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Optimized multi-satellite merger of primary production estimates in the California Current using inherent optical properties

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ABSTRACT

Building a multi-decadal time series of large-scale estimates of net primary production (NPP) requires merging data from multiple ocean color satellites. The primary product of ocean color sensors is spectral remote sensing reflectance (*Rrs*). We found significant differences (13–18% median absolute percent error) between *Rrs* estimates at 443 nm of different satellite sensors. These differences in *Rrs* are transferred to inherent optical properties and further on to estimates of NPP. We estimated NPP for the California Current region from three ocean color sensors (SeaWiFS, MODIS-Aqua and MERIS) using a regionally optimized absorption based primary production model (Aph-PP) of Lee et al. (2011). Optimization of the Aph-PP model was required for each individual satellite sensor in order to make NPP estimates from different sensors compatible with each other. While the concept of Aph-PP has advantages over traditional chlorophyll-based NPP models, in practical application even the optimized Aph-PP model explained less than 60% of the total variance in NPP which is similar to other NPP algorithms. Uncertainties in satellite *Rrs* estimates as well as uncertainties in parameters representing phytoplankton depth distribution and physiology are likely to be limiting our current capability to accurately estimate NPP from space. Introducing a generic vertical profile for phytoplankton improved slightly the skill of the Aph-PP model.

1. Introduction

Oceanic primary production and phytoplankton biomass (often represented by chlorophyll-a concentration), estimated by satellite ocean color sensors have become important datasets to validate global earth system models (Gregg et al., 2003; Yoder et al., 2011). In fact, estimation of oceanic net primary production (NPP) is considered one of the principal applications of satellite ocean color measurements (McClain, 2009). While the first attempts to use satellite ocean color to estimate oceanic NPP (Eppley et al., 1985) were promising, subsequent progress has been modest. Algorithm testing and comparison campaigns (Campbell et al., 2002; Carr et al., 2006; Friedrichs et al., 2009; Saba et al., 2011) have shown clear limitations of current NPP models. In particular, most of the variability in modeled NPP estimates is directly related to the variability in surface chlorophyll-a concentration whereas including other variables adds little to the skill of the models. It appears that model performance is not directly related with model complexity. Models underestimate observed NPP variability and fail to capture changes in productivity due to shifts in phytoplankton community composition (Friedrichs et al., 2009).

The primary input to most ocean primary productivity models (Behrenfeld and Falkowski, 1997) has been the concentration of chlorophyll-a (mg m^{-3}, *Chla*). However, operational satellite *Chla* algorithms (O'Reilly et al., 1998, 2000) are based on the ratio of remote sensing reflectance (*Rrs*) at blue and green wavelengths and primarily represent changes in the total absorption at blue wavelengths. Total absorption of blue light is affected not just by chlorophyll and other phytoplankton pigments but also by colored dissolved organic matter (CDOM) and non-phytoplankton particulates (Siegel et al., 2005). Errors in estimating *Chla* are directly transferred to errors in estimated NPP — not just due to the biased phytoplankton biomass but also due to the wide variation of biomass-normalized growth rate (Behrenfeld and Falkowski, 1997). Lee et al. (1996, 2011) proposed primary production algorithms that use phytoplankton absorption, $aph(\lambda)$, instead of *Chla* as the primary input variable. At least in principle, those algorithms, based on inherent optical properties (IOPs), have some advantages over NPP algorithms using *Chla*. First, when using $aph(\lambda)$ estimated with an inversion model from $Rrs(\lambda)$ instead of a band-ratio derived

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Chla, the influence of absorption by CDOM is minimized. Second, the uncertainty associated with *Chla*-specific absorption coefficient is avoided. The absorption-based productivity algorithm (Aph-PP) proposed by Lee et al. (2011) separates variables determined by phytoplankton physiology (e.g. the photosynthetic quantum yield) from the variables primarily determined by optics (e.g. IOPs). In a case study using a limited in situ dataset from the Southern Ocean, Lee et al. (2011) showed that the Aph-PP algorithm improved the estimates of NPP compared to traditional *Chla*-based methods. Here we apply the Lee et al (2011) Aph-PP method to satellite data from three ocean color sensors (SeaWiFS, MODIS-Aqua, MERIS) and evaluate its performance compared to a large in situ dataset collected by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) and the closely related California Coastal Ecosystem-Long Term Ecological Research (CCE-LTER) program (Ohman and Venrick, 2003).

We start by showing differences between *Rrs* estimates obtained by different sensors. We then show that these differences are transferred to differences in NPP estimates in spite of using a formerly adapted set of algorithms to derive IOPs (*aph*(440)). We emphasize that this study is not aiming to find the best parameters of the NPP model derived from fundamental studies of phytoplankton photophysiology. Rather, we show problems encountered when applying an NPP model to noisy satellite data with sensor-specific anomalies and our empirical attempts to find optimal values for the model parameters.

