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Satellite derived euphotic depth in the Southern Ocean: Implications for primary production modelling

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ABSTRACT

The euphotic depth (Z_{eu}) is a key parameter in modelling primary production (PP) using satellite ocean colour. However, evaluations of satellite Z_{eu} products are scarce. The objective of this paper is to investigate existing approaches and sensors to estimate Z_{eu} from satellite and to evaluate how different Z_{eu} products might affect the estimation of PP in the Southern Ocean (SO). Euphotic depth was derived from MODIS and SeaWiFS products of (i) surface chlorophyll-a (Z_{eu}-Chla) and (ii) inherent optical properties (Z_{eu}-IOP). They were compared with *in situ* measurements of Z_{eu} from different regions of the SO. Both approaches and sensors are robust to retrieve Z_{eu}, although the best results were obtained using the IOP approach and SeaWiFS data, with an average percentage of error (E) of 25.43% and mean absolute error (MAE) of 0.10 m (log scale). Nevertheless, differences in the spatial distribution of Z_{eu}-Chla and Z_{eu}-IOP for both sensors were found as large as 30% over specific regions. These differences were also observed in PP. On average, PP based on Z_{eu}-Chla was 8% higher than PP based on Z_{eu}-IOP, but it was up to 30% higher south of 60°S. Satellite phytoplankton absorption coefficients (a_{ph}) derived by the Quasi-Analytical Algorithm at different wavelengths were also validated and the results showed that MODIS a_{ph} are generally more robust than SeaWiFS. Thus, MODIS a_{ph} should be preferred in PP models based on a_{ph} in the SO. Further, we reinforce the importance of investigating the spatial differences between satellite products, which might not be detected by the validation with *in situ* measurements due to the insufficient amount and uneven distribution of the data.

1. Introduction

Phytoplankton primary production (PP) is one of the key drivers regulating the ocean carbon cycle. In the Southern Ocean (SO), phytoplankton blooms develop with the retreat of sea ice in the springtime and, as a result, surface waters turn into a strong sink of CO_2 (Takahashi et al., 2009). Because PP has a high spatial and temporal variability within this part of the global ocean, it is difficult to assess and monitor it with *in situ* measurements. Despite the efforts to accurately estimate PP from ocean colour, studies showed large differences in the SO estimates (Campbell et al., 2002; Carr et al., 2006).

A common parameter shared by different ocean colour PP models is the euphotic depth (Z_{eu}). In biological terms, Z_{eu} is the bottom of the euphotic zone; the part of the water column with sufficient light for supporting photosynthesis and thus PP (Falkowski & Raven, 2007, chap. 9; Kirk, 2011, chap. 1). In physical terms, Z_{eu} is the depth where the downward photosynthetic available radiation (PAR), the radiation in the spectral range of 400–700 nm, is reduced to 1% of its value beneath the surface (Morel & Berthon, 1989).

In ocean colour remote sensing Z_{eu} can be estimated (i) empirically from the surface chlorophyll-a concentration (Chla, Z_{eu}-Chla) (Morel, in Lee et al., 2007) and (ii) semi-analytically from the inherent optical properties of the water (IOPs, Z_{eu}-IOP) (Lee, Du, Arnone, Liew, & Penta, 2005). The main difference between the two approaches is that the derivation of Z_{eu} from Chla assumes that the optical properties of the optically active constituents co-vary with Chla (so-called Case 1 waters). On the other hand, the IOP approach determines the vertical distribution of light from the IOPs and therefore Z_{eu} can be retrieved in optically complex waters too, as shown by Lee et al. (2007) and Shang, Lee, and Wei (2011).

Uncertainties in Z_{eu} estimated from satellite data in the China Sea were investigated by Shang, Lee, et al. (2011). However, to our knowledge, there is no detailed evaluation of the satellite Z_{eu} in the SO. A comparison of ocean colour sensor/retrievals with *in situ* measurements, as well as the further impact on the PP modelling is thus necessary.

In this context, the main goal of this paper is to investigate the differences in estimating Z_{eu} from satellite remote sensing using different approaches and sensors in the SO. We compute Z_{eu} from ocean colour products of (i) Chla and (ii) IOP and validate those using *in situ*

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measurements of Z_{eu}. In addition, we compare Z_{eu} derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) sensors. The approaches and sensors are further examined in terms of the spatial distribution of Z_{eu}. Since phytoplankton absorption coefficient (a_{ph}) data are used in the PP calculation, we also examine the uncertainties of MODIS and SeaWiFS a_{ph} derived with the Quasi-Analytical Algorithm (QAA, Lee et al., 2005). Finally, we apply the absorption based primary production model (ABPM, Hirawake et al., 2011; Hirawake, Shinmyo, Fujiwara, & Saitoh, 2012) to investigate how different Z_{eu} products might affect the estimation of PP in the SO.

