Remote Sensing of Environment 139 (2013) 398–414

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Evaluation of the VIIRS ocean color monitoring performance in coastal regions

Soe Hlaing [a], Tristan Harmel [b], Alexander Gilerson [a,*], Robert Foster [a], Alan Weidemann [c], Robert Arnone [d], Menghua Wang [e], Samir Ahmed [a]

[a] Optical Remote Sensing Laboratory, City College, New York, NY 10031, USA
[b] Laboratoire d'Océanographie de Villefranche, Université Pierre et Marie Curie, Centre National de la Recherche Scientifique, Villefranche-sur-Mer, France
[c] Naval Research Laboratory, Stennis Space Center, MS 39529, USA
[d] University of Southern Mississippi, MS 39529, USA
[e] NOAA/NESDIS Center for Satellite Applications and Research, College Park, MD 20740, USA

ARTICLE INFO

Article history:
Received 21 March 2013
Received in revised form 22 July 2013
Accepted 17 August 2013
Available online 17 September 2013

Keywords:
Ocean color radiometry
Coastal waters
Satellite
VIIRS
MODIS
AERONET-OC
SeaPRISM
Validation
Water-leaving radiance
Angstrom coefficient
Aerosol optical thickness
Atmospheric correction

ABSTRACT

Ocean color (OC) remote sensing has entered a new phase with the successful deployment of the Visible Infrared Imager Radiometer Suite (VIIRS) sensor aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite. The representativeness and accuracy of the VIIRS geophysical products need to be assessed before a wide use of these data by the scientific community. As an integral part of the VIIRS sensor calibration and validation efforts, our group has been continuously monitoring the validity of the VIIRS's OC and atmospheric data stream through time-series in-situ data acquired at the observatory sites which are part of the AERONET-OC network. This paper addresses the preliminary evaluations of the VIIRS sensor's performance for retrieving OC data of typical coastal water environments, by carrying out time-series, as well as qualitative and quantitative match-up comparisons analysis between in-situ and satellite retrieved OC data. Initial time-series match-up comparisons carried out for a year period (January to December, 2012) show that VIIRS data exhibits strong temporal and statistical agreements with AERONET-OC data demonstrating a potential in enhanced coastal water monitoring from space. VIIRS data of two NASA-OBPG processing schemes which apply different vicarious calibration gains and NOAA-IDPS system are analyzed based on in-situ data of LISCO and WaveCIS AERONET-OC sites which are located in Long Island Sound and Gulf of Mexico respectively as well as OC retrievals of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the Aqua satellite. The underlying cause of the discrepancies observed in VIIRS retrieved normalized water-leaving radiances is also investigated. Finally, as the NASA-OBPG and NOAA-IDPS processing schemes for ocean color data of the VIIRS sensor continue to evolve, the results underline the necessity for monitoring and assessing the validity and consistency of VIIRS' ocean color products, especially for coastal waters.

1. Introduction

The Suomi National Polar-orbiting Partnership (SNPP) spacecraft was successfully launched on October 28, 2011 bearing several Earth observing instruments, including the Visible-Infrared Imager Radiometer Suite (VIIRS). This mission enables the scientific community to pursue the Earth observation effort initiated by, among others, the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) to provide long time-series of accurate data required for global climate monitoring (Murphy et al., 2001). The VIIRS characteristics are especially well-suited for ocean color (OC) radiometry applications such as oceanic algal biomass or coastal waters monitoring. The recent National Research Council report (Committee on Assessing Requirements for Sustained Ocean Color Research, 2011) defined several requirements in order to ensure the sufficient data quality for OC scientific exploitation. Among them, calibration methods and algorithms have been developed based on lessons learned from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), which was operational between 1997 and 2010, and the currently operational MODIS sensors. These products are being distributed as evaluation products for assessment by the SNPP Science Team and the research community. With a view to producing the standard suite of ocean color products from the VIIRS mission, it is now time to evaluate and validate the OC products estimated from the VIIRS measurements and to highlight their specific quality and sensitivity to the environmental conditions.

