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Blending of ocean colour algorithms applied to the Southern Ocean

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A method of blending of a specific satellite ocean colour algorithm in the Southern Ocean (SO) with a generic algorithm elsewhere is proposed. The SO is known to have bio-optical properties that require a different bio-optical algorithm for retrieving chlorophyll-*a* concentration. Merging data retrieved with a specific algorithm in one area with data retrieved with another algorithm elsewhere has remained a problem. We use a blending scheme that uses both bio-optical properties and the location of the pixel relative to the mean position of the Subtropical Front to create a smooth transition from one algorithm to another. The method can be applied to other regions or variables after modification.

1. Introduction

Satellite measurements of ocean colour (McClain 2009) are a primary tool for assessing ocean productivity and its response to climate change (Behrenfeld *et al.* 2006). Improving the accuracy of the ocean colour algorithms is therefore a high priority. It is known that bio-optical relationships between chlorophyll-*a* concentration (chl-*a*, mg m^{-3}) and water-leaving radiances differ from those at lower latitudes (Mitchell and Holm-Hansen 1991, Dierssen and Smith 2000, Garcia *et al.* 2005, Mitchell and Kahru 2009) and that standard ocean colour algorithms have a significant bias in the Southern Ocean (SO). The errors in estimating chl-*a* are transferred to estimates of primary productivity and carbon fluxes. Despite the importance of the SO, incorporating this information into a standard satellite algorithm has remained elusive. Specific algorithms for the SO have been proposed (Mitchell and Kahru 2009), but the problem remains how to merge seamlessly satellite products over regions that cover domains of application of different algorithms. This letter describes a method of how to blend a specific SO chl-*a* algorithm with the standard chl-*a* algorithm elsewhere.

2. Southern Ocean chl-*a* algorithm

The standard NASA ocean colour chl-*a* algorithms (O'Reilly *et al*. 1998, Werdell 2009) use the maximum band ratio (MBR) principle applied to remote sensing reflectances, R_{rs} (or to normalized water-leaving radiances, L_{wn}). Our SO-specific algorithm, called SPGANT, uses a similar form and separate versions have been developed for the major ocean colour sensors (Mitchell and Kahru 2009).

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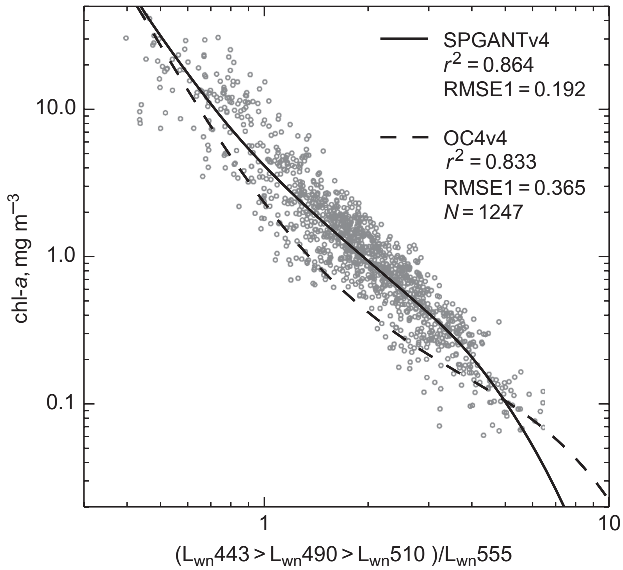

Figure 1. The Southern Ocean chl-*a* algorithm SPGANTv4 (solid curve) as applied to SeaWiFS bands compared to the standard OC4v4 algorithm (dashed) using in situ data (small black circles).

