

CALCULATION OF PRIMARY PRODUCTION FROM REMOTELY-SENSED OCEAN COLOR DATA: SE BRAZIL, SW ATLANTIC

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Abstract. This paper presents a first effort in transforming a map of surface chlorophyll, obtained from an ocean color image (SeaWiFS) into a map of primary production of the SE Brazilian coastal region, SW Atlantic. The main steps involved in the computation of the daily primary production integrated in the water column are summarized. *In situ* primary production experiments provided the biomass-normalized photosynthesis parameters a^B, P_m^B used in the calculation. Principal limitations are that the SeaWiFS sensor sample only the surface of the ocean, neither can see through clouds.

Keywords: primary production, ocean color.

1. Introduction

Characterizing the spatial and temporal patterns of phytoplankton biomass and primary production is a central topic in biological oceanography. The topic is important not only for commercial applications and management of marine resources but also for questions regarding the global carbon cycle. Determination of the time-varying flux of carbon (and associated elements) in the world ocean is a focused objective of programs such as the International Geosphere Biosphere Program (IGBP, 1988) and its Joint Global Ocean Flux Study (JGOFS, 1988).

To quantify the primary production of the world oceans and to characterize its variability at the global scale, frequent and well-distributed measurements over large sites, basins, and oceans are required. This is practically impossible with traditional *in situ* methods, particularly in offshore regions. Observations of the ocean by satellites make this global scale approach possible if radiometric measurements can be interpreted quantitatively in terms of primary production (Berthelot and Deschamps, 1994).

The fundamental difficulty in estimating primary production from satellite-derived chlorophyll is that an indicator of standing stock (phytoplankton pigment), with dimensions of $[ML^{-3}]$, is being used to calculate a rate (carbon fixation), with dimensions of $[ML^{-3}T^{-1}]$ (Balch and Byrne, 1994). It could be argued that the rate of carbon fixation by any particular phytoplankton biomass might be dependent on factors other than the amount of pigment present. For example, nutrient limitation, depth distribution of biomass in the water column and temperature might all be expected to influence the rate of primary production (Joint and Groom, 2000). However, it appears that these processes have little influence on production estimates and a great deal of progress has been made in estimating primary production from pigment concentration alone (Behrenfeld and Falkowski, 1997).

Models that have been applied to satellite remote sensing have basically been of two types – empirical and semi-analytical (Behrenfeld *et al.*, 1998). Those that estimate primary production from standing stock are essentially empirical. They may be influenced by local

conditions, and it is possible that they can only be applied to those oceanic provinces for which the algorithms were originally derived; that is, these relationships may prove to be geographically specific. In an attempt to obtain globally applicable models, more complex algorithms have been developed which utilize knowledge of physiological response and light absorption properties. Both empirical and semi-analytical models have advantages and disadvantages. Joint and Groom (2000) present a good comparison between these two types of algorithms. Sathyendranath and Platt (1994a,b) and Falkowski *et al.* (1998) give a critical revision of many existing algorithms.

This paper presents a first effort in transforming a map of surface chlorophyll, obtained from an ocean color image (SeaWiFS) into a map of primary production of the SE Brazilian coastal region, SW Atlantic. The main steps involved in computation of daily primary production integrated in the water column are summarized. *In situ* primary production experiments provided the biomass-normalized photosynthesis parameters a^B, P_m^B used in the calculation.

2. Study Area

The Southeast coast of Brazil is the most populated and economically developed region of the country. The study area considered here is inserted in the Southeastern continental shelf between Sao Tome Cape (22°S), in the State of Rio de Janeiro, and Ilha de Sao Sebastiao (24°S), in the State of Sao Paulo (**Figure 1**). The narrower part of this continental shelf is located close to Cape Frio (50km). With the exception of a few big islands and many small islands, the bathymetry of this oceanic region is relatively smooth with the isobaths parallel to the coastline. The shelf break is located at depths of 120m to 180m (Zembrusky, 1979).

Even being situated in a tropical region, the SE continental shelf is located far enough from the Equator to has the geostrophy being dominant over movements with sub-inertial frequency scales (temporal scales ranging from 2 and 15 days) and seasonal (1 year) (Castro Filho, 1996).

