a). Predictably, uncertainty increases for secondary algorithms that require derived products as input (Behrenfeld & Falkowski, 1997b).

Global accuracy goals for spectral reflectance and C_a for modern sensors are commonly defined as 5% and 35%, respectively, in clear, natural waters (Hooker et al., 1992). As such, statistical validation of these products is prerequisite in verifying that such goals are being met. Following McClain et al. (2002), we define validation as "the process of determining the spatial and temporal error fields of a given biological or geophysical data product". The NASA Ocean Biology Processing Group (OBPG) at the Goddard Space Flight Center executes satellite validation activities via the direct comparison of remotely sensed measurements with coincident in situ measurements. The OBPG maintains responsibility for the operational processing of ocean color data within NASA, as well as the post-launch calibration, validation, and subsequent distribution of the data products. A significant component of

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this responsibility is quantifying how well the satellite-retrieved products reflect true conditions. As will be highlighted in a subsequent section, a comprehensive in situ data set with measurements covering a wide range of oceanographic conditions is essential in this process (Werdell & Bailey, 2005).

Much recent refereed research on ocean color validation efforts focuses on comparisons of satellite-derived C_a retrievals with regional in situ data sets, many of which are based on specific, or single, field campaigns (e.g. Barbini et al., 2005; D'Ortenzio et al., 2002; Gohin et al., 2002; He et al., 2000; Smyth et al., 2002). While a necessary step towards a comprehensive understanding of the uncertainties in global primary production models, validation of satellite-retrieved C_a alone is insufficient, as uncertainties in the retrievals are strongly affected by the uncertainties in the C_a algorithm applied. Moreover, as many C_a algorithms make use of reflectance ratios (O'Reilly et al., 1998), underlying problems with radiometry are often masked. Since the primary measurement of satellite-based sensors is spectral radiance, the focus of the OBPG validation activity is on the retrieved water-leaving radiance ($L_{\mathrm{wn}}(\lambda)$) estimates. Several other independent studies include validation of spectral reflectance (e.g., Froidefond et al., 2002; Gordon et al., 1983; Pinkerton & Aiken, 1999); however, these also suffer from the limitations imposed by short-term, regional or cruise-specific data sets.

In developing their calibration and validation program, the OBPG adopted the approach of globally validating satellite ocean color sensors throughout the life of their missions, particularly for data products to be used in long-term multi-sensor time series (Barnes et al., 2003; Donlon et al., 2002). Without continuous validation for monitoring the long-term stability of satellite instruments, such efforts are hindered as uncertainties in sensor calibration are not tracked, and potential instrument effects may, therefore, be misinterpreted as geophysical phenomena. This is particularly true for remotely sensed ocean color as the $L_{\mathrm{wn}}(\lambda)$ component accounts for only about 10% of the total reflectance signal received by the sensor at the top of the atmosphere in the visible wavelengths (Gordon, 1998).

Ultimately, experience has demonstrated that a number of benefits are realized with a rigorous validation activity, including: (i) the assignment of a measure of accuracy to satellite-derived products, which lends confidence to their scientific utility in higher-order derived products (Behrenfeld & Falkowski, 1997b); (ii) the verification of on-orbit satellite calibration (Barnes et al., 2001); (iii) the evaluation of the long-term stability of satellite measurements (Franz et al., 2005); and (iv) the identification of conditions, either oceanic, atmospheric or satellite specific, for which satellite-derived products are invalid. In this paper, we outline and define the NASA OBPG satellite validation approach. The method described may be applied to most sensors with few modifications, and in fact, the OBPG incorporates these methods in their current OCTS, SeaWiFS, and MODIS validation activities. Results for SeaWiFS are presented.

4. Discussion

Given the rate of return of approximately 15%, the task of validating ocean color sensors requires a dedicated in situ data collection effort to ensure that sufficient data are available to assess the satellite sensor performance on regional, global, and mission-long scales. The SeaWiFS Project Office (the precursor of the OBPG) understood this requirement early in mission planning (Hooker & McClain, 2000; Hooker et al., 1992), and initiated the development of SeaBASS to address this need. As a direct result of this foresight, the data set presented here covers a wide geographic diversity (Fig. 2) and spans the three trophic regimes–oligotrophic ($C_a \leq 0.1$ mg m^{-3}), mesotrophic ($0.1 < C_a \leq 1.0$ mg m^{-3}) and eutrophic ($C_a > 1.0$ mg m^{-3})–as defined by Antoine et al. (1996) (Fig. 8). Despite the fact that nearly 40% of the radiometric measurements are in the deepwater subset, less than 5% are from oligotrophic waters. As for chlorophyll, only slightly more than 5% of the measurements are from oligotrophic waters. The vast majority of the data, both radiometric and chlorophyll, are within the mesotrophic and eutrophic ranges.

The global SeaWiFS comparisons indicate that the remote sensor typically retrieves water-leaving radiance within 14–24% of the coincident in situ measurements. This is 3–5 times the stated goal of a 5% absolute water-leaving radiance accuracy (Hooker et al., 1992). However, as reported in Hooker and Maritorena (2000), most, if not all, of this target uncertainty can be absorbed by the uncertainty in the in situ measurements. In an effort to minimize the uncertainties with the processing of the in situ radiometric profile data, tools were developed for consistently processing data archived within SeaBASS (Werdell & Bailey, 2005). In the best case scenario, however, these uncertainties remain on the order of 3–5% (Hooker & Maritorena, 2000). If we assign a nominal (and likely conservative) 5% uncertainty to the in situ measurement, the global SeaWiFS accuracy may be considered to lie within 9–19%. Further reducing the analysis to the deepwater subset puts the SeaWiFS radiance accuracy within 6–12% for the majority of the global ocean. Note that the Level 3 products (4 km and 9 km) used in most climate research are dominated by the deepwater pixels.

A serious limitation of the current atmospheric correction algorithm is its inability to correct for absorbing aerosols. This limitation will affect the water-leaving radiance retrievals for the shorter wavelengths (e.g. 412 nm) more than those for longer wavelengths. The effect will be limited to moderate-to-low concentrations of absorbing aerosols as higher concentrations are often flagged as clouds by the MSL12 processing code. Until such time as absorbing aerosol detection and correction is successfully implemented in the atmospheric correction algorithm (e.g. Nobileau and Antoine, 2005), satellite ocean color measurements over areas with absorbing aerosols will be severely, and negatively, affected.

For both the global data set and the deepwater subset, the median satellite to in situ ratio shows a negative bias for all bands, except the deepwater $L_{\mathrm{wn}}(412)$, which has a slight positive bias. The negative bias is consistent at approximately 9% for the global L_{wn}. For the deepwater subset, the bias is less, at about 2.5%–4%. This suggests a potential error in the estimation of the magnitude of the aerosol radiance by the atmospheric correction algorithm.

Ocean color data products are by their very nature *derived* products. For all instruments, the sensor measures top of atmosphere (TOA) radiance, and an atmospheric correction algorithm is applied to retrieve estimates of spectral water-leaving radiance.