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# On the temporal consistency of chlorophyll products derived from three ocean-colour sensors

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Satellite ocean-colour sensors have life spans lasting typically five-to-ten years. Detection of long-term trends in chlorophyll-a concentration (Chl-a) using satellite ocean colour thus requires the combination of different ocean-colour missions with sufficient overlap to allow for cross-calibration. A further requirement is that the different sensors perform at a sufficient standard to capture seasonal and inter-annual fluctuations in ocean colour. For over eight years, the SeaWiFS, MODIS-Aqua and MERIS ocean-colour sensors operated in parallel. In this paper, we evaluate the temporal consistency in the monthly Chl-a time-series and in monthly inter-annual variations in Chl-a among these three sensors over the 2002–2010 time period. By subsampling the monthly Chl-a data from the three sensors consistently, we found that the Chl-a time-series and Chl-a anomalies among sensors were significantly correlated for >90% of the global ocean. These correlations were also relatively insensitive to the choice of three Chl-a algorithms and two atmospheric-correction algorithms. Furthermore, on the subsampled time-series, correlations between Chl-a and time, and correlations between Chl-a and physical variables (sea-surface temperature and sea-surface height) were not significantly different for >92% of the global ocean. The correlations in Chl-a and physical variables observed for all three sensors also reflect previous theories on coupling between physical processes and phytoplankton biomass. The results support the combining of Chl-a data from SeaWiFS, MODIS-Aqua and MERIS sensors, for use in long-term Chl-a trend analysis, and highlight the importance of accounting for differences in spatial sampling among sensors when combining ocean-colour observations.



## 1. Introduction

Understanding how phytoplankton biomass is responding to variability in climate is key to predicting how the ocean will respond to continued $CO_2$ emissions. Owing to the spatial and temporal sampling capabilities of satellite data, remote sensing of ocean colour is likely to feature as the principal source of data for assessing long-term change in phytoplankton biomass (Siegel and Franz, 2010). Nonetheless, current satellite missions have lifespans lasting typically five-to-ten years, too short to assess the response of phytoplankton biomass to variability in climate (Henson et al., 2010). To establish a sufficiently long satellite dataset to address such issues requires combining data from several satellite missions (Maritorena and Siegel, 2005; Mélin and Zibordi, 2007; Mélin et al., 2009; Maritorena et al., 2010), ideally processed in a consistent manner to ensure any potential changes in phytoplankton biomass are not confounded by mission transitions or instrument change (Antoine et al., 2005; Maritorena and Siegel, 2005).

Over the past 15-years, three satellite ocean-colour sensors have been used extensively in biological oceanography, owing to their instrument accuracy, stability, and absolute sensor calibration: the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), launched by the US National Aeronautics and Space Administration (NASA) on the ORBVIEW-2 satellite in August 1997, operating until December 2010; the Moderate Resolution Imaging Spectroradiometer

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(MODIS), launched by NASA on the Aqua satellite in May 2002 (also on the Terra satellite in 1999); and the Medium Resolution Imaging Spectrometer (MERIS), launched by the European Space Agency (ESA) on-board the ENVISAT platform in March 2002, operating until April 2012. Between July 2002 and December 2010 ($\sim$8.5 years), SeaWiFS, MODIS-Aqua and MERIS operated in parallel.

There have been several efforts to document changes in the total chlorophyll-a concentration (herafter denoted Chl-a) across two or more satellite missions (e.g. Gregg and Conkright, 2002; Gregg et al., 2003; Antoine et al., 2005; Zhang et al., 2006; Gregg and Casey, 2010; Maritorena et al., 2010; Djavidnia et al., 2010; Raitsos et al., 2014). There are also various studies that have compared differences in absolute Chl-a concentrations and seasonal cycles estimated from different ocean-colour sensors (e.g. Bricaud et al., 2002; Zhang et al., 2006; Morel et al., 2007; Djavidnia et al., 2010). However, knowledge on the consistency in seasonal and inter-annual variations in Chl-a, among the SeaWiFS, MODIS-Aqua and MERIS satellite sensors, at a monthly time-scale and over a long time period (e.g. >8 years), is relatively limited (but see Djavidnia et al., 2010). Furthermore, the sensitivity of the comparison to variations in the chosen Chl-a algorithm and atmospheric-correction algorithm has not received the attention it deserves. Even less is known about the consistency in temporal correlations between Chl-a and physical variables, such as Sea Surface Temperature (SST) and Sea Surface Height (SSH), among the three ocean-colour sensors.

In this paper, we demonstrate using simple statistics that seasonal and inter-annual variations in monthly Chl-a products for SeaWiFS, MODIS-Aqua and MERIS, when subsampled consistently, are highly correlated over the majority of the global ocean. We also demonstrate consistency in the relationships between Chl-a and physical variables (SST and SSH) across the three ocean-colour sensors.