2. Material and methods

2.1. In situ data

A data set of *in situ* measurements of Chla ($N = 1032$) and Z_{eu} ($N = 1288$) in the SO was built to validate the satellite measurements. The data set compiled measurements from 1997 to 2008 taken by several investigators (Fig. 1 and Table A1). The Chla data were restricted to Chla derived from High Performance Liquid Chromatography (HPLC) pigment analysis, within 12 m surface layer and taken within 3 h of the Z_{eu} *in situ* measurements. An average value of Chla was calculated if two or more samples were collected within the surface layer. We used Z_{eu} data provided in the databases that were calculated from *in situ* measurements of vertical profiles of PAR ($N = 977$). In addition, vertical profiles of PAR were also available in the SeaBASS database (cruises are marked with * in Table A1, Appendix) and those were used to calculate Z_{eu} ($N = 311$). We corrected surface measurements for wave perturbations when necessary as described in Taylor et al. (2011) and profiles not deep enough to reach the 0.01 of PAR at surface were discarded. A third data set of *in situ* measurements of a_{ph} ($N = 465$) was compiled to validate the a_{ph} derived from satellite remote sensing reflectance (R_{rs}). The a_{ph} data are derived from filter pad measurements taken in the years 2007, 2008, 2010 and 2012. The ANT-XXVI/3 and ANT-XXVIII/3 data were measured according to the filter pad method described in Taylor et al. (2011). Fig. 1 presents the relative frequency distribution of the Z_{eu}, Chla and spectrally averaged a_{ph} coefficient over 400–700 nm ($\overline{a}_{ph,}$ see Section 2.4) *in situ* measurements that matched with SeaWiFS and MODIS data. Their relative frequency distribution by latitude and longitude is presented in the Appendix (Fig. A1).

2.2. Satellite data

MODIS-Aqua (R2012.0) and SeaWiFS (R2010.0) level 3 products of Chla (CHL1), PAR, R_{rs} were obtained at http://oceancolor.gsfc.nasa.gov/.

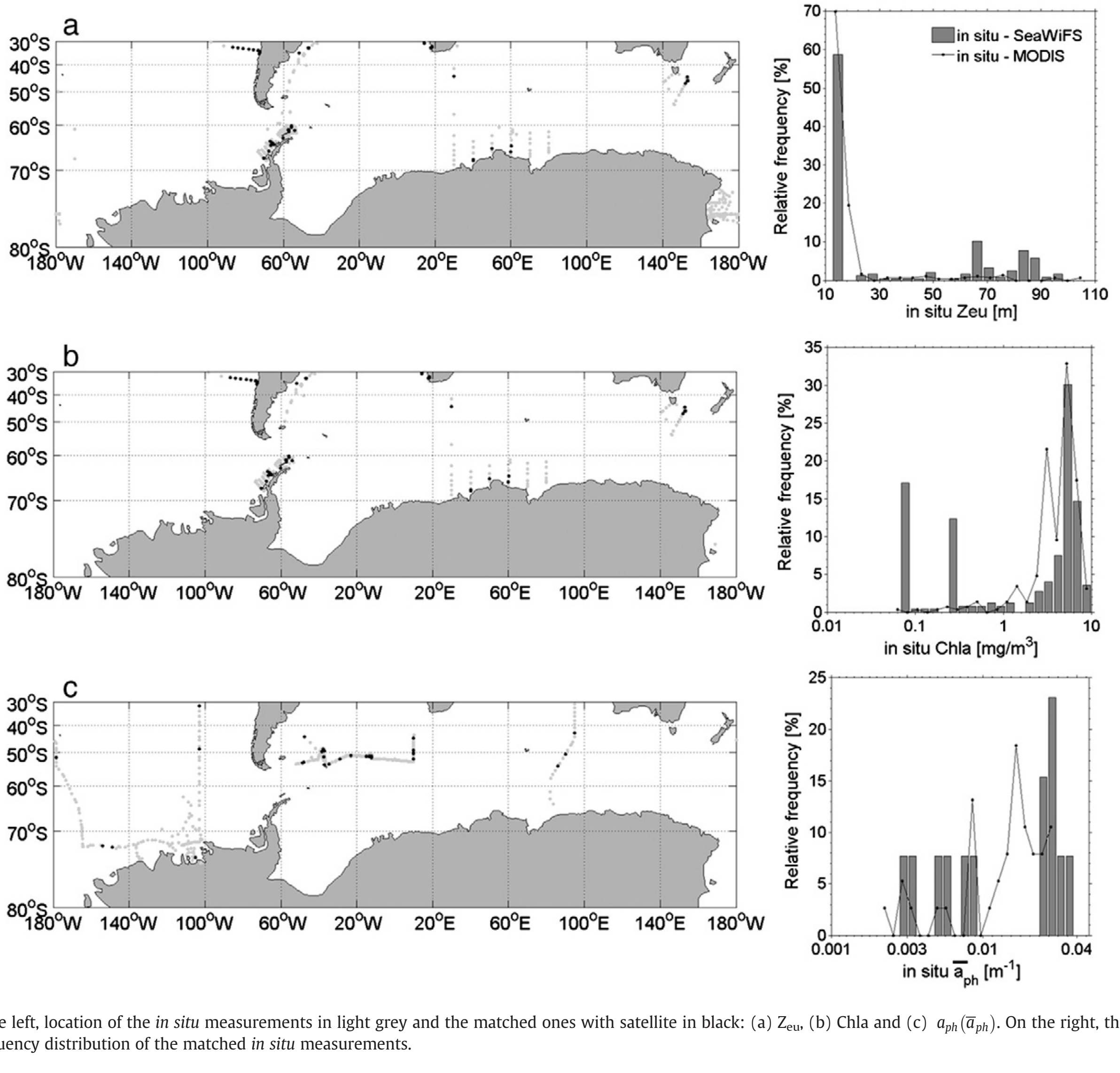

Fig. 1. On the left, location of the *in situ* measurements in light grey and the matched ones with satellite in black: (a) Z_{eu}, (b) Chla and (c) a_{ph} ($\overline{a}_{ph}$). On the right, the respective relative frequency distribution of the matched *in situ* measurements.