In processing of these evaluation products, NASA is deriving a continuous temporal calibration based on the on-board calibration measurements for the visible bands, and then reprocessing the full mission to produce a continuously calibrated sensor data records (SDR) product. The calibration of the NASA-VIIRS ocean color products is based on

* Corresponding author. Tel.: +1 212 650 8413.
E-mail address: gilerson@ccny.cuny.edu (A. Gilerson).

0034-4257/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2013.08.013

results from the prelaunch characterization (e.g., spectral response, polarization sensitivity, and response versus scan), and on-orbit temporal calibration (lunar measurements and solar diffuser measurements). In addition, the Ocean Biology Processing Group (OBPG) of NASA applies an additional vicarious calibration during SDR to OC Level-2 processing (Franz, Bailey, Werdell, & McClain, 2007; Gordon, 1998; Wang & Gordon, 2002; Werdell, Bailey, Franz, Morel, & McClain, 2007). In this latest processing (version 2012.2), the vicarious calibration is derived from the Marine Optical Buoy (MOBY) data (Clark et al., 1997, 2003). However, the MOBY mooring is located amid open ocean environment near Hawaii islands. Thus, evaluation of the VIIRS ocean color product is still necessary for coastal waters to assess the consistency of the overall calibration process. On the other hand, fulfilling the mission of the U.S. National Oceanic and Atmospheric Administration (NOAA), Interface Data Processing Segment (IDPS) developed by Raytheon Intelligence and Information Systems for the processing of the environmental data records (EDR) from SDR has gained beta status in January 2013 for evaluation. IDPS processing schemes for the VIIRS data differ from those of NASA in significant ways even at the SDR level. First, NOAA temporal calibration is changed at discrete intervals (currently daily, but less frequent in early mission) whereas NASA calibration is derived as a continuous trending from the start of the mission as mentioned above. Second, the NOAA calibration currently primarily uses the solar calibration (i.e., measurements from Solar Diffuser), while NASA OBPG uses both solar and lunar data. The procedure effectively supersedes the prelaunch absolute calibration. This step is applied as an effort to resolve absolute and spectral-relative calibration errors, which the NASA OBPG is currently resolving through a vicarious calibration that is applied in Level-2 processing. Thus, assessments are also necessary to evaluate the validity of the IDPS processing scheme.

The overall optical complexity of the atmospheric-water system makes observation of coastal waters from space highly challenging but of paramount importance for monitoring global water quality and assessing anthropogenic impacts (IOCCG, 2008). The ocean color component of the Aerosol Robotic Network (AERONET-OC) has been designed to support long-term satellite ocean color investigations through cross-site measurements collected by autonomous multispectral radiometer systems deployed above water (Hooker, Zibordi, Berthon, & Brown, 2004; Zibordi, Mélin, Hooker, D'Alimonte, & Holben, 2004; Zibordi, Mélin, et al., 2009). As part of this network, the Long Island Sound Coastal Observatory (LISCO) near New York City and WaveCIS in the Gulf of Mexico expand those observational capabilities with continuous monitoring as well as (for the LISCO site) additional assessment of the hyperspectral properties of coastal waters (Harmel et al., 2011).

In this study, the quality of the VIIRS products estimated through the OC processing, namely the normalized water-leaving radiances and atmospheric products (i.e., aerosol optical thickness and Angstrom exponent), are analyzed for typical coastal waters conditions encountered at LISCO and WaveCIS sites. Through statistical analysis carried out between the VIIRS, MODIS-Aqua and AERONET-OC data, the impacts of the different processing schemes (NASA's initial and latest version 2012.2, as well as IDPS) on the VIIRS's OC data retrievals are assessed. In particular, the impacts of the different processing procedures on the retrieved data quality are scrutinized in order to aid the scientific community to better interpret the physical or biogeochemical meanings of the VIIRS data in coastal areas. In the following section, the Background of the NASA ocean color satellite data processing is discussed along with the instruments and environmental characteristics of AERONET-OC sites used in this study. In Section 3, the spectral consistency of the VIIRS normalized water-leaving radiance retrievals of NASA OBPG processing schemes is firstly analyzed based on MODIS and in-situ SeaPRISM data. Then, the consistency, quality and uncertainty of those VIIRS data are also quantified through the time-series and match-up inter-comparison carried out with MODIS as well as SeaPRISM data. Processing algorithms employed in the IDPS system for OC data processing are firstly discussed in Section 4 and initial assessments of the IDPS VIIRS OC products are also made. In Section 5, the impacts of the retrieved atmospheric parameters on the estimation of the water-leaving radiance are discussed in order to delineate possible room for improvement in the overall VIIRS data processing. Summary and conclusions are presented in the last section.

