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# Temporal and meridional variability of Satellite-estimates of surface chlorophyll concentration over the Brazilian continental shelf

ÁUREA M. CIOTTI[1], CARLOS A. E. GARCIA[2] & DANIEL S. F. JORGE[1]

[1]*Laboratório Aquarela, UNESP- Campus Experimental do Litoral Paulista, Praça Infante Dom Henrique S/N Parque Bitaru, São Vicente (SP), 11330-900, Brazil.*
[2]*Instituto de Oceanografia, Universidade Federal do Rio Grande , Av Itália km 8, Rio Grande (RS), 96201-900, Brazil.*

**Abstract.** Forecast of biological consequences of climate changes depend on both long-term observations and the establishment of carbon budgets within pelagic ecosystems, including the assessment of biomasses and activities of all players in the global carbon cycle. Approximately 25% of oceanic primary happen over continental shelves, so these are important sites for studies of global carbon dynamics. The Brazilian Continental Shelf (BCS) has sparse and non-systematic *in situ* information on phytoplankton biomass, making products derived from ocean color remote sensing extremely valuable. This work analyzes chlorophyll concentration (Chl) estimated from four ocean color sensors (CZCS, OCTS, SeaWiFS and MODIS) over the BCS, to compare Chl and annual cycles meridionally. Also, useful complementary ocean color variables are presented. Chl gradients increased from the central region towards north and south, limited by estuarine plumes of Amazon and La Plata rivers, and clear annual Chl cycles appear in most areas. In southern and central areas, annual cycles show strong seasonal variability while interannual and long-term variability are equally important in the remaining areas. This is the first comparative evaluation of the Chl over the BCS and will aid the understanding of its long-term variability; essential initial step for discussions of climate changes.

**Keywords:** South West Atlantic, ocean color remote sensing, chlorophyll concentration, Annual Variability, CDOM index, Fluorescence Line Height

**Resumo. Variabilidade temporal e meridional de estimativas de Satélite da concentração de clorofila superficial na plataforma continental brasileira.** Previsões de conseqüências biológicas nos oceanos às alterações do clima dependem de bases de dados longas e da quantificação das trocas de carbono nos ambientes pelagiais, incluindo a caracterização das biomassas e atividades de organismos-chave do ciclo global de carbono. Cerca de 25% da produtividade primária global acontece nas plataformas continentais, assim essas são regiões de estudo essenciais na dinâmica ciclo de carbono. Na Plataforma Continental Brasileira (PCB), as informações sobre a biomassa do fitoplâncton são esparsas, tornando dados de satélite da cor do oceano valiosos. Nesse trabalho, analisamos concentrações de clorofila (Chl) estimadas por quatro sensores (CZCS, OCTS, SeaWiFS e MODIS) sobre a PCB para compará-la meridionalmente e sazonalmente. Apresentamos ainda duas variáveis (linha de fluorescência e o índice de Matéria Orgânica Dissolvida) que podem ser usadas para a interpretação da Chl. Os gradientes de Chl enfatizam duas áreas extremas, influenciadas pelas plumas dos rios Amazonas e La Plata, e forçantes interanuais nas regiões centrais. Os resultados são a primeira comparação da Chl na PCB, que poderá guiar estudos futuros para o entendimento de suas variabilidades em longa escala, etapa inicial fundamental para estudos sobre mudanças climáticas.

**Palavras-chave:** Atlântico Sul Ocidental, Cor do Oceano por sensoriamento remoto, Concentração de Clorofila, Variações Anuais, Altura da Linha de Fluorescência, Índice de MODC

## Introduction

The discussion of effects of climate change in oceanic biological processes remains controversial. While reports show fast increases in both $CO_2$ concentrations in the atmosphere and in ocean's temperatures (IPCC 2007), the biological consequences directly related to these changes are often questionable. Detailed budgets for the global carbon cycle are oversimplified (Houghton 2007), and current predictive models do not accommodate the role of biological processes. More importantly, the lack of long-term biological observations makes it difficult to detect robust changes with time in the oceanic biota. Therefore, efforts are needed to quantify abundances and distributions of key biological marine players in the carbon cycle, such as phytoplankton (Anderson 2005), and to describe quantitatively the processes in which they participate (Le Quere *et al.* 2009).

In the open ocean, the influence of climate changes in processes mediated by phytoplankton are generally based on trends with time, derived from variables such as chlorophyll concentration or primary productivity (PP) rates (Sarmiento *et al.* 2004). Decreases in PP rates have been related to enhancement of vertical stratification in warm waters (Polovina *et al.* 2008), while increases are associated with increases in sea water temperature in cold regions (Rysgaard *et al.* 1999). Biological effects are also link to episodic events such as increases on chlorophyll concentration after passages of hurricanes (Goldenberg *et al.* 2001). In continental shelves, expected changes include altering freshwater outflows (Belkin 2009) and the strength and temporal scales of costal upwelling events (Bakun 1990, Mote & Mantua 2002), and hence nutrient inputs and circulation patterns. All these biological processes will vary regionally, making it imperative to characterize them within these scales.