The oceanic flow in the region is perturbed by the presence of an abrupt change of the coastline orientation at Cape Frio, inducing topographic steering of the flow and regular mesoscale activity such as eddies and meanders (Lima *et al.*, 1999). The Tropical Water ($S > 36$; $T > 20^\circ$), formed at low latitudes, is observed at the surface layers (Miranda, 1982). The Brazil Current (BC), is a western boundary current flowing Southwestwards over the continental slope, all year round. The presence of meanders and mesoscale eddies can induce large perturbation in the main flow (Stech *et al.*, 1996; Kampel *et al.*, 2000).

The Coastal Water ($33 < S < 33.7$ and $4^\circ < T < 21^\circ\text{C}$) dominates most of the continental shelf area. However, intense and frequent upwelling events occur in the same region predominantly from September through April. These events are associated with the intrusion of the South Atlantic Central Water ($34.5 < S < 36$; $6 < T < 20^\circ\text{C}$) (Kampel *et al.*, 1997). The upwelling plumes are considered as one of the most significant mechanisms responsible for the biological production enhancement in the region.

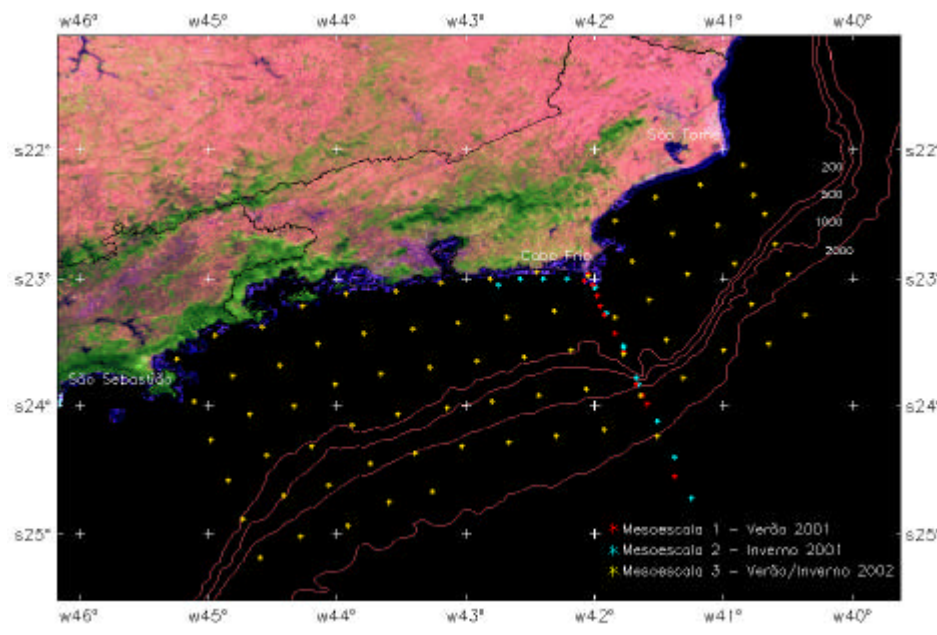


Figure 1 – Study area in the SE Brazilian coast, SW Atlantic. The oceanographic stations occupied during the DEPROAS Project are also shown. Mesoescala 1 cruise station's (summer 2001) are in red. Isobaths are in meters. (Background: SPOT 5 Vegetation image).

3. Data and Methods

SeaWiFS Data

The Chlorophyll *a* map of the region of interest was derived from data collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). This data was recorded in HRPT and Store modes (Level 0) by INPE's station with a nominal 1.1 km resolution at nadir. The raw data was delayed decrypted and converted to a Level-1A file in Hierarchical Data Format (HDF) using the routines Sw110 and the SeaDAS software (Fu et al., 1998), both distributed by the SeaWiFS Project (NASA). The digital processing involved: a) Level-1A image ingestion and generation of Level-2 geophysical products (chlorophyll *a* - Chl, photosynthetic active radiation - PAR, and diffuse vertical attenuation coefficient - K_{490}) by applying atmospheric corrections and bio-optical algorithms to the SeaWiFS data. Accurate atmospheric correction requires adjustments for O_3 and O_2 absorption as well as atmospheric pressure variations described in various sensitivity analyses (Gordon and Wang, 1994). Daily atmospheric data were acquired from NASA GSFC's Distributed Active Archive Center. Algorithms for cloud and land masking were applied following McClain et al. (1995). The algorithm used to calculate chlorophyll concentrations was de OC2, as recommended by O'Reilly et al. (1998). b) Mapping to cylindrical lat/lon projection and geographic gridding; c) Digital image enhancement to increase the contrast and color slicing (logarithmic scale) to facilitate interpretation of the pigment fields present; d) Chl satellite estimates were scaled to a maximum of 32 mg.m^{-3} .