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Figure 1 shows the difference between the standard OC4 and the SPGANT algorithms for SeaWiFS. In essence, over the middle chl-*a* range (0.2–2 mg m^{-3}) the standard chl-*a* algorithms (OC4 for SeaWiFS, OC3m for MODIS and OC4-GLI for GLI) underestimate chl-*a* by 2–3 times. SPGANT has higher r^2, lower RMS error and, most significantly, it produces significantly higher chl-*a* at midrange of chl-*a*. The range 0.2–2 mg m^{-3} is the typical chl-*a* range in moderate phytoplankton blooms in the SO and is therefore important for the accurate detection of primary production and export fluxes in these regions. This underestimation by the standard algorithms in the chl-*a* mid-range by 2–3 times has been independently confirmed by several studies (Dierssen and Smith 2000, Holm-Hansen *et al.* 2004, Garcia *et al.* 2005). At low chl-*a* ($\leq$0.1 mg m^{-3}) the algorithm curves merge. At high chl-*a* ($\geq$10 mg m^{-3}) the algorithm curves also merge but the relationship between chl-*a* and the MBR is highly variable and dependent on the particular phytoplankton type and other bio-optical characteristics.

The SPGANTv4 algorithm has been developed using I data collected by the Scripps Photobiology Group and by adding all data from NOMAD (Werdell and Bailey 2005) south of 55°S latitude.

3. Blending of the Southern Ocean algorithm with the standard algorithm

Currently we have no acceptable bio-optical model that provides equally good chl-*a* estimates in the SO and in other parts of the World Ocean. Although the SPGANTv4 provides improved chl-*a* estimates in the SO, it is not applicable for the rest of the World Ocean where the standard algorithm should be used. In producing global or regional chl-*a* maps we need to have a realistic transition from the SO to the rest of the World Ocean without a discontinuity between the different domains. Similar problem arises when transitioning between other regions with localized algorithms. We have designed

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a method to blend the SO algorithm with the standard ocean colour algorithms. We note that the SO with relatively high chl-*a* is bounded by the oligotrophic gyres with very low chl-*a* to the north and that the boundary between them coincides roughly with the Subtropical Front (STF) (Orsi *et al.* 1995). We also note (figure 1) that at low chl-*a* ($\sim$0.1 mg m^{-3}, MBR $\sim$5) the standard chl-*a* model and the SO-specific model converge. Below $\sim$0.1 mg m^{-3} the polynomial curves diverge again but this is due to the lack of data and not due to a known difference in the algorithms. We assume that at low chl-*a* ($\leq$0.1 mg m^{-3}) the standard algorithm is applicable in the SO. In summary, we use the standard algorithm at MBR ≥ 5, the SO algorithm when MBR < 3 and blend the two algorithms when $3 <$ MBR < 5. In the transition zone ($3 <$ MBR < 5) the weight of the SO algorithm (w_{MBR}) changes linearly from 1 at MBR $= 3$ to 0 at MBR $= 5$ (figure 2). This assumes that the northern boundary of the SO coincides with low chl-*a* (high MBR), and we will use the standard algorithm north of the boundary. However, the natural boundary of the SO formed by the oligotrophic gyres (MBR > 3) to the north is not continuous along the coasts and in some other productive areas (around island and continental shelves). In those productive areas we use the mean position of the STF as the boundary. The position of STF is not fixed in space but can vary over a broad range; therefore, we use a range of approximately $\pm$500 km centred at the mean position of STF as the north–south transition zone. In this transition zone the geographic weight of the SO algorithm (w_{Geo}) changes from 1 at the southern border to 0 at the northern border. The weight of the SO algorithm is based on both MBR (w_{MBR}) and location compared to STF (w_{Geo}) and the final weight of the SO algorithm (w) is taken as the minimum of w_{MBR} and w_{Geo}. Figure 3(*a*) shows the resulting weighting function that provides a smooth transition in the STF zone and also uses the low MBR in the blending of the low-chl-*a* waters south of the northern border of the transition zone. Blending of the chl-*a* value for a pixel is done according to the following formula: $\mathrm{chl}_{\mathrm{Blended}} = w \times \mathrm{chl}_{\mathrm{SPGANT}} + (1 - w) \times \mathrm{chl}_{\mathrm{Standard}}$, where $\mathrm{chl}_{\mathrm{Blended}}$ is the blended chl-*a*, $\mathrm{chl}_{\mathrm{SPGANT}}$ is the value returned for a pixel using the SPGANT algorithm and $\mathrm{chl}_{\mathrm{Standard}}$ is the value returned by the standard algorithm. This blending scheme works well and produces chl-*a* maps without discontinuities (figure 3(*b*)). We acknowledge that the geographic blending is set to depend on the climatological location of STF and not on the current location. This is a compromise as the current location of the SO boundary is