Long-existent observational sites that include systematic acquisition of biological data are infrequent in the global ocean, but recent international programs and funding efforts (Dickey *et al.* 2009, Johnson *et al.* 2009) will certainly change this panorama the future (*e.g.* complementary sensors in Argo floats, see http://www.argo.ucsd.edu/). Nonetheless, a key source for observing and understanding the upper ocean layer remain satellite data, which provide sinoptic views of biological oceanographic processes through variables retrieved from ocean color sensors. The spectral reflectance emerging from the oceans are used in empirical algorithms and modeling techniques to estimate phytoplankton biomass (i.e, chlorophyll concentration; see O'reilly *et al.* 1998) and other dissolved and particulate components (Carder *et al.* 1986, Ciotti *et al.* 1999, Lee *et al.* 1998, Maritorena *et al.* 2002, Roesler & Perry 1995). Ocean color data combined with information on sea surface temperature, downwelling irradiance and mixed layer depth allow for estimates of primary production rates (Campbell *et al.* 2002, Carr *et al.* 2006, Friedrichs *et al.* 2009). More recently, a number of bio-optical models were designed to discriminate among phytoplankton types or communities (Alvain *et al.* 2005, Ciotti & Bricaud 2006, Sathyendranath *et al.* 2004).

Freely available ocean color data exists since 1978 (McClain 2009) being global for the past 12 years (http://oceancolor.gsfc.nasa.gov). Logically, decade-long time series are inadequate to subsidize climate change studies, but these data has improved our knowledge on annual cycles of phytoplankton biomass (Kahru *et al.* 2004, Longhurst 1995), and can also be helpful to identify inter-annual variability (Henson and Thomas 2007). It is essential to understand how phytoplankton biomass change in time in order to develop conceptual models on phytoplankton dynamics, and ocean color is still the only source of information in many regions where observational studies have been sparse.

The Brazilian Continental Shelf (BCS) occupies over 40º degrees of latitude (Fig. 1) and contains significant regional differences concerning mainly its extension, the influence of offshore circulation, the overall area of the continental shelf and continent runoff inputs (Castro & Miranda 1998, Castro *et al.* 2006). Thus, the physical processes controlling nutrients and light availability for phytoplankton growth or accumulation vary meridionally. Surveys performed on the BCS describing temporal and spatial distributions of phytoplankton biomass and primary production have been fairly unsystematic, but latitudinal differences were reported and temporal patterns have already been showed in some areas (Brandini 1997, Gaeta & Brandini 2006, Ciotti *et al.* 2006). It is important also to mention that these sparse observations have been derived from a variety of methods, which despite of being standard oceanographic procedures have never being inter-compared to date.

It is acknowledged that ocean color products have been developed for open ocean and their use over continental shelves can be sometimes problematic, especially in areas receiving considerable amounts of continental outflows. The global algorithms that retrieve chlorophyll concentration (Chl) presume a covariance between in situ Chl and the relative contributions of all other optically active components in the light field, thus, so when them effectively absorb blue-light, which is the case for detritus or colored dissolved matter (CDOM), Chl is overestimated. The MODIS/Aqua ocean color sensor has additional spectral red bands that are sensitive to the natural fluorescence for chlorophyll present in living cells (Esaias *et al.* 1998, Gower *et al.* 2004). NASA is currently distributing these data as "evaluation products" named fluorescence line height (FLH). The interpretation of FLH is not trivial (Huot *et al.* 2005, 2007), and many issues regarding the role of phytoplankton physiology and taxonomy over the FLH signal and on the actual efficiency of fluorescence by phytoplankton living at the surface of the ocean remain unresolved (Schallenberg *et al.* 2008). Nonetheless, in a first approximation, FLH registered over continental shelf areas that receive significant continental outflow can be an alternative or a complement for blue-green ratios algorithms' for Chl estimates, as the contribution of detritus and CDOM to FLH tend to be minimal (Gower *et al.* 2004). Even in the open ocean, CDOM is an important optical component for light absorption (Siegel *et al.* 2002), and recently, an additional bio-optical product has been developed (Morel & Gentili 2009) and distributed by NASA - the CDOM index- that intends to offer a metric option to observe CDOM versus phytoplankton influences in a given area.

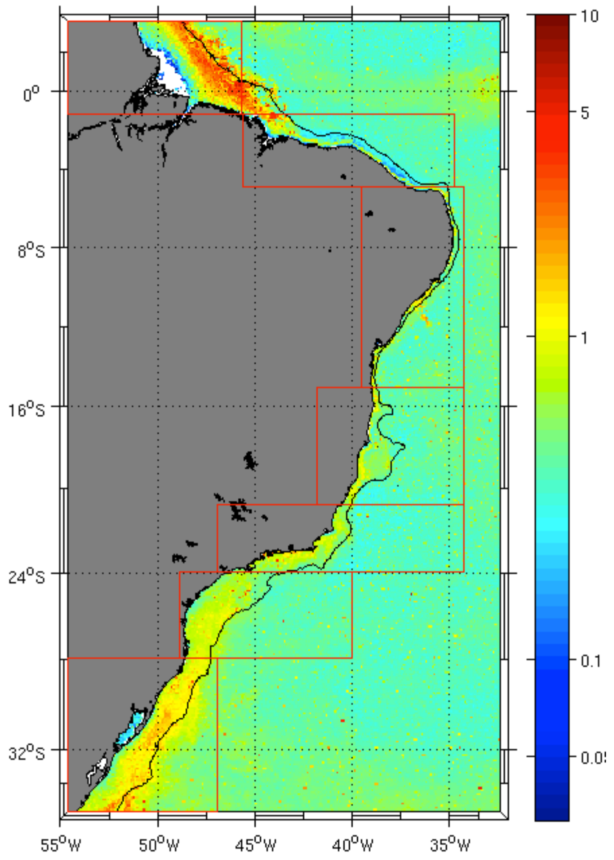


**Figure 1.** The Brazilian Continental Shelf (BCS) and the subdivision used in this work (Areas 1 to 7 from North to South). Image color gradients show the annual standard deviation of the annual mean chlorophyll concentration ($mg.m^{-3}$) in log scale, for the combined 2000 to 2005 data derived from SeaWIFs. Line represents the 200 m isobath that defines the continental shelf boundary.

