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BIO-OPTICAL MEASUREMENTS IN THE SOUTHWESTERN ATLANTIC AND SOUTHERN OCEANS FOR CHLOROPHYLL-A CONCENTRATION MAPPING FROM SPACE

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ABSTRACT

Bio-optical data consisting of radiometric (upwelling spectral radiance) and surface pigment concentration measurements (chlorophyll-a) have been collected between 1995 and 2002 in the Southwestern Atlantic and Southern Oceans (1.8^o-72^{o}S and 18.5^o-60^{o}W). This data set has been used to derive bio-optical algorithms for mapping chlorophyll-a concentrations from space. Samplings during nine oceanographic cruises were carried out on different water types, including Brazilian coastal waters, open ocean waters and Antarctic waters. Comparisons are made between bio-optical algorithms generated in this work to those normally used by the SeaWiFS community users. The results show greatest differences for algorithms generated for the Southern Ocean region, where the global SeaWiFS algorithm underestimates chlorophyll values, which confirms previously observations by others investigators.

INTRODUCTION

Remote sensing techniques have been successfully used to provide a synoptic coverage of large-scale surface patterns of phytoplankton biomass distribution at a global scale. This is based on relationships between the radiometric spectral signature of surface waters and its pigment concentration. The empirical ocean color algorithms widely used in the processing of Coastal Zone Color Scanner (CZCS) for this purpose was derived from fewer than 60 coincident radiometric and pigment concentration data sets.

Several efforts over the past few years have been made to gather *in situ* spectral radiometric data for ocean color chlorophyll algorithm development and remote sensing data validation. These observational experiments have contributed with NASA's algorithms for Sea-viewing Wide Field-of-view Sensor (SeaWiFS) to estimate chlorophyll-a concentration from space (Hooker and Firestone, 2000; Fargion and McClain, 2002). O'Reilly *et al.* (2000)

presented an update of NASA'S OC2 and OC4 SeaWiFS algorithms, based on a large *in situ* data set, including measurements in oligotrophic and eutrophic waters.

Bio-optical properties of seawater in the South Atlantic and Southern Oceans are poorly known despite the efforts of some researchers (Mitchel and Holm Hansen, 1991, Omachi and Garcia, 2000; Mitchel et al, 2001). A greater effort should be placed on sampling the Southern Ocean, because of its importance for understanding biogeochemical processes, which contribute for the global carbon cycle. Moreover, a significant difference has been found in bio-optical algorithms in this region, as compared with those of lower latitude (Mitchell and Holm-Hansen, 1991) and a specific SeaWiFS algorithm has been suggested by Mitchell *et al.* (2001).

This work presents results of *in situ* spectral upwelling radiance and chlorophyll concentration collected over the past years, during cruises to the Southwestern Atlantic and Southern Oceans. Chlorophyll algorithms have been generated with this data set and compared with NASA's OC2v4 model (O´Reilly *et al*, 2000), widely used to map pigment concentration from space.

METHODS AND DATA SET

Oceanographic cruises

Nine cruises have been conducted in the Southwestern Atlantic and Southern Ocean, between 1995 and 2002 (Table 1) resulting in 120 sampling stations covering a very wide region (0^o - 80^oS and 15^o - 60^oW). Figure 1 shows the geographical extent of the study region and sampling stations on a SeaWiFS binned (9kmx 9km resolution) mean image for the year 2000. The latter was generated by SeaWiFS Project Team in the 4th data reprocessing. It can be seen that the bio-optical data used in this work were collected from several biogeochemical provinces, ranging from equatorial to polar region.

Bio-optical Data

In-water radiometric measurements were made using a Satlantic-Tethered Spectral Radiometer Buoy (TSRB). The instrument collects spectral upwelling radiance at 50cm depth - L_u (λ,0.5m) - at 412, 443, 490, 510, 555, 670 and 683nm and downwelling irradiance at sea surface at 490 nm (Cullen *et al*., 1994). The instrument was always kept 70-90m away from ship to avoid shadowing. Time interval for measurements varied from 10-20 minutes at 1 Hz frequency. Spikes were removed prior to analyses. A smoothing method was applied to radiometric data using a window size equivalent to 3% of the respective number of data. The mean spectral upwelling radiances at 50cm depth for each station are used in this work.