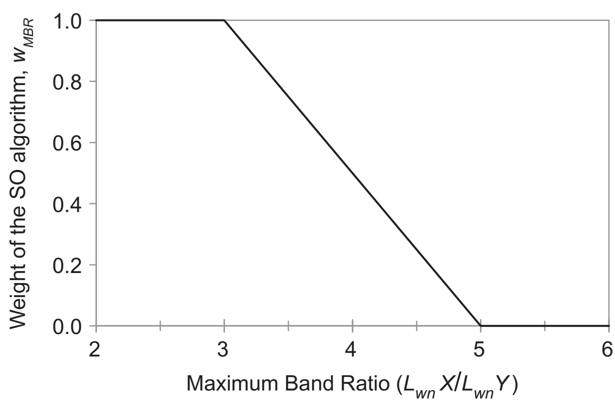

Figure 2. Blending of the Southern Ocean algorithm with the standard algorithm: the weight of the SO algorithm based on maximum band ratio as a function of MBR.

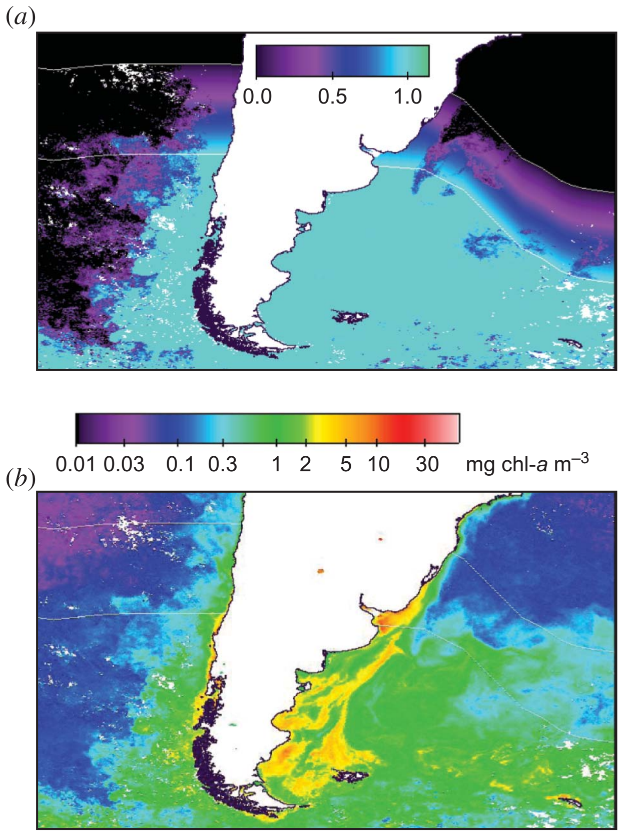

Figure 3. An example of the blending results. The white curves show the boundaries of the transition zone, ±500 km on either side of the mean position of STF. (*a*) Blending weight of the SO algorithm (*w*) in a section of the Southern Ocean (December 1997) depending on the maximum band ratio and distance from the Subtropical Front (STF). (*b*) Blended chl-*a* map.

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difficult to determine. If such information is available then the scheme could be changed easily.

In summary, the blending scheme is applied to all pixels south of the northern boundary of STF as following:

At MBR ≥ 5 it switches to the standard algorithm;
At MBR between 3 and 5, $w_{\mathrm{MBR}} = (5.0 - \mathrm{MBR})/2.0$ and the weight of the standard algorithm is$1 - w_{\mathrm{MBR}}$.

In the transition zone (±500 km north-south of the mean STF position) the geographic weight of the SO algorithm w_{Geo} is calculated as a linear function between 1 at the southern boundary and 0 at the northern boundary. The weight of the SO algorithm w is the minimum of w_{MBR} and w_{Geo} and $\mathrm{chl}_{\mathrm{Blended}} = w \times \mathrm{chl}_{\mathrm{SPGANT}} + (1 - w) \times \mathrm{chl}_{\mathrm{Standard}}$.

