Remote Sensing of Environment 114 (2010) 1791–1804

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Merged satellite ocean color data products using a bio-optical model: Characteristics, benefits and issues

Stéphane Maritorena [a,*], Odile Hembise Fanton d'Andon [b], Antoine Mangin [b], David A. Siegel [a,c]

[a] Institute for Computational Earth System Science, University of California, Santa Barbara, Santa Barbara, CA 93106-3060, USA
[b] ACRI-ST, 260, route du Pin Montard — B.P. 234, 06904 Sophia Antipolis Cedex, France
[c] Department of Geography, University of California, Santa Barbara, Santa Barbara, CA 93106-4060, USA

ARTICLE INFO

Article history:
Received 28 August 2009
Received in revised form 2 February 2010
Accepted 3 April 2010

Keywords:
Ocean color
Merged data
SeaWiFS
MODIS-AQUA
MERIS
Semi-analytical model
Uncertainties
Time-series
Climate Data Records

ABSTRACT

The characteristics and benefits of ocean color merged data sets created using a semi-analytical model and the normalized water-leaving radiance observations from the SeaWiFS, MODIS-AQUA and MERIS ocean color missions are presented. Merged data products are coalesced from multiple mission observations into a single data product with better spatial and temporal coverage than the individual missions. Using the data from SeaWiFS, MODIS-AQUA and MERIS for the 2002–2009 time period, the average daily coverage of a merged product is ~25% of the world ocean which is nearly twice that of any single mission's observations. The frequency at which a particular area is sampled from space is also greatly improved in merged data as some areas can be sampled as frequently as 64% of the time (in days). The merged data presented here are validated through matchup analyses and by comparing them to the data sets obtained from individual missions. Further, a complete error budget for the final merged data products was developed which accounts for uncertainty associated with input water-leaving radiances and provides uncertainty levels for the output products (i.e. the chlorophyll concentration, the combined dissolved and detrital absorption coefficient and the particulate backscattering coefficient). These merged products and their uncertainties at each pixel were developed within the NASA REASON/MEaSUREs and ESA GlobColour projects and are available to the scientific community. Our approach has many benefits for the creation of unified Climate Data Records from satellite ocean color observations.

1. Introduction

Remote sensing of the Earth system has been an invaluable tool to study and monitor the biosphere and its components (land, ocean or atmosphere) and over the years a wide variety of physical or biogeochemical variables have been collected by various Earth observing satellite sensors. Passive-microwave and thermal infrared (e.g. AVHRR) satellite data are collected over the oceans since about 3 decades to monitor sea surface temperature (see e.g. Reynolds et al., 2007; Parkinson & Cavalieri, 2008) while others like altimetry or ocean color are more recent and observations have been made on a global scale for more than a decade (e.g. Merrifield et al., 2008; McClain, 2009). For each of these variables, multiple sensors with similar characteristics have contributed to the development of the satellite time-series through a succession of missions designed to provide one or more specific products. The planning and timing of satellite missions are generally designed to allow some overlap between successive generations of a sensor, which permits sensor intercomparisons and allows biases across missions to be quantified and accounted for (e.g. Castro et al., 2008).

Presently, there are several global satellite sensors orbiting the Earth and sampling the color of the oceans (e.g. GeoEye's SeaWiFS, NASA's MODIS on the TERRA and AQUA platforms and ESA's MERIS on Envisat). It seems logical to attempt to merge the data sets from these missions to create unified data products. This would result in sets of single synthetic products with greater coverage of the world's oceans on shorter time scales instead of several, possibly divergent, data sets. If the data products are well characterized and consistent among missions, their unification as a single synthetic product is a way to build a univocal time-series of a particular product over the lifetimes of several missions. It is also a way to develop consistent Essential Climate Variables time-series (GCOS, 2003) or Climate Data Records (NRC, 2004; Loeb et al., 2009; Siegel et al., in preparation) and international planning for a virtual constellation of ocean color satellite missions which would satisfy these needs has recently begun (e.g., IOCCG newsletter Sept. 2008, http://www.ioccg.org/news/Sept2008/news.html). Such a unification can be conducted by merging the data from the different sensors.

* Corresponding author.
E-mail address: stephane@icess.ucsb.edu (S. Maritorena).

0034-4257/$ – see front matter
doi:10.1016/j.rse.2010.04.002

In the case of ocean color, several data merging efforts have taken place in recent years (Gregg and Conkright, 2001; Kwiatkowska & Fargion, 2002; Maritorena & Siegel, 2005; Pottier et al., 2006; IOCCG, 2007) under the NASA SIMBIOS and REASoN projects or the ESA GlobColour program. This merger can be performed on final data products, literally compositing observations from different missions into a single data set, or by intermixing observations of the spectral water-leaving radiance, NLw(λ), from different sources in a bio-optical model to derive merged products (e.g., IOCCG, 2007). Both approaches have been used and merged data sets are now available to the scientific community. For example, the NASA Ocean Biology Processing Group (OBPG) distributes a merged Chlorophyll (CHL) product from SeaWiFS and MODIS-AQUA CHL data while fields of CHL and Inherent Optical Property (IOP) products from the inversion of merged NLw(λ) of SeaWiFS, MODIS-AQUA and MERIS are available through the UCSB-NASA Ocean Color MEaSUREs (formerly REASoN) and the ESA GlobColour projects (see Table 1 for URLs). This paper will focus on the latter approach where combined NLw(λ) spectra from different sensors are used in a bio-optical model (Maritorena & Siegel, 2005) to simultaneously derive several "merged" ocean color products as well as uncertainty determinations for each of them. Maritorena and Siegel (2005) presented only a demonstration of this approach using a limited number of scenes (18) from SeaWiFS and MODIS-TERRA. Since then, data from other ocean color sensors (MODIS-AQUA and MERIS) have become available while issues with the MODIS-TERRA data made that sensor unreliable for climate-scale ocean color studies (Franz et al., 2008).

