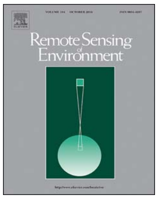
Remote Sensing of Environment 209 (2018) 275–290

Contents lists available at ScienceDirect

Remote Sensing of Environment

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



Use of bio-optical profiling float data in validation of ocean colour satellite products in a remote ocean region

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ARTICLE INFO

Keywords:
Autonomous profiling floats
Remote sensing reflectance
Chlorophyll
Ocean colour
Validation
Indian Ocean

ABSTRACT

Utility of data from autonomous profiling floats for the validation of satellite ocean colour products from current satellite ocean colour sensors was assessed using radiometric and chlorophyll *a* fluorescence data from biogeochemical profiling floats (BGC-Argo) deployed in the subtropical gyre of the Indian Ocean. One of the floats was equipped with downward irradiance and upwelling radiance sensors, allowing the remote sensing reflectance, R_{rs}, to be determined. Comparisons between satellite and *in situ* R_{rs} indicated good agreement for the shorter wavelengths, but weak relationships for both satellites for the 555 nm channel, and showed that radiometers deployed on multipurpose, off-the-shelf BGC-Argo floats can provide validation-quality measurements. About 300 chlorophyll *a* concentration match-ups were achieved within 18 months, which increased the number of validation data points available for the Indian Ocean as a whole by a factor of ~4 from the previous historical record. Generally, the satellite data agreed with the float-derived chlorophyll concentration within the uncertainty of ± 35%, for the band-difference (OCI) and band-ratio (OC3) algorithms, but not for a semi-analytical ocean colour model (GSM) that exhibited significantly higher chlorophyll values (> 100% mean difference). Our results indicate that autonomous float-based measurements provide substantial potential for improving regional validation of satellite ocean colour products in remote areas.

1. Introduction

Accurate assessment of bio-optical variability in the ocean, and its causes, is essential to interpret observations from satellite ocean colour sensors that can be used to monitor marine ecosystems at large spatial and temporal scales. Relationships between inherent optical properties (IOPs) of seawater and remote sensing reflectance, R_{rs}, have been intensively studied since the 1980s, to advance the development of ocean colour algorithms for biogeochemical and bio-optical variables such as chlorophyll *a* concentration, coloured dissolved organic matter (CDOM) absorption, and particulate backscattering. However, evaluating the accuracy of ocean colour algorithms for the retrieval of bio-optical variables is challenging in many cases and appears to be regionally variable (*e.g.* Johnson et al., 2013), making broad-scale validation against *in situ* data from a range of oceanic regions essential.

Many studies have undertaken validation of satellite ocean colour products on both local (*e.g.* Antoine et al., 2008; Zibordi et al., 2015) and global scales (Arnone et al., 2012). Most of the global studies are based on data sets like the NASA bio-Optical Marine Algorithm Dataset (NOMAD), the MERIS Match-up *In situ* Database (MERMAID), the SeaWiFS Bio-optical Archive and Storage System (SeaBASS) or the ESA's Ocean Colour Climate Change Initiative (OC-CCI) (Valente et al., 2016). However, these data sets are built mostly from observations in the Atlantic and Pacific Oceans. For example, NOMAD contains only 121 chlorophyll *a* match-ups for the Indian Ocean among the total of 2365 (Szeto et al., 2011). Oceans differ in the amount of coloured detrital matter (CDM) for a given phytoplankton biomass, as well as in phytoplankton community structures, particle size distributions and pigment compositions (Szeto et al., 2011). Therefore, it is necessary to conduct satellite algorithm validation studies using more evenly distributed data, in particular from sparsely sampled regions like the Indian Ocean. Moreover, the data sets acquired during traditional ship-

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https://doi.org/10.1016/j.rse.2018.02.057
Received 14 July 2017; Received in revised form 17 January 2018; Accepted 22 February 2018

based campaigns, apart from being affected by the aforementioned regional biases and sparsity, are also very expensive and time-consuming to obtain.

An alternate source of validation data comes from biogeochemical autonomous profiling floats (BGC-Argo), which can be deployed in remote parts of the global ocean and provide observations of the optical backscattering, chlorophyll *a* fluorescence and radiometry. The launch of the first in the series of new European Sentinel-3 satellites in early 2016, carrying the Ocean and Land Colour Imager (OLCI) instrument, increases the need for collecting good-quality *in situ* data that can be used in the validation of radiometric and biogeochemical products. The concept of using autonomous floats to measure bio-optical properties was outlined by IOCCG (2011). Recently, the utility of float measurements in validation of remote sensing reflectance (Gerbi et al., 2016), chlorophyll and POC concentration (Haëntjens et al., 2017) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible and Infrared Imaging Radiometer Suite (VIIRS) has been demonstrated.