4. Discussion and conclusions

A more generic blending method for ocean colour algorithms based on fuzzy logic and weights determined by statistical procedures has been proposed (Moore *et al.* 2001) and is potentially applicable. However, here we use a more specific approach adjusted for the SO that uses the bio-optical properties of the SO and location of a pixel compared to the mean boundary of the SO. Using this approach we can create global chl-*a* maps while using a SO-specific algorithm in the SO and the standard algorithm (e.g. OC4 for SeaWiFS) elsewhere. The blending scheme proposed here can be modified and improved if more information on bio-optical properties in the transition zone becomes available.

To calculate global fluxes because of net primary production (NPP) and export production, the SO estimates need to be combined with estimates elsewhere. Using a specific algorithm in the SO is important as the standard algorithms typically underestimate chl-*a* by 2–3 times compared to in situ measurements, and these errors are typically transferred to the estimates of NPP and export fluxes of carbon that are critical to assessment of climate change and the role of the SO in it. The blending scheme used for chl-*a* can also be used for blending of NPP and other fluxes to derive global estimates that seamlessly transcend boundaries.

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References

BEHRENFELD, M.J., O'MALLEY, R.T., SIEGEL, D.A., MCCLAIN, C.R., SARMIENTO, J.L., FELDMAN, G.C., MILLIGAN, A.J., FALKOWSKI, P., LETELIER, R.M. and BOSS, E.S., 2006, Climate-driven trends in contemporary ocean productivity. *Nature*, **444**, pp. 752–755.

DIERSSEN, H.M. and SMITH, R.C., 2000, Bio-optical properties and remote sensing ocean color algorithms for Antarctic Peninsula waters. *Journal of Geophysical Research*, **105**, pp. 26301–26312.

GARCIA, C.A.E., GARCIA, V.M.T. and MCCLAIN, C.R., 2005, Evaluation of SeaWiFS chlorophyll algorithms in the Southwestern Atlantic and Southern Oceans. *Remote Sensing of Environment*, **95**, pp. 125–137.

HOLM-HANSEN, O., KAHRU, M., HEWES, C.D., KAWAGUCHI, S., KAMEDA, T., SUSHIN, V.A., KRASOVSKI, I., PRIDDLE, J., KORB, R., HEWITT, R.P. and MITCHELL, B.G., 2004, Temporal and spatial distribution of chlorophyll-*a* in surface waters of the Scotia Sea as determined by both shipboard measurements and from satellite data. *Deep-Sea Research Part II*, **51**, pp. 1323–1331.

MCCLAIN, C.R., 2009, A decade of satellite ocean color observation. *Annual Reviews in Marine Science*, **1**, pp. 19–42.

MITCHELL, B.G. and HOLM-HANSEN, O., 1991, Bio-optical properties of Antarctic Peninsula waters: differentiation from temperate ocean models. *Deep-Sea Research*, **38**, pp. 1009–1028.

MITCHELL, B.G. and KAHRU, M., 2009, Bio-optical algorithms for ADEOS-2 GLI. *Journal of Remote Sensing Society of Japan*, **29**, pp. 80–85.

MOORE, T.S., CAMPBELL, J. and FENG, H., 2001, A fuzzy logic classification scheme for selecting and blending satellite ocean color algorithms. *IEEE Transactions on Geoscience and Remote Sensing*, **39**, pp. 1764–1776.

O'REILLY, J.E., MARITORENA, S., MITCHELL, B.G., SIEGEL, D.A., CARDER, K.L., GARVER, S.A., KAHRU, M. and MCCLAIN, C.R., 1998, Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysical Research*, **103**, pp. 24937–24953.

ORSI, A.H., WHITWORTH, T. and NOWLIN, W.D., 1995, On the meridional extent and fronts of the Antarctic circumpolar current. *Deep-Sea Research Part I*, **42**, pp. 641–673.

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Werdell, P.J., 2009, *Ocean Color Chlorophyll (Oc) v6*. Available online at: http://oceancolor.gsfc.nasa.gov/Reprocessing/R2009/ocv6/ (accessed 27 October 2009).

Werdell, P.J. and Bailey, S.W., 2005, An improved in-situ bio-optical dataset for ocean color algorithm development and satellite data product validation. *Remote Sensing of Environment*, **98**, pp. 122–140.

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