At each station surface water samples were filtered onto 25 mm Whatman GF/F filters for fluorometric chlorophyll-a analysis (Holm-Hansen et al, 1965) using either a TURNER 111 or a TD-700 TURNER DESIGNS fluorometer. Surface chlorophyll concentration varied from 0.02 to 5.3 mg/m^3. Figure 2 shows the frequency distribution of surface chlorophyll concentrations for all stations.

Chlorophyll Algorithms

The spectral upwelling radiance just below sea surface, $L_u(\lambda,0^-)$, is related to remote sensing reflectance, $R_{rs}(\lambda)$ as follows:

$$R_{rs} = 0.54 \frac{L_u(\lambda,0^-)}{E_d(\lambda,0^+)}$$

where $E_d(\lambda,0^+)$ is the downwelling irradiance above the sea water and the factor 0.54 accounts for radiant energy loss at sea-water interface.

Omachi and Garcia (2000) using a smaller bio-optical data set calculated $E_d(\lambda,0^+)$ from atmospheric transmission models as the TSRB drifter does not measure $E_d(\lambda,0^+)$ and skylight conditions varied enormously between sampling. In this work we derived chlorophyll algorithms based on logarithm of upwelling radiance ratios $R=\log(L_u(\lambda_1)/L_u(\lambda_2))$ rather than logarithm of reflectance ratios $R=\log(R_{rs}(\lambda_1)/R_{rs}(\lambda_2))$ as recommended.

RESULTS AND DISCUSSION

Initially, several attempts were made in this work to derive empirical relationships between spectral radiance at 412, 443, 490 and 555 nm and surface chlorophyll a concentration. The well-known 2-band and 4-band NASA algorithms were thoroughly tested but the first presented better results. Omachi and Garcia (2000) also evaluated a variety of bio-optical algorithms and concluded that a 2-band (490 and 555) ratio performs well (r^2=0.90) and better than a 4-band algorithm type in the Southwestern Atlantic and Southern Oceans. Also, the modified cubic polynomial equation for OC2 version 4 used by NASA (hereinafter NASA OC2v4) presents high similarities to OC4 version 4 (hereafter NASA OC4v4) in the range 0.2-2.0 mg/m^3 (O'Reilly *et al*, 2000) which dominates our chlorophyll concentration distribution.

The overall data sets of chlorophyll values and radiance ratios in this work are shown in figure 3, together with the derived algorithm. NASA OC2v4 has also been plotted for comparison. It can be seen that the fitted algorithm line falls quite well on the OC2 curve. The data set has a total of 120 *in situ* observations and represents a reasonably large diversity of provinces in the Southern Hemisphere. Some discrepancies exist at very high and at very low chlorophyll concentrations, however, most chlorophyll estimates by both models are coincident. The empirical equation which relates chlorophyll-a concentration [chla] to radiance ratio $R35=\log(L_u(490)/L_u(555))$ is

$$[Chla] = 10^{(a+bR35)}$$

where a= 0.28 and b= -2.19. The root mean square error (rms) of log[chla] is 0.20 and r^2 = 0.85 (see table 1).

After inspection of the bio-optical data set and their respective regions or provinces, we have decided to subdivide the data into 3 categories. They are named the South Atlantic Gyre Open Waters (OPW), the Southern Ocean Waters (SOW) and the Brazilian Coastal Waters (BCW). Bio-optical observations at latitudes higher than 36^o S was considered to be from SOW province while stations closer to southern Brazilian coast were classified as BCW (see fig 1). First order polynomial equations were derived from the bio-optical data for these 3 sub-regions.

Figure 4 shows the statistical and graphical characteristics of these algorithms. The NASA OC2v4 equation is also plotted for comparisons. Table 1 shows some bio-optical and statistical characteristics for all points and for separate regions. Generally, chlorophyll-a values were quite small in the oligotrophic waters of the South Atlantic Gyre (mean of 0.09 mg/m^3) and higher in the SOW region (mean of 0.44 mg/m^3). The BCW province presented a wider range of chlorophyll values (0.07 to 5.30 mg/m^3)

As it can be seen in figure 4, despite some random deviations, the data for OPW and BCW regions agree reasonably well with the OC2v4 model. However, data points from the Southern Ocean are mostly higher than predicted by NASA’s OC2. This has also been observed by other authors (e.g. Mitchell *et al.*, 2001) and calls for a closer investigation of this region, concerning the use of a regional model for deriving ocean color chlorophyll estimation.