In this study, we describe the use of BGC-Argo floats deployed in the Indian Ocean as a source of data for validation of satellite estimates of remote sensing reflectance and chlorophyll *a* concentration. The Indian Ocean plays a significant role in controlling the climate and is of major strategic and economic importance, because the population of the Indian Ocean rim nations contributes to 25% of the world's population and is still rapidly increasing (*e.g.* Hood et al., 2015). Despite its importance, we did not want to focus on the region itself because the results are of global significance. One of the main points of this study was to show the potential of autonomous platforms in providing robust and cost-effective validation measurements for ocean colour remote sensing in the most inaccessible ocean regions. Unlike in previous study focusing on the validation of radiometric data from BGC-Argo floats that used prototype sampling design (Gerbi et al., 2016), we used radiometers deployed on multipurpose, off-the-shelf BGC-Argo floats. We obtained a data set containing 228 profiles of radiometric quantities and > 1600 profiles of phytoplankton chlorophyll concentration derived from fluorescence. In the methodology section, we present a detailed description of data processing as well as the measurement uncertainty estimation. Based on the analysis of our dataset we also provide some recommendations for future BGC-Argo mission plans and sensor configurations for deployments with the objective of ocean colour product validation.

2. Methods

2.1. BGC-Argo float sensor configuration and mission details

Four autonomous biogeochemical profiling floats (Navis-BGCi, Sea-Bird Scientific, Inc., Bellevue, WA, USA) were deployed in July 2015 in the subtropical gyre of the South Indian Ocean during a research cruise of the EAF-Nansen Project of the United Nations Food and Agriculture Organization. Location of deployment sites, as well as general information on the floats, is given in Table 1. In addition to standard Argo CTD sensors (SBE41-CP, Sea-Bird Scientific, Inc.), the floats were equipped with an SBE63 oxygen optode (Sea-Bird Scientific, Inc.) and a set of bio-optical and radiometric sensors, for which details are given in Table 2. All sensors, apart from the upwelling radiance (L_u) sensor on float 392, were installed on top of the float, with the upward-looking radiometer (downward irradiance, E_d) located 20 cm above the pressure sensor to avoid shading by the iridium antennae. The downward looking L_u sensor was located near the bottom of the float, 166 cm below the pressure sensor. The sensor was not placed exactly at the bottom of the float for protection of its optical surface, however, it was positioned such that the hull was outside of its field of view. The differences in the position of the sensors compared to the pressure sensor were accounted for when deriving radiometric surface values. Calibration of all sensors was performed by the manufacturers before installing them on the float. Additional effort was taken to calibrate the chlorophyll fluorescence sensor, as described in detail in Section 2.1.2.

Table 1
General information on the floats in the subtropical South Indian Ocean during 2015–2017.

Float ID	WMO ID	Deployed	Latitude	Longitude	# profiles	Date of last profile
387	5904923	5/07/2015	20.0°S	88.7°E	374	15/07/2017
388	5904924	6/07/2015	20.0°S	86.9°E	377	30/07/2017
390	1901347	8/07/2015	20.5°S	78.5°E	282	18/10/2016
392	1901348	8/07/2015	20.5°S	78.5°E	228	02/06/2016

The sampling frequency for the floats was pre-set within the floats firmware. As such, the floats sampled at 2-meter vertical resolution during the ascent and the sampling resolution remained constant throughout the entire profile. No radiometric data were collected at the surface in a buoy phase, when the float drifts at the surface with the upward-looking radiometer above the surface. At the beginning of the mission, all floats were programmed to profile the water column about every 6 h. After about 3 weeks, the profile frequency was changed to once a day, close to local noon for the float equipped with radiometers or at night for other floats, in order to avoid the influence of non-photochemical quenching (NPQ) on the chlorophyll *a* fluorescence signal at the surface. After about 4 months from deployment, the profiling frequency was decreased again to once every 3 days. All data from these floats are available at ftp://ftp.ifremer.fr/ifremer/argo/dac/csiro/ (http://doi.org/10.17882/42182).

2.1.1. Radiometric data processing and uncertainty

Using radiometric data from autonomous floats is a challenge as the measurements are taken without operator control under various sea states and atmospheric conditions that can significantly influence the quality of collected data. All day-time profiles of E_d at 412, 443, and 490 nm showed a slight increase at depths below their minimum value of about 250–300 m (Fig. 1). This unrealistic increase with depth was reduced for the 490-nm channel and was not noted for the 555-nm one. A similar sensor behaviour, but distinctly weaker, was observed for L_u profiles with the effect being stronger for longer wavelengths (Fig. 2). At the beginning of the mission the 392 float was profiling a couple times a day, thus some of the profiles were collected at night. In the case of radiometric measurements these measurements are in fact the measurements of the dark count. The above-mentioned increase in the dark response of radiometric sensors is clear in all profiles measured at night-time as a steady increase of the signal with depth (Fig. 3). It has been suggested that such a response is related to temperature rather than pressure changes impact on the sensors (Nathan Briggs, personal communication), although an impact of pressure on the sensor is also a possible cause. The maximum increase of the signal with depth observed in the night-time profiles, calculated as the difference between the minimum and maximum value within the entire profile, was always lower than 0.1% of the irradiance measured at the surface during day time, therefore we consider its effect on our results to be negligible. Subsequently, we applied a cut-off limit for all channels by finding the maximum value of E_d and L_u at 500 m for all profiles (dashed line in Figs. 1 and 2). We then discarded all values lower than this cut-off limit. As the remaining part of the profile could also contain some deep measurements taken in the dark, the remaining dark values in the profiles were detected with the use of a normality test, assuming that dark values are characterised by a normal distribution (Organelli et al., 2016). The remaining portion of the profiles was retained for further analysis.