In situ Data

Hydrographic, nutrients, biomass and phytoplankton primary production data were collected during an oceanographic cruise (DEPROAS Mesoescala 1), from 5-15 of February 2001. A section perpendicular to the coast, in front of Cape Frio, was repeated 4 times with the

objective of observe the water masses variation in the continental shelf and slope regions in a quasi-synoptic mode (**Figure 1**). 35 stations were occupied and sampled up to 10 depth levels (0, 5, 10, 25, 50, 75, 100, 125, 150, 200m).

Hydrographic data were reduced following the UNESCO (1988) standard procedures. The nutrients NO_2 , NO_3 , NH_4 , $\text{Si}(\text{OH})_4$, and PO_4 were analyzed following the methodologies described in Grasshoff (1983), Strickland and Parsons (1972) and Paranhos (1996), respectively. The chlorophyll estimates follows the methodology indicated in Holm-Hansen et al. (1965), Shoaf and Lium (1976), Stramski and Morel (1990), and Welschmeyer (1994). *In situ* simulated ^{14}C primary production experiments were conducted as suggested by Teixeira (1972). The Light – Photosynthesis curves were adjusted as suggested by Platt et al. (1980). The diffuse attenuation vertical coefficient was estimated with the use of a natural fluorescence profiler (PNF-300, Biospherical Instruments Inc.) and/or a Secchi disk. Surface irradiance was measured with the PNF-300 surface unit or estimated using the spectral solar irradiance model of Gregg and Carder (1990). The base of the euphotic layer was considered as the 1% light level depth.

Calculation of Primary Production from SeaWiFS Ocean Color Data

The standard model used in this paper was that for a vertically homogeneous, non-spectral model. This has the following solution for the daily water column production $P_{Z,T}$:

$$P_{Z,T} = \frac{BP_m^B D}{K} f(I_*^m), \quad (1)$$

where B is the pigment biomass (indexed as the satellite chlorophyll retrieval), D is the daylength, P_m^B is the assimilation number, K is the diffuse attenuation coefficient for downwelling light and $f(I_*^m)$ is a function of the dimensionless irradiance whose form is determined once the mathematical representation of the light – saturation curve has been selected. The quantity I_*^m is given by $I_*^m = I_0^m / I_K$ where I_0^m is the local irradiance at noon, and I_K is the photoadaptation parameter. Equation (1) is so basic to the field that is referred as the canonical form of daily, water column production. It is robust no matter what the choice of the light – saturation curve. It is often written in the compact form

$$P_{Z,T} = Af(I_*^m), \quad (2)$$

where the scale factor $A = BP_m^B D / K$.

For convenience of application, $f(I_*^m)$ is usually replaced, since it may be a slowly-converging series, by a low-order polynomial (Platt et al., 1990; Platt and Sathyendranath, 1993). Thus

$$f(I_*^m) = \sum_{x=1}^N \Omega_x (I_*^m)^x, \quad (3)$$

where the weights Ω_x are determined by the least-squares fitting to the numerical solution of equation (2). The magnitudes of the weights will depend on the number of terms N in the polynomial series and on the range of I_*^m for which they are computed. Usually, it is sufficient to take $N = 5$ and compute for a range $0 < I_*^m < 20$. The weights need to be determined only once. They are given in **Table 1** for the case when the light – saturation curve is represented by the exponential equation (Platt et al., 1980),

$$P^B(I) = P_m^B(1 - \exp(-a^B I/P_m^B)). \quad (4)$$

where P^B is the primary production normalized to biomass (chlorophyll $a - B$), I is the irradiance, a^B is the initial slope, and P_m^B is the assimilation number.