2. Data and methods

2.1. In situ measurements of NPP

On-deck ^{14}C incubations have been performed on quarterly CalCOFI cruises since 1984. The half-day (local noon to sunset) primary production values, integrated over the euphotic depth, are multiplied by 1.8 to obtain equivalent 24 h productivity (Eppley, 1992). In this study we used a subset of 861 stations occupied over the time period from 18-Sept-1997 to 12-Feb-2012 when satellite data from at least one of the three sensors of SeaWiFS, MODIS-Aqua (MODISA) and MERIS were available. The CalCOFI study area covers different regions of the California Current from coastal to about 600 km offshore (Fig. 1). In situ NPP measurements have considerable uncertainty with more uncertainty at low values. Saba et al. (2011) assumed uncertainties in NPP decreasing as a linear function of increasing $\log_{10}$(NPP), from 50% for NPP $\leq$50 mg C m^{-2} d^{-1} to 20% for NPP $\geq$ 2000 mg C m^{-2} d^{-1}. The distribution of in situ CalCOFI vertically integrated NPP values is log-normal with the mode between 200 and 400 mg C m^{-2} d^{-1} (Fig. 1 in Kahru et al., 2009).

2.2. Match-ups between satellite and in situ data

The validation of satellite products using quasi-simultaneous and spatially collocated measurements (match-ups) of satellite and in situ data followed the general procedures of previous studies (e.g. Bailey and Werdell, 2006; Kahru and Mitchell, 1999; Kahru et al., 2012; Werdell and Bailey, 2005). We acquired coincident Level-2 (i.e. processed to surface quantities but unmapped) data of SeaWiFS (1997–2010, version 2010.0), MODISA (2002–2012, version 2012.0) and MERIS (2002–2012, 3rd reprocessing). Full resolution (~1 km) SeaWiFS and MODISA data were obtained from NASA's Ocean Color web (http://oceancolor.gsfc.nasa.gov/) and the RR data (~1 km) of MERIS were obtained from ESA's MERIS Catalogue and Inventory (http://merci-srv.eo.esa.int/merci/welcome.do). For each Level-2 pixel we used the corresponding Level-2 flags. A pixel was determined valid if none of the following flags were set: ATMFAIL, LAND, HISATZEN, CLDICE, CHLFAIL, SEAICE, NAVFAIL, HIPOL and PRODFAIL (see http://oceancolor.gsfc.nasa.gov/VALIDATION/flags.html for explanation of the flags). For MERIS the following flags made the pixel invalid: LOW SUN, HIGH_GLINT, ICE_HAZE, SUSPECT, COASTLINE, PCD_19,

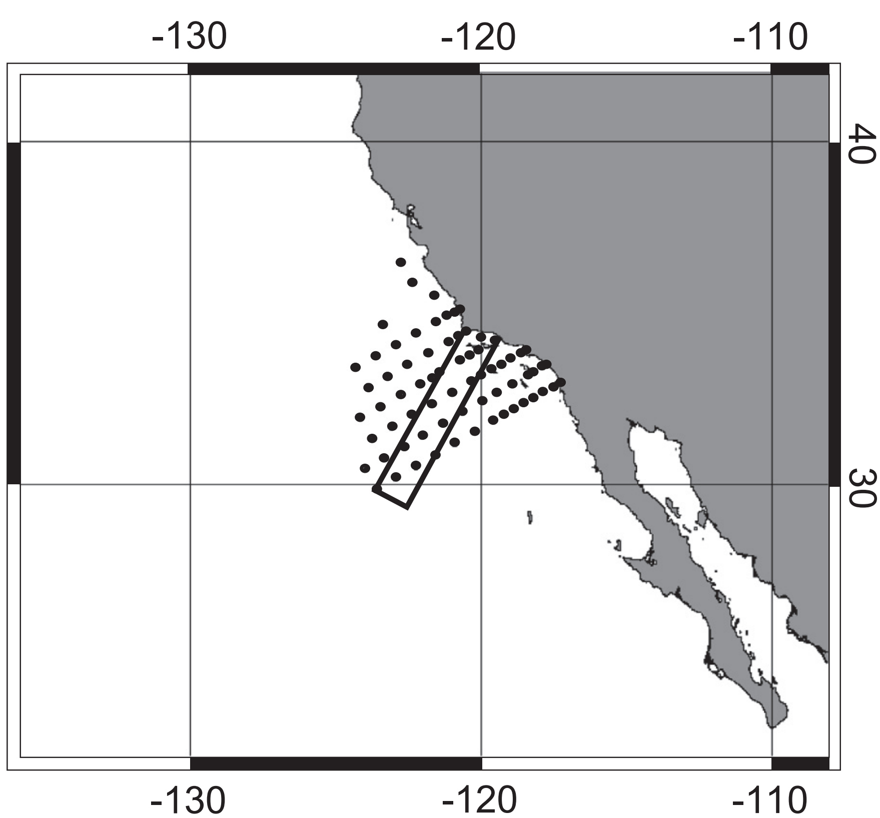

Fig. 1. Locations of the satellite (MODIS-Aqua, MERIS and SeaWiFS) match-ups (filled circles) with in situ primary productivity measurements. The rectangle shows the location of the strip from coast to offshore where satellite-to-satellite *Rrs443* match-ups were assembled.