Here, the model-based approach for ocean color data merging described in Maritorena and Siegel (2005) is applied to the SeaWiFS, MODIS-AQUA (hereafter referred to as "AQUA") and MERIS NLw(λ) data to create long time-series of merged data produced under the NASA Ocean Color MEaSUREs and the ESA GlobColour projects. In the present paper, some of the characteristics and benefits of these merged data sets are documented for the 2002–2009 period for which the three sensors are simultaneously operational. We provide coverage estimates to demonstrate the benefits of merging and present a validation of the final merged products. An error budget is also presented where uncertainties in the input NLw(λ) from each sensor and model errors are quantified and taken into account to generate uncertainty estimates for each output product and at each pixel of an image. Outstanding issues associated with sensors data or inter-sensor biases are also discussed as well as how data merging could be the path toward building consistent Climate Data Records.

2. Methods

The bio-optical model-based merging procedure and its associated features are described in Maritorena et al. (2002) and Maritorena and Siegel (2005) and its main traits are briefly summarized below. One of the major features of the approach is that it combines the normalized water-leaving radiances from different sensor data sets. Over each particular pixel of a geographical grid common to SeaWiFS, AQUA and MERIS, the NLw(λ) spectra from the available sensors at that pixel are selected and combined in a single, multi-source, spectrum which is then used in the inversion of the GSM01 semi-analytical ocean color model (Maritorena et al., 2002). The model inversion results in the simultaneous retrieval of multiple ocean color related variables, namely the sub-surface chlorophyll-a concentration, CHL, the combined absorption coefficient of the particulate and dissolved organic material at 443 nm, CDM, and the particulate backscattering coefficient at 443 nm, BBP, as well as uncertainty levels and covariance matrices of the retrievals. Only the bands in the visible are used in the inversion and, depending on which sensors collected data for a particular bin, the NLw(λ) spectrum that enters the model is made from 6 to 19 spectral data points. When more than one sensor is available, the resulting radiance spectrum will consist of a mix of spectral bands that are either unique, coming from only one sensor, or replicated for bands that are common to several sensors (Fig. 1). In other words, the resulting NLw(λ) combined spectrum has improved spectral resolution and contains replicated measurements for some bands as illustrated in Fig. 1. While both the MEaSUREs and GlobColour projects use the GSM01 model to generate merged products, there are some differences in data processing and data handling which result in differences between the two sets of products, mostly in eutrophic waters and coastal areas. The differences between the MEaSUREs and GlobColour projects are summarized in Table 1.

Merged products were generated using the GSM01 model from SeaWiFS (version 5.2), AQUA(v1.1) and MERIS (v2.0/Q) daily NLw(λ) fields for the time period common to the three sensors (July 2002–2009). The complete archives of SeaWiFS, AQUA and MERIS were also individually processed using the GSM01 model in order to compare merged and individual mission data sets. The three main variables (CHL, CDM and BBP) are produced along with their uncertainty estimates. In addition, metrics of the quality of the retrievals, like the χ^2, the covariance matrix of the retrievals and residuals (spectral differences between observed and modeled radiances re-built from the retrieved variables) are also available. The products are also time-

Table 1
Differences between the MEaSUREs and GlobColour data processing using the GSM01 model. For GlobColour, the data are processed from level-2, 1 km resolution NLw(λ) data that include the red bands and output products are at a 4.6 km resolution. In the MEaSUREs project the MODIS-AQUA and MERIS level-3 binned NLw(λ) data are first converted to 9 km data to match the resolution of SeaWiFS which is also the resolution of the output products. Note that the MEaSUREs project initially merged the SeaWiFS and AQUA data only but it now includes the MERIS data. The NASA Ocean Biology Processing Group CHL merged product is available at http://oceancolor.gsfc.nasa.gov/cgi/l3. Some of the NASA OBPG and UCSB GSM products are also available through the NASA Giovanni system: http://reason.gsfc.nasa.gov/Giovanni/.

	MEaSUREs	GlobColour
Sensors	SeaWiFS MODIS-AQUA (MERIS)	SeaWiFS MODIS-AQUA MERIS
Input data	Level 3 binned	Level 2
Bands used	SeaWiFS: 412, 443, 490, 510, 555 AQUA: 412, 443, 488, 531, 551 MERIS: 412, 443, 490, 510, 560	SeaWiFS: 412, 443, 490, 510, 555, 670 AQUA: 412, 443, 488, 531, 551, 667 MERIS: 412, 443, 490, 510, 560, 620, 665
Sensor specific weighting of NLw(λ)	None	Derived from matchup statistics (see text)
Spatial resolution of output products	9 km	4.6 km
Products uncertainties and QC products	Confidence intervals (linear approximation of nonlinear regression inference region; Bates & Watts,1988)	Standard deviation (diagonal elements of the retrievals covariance matrix). Available on request: χ^2, residuals, covariance matrices
Data file format	HDF	NetCDF
Data access	http://wiki.icess.ucsb.edu/measures/	http://www.globcolour.info/ http://hermes.acri.fr/