Table 1 – The weights Ω_x for the polynomial approximation to $f(I_*^m)$ computed for the range $0.2 \leq I_*^m \leq 20$.

x	Ω_x
1	6.1035×10^{-1}
2	-8.9251×10^{-2}
3	8.1477×10^{-3}
4	-3.7427×10^{-4}
5	6.6103×10^{-6}

4. Results and Discussion

The SeaWiFS image (**Figure 2**) shows the oligotrophic Tropical Water of the Brazil Current (blue tones) with low levels of chlorophyll, in contrast to the continental shelf Coastal Water (green to red tones), with relatively higher pigment concentrations. It is also possible to note in this image the presence of plumes of wind induced upwelling events associated with the Cape Frio, Sao Tome Cape and Vitoria (more to the North) cores at the coast.

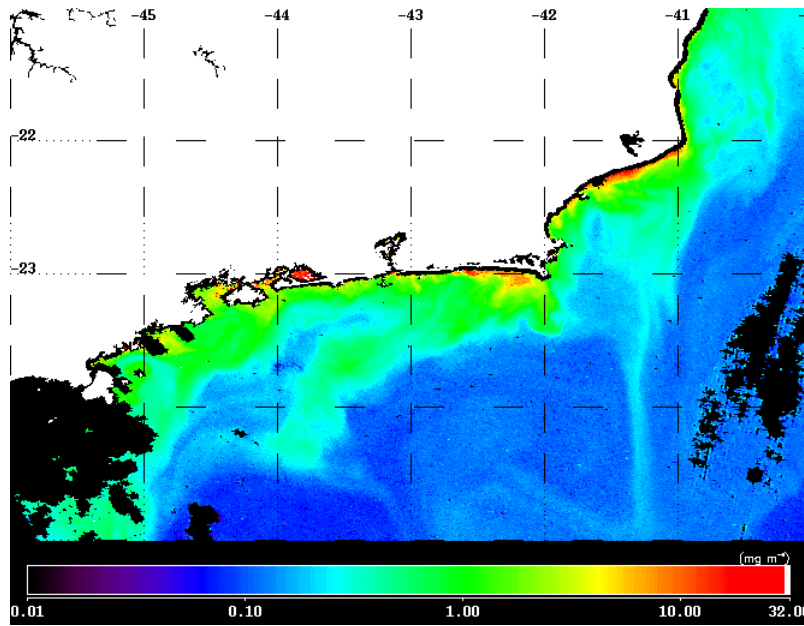


Figure 2 – SeaWiFS Chl image acquired on February 15, 2001, 14:43 GMT. Lower pigment values are in blue tones, typical of the Brazil Current oligotrophic waters. Relatively higher chlorophyll concentrations ($\text{mg}\cdot\text{m}^{-3}$), in green to red shades, are found over the continental shelf, associated with wind induced upwelling plumes, continental runoff and the possible presence of more coloured dissolved organic matter. Clouds are in black

Satellite pigment estimates were compared to *in situ* data collected during an oceanographic cruise of the DEPROAS Project (summer 2001) (Kampel and Gaeta, 2002). The results (not shown) are in good agreement at this point of development of the work. In this sense, no correction was applied to the Chl image.

In situ primary production experiments provided the biomass-normalized photosynthesis parameters a^B , P_m^B used in the calculation.

Figure 3 presents a map of the photosynthetic active radiation (PAR) obtained from the SeaWiFS data. The algorithm estimates daily (i.e., 24-hour averaged) PAR reaching the ocean surface. PAR is defined as the quantum energy flux from the Sun in the spectral range 400-700 nm. It is expressed in $\text{Einstein}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. The applied PAR model uses plane-parallel theory and assumes that the effects of clouds and clear atmosphere can be de-coupled. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer. This approach was shown to be valid by Frouin and Chertock (1992). The great strength of such a de-coupled model resides in its simplicity. It is unnecessary to distinguish between clear and cloudy regions within a pixel, and this dismisses the need for often-arbitrary assumptions about cloudiness distribution.