## 2. Methods

### 2.1. Data

Table 1 provides a summary of the satellite datasets used in the study. To compare the Chl-a time-series of SeaWiFS, MODIS-Aqua and MERIS, and for comparison of the Chl-a time-series of each sensor with physical variables, monthly level-3 Standard Mapped Imagery ($\sim$9 km) of Chl-a were downloaded from the NASA ocean-colour website (http://oceancolor.gsfc.nasa.gov/) for the time period July 2002–December 2010 (see Table 1, Comparison I). This imagery was processed using a common framework including a conceptually similar atmospheric correction algorithm (SeaDAS; Fu et al., 1998; Franz et al., 2007; Mélin et al., 2011), that removes data affected by factors such as high sensor view angle, high solar-zenith angles, high aerosol load, sun glint and straylight contamination. Chlorophyll-a concentrations were also estimated using similar, empirical blue-green reflectance ratio algorithms, tuned to the specific wavelengths of each sensor and parameterised using a common database (see NASA, 2010, for further details). Monthly data, as opposed to daily or weekly imagery, were used as: (i) monthly data are typically the shortest time interval for which global coverage is obtained for a single sensor (>80%, see Uitz et al., 2010); (ii) the analysis performed here may be more readily compared with previous studies that used monthly products for long-term trend analysis and climate studies (e.g. Gregg et al., 2003; Behrenfeld et al., 2006; Vantrepotte and Mélin, 2009, 2011; Brewin et al., 2012; Siegel et al., 2013); (iii) averaging data at a monthly timescale filters some noise in the satellite observations; and (iv) it kept the computing time of the analysis at a reasonable level.

In addition to standard Chl-a products, other Chl-a products were also downloaded from the NASA ocean-colour website for the same time period, for use in evaluating how sensitive the consistency in the Chl-a time-series is to variations in the chosen Chl-a algorithm on a single sensor (Table 1, Comparison II), and among the three sensors (Table 1, Comparison III). These additional Chl-a products were processed using either the GSM or OCI bio-optical algorithms. The GSM algorithm is a semi-analytical inversion model designed to retrieve Chl-a in addition to absorption by combined detrital and dissolved matter (CDM) and particle backscattering. The OCI is based on a band-difference between remote-sensing reflectance in the green part of the visible spectrum and a baseline formed linearly between the blue and red wavebands. It is applied only in oligotrophic waters (Chl-a < 0.25 mg m$^{-3}$), which constitute $\sim$70% of the global ocean, reverting to standard band-ratio algorithms (e.g. OC4 or OC3) at higher Chl-a values (Chl-a > 0.3 mg m$^{-3}$). The performance of both the GSM and OCI algorithms at retrieving Chl-a from satellite has been well documented, and both algorithms are comparable in performance to other standard algorithms (Hu et al., 2012; Siegel et al., 2013; Brewin et al., 2013).

To evaluate how sensitive the consistency in the Chl-a time-series among the three sensors is to variations in atmospheric correction algorithms, MERIS ocean-colour data were also reprocessed using a different atmospheric correction algorithm called POLYMER (Table 1, Comparison IV; Steinmetz et al., 2011). The POLYMER algorithm is conceptually different to the SeaDAS approach in that it is a coupled ocean-atmosphere algorithm based on spectral optimisation. Unlike SeaDAS, it retrieves atmospheric and oceanic properties simultaneously. The algorithm has been found to perform with high accuracy on the MERIS sensor (Steinmetz et al., 2011; Müller et al., accepted for publication), and its advantage over other atmospheric correction algorithms lies in its ability to perform in the presence of sun glint, and thus significantly increase ocean-colour coverage for sensors such as MERIS that did not have tilting capacity. MERIS daily binned level-3 remote-sensing reflectance ($R_{rs}$) data at 4 km resolution were produced using the POLYMER algorithm. Whereas POLYMER produces its own ocean-colour products, the OC4E algorithm (NASA, 2010) was applied to the daily binned level-3 POLYMER $R_{rs}$ data to estimate Chl-a as the focus here was to test differences associated with atmospheric correction, as opposed to differences in the Chl-a algorithm. Acronyms for all satellite Chl-a datasets using in the study are shown in Table 1.

For comparison with physical variables, MODIS-Aqua night-time 11 μm Sea Surface Temperature (SST) data and monthly-mean multi-mission gridded Sea Surface Height (SSH) products were downloaded from the NASA ocean-colour website and the Archiving, Validation and Interpretation of Satellite Oceanographic Data website (AVISO, http://www.aviso.oceanobs.com/) respectively (Table 1). Night-time SST imagery were used to minimise effects of diurnal heating. The monthly-mean multi-mission gridded SSH products were computed with respect to a 7-year mean. For all products (Table 1), monthly imagery were rescaled to 1/3° by 1/3° resolution plate carrée projection, using bilinear interpolation when magnifying and neighbourhood averaging when minifying, in order to keep the computing time of the analysis at a reasonable level. All Chl-a imagery were $\log_{10}$-transformed prior to further analysis, considering Chl-a is approximately log-normally distributed over the global ocean (Campbell, 1995).

### 2.2. Data subsampling

When comparing monthly imagery of Chl-a for MODIS-Aqua, SeaWiFS and MERIS, data were re-sampled excluding all grid points without data from all three satellite sensors. An example