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Table 1. Chlorophyll concentrations and algorithm statistical details for the 3 sub-regions identified in this study and for the overall data set. BCW= Brazilian Coastal Waters; SOW= Southern Ocean Waters; OPW= South Atlantic Gyre Open Waters.

Province	Mean Chla (mg/ m^3)	Chla Range (mg/ m^3)	a	b	r^2	rms of log[chla]	Number of data
BCW	0.89	0.07-5.30	0.15	- 1.91	0.82	0.21	35
SOW	0.44	0.10-1.97	0.39	- 2.24	0.81	0.13	50
OPW	0.09	0.02-0.23	1.20	- 3.79	0.63	0.17	35
Overall	0.47	0.02-5.30	0.28	-2. 19	0.85	0.20	120

Figure 1. Mean SeaWiFS chlorophyll image (year 2000) showing the study region and position of the sampling stations: Brazilian coastal region (+), Southern Ocean (o) and Southwestern Atlantic Gyre (*) are marked on the image.

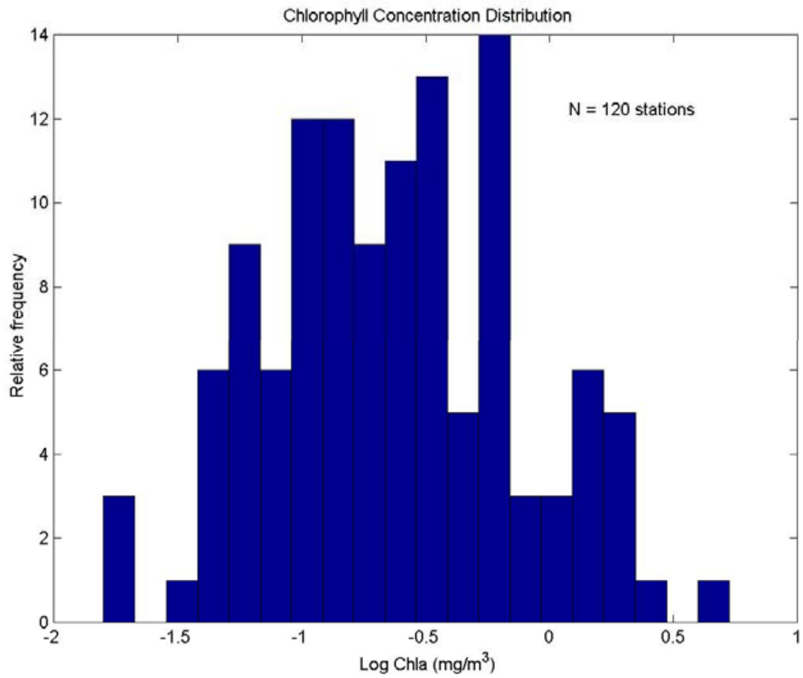

Figure 2. Histogram showing distribution frequency of the log chlorophyll values used in this work