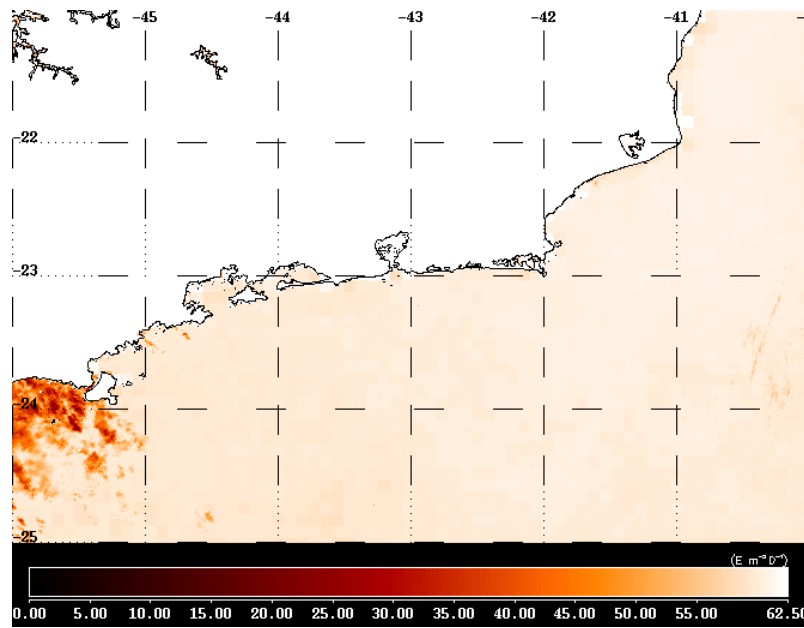


Figure 3 – Photosynthetic Active Radiation – PAR ($E.m^{-2}.d^{-1}$) estimated with the use of SeaWiFS data for February 15, 2001. Almost all the area is very homogeneous. Continent is in white.

The histogram on **Figure 4** contains the PAR values taken from the map shown on **Figure 3**. The mean value of $59.75 E.m^{-2}.d^{-1}$ (std 2.88) was considered representative of the majority of the region, for the day when the SeaWiFS image was acquired.

Figure 5 presents the diffuse attenuation coefficient map (K_{490}) obtained from the SeaWiFS data. Attenuation is markedly stronger in areas closer to the shore or under the influence of the upwelling plumes. Lower values of K_{490} are found in the area dominated by the Brazil Current clear waters. The histogram containing the K_{490} values taken from **Figure 5** is shown on **Figure 6**. The mean value of $0.058m^{-1}$ was then used in the primary production map computation.

Finally, **Figure 7** shows the resulted daily integrated on the water column primary production map, considering an approach for a vertically homogeneous, non-spectral model. The oligotrophic waters of the Brazil Current are shown in blue tones, with lower values of primary production. Closer to the coast and associated to the upwelling plumes, the values of primary production are relatively higher ($>80 mgC.mgChl^{-1}.m^{-2}.d^{-1}$). A cyclonic eddy centered on $22.15^{\circ}S-40.5^{\circ}W$, in front of Sao Tome Cape, could be better noted in this map of primary production, than in the chlorophyll map (**Figure 2**). Similarly, a relative maximum value of biological productivity centered on $23.5^{\circ}S-43.3^{\circ}W$, approximately, south of the Guanabara Bay, could be observed on **Figure 7**, but not so well on **Figure 2**. It is interesting to note that even having an intrinsic relationship between the two maps – chlorophyll and primary production, it is possible to observe a few interesting differences.

The quantification in time and space of mechanisms that promote the enrichment of these waters is extremely relevant for the general understanding of the factors controlling primary production, and the resultant impact on biogeochemical cycles and management of ocean's living resources.