2. Data and methods

2.1. Background of the NASA ocean color satellite data processing

In the ocean color satellite data processing, the atmospheric correction procedure, which eliminates the perturbing effects of the atmosphere and ocean surface, is the most important step. Notably the Near Infrared (*NIR*) algorithm developed by Gordon and Wang (1994a) which makes use of near infrared bands in initial estimations of water-leaving radiance, and the Short Wave Infrared (*SWIR*) algorithm that uses short wave infrared bands (Wang, 2007; Wang & Shi, 2005) and an approach which makes combined use of both *NIR* and *SWIR* algorithms (Wang & Shi, 2007) have been successfully used in the processing of ocean color (OC) data.

Total reflectance measured from the space-borne OC sensor at a wavelength (λ), denoted as $\rho_t(\lambda)$, can be described as following (Gordon & Wang, 1994a; IOCCG, 2010; Tanre, Herman, Deschamps, & Deleffe, 1979):

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + T_s(\lambda)\rho_g(\lambda) + t(\lambda)\rho_f(\lambda) + t(\lambda)\rho_w(\lambda) \tag{1}$$

where ρ_r and ρ_a are the reflectances resulting from multiple scattering by air molecules (Rayleigh scattering) and aerosols, respectively. ρ_{ra} is the interaction term between molecular and aerosol scattering (Deschamps, Herman, & Tanre, 1983), ρ_f is the reflectance contribution from surface whitecaps and foam, ρ_g is the reflectance of the direct solar beam, and ρ_w is the water-leaving reflectance. T_s and t are the direct and diffuse atmospheric transmittance from surface to sensor direction respectively. In the current standard NASA processing, ρ_f is estimated according to Frouin, Schwindling, and Deschamps (1996) and Gordon and Wang (1994b). The ρ_g term is generally parameterized on the wind speed for a given viewing geometry (Wang & Bailey, 2001) using the Cox and Munk (1954) model. Similarly, ρ_r can be also well predicted from the atmospheric pressure and wind speed (Gordon & Wang, 1992; Hansen & Travis, 1974; Wang, 2002, 2005). The aerosol component ($\rho_a + \rho_{ra}$) is estimated through the *NIR* atmospheric correction algorithm (Gordon & Wang, 1994a), which is currently implemented with the set of aerosol models defined by Ahmad et al. (2010). In the standard NASA VIIRS processing, the *NIR* correction is applied iteratively in order to circumvent the difficulties associated with non-negligible water leaving radiance in *NIR* part of spectrum (Hu, Carder, & Muller-Karger, 2000; Ruddick, Ovidio, & Rijkeboer, 2000; Siegel, Wang, Maritorena, & Robinson, 2000; Stumpf, Arnone, Gould, Martinolich, & Ransibrahmanakul, 2003; Wang & Shi, 2005), the condition typically observed for turbid and highly productive coastal waters (Bailey, Franz, & Werdell, 2010; Siegel et al., 2000). In this approach, ρ_w is retrieved iteratively based on bio-optical models (Bailey et al., 2010; Bricaud, Morel, Babin, Allali, & Claustre, 1998; Sydor & Arnone, 1997). Finally, the standardized parameter, normalized water-leaving radiance $nLw(\lambda)$, is calculated as:

$$nLw(\lambda) = BRDF(\lambda)\frac{F_0(\lambda)}{\pi t_d(\lambda)}\rho_w(\lambda) \tag{2}$$

where *BRDF* is the correction factor for illumination and viewing geometries dependency which is the function of the constituents of water (Gordon, 2005; Hlaing et al., 2012; Morel, Antoine, & Gentili, 2002; Voss & Morel, 2005; Wang, 2006), F_0 is the extraterrestrial irradiance