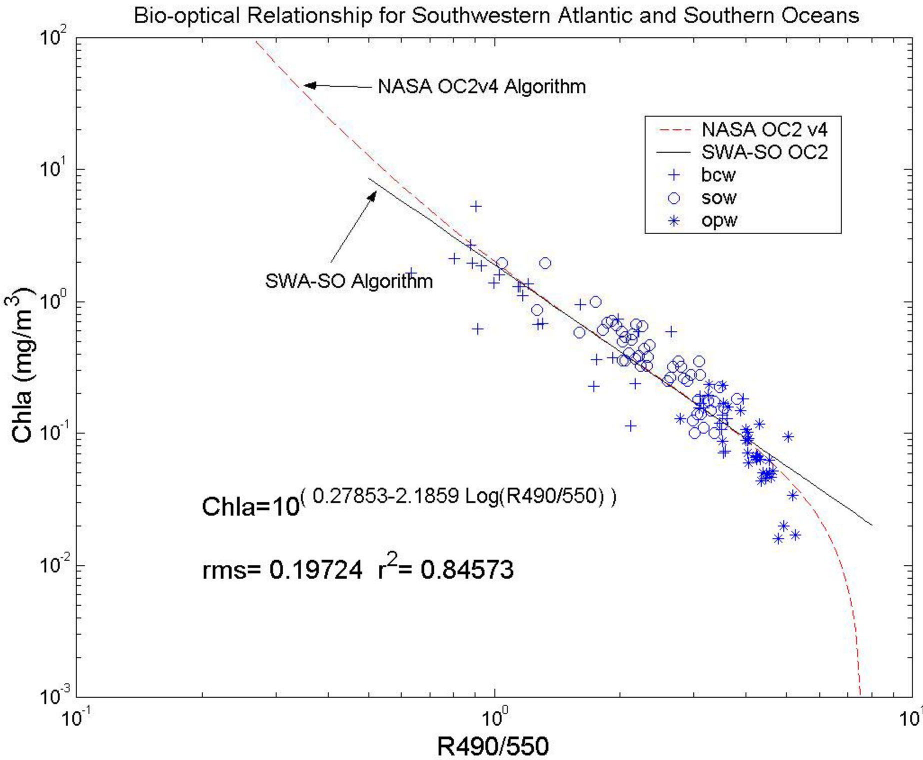

Figure 3. A scatterplot of upwelled radiance ratio (R490/555) versus chlorophyll concentrations for the whole data set. The dashed curve represents the NASA OC2v4 algorithm while the solid line represents the fitted equation. Different data point symbols refer to the 3 types of provinces sampled in the period 1995-2002 (see text for details).

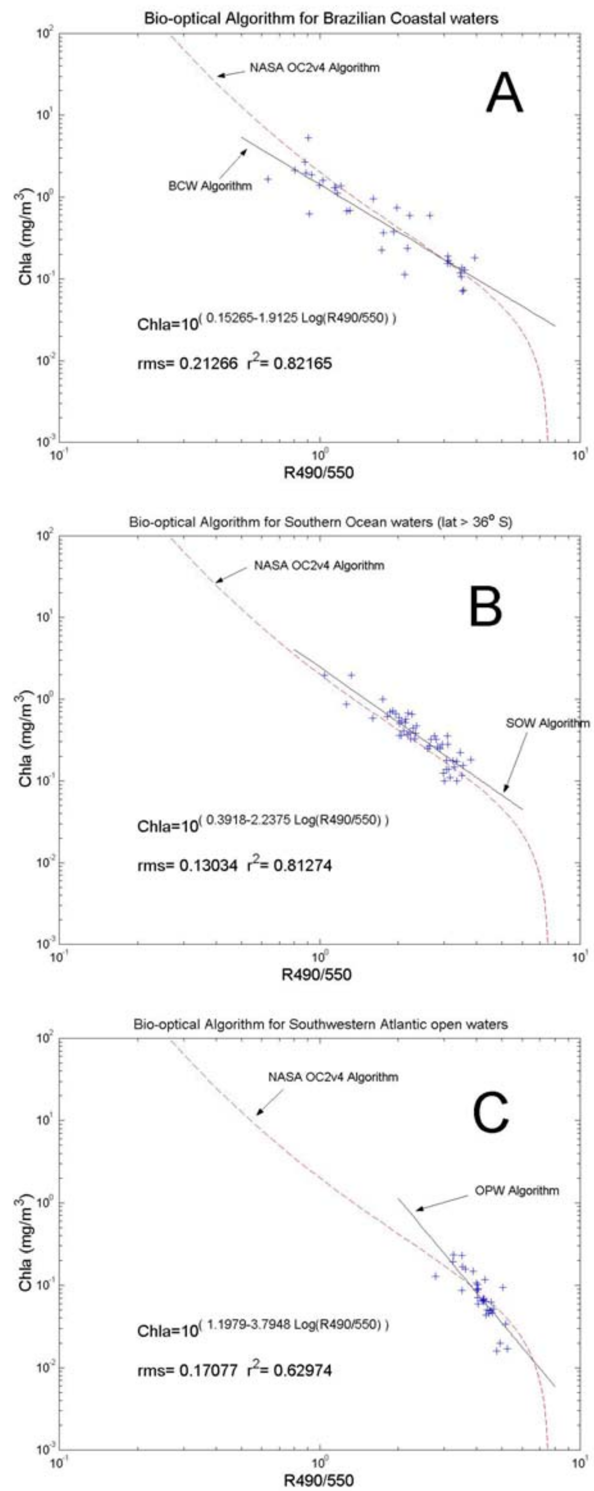

Figure 4. A scatterplot of R490/555 versus chlorophyll values for the 3 different regions. (A): Brazilian Coastal Waters, BCW; (B): Southern Ocean Waters, SOW; (C): Southwestern Atlantic Gyre Open Waters, OPW. The dashed curve represents the NASA OC2v4 algorithm while the solid line represents the respective fitted equation.