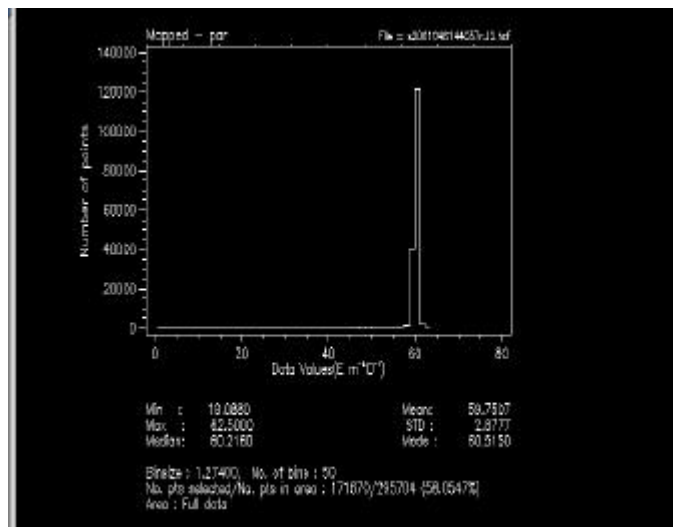


Figure 4 – Histogram of the PAR values ($E.m^{-2}.d^{-1}$) taken from the map shown on Fig. 3. Statistical computations (mean, std, max, min, median, mode) are also included.

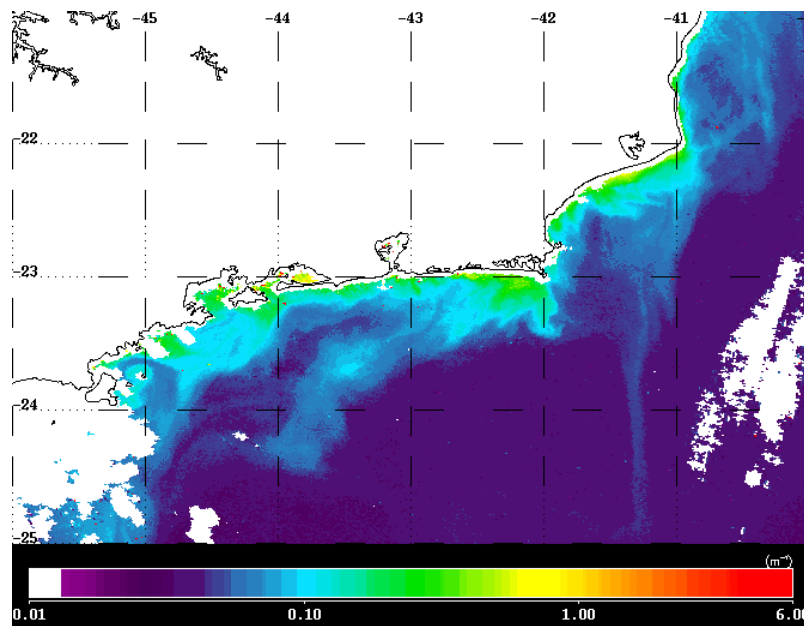


Figure 5 – Map of diffuse attenuation coefficient (m^{-1}) - K_{490} estimated from the SeaWiFS data. Yellow-green-light blue colors are indicative of stronger attenuation of underwater light in more coastal waters. Dark blue tone, associated with the Brazil Current waters, indicates lower values of K_{490} . Clouds and continent are in white.

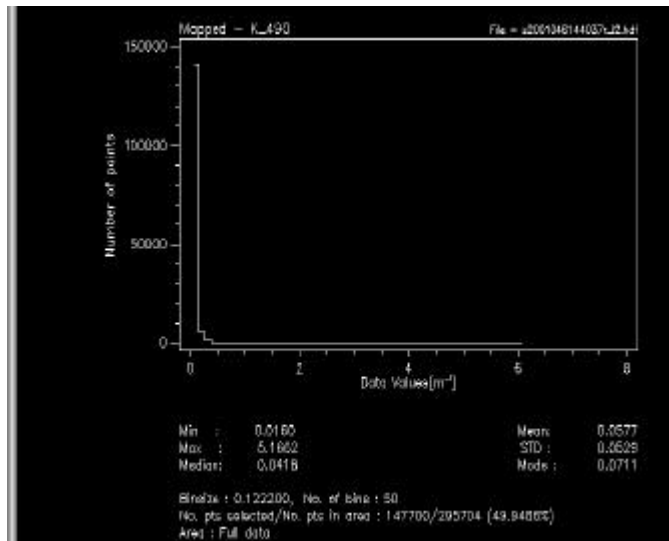


Figure 6 – Histogram of the diffuse attenuation coefficient (m^{-1}) taken from the map shown on Fig. 5. Statistical computations (mean, std, max, min, median, mode) are also presented.

