Remote Sensing of Environment 124 (2012) 627–636

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Intra-annual variations of biases in remote sensing primary ocean color products at a coastal site

Giuseppe Zibordi *, Frédéric Mélin, Jean-François Berthon

Institute for Environment and Sustainability, Joint Research Centre, European Commission, Ispra, Italy

ARTICLE INFO

Article history:
Received 21 December 2011
Received in revised form 7 June 2012
Accepted 18 June 2012
Available online 15 July 2012

Keywords:
Ocean color
Remote sensing
Radiometry

ABSTRACT

The assessment of uncertainties and biases affecting remote sensing products is a pre-condition for an effective exploitation of these data in climate studies. Within such a context, this work presents and discusses the intra-annual variations of biases in primary satellite ocean color products (i.e., normalized water-leaving radiance and aerosol optical thickness) at a coastal site in the northern Adriatic Sea for the period 2002–2010. The analysis is performed using *in situ* data from the Ocean Color component of the Aerosol Robotic Network (AERONET-OC) and satellite data products from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS-A and MODIS-T) onboard the Aqua and Terra platforms. Results indicate biases in the normalized water leaving radiance significantly increasing with the sun zenith angle and, to a lesser extent, also affected by variations in chlorophyll concentration and aerosol optical thickness.

1. Introduction

Satellite remote sensing significantly contributes to climate studies through spatial and temporal mapping of key climate variables related to ocean, land and atmosphere (e.g., Achard et al., 2002; Behrenfeld et al., 2006; Kaufman et al., 2002; Stroeve et al., 2007). Nevertheless, the confident use of time series of satellite derived climate variables to detect temporal changes and trends imposes strict thresholds to uncertainties of applied data (Ohring et al., 2005).

Among remote sensing technologies, satellite ocean color contributes to the mapping of climate variables like phytoplankton concentration and aerosol optical thickness. The basic assessment of these products is generally performed using *in situ* measurements. This step is however hindered by the cost of operations at sea, the complexity of measurements, regional and seasonal variability of seawater and atmospheric constituents. Because of this, the evaluation of primary ocean color products (i.e., the normalized water-leaving radiance, L_{WN}, and the aerosol optical thickness, τ_a) frequently relies on a relatively small number of match-ups (i.e., pairs of *in situ* and satellite data from the same location collected within a given time interval) not always representing the variety of observation conditions.

Progress in the assessment of satellite ocean color products is now expected from autonomous measurement systems operated on bio-optical buoys (e.g., Antoine et al., 2008; Clark et al., 2002), gliders and floats (Xing et al., 2011), and fixed deployment platforms generally located in coastal regions (e.g., Zibordi et al., 2009a). These networks will likely provide the capability of producing a large number of match-ups across several geographic areas or at given sites. This massive quantity of measurements will hopefully help to comprehensively address the assessment of satellite ocean color products with attention to both temporal and spatial scales. It is evident that, while globally distributed *in situ* measurements allow for addressing accuracy of remote sensing products in regions characterized by different environmental conditions (e.g., seawater types), time series of *in situ* measurements at specific sites are essential to investigate the temporal evolution of products bias and uncertainty as a function of observation geometry (e.g., sun zenith angles, θ_0) and environmental conditions (e.g., phytoplankton cycles).

The objective of this work is to explore the intra-annual variation of biases in primary satellite ocean color products. The study has been conducted using time-series of *in situ* measurements performed at a coastal site in the northern Adriatic Sea during the period 2002–2010. The data analysis focuses on ocean color products derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometers (MODIS-A and MODIS-T) onboard the Aqua and Terra platforms.

2. Data and methods

The study exploits *in situ* data collected at the Acqua Alta Oceanographic Tower (AAOT) site located at approximately 8 nautical miles south-east of the Venice Lagoon in the northern Adriatic Sea. The site has the peculiarity of representing a variety of water types (Berthon & Zibordi, 2004; D'Alimonte et al., 2007) ranging from those having bio-optical properties driven by phytoplankton and its derived

* Corresponding author.
E-mail address: giuseppe.zibordi@jrc.it (G. Zibordi).

0034-4257/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2012.06.016

components (Case 1), to those characterized by moderate concentrations of suspended sediments or colored dissolved organic matter not correlated with phytoplankton (Case 2). In fact the seasonal bio-optical cycle determined by phytoplankton blooms during spring and fall (Berthon et al., 2002) is affected by short term changes in the concentration of suspended sediments and colored dissolved organic matter due to water discharges from regional rivers.

The aerosol type at the AAOT site is mostly continental even though it occasionally exhibits maritime characteristics. The seasonal cycle indicates a lower aerosol particle load in fall and winter in conjunction with the higher occurrence of precipitation events (Mélin & Zibordi, 2005).

The former bio-optical and atmospheric features make the AAOT site suitable to investigate the accuracy of multi-mission ocean color products for relatively optically complex regions (Mélin et al., 2007; Zibordi et al., 2006). Additionally, the existence of time-series of *in situ* data favors seasonal investigations on satellite products.

This section introduces the *in situ* and satellite data relevant to the study, together with the methods applied.