The studies conducted over the BCS using ocean color data were mostly regional, except by that from Gonzalez-Silvera *et al.* (2004), which also included observations in the open ocean. Published work comprise studies on the behavior of North Brazil Current (Johns *et al.* 1990, Richardson *et al.* 1994, Fratantoni & Glickson 2002), the confluence of Brazil and Malvinas Currents (Garcia *et al.* 2004, Saraceno *et al.* 2005, Barre *et al.* 2006, Gonzalez-Silvera *et al.* 2006), Amazon & La Plata Plumes signatures (Froidefond *et al.* 2002, Hu *et al.* 2004, Del Vecchio & Subramaniam 2004, Cherubin & Richardson 2007, Garcia & Garcia 2008, Piola *et al.* 2008, Molleri *et al.* 2010), and the tracking of mesoscale features (Bentz *et al.* 2004). Validation and verification of ocean color models have also been conducted (Garcia *et al.* 2005, 2006, Ciotti & Bricaud 2006).

Descriptions and comparative analyses are needed to better understand seasonal and interannual changes of the phytoplankton standing stock over the BCS, as space and time characterizations are crucial initial steps for studies of eventual global change effects. In this work, we gathered all available remote sensing ocean color data for the BCS, derived from 4 ocean-color sensors, to quantify and compare observed Chl, FLH and the CDOM-index over time. We divided the BCS into 7 large regions following Castro *et al.* (2006). Our main objectives were: i) to examine meridional variability in chlorophyll concentrations derived by satellite; ii) to assess the quality of the data available, concerning mainly data coverage; iii) inter-compare chlorophyll products from two sensors (SeaWiFS and MODIS/Aqua); and iv) to establish annual cycles and interannual variability of chlorophyll concentration for all regions. We will also describe spatial and temporal trends of FLH and the CDOM-index over the subareas, and compare these indices to Chl.

## Data and Methods

### Satellite Data

Data from mapped, 8-Day, global composite images (L3) were downloaded from Ocean Color Home Page (http://oceancolor.gsfc.nasa.gov) and consist of the entire data sets available for Coastal Zone Color Scanner (CZCS), Ocean Color Temperature Sensor (OCTS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer on the Aqua satellite (MODIS/Aqua) up to 31 December 2009 (see Table I). These data sets are reprocessed from time to time, which is necessary for sensor calibration and algorithm improvements. In the present work, data from SeaWiFS refer to reprocessing 2009.1 (December 2009), data from MODIS/Aqua refer to reprocessing 1.1 (August 2005), and data from both CZCS and OCTS were last reprocessed in October 2006. MODIS/Aqua has been fully operational since its launch while a number of gaps for SeaWiFs data, due to problems with the instrument, occurred in 2008 (January 3 to April 3; July 2 to August 18) and 2009 (April 24 to June 15; July 3 to July 17; August 31 to November 5; and November 14 to 30). Further details on each sensor and respective data sets can be found in the official distribution site (http://oceancolor.gsfc.nasa.gov).

Products distributed as Level 3 used in this work included chlorophyll concentration (all sensors), sea surface temperature (MODIS/Aqua), fluorescence line height (MODIS/Aqua) and the CDOM index (SeaWiFS), computed by the respective standard global algorithms and masks. Note that spatial resolutions for L3 images are 4 km for CZCS and MODIS/Aqua, and 9 km for OCTS and SeaWiFS, and were preserved as such.

Images were processed using SeaDAS (v5.4) - a multi-platform software freely distributed by NASA (http://oceancolor.gsfc.nasa.gov/seadas). The bathymetry dataset from SEADAS was used to set apart image pixels occurring over the continental shelf, assumed here as those where local depths ranged from 20 to 200 m. The lower limit of 20 m was set to exclude the effects of both local geography and possible bottom effects. For each satellite product and sensor, the proportion of data coverage was computed as the number of pixels with valid data (i.e., those not masked by land, clouds or algorithm’s failures) over the total number of pixels expected between 20 and 200 meters. We used 8-Day spatial resolution of all products and sensors that yielded 46 observations per year. We also grouped SeaWiFS and MODIS/Aqua chlorophyll concentration and data coverage by seasons, so that Fall refers to images starting on days of the year 80 to 162, Winter images from days 168 to 258, Spring images from days 264 to 346 and Summer images from days 352 to 361 and days 1 to 74.

**Meridional Division and Basic Statistics**

The BCS was divided into 7 (seven) large areas, which are a slight modification of the division into six compartments proposed by Castro and Miranda (1998). The original 6 (six) areas were divided according with physical processes and presence of distinct water masses. Our modification scheme was basically shifting latitudinal boundaries necessary to i) keep the areas more comparable in size; and ii) to accommodate, within each area, similar values for mean and standard deviations of satellite surface chlorophyll (Fig. 1). For each 8-Day satellite product and area, basic statistics (mean, median, standard deviation) were computed, but respective time series represent the median values, rather the mean, in order to focus our discussion on central values and also to avoid extreme or too localized values. Nonetheless, we present the entire statistical distributions by area and ocean color sensor (see Fig. 2).