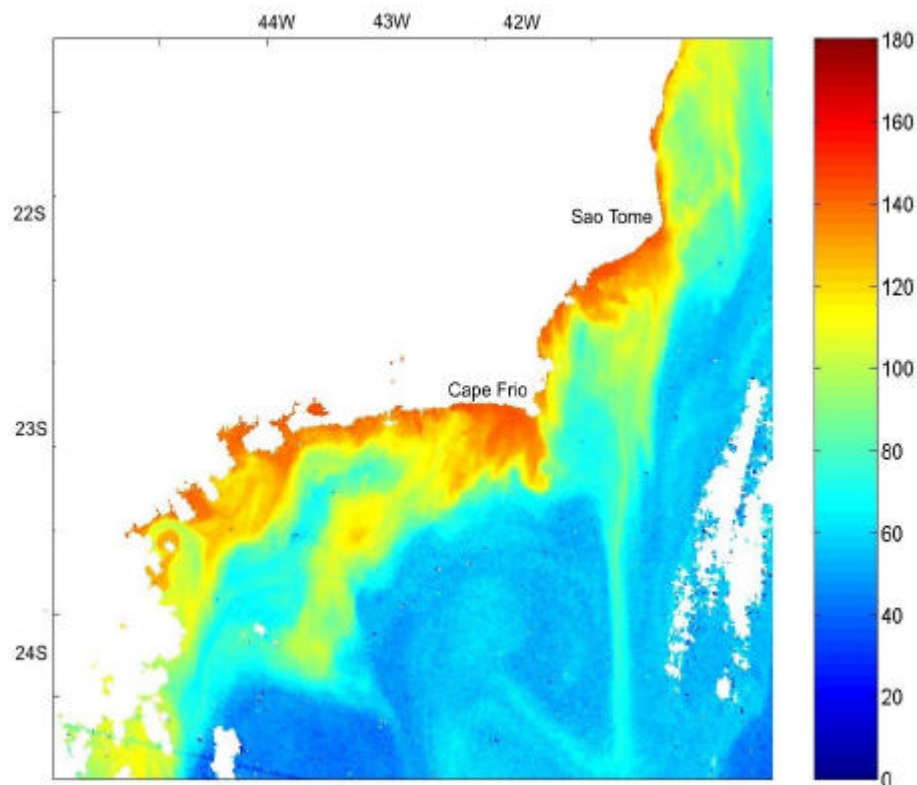


Figure 7 – Daily integrated on the water column primary production map ($mgC \cdot mgChl^{-1} \cdot m^{-2} \cdot d^{-1}$) obtained from the SeaWiFS image acquired on February 15, 2001, with the use of a vertically homogeneous, non-spectral model. Green to red colors, representative of relatively higher values of primary production, are seen closer to the shore and associated with upwelling plumes and eddies (see text). Blue tones indicate the presence of more oligotrophic waters of the Brazil Current. Clouds and continent are in white.

5. Conclusions

The purpose of this paper was to show how a map of primary production of the SE Brazilian coast could be obtained from a SeaWiFS image and *in situ* data. The steps involved in the calculation of the daily primary production integrated in the water column were presented. The approach adopted was for a vertically homogeneous, non-spectral model.

The surface fields generated from the satellite data contains interesting oceanographic patterns of importance in the dynamical and ecological understanding of this oceanic region. Principal limitations are that the SeaWiFS sensor sample only the surface of the ocean, neither can see through clouds.

Understanding the physical and biological processes, as well as their interaction, is a central goal for the management of fisheries over continental shelf areas. In one of the most economically important regions of Brazil (SE coast), phytoplankton productivity and standing crops are influenced by a complex suite of seasonal physical processes. One of these physical processes involves the relationship between the coastal upwelling near Cape Frio and the displacement of a cold-nutrient-rich water mass (South Atlantic Central Water) towards the coast. An oceanographic project (DEPROAS) is being carried out in this region, and this work is a preliminary contribution to our dynamical and ecological understanding of this oceanic region.

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