2.1. In Situ measurements

Since 2002, systematic *in situ* measurements of L_{WN} and τ_a have been performed at the AAOT using autonomous above-water radiometer systems called SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM), included in the Ocean Color component of the Aerosol Robotic Network (AERONET-OC, see Zibordi et al., 2009a, 2010). These activities, mostly performed to support the validation of satellite ocean color products, are complemented by comprehensive measurements of seawater inherent and apparent optical properties carried out for a few days several times a year within the framework of the Coastal-Atmosphere and Sea Time Series (CoASTS) program (Berthon et al., 2002 & Zibordi et al., 2002). This program was started in 1995 to support bio-optical modeling for optically complex waters (Berthon & Zibordi, 2004; D'Alimonte et al., 2007; Zibordi & Berthon, 2001) and, additionally to sustain the comprehensive validation of satellite ocean color products (Mélin et al., 2005, 2007). CoASTS data include L_{WN} products determined through an in-water optical profiling system called Wire-Stabilized Profiling Environmental Radiometer (WiSPER, Zibordi et al., 2004a). In this work the autonomous AERONET-OC data are used for investigating biases in primary satellite ocean color products, while manned CoASTS radiometric data collected for short periods through the year are utilized to verify the intra-annual consistency of AERONET-OC L_{WN}.

AERONET-OC L_{WN} and τ_a produced at the AAOT site include data at the nominal center-wavelengths 412, 443, 488, 551, 667 nm (or slightly different in the early stage of the network, see Zibordi et al., 2004b). Similarly, CoASTS L_{WN} data are produced at the 412, 443, 490, 510, 555 and 665 nm center-wavelengths. It is anticipated that the effects of differences in center-wavelength between satellite and *in-situ* data, are minimized through band-shift corrections applied to the latter ones (Zibordi et al., 2009b). The correction for L_{WN} is performed relying on a bio-optical model requiring chlorophyll-a concentration (Chl*a*) and inherent optical properties, estimated through regional empirical algorithms applied to spectral ratios of L_{WN}. Both AERONET-OC and CoASTS L_{WN} data are corrected for the effects of anisotropy of in-water light distribution following Morel et al. (2002).

Regular pre- and post-field absolute calibration is applied to both AERONET-OC and CoASTS radiometers as a fundamental step toward traceability of measurements. Estimate of uncertainties for AERONET-OC L_{WN} has been performed by accounting for contributions from: in-air absolute calibration; correction factors applied to remove the effects of off-nadir viewing angle and anisotropy of the in-water light distribution; input processing quantities like the atmospheric diffuse transmittance and the sea surface reflectance; wave induced perturbations, and changes in seawater optical properties and illumination conditions during measurements. Uncertainties for CoASTS L_{WN} data have been estimated by accounting for contributions from: absolute in-air calibration and immersion factor; correction values applied to remove instrument self-shading, superstructure perturbations and effects of the anisotropy of the in-water light distribution; determination of total downward irradiance; determination of sub-surface values from in-water profile measurements; wave induced perturbations and, seawater variability and illumination changes. Overall results indicated uncertainty values close to 5% in the blue–green spectral region for both AERONET-OC and CoASTS L_{WN}. These uncertainties reach approximately 6% for CoASTS measurements in the red and 8% for AERONET-OC (Zibordi & Voss, 2010). Uncertainty estimates for τ_a indicate absolute values of 0.015 at all considered wavelengths in the visible and near infrared (Eck et al., 1999).

2.2. Satellite data

Remote sensing primary products analyzed in this study comprise L_{WN} and τ_a obtained with the SeaWiFS Data Analysis System (SeaDAS, version 6.2) from SeaWiFS, MODIS-A and MODIS-T data. The atmospheric correction implemented in SeaDAS for the determination of primary products from top-of-atmosphere radiance, follows the scheme introduced by Gordon and Wang (1994) and its successive revisions (Franz et al., 2007; Wang et al., 2005). These include the use of a revised set of aerosol models (Ahmad et al., 2010) and an improved bio-optical model for seawater in the near-infrared spectral region (Bailey et al., 2010). SeaWiFS and MODIS L_{WN} data products are corrected for bi-directional effects following Morel et al. (2002) consistently with the *in situ* data. The values of Chl*a* applied for the specific correction are determined using the same regional algorithm (Berthon & Zibordi, 2004) utilized for the correction of bi-directional effects of *in situ* radiometric data. This solution aims at minimizing differences due to unequal input parameters in the comparison scheme applied for satellite and *in situ* data products. Its impact, however, does not appear significant in this analysis. In fact the use of Chl*a* determined from the regional bio-optical product with respect to the standard satellite product, leads to average differences between satellite and AERONET-OC L_{WN} generally lower than $+2\%$.

Products from the Medium Resolution Imaging Spectrometer (MERIS) were deliberately not included in the analysis because of the relatively small number of matchups available at the AAOT site (i.e., approximately one third of those produced for SeaWiFS during the same period) that would not allow for a confident statistical evaluation of intra-annual changes in biases.

Data for matchup analysis are extracted from satellite products and specifically from the 3×3 pixel area centered at the AAOT location. Valid matchups, leading to the determination of satellite average L_{WN} and τ_a from the 3×3 matrix, are identified when: i. times of field measurements and satellite overpass are within ±1 h; ii. all 9 pixels are not affected by failure of the atmospheric correction, clouds, sun glint, stray light conditions; iii. L_{WN} is positive at 412 nm for all 9 pixels; iv. the maximum viewing angles are lower than 60° and sun zeniths, θ_0, lower than 70°; v. the coefficient of variation (i.e., the ratio of standard deviation to average) is lower than 20% at 490 nm.

The comparison of satellite and *in situ* intra-annual data for N matchups is presented through the median of percent differences (*m*) and the root-mean-square difference (*rmsd*). The quantity *m* determines the median relative bias of data points (it is preferred here to the mean value, to reduce the impact of outliers). The *rmsd* value is used as a statistical index for absolute uncertainty in physical units.

The value of *m* for the quantity $\Re$ representing either L_{WN} or τ_a, is computed as

$$m = median[d_1, \ldots, d_i, \ldots, d_N] \quad (1)$$