**Annual Cycle and Long-Term Variability of Chlorophyll**

Chlorophyll data for SeaWifs were averaged over the 46 8-Day composites to produce a pseudo-climatology, or general mean, for the 12 years (up to 31 December 2009). The 8-Day general means were in turn used to compute 8-Day “anomaly” values for all the composites. The “chlorophyll anomalies” were then log-transformed and used to model the amplitude and phase of the mean annual cycle observed over each area throughout the 12-year series. The annual mean model is based on a nonlinear least square procedure (see Garcia *et al.* 2004 for details), that assumes a sinusoidal form with a single amplitude over the 46 composites registered in a year. The ratio of the variance explained by the annual model to the total variance - correlation of determination ($r^2$) - for each time series per area was also calculated to verify the goodness of the model, and here describe the consistence of a seasonal variability in the chlorophyll concentration. It is important to note that low correlation of determination observed per area reflects both the inadequacy of the single amplitude (*e.g.*, seasonal cycles can have more than an oscillation per year) and also interannual variability, but in this case we expect the latter to be more important as the majority of BCS is located in tropical and subtropical areas.

To observe long-term variability in SeaWiFS Chl anomaly per area, we first applied a running mean filter (equivalent to 46, or a year of 8-Day mean observations), to create smoothed series, each being normalized by their respective standard deviation. The filtered data were then subjected to spectral analysis, which used the variance-preserving form of the energy spectrum (Emery & Thomson 2004) so to make the total energy of the signals observed among areas comparable. These are simple techniques, that were chosen to accommodate our present goals, but future work should include a number of more sophisticated time-series techniques (*e.g.*, EOFs; wavelets) to better understand the long-term variability of chlorophyll fields in the different

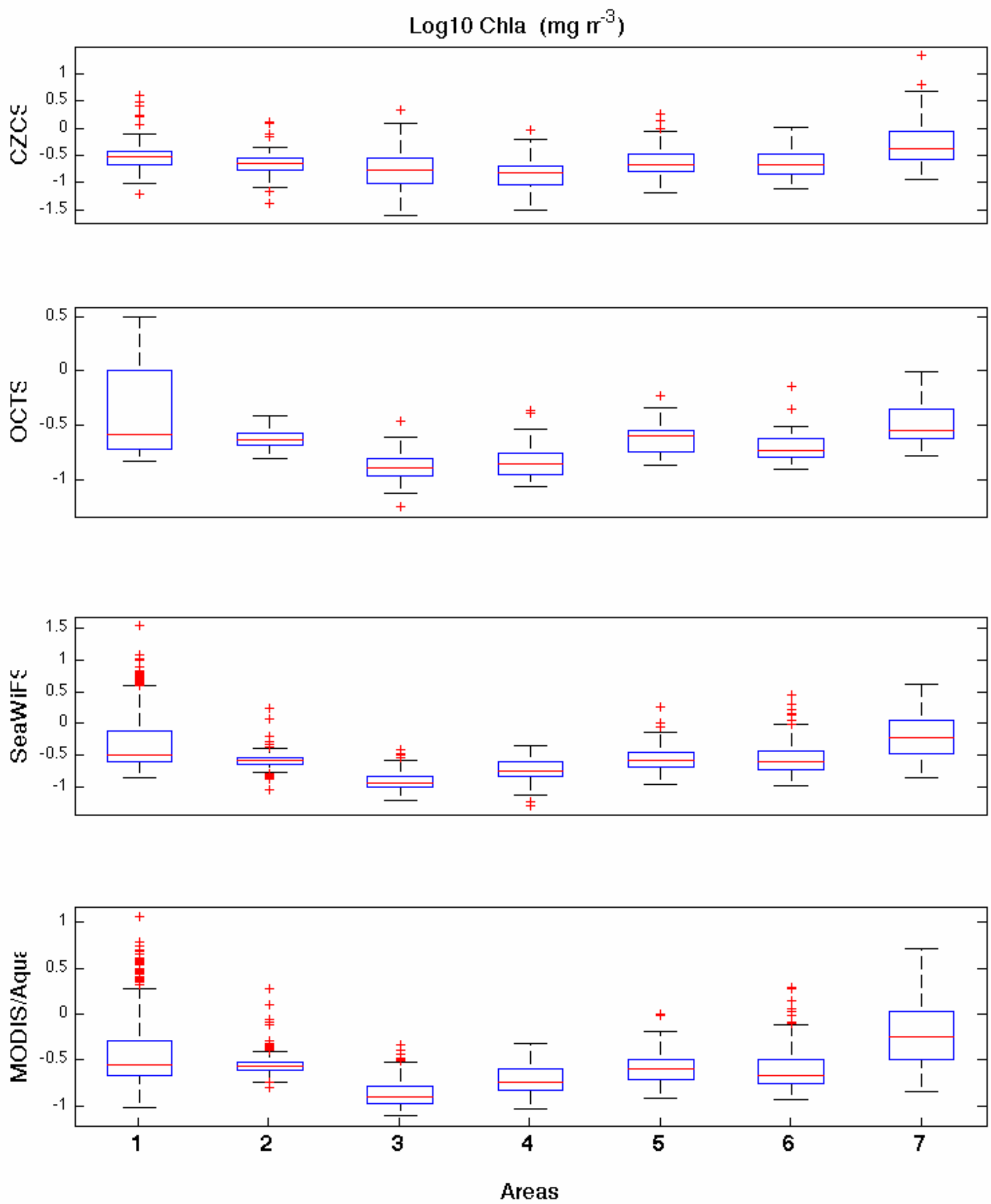


**Figure 2.** Box plots showing the range and statistics of chlorophyll values observed by the different sensors over the seven subareas of the Brazilian Continental Shelf. Red lines represent the medians and each box represents the 50% percentile (i.e., mean is the center of the box). Note that the distributions are derived from different temporal resolutions from each sensor (see Table I). Red crosses are outliers.

zones of the BCS and their relation to other environmental variables (ex. river discharge, wind stress, surface current, etc.).

## Results and Discussion

Despite of the smaller area compared to the open ocean, continental shelves account for about 25% of oceanic global primary production (Longhurst *et al.* 1995). However, it is difficult to quantify time and spatial variability of phytoplankton biomass over these areas. A number of complex, and not yet fully quantifiable processes, interfere on observed phytoplankton standing stocks, usually estimated with chlorophyll concentration (Chl). General spatial patterns for Chl do exist in the surface ocean, resulting from differences in nutrient and light availability for phytoplankton growth (or Chl accumulation) governed by regional and global physical processes (see Holt *et al.* 2009 and references therein). However, other important terms to be considered when Chl distributions are compared in time and space include less understood processes as grazing, sedimentation and advection rates for phytoplankton cells (Banse 1994) because they depend on ecological and physiological components that are difficult to observe. Over continental shelves, all chemical and biological processes are associated with larger Chl in

**Table I.** Characteristics of the four ocean color sensors that can provide information on the Brazilian Continental Shelf on chlorophyll concentration. Note operating periods.

| | Spectral Bands (only visible and near infrared only) | | | |
|---|---|---|---|---|
| Sensor | Central wavelength (nm) | Spectral resolution (nm) | Spatial resolution (m) | Operating dates |
| CZCS[1] | 443; 520; 550; 670 | 20 | 825 | 24/10/1978 - |
| | 750 | 100 | | 22/6/1986 |
| OCTS[2] | 412; 443; 490; 520 | 20 | 700 | |
| | 565; 670 | 20 | | 03/9/1996 - |
| | 765; 865 | 40 | | 29/6/1997 |
| SeaWiFS[3] | 412; 443; 490; 510 | 20 | 1100 | |
| | 555; 690 | 20 | | 29/8/1997 - |
| | 765; 865 | 40 | | present |
| | 531 | 5 | 1000 | |
| | 443; 488; 551 | 10 | 1000 | |
| | 667; 678; 936 | 10 | 1000 | |
| MODIS[4]/ | 412; 748; 869 | 15 | 1000 | |
| Aqua | 469; 555; 1240 | 20 | 500 | 04/07/2002 -present |
| | 858 | 25 | 250 | |
| | 905; 1375 | 30 | 1000 | |
| | 940 | 40 | 1000 | |
| | 645 | 50 | 250 | |

Obs:[1]Coastal Zone Color Scanner; [2]Ocean Color Temperature Sensor, [3]Sea-viewing Wide Field-of-view Sensor, [4]Moderate Resolution Imaging Spectroradiometer

comparison with the open ocean, within also a more complex physical dynamics (Longhurst 2006). Thus, we stress that the patterns presented here for meridional and seasonal Chl are a result from a number of processes yet to be quantified, so they neither translate directly into primary production nor exportation rates for phytoplankton carbon.

**Remote Sensing Chlorophyll Observed in the BCS**

The meridional and seasonal distributions of Chl over the large and heterogeneous BCS (Fig. 1) can be related to the equally diverse dominant physical influences (Castro & Miranda 1998). When data from the four ocean color sensors are compared, similar general statistical distributions for Chl (Fig. 2) emerged, especially for SeaWiFS and MODIS/Aqua sensors, which result from almost a decade of their simultaneous data acquisition (Table II). The OCTS sensor operated for less than a year, and there are only about 30 8-Day images available for the BSC. Lacks in data acquisition (Table II) represent besides instrument problems, cloud coverage and algorithm failures.

The highest degree of Chl variability was found in the latitudinal extremes of BCS (Areas 1 and 7) while Chl was remarkable constant in Area 2. The highest and lowest mean Chl values were found in Areas 7 and 3, respectively (Fig. 2) differing about an order of magnitude from each other (*e.g.*, ~1.0 versus ~0.1 mg.m$^{-3}$). Meridional 8-Day median Chl variability as a function of time and the Chl statistical distribution (Figs. 2 and 3) suggest the importance of the distinct degrees of seasonality in the different areas, but as indicated by some recent studies on physical processes (*e.g.*, Dotori & Castro 2009) we also expect a significant contribution of interannual variability may also be expected.

Data coverage by the distinct sensors also showed important seasonal patterns (Fig. 4) that will be assessed below, but we found no significant statistical relationships between data coverage and Chl for a given Area or sensor. For instance, both SeaWiFS and MODIS/Aqua coverage were remarkable poor in Area 1 during the summer months, period when Chl was also low, while Areas 3 and 7 showed good data coverage year round, and a clear seasonal Chl pattern. Figures 3 and 4 point out the discontinuity for CZCS data coverage in the BSC (see also Table II), which is a result of NASA's strategy of turning off the sensor when it was outside the main interest areas due to limited on-board storage data and to preserve the sensor (Mcclain, 2009). Indeed, CZCS had its life expectancy expanded for several years, but unfortunately, the low data coverage over the BSC prevent studies to integrate its data with those acquired by the current operational sensors (*e.g.*, SeaWiFs and MODIS/Aqua - but see also www.ioccg.org/ sensors/current.html) in order to produce longer time-series. Recent literature show, for areas where CZCS data is available, detectable trends in Chl with time that suggested alterations in the marine biota (*e.g.*, Antoine *et al.* 2005). Studies like these at the BSC are, unfortunately, limited today to 12 years of continuous ocean color data data (i.e., SeaWiFs and MODIS/Aqua), and none our chosen Areas has showed strong positive or negative Chl trends with time. It is worth mentioning that understanding the impacts of global change demands long-term biological observations and that will be jeopardized for the BCS if the current NASA's programs are discontinued. Thus, it is imperative to create and maintain new ocean color programs and to involve the Brazilian scientific community on using and interpreting its potential products.

**Seasonal and Meridional Chl variability**

The seasonal mean Chl per area derived by SeaWiFS and MODIS/Aqua (Table III), place Area 3 as a boundary of low Chl that separates gradients towards north and south. Maximum Chl per area increases steeply towards north (3-fold in Area 2 and an order of magnitude in Area 1) occurring during fall while towards south, Chl gradients were gradual and occurred during winter. In Areas 3 and 4, Chl was high and similar in fall and winter, and low and similar in spring and summer. Area 2 showed a single and modest Chl peak in the fall. Periods with minimum Chl values also varied meridionaly, and were observed during spring in Area 1 and during summer in Areas 5, 6 and 7.

The seasonal and meridional distribution of mean data coverage per Area and instrument (Tab. III), showed that only half of the 8-Day composite images were available most of the year in Area 1 and that data coverage was about 13 to 18% during summer and 23 to 27% during fall. Area 2 has also showed poor data coverage during summer (29 to 33%) and fall (44 to 53%).

It was possible to model significant annual cycles in all Areas, except for Area 2 (Table IV). The best fits were found in Areas 7 and 4, suggesting that the main processes for accumulation and loss of phytoplankton biomass operate rather seasonally, especially in Area 7 ($r^2$=0.78). All remaining Areas showed correlations of 0.52 to 0.58 to the annual model, probably a result of important inter-annual variability as in Area 1 in 2001 and Area 6 during 2007 (Fig. 5), for instance.

The meridional patterns of Chl were indeed related to the main reported seasonal changes in hydrography. In Area 1, the most prominent feature is the Amazon River discharge, which provides seasonally dissolved colored material, nutrients, sediments and detritus to larger extensions of the continental shelf. During the rainy seasons (summer and spring) larger river discharge is combined with changes in both wind direction (from SE to NE) and in transport rates of the North Brazil Current (Molleri *et al.* 2010). Both the size and the orientation of the Amazon plume are responsible for the magnitude and seasonal Chl variability and also reflect the amount of particles and dissolved load that can interfere in the Chl algorithm performance.

Chl changes in Areas 2 and 3 are likely to be associated with variability in the biological processes, probably driven by changes in water temperature and irradiance, since neither major river flow nor relevant oceanographic features (*e.g.*, upwelling) are reported for those two areas, which are the least studied ones of our BSC subdivision. In Area 2, no significant parameters could be found for the annual variability in Chl (Table IV), which showed a fall Chl peak only about 25% higher than that for the remaining of the year. Area 3 showed the lowest Chl in comparison to all other Areas, with a strong seasonal cycle. The annual amplitudes detected by the SeaWiFs time series were 0.04 and 0.12 mg.m$^{-3}$ for Areas 2 and 3, respectively (Table IV). It is important to remember that Area 3 is the smallest despite occupying over 10 degrees of latitude.

Areas 2 to 4 are also under direct influence of the seasonal and meridional migration of the Inter-Tropical Convergence Zone (ITCZ) in the south Atlantic and thus they will likely respond to any mode of change in the wind fields. Northern and weak winds occur in the summer, enhancing vertical stratification that in turn is expected to disfavor Chl accumulation. In the winter, southern and stronger winds have been already linked to increases in Chl in Area 4 due to the erosion of the picnocline and consequent fertilization of the surface layers (Ciotti *et al.* 2006). In addition, Area 4 comprises the Abrolhos region with a shallow continental shelf, allowing addition of nutrients by ressuspension of bottom water masses. The seasonal influence of wind regimes on vertical mixing is suggested by the good adjustment of the Chl series to the annual model (Table IV). Abrolhos, and a number of banks adjacent to Area 4 affect the flow and direction of the Brazil Current (BC). As a consequence, the main flow of the BC shows mesoscale instabilities and meanders (Gaeta *et al.* 1999) that have a significant impact on the circulation of the Areas towards the south (Calado *et al.* 2008, Silveira *et al.* 2008).

Areas 5 and the northern third of Area 6 encompass the most studied regions of the BSC (see review in Castro *et al.* 2006). Areas 5 and 6 were separated at São Sebastião Island latitude because of their important distinct oceanographic features. Area 5 includes Cabo São Tomé and Cabo Frio, where

**Table II.** Division for the BSC in subareas based on Castro *et al.* (2006). For each sensor and area, columns represent the number of 8-Day images with no data; n is the length of each sensor data sets (up to the end 2009 for those operational) for 8-Day images. Also, the total number of Pixels over the delimited continental shelf (20 to 200 m): 9 km for OCTS and SeaWiFS and 4 km for CZCS and MODIS/Aqua.

| Area and latitudinal range | SeaWIFS (n=568) | Modis/Aqua (n=345) | OCTS (n=30) | CZCS (n=353) | Number of 9 Km pixels | Number of 4 Km pixels |
|---|---|---|---|---|---|---|
| 1 - 04N-01S | 37 | 3 | 3 | 282 | 1742 | 6918 |
| 2 - 01S-05S | 35 | 2 | 2 | 240 | 561 | 2237 |
| 3- 05S-15S | 36 | 2 | 0 | 259 | 258 | 1017 |
| 4- 15S-21S | 39 | 2 | 1 | 285 | 656 | 2587 |
| 5- 21S-24S | 39 | 2 | 3 | 298 | 689 | 2727 |
| 6- 24S-28S | 37 | 2 | 0 | 297 | 1229 | 4937 |
| 7- 28S-34S | 37 | 2 | 0 | 270 | 1288 | 5168 |

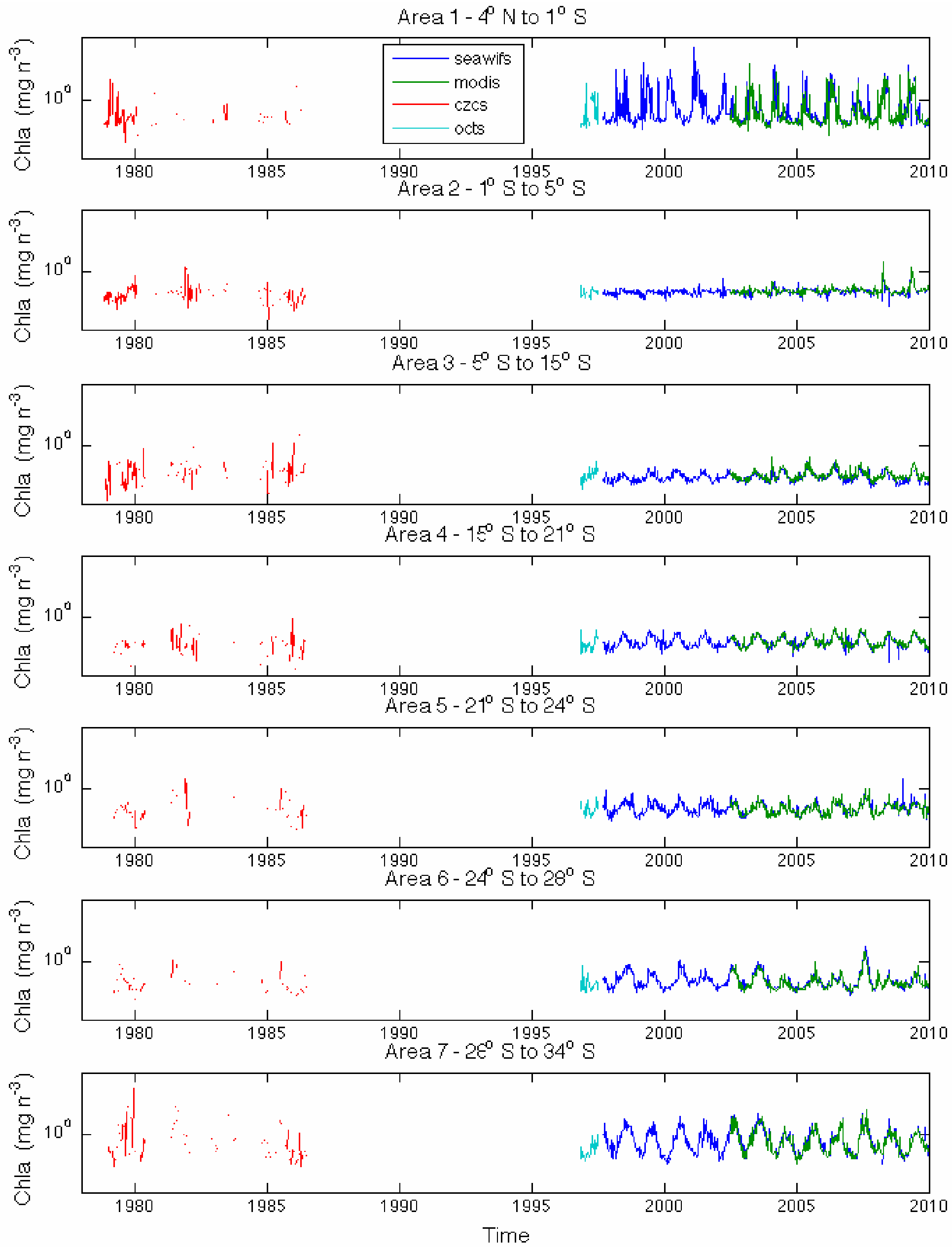


**Figure 3.** Time series of 8-Day median chlorophyll concentration over the seven Areas of the BCS (see Table I for limits), provided by the four ocean color sensors (see legend) during their respective operation periods.

costal upwelling occurs in the summer (see Guenther *et al.* 2008 and references). The upwelling plumes tend to move offshore in São Tomé, and towards south through the inner and median continental shelves in Cabo Frio. In the revision by Guenther *et al.* (2008), it is presented that the upwelling of the South Atlantic Central Water (ACAS) to the surface, shifs the system from oligotrophic to eutrophic conditions, and thus, Chl accumulation would be expected during the summer (period where the upwelling events are more intense), which was not shown in the present analyses (Table III). Indeed, maximum Chl occur in winter in Area 5. Numerical models and observations, however, show that the shelf currents respond to mesoscale wind fields, which are most intense during winter in response to passages of atmospheric cold front systems (Dotori & Castro 2009). Also, it is important to note that a strong deep Chl maximum associated with the permanence of ACAS intrusions at the subsurface have been observed in Area 5 (Sumida *et al.* 2005) which perhaps the ocean color sensors do not not efficiently detect (André 1992). Other possible cause of the seasonal Chl pattern observed in Area 5 (and 6) is related to the flow of BC that in the summer is closer to the coast (Silva Jr. *et al.* 1996) inducing

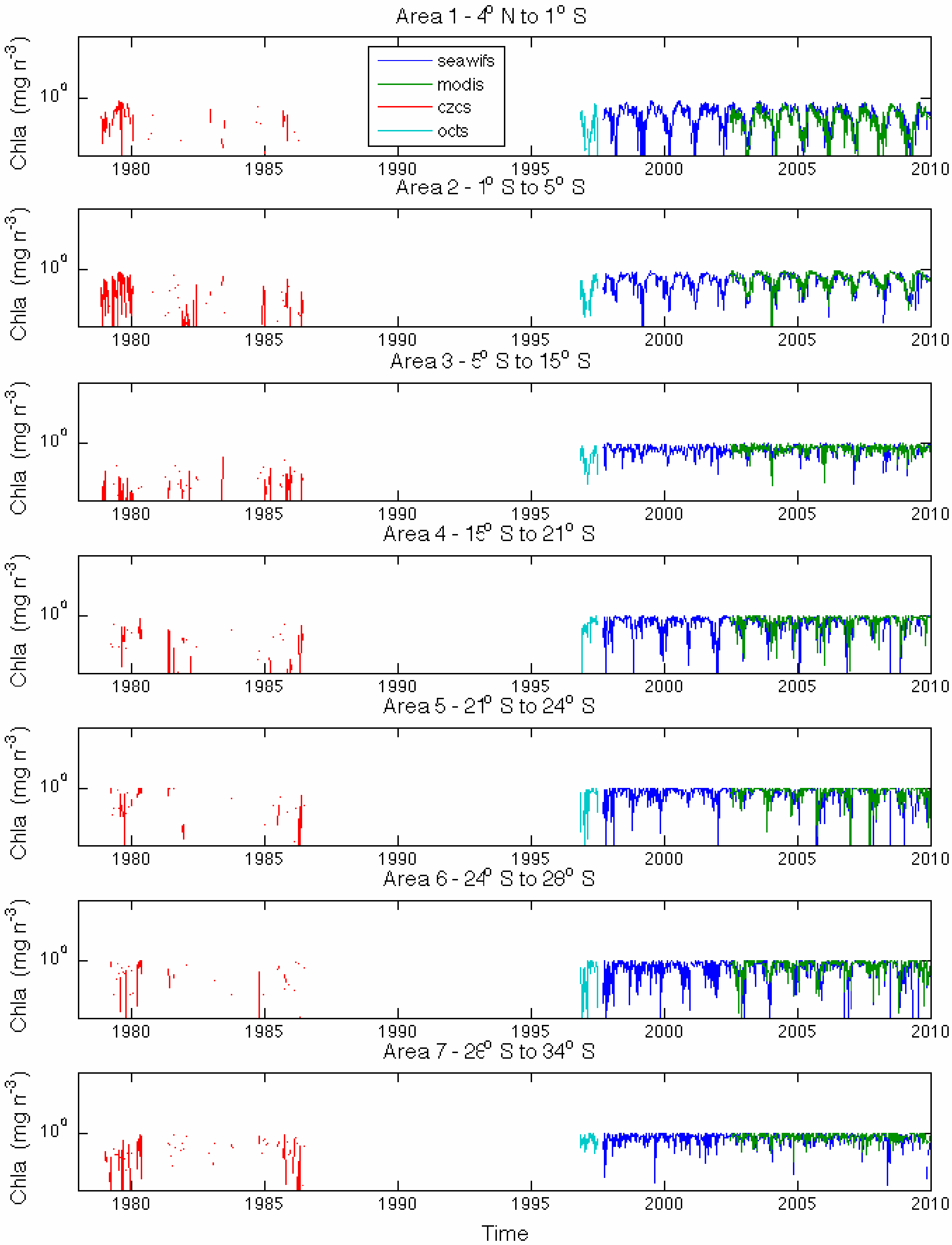


**Figure 4.** Time series of 8-Day median data coverage (i.e., 1 would represent that 100% of the subarea had valid data) concentration over alternated subareas of the BCS (see Table I), provided by the four ocean color sensors (see legend).

coastal downwelling of oligotrophic warm waters at Areas 5 and 6. Upwelling events in Cabo Frio are usually short, and our approach compared large Areas and 8-Day image composites, therefore, the relative importance of the coastal upwelling process may have been masked. Nonetheless, we cannot exclude the role of biological factors such as grazing and sedimentation explaining these patterns. Note also that the upwelling plumes tend to stay in Area 5, but the modeled annual amplitudes for both Areas 4 and 5 are exactly the same (Tab. IV). Mean Chl is only slightly higher in Area 5 during winter, while the goodness for the annual fit is higher in Area 4, suggesting that interannual influences on Chl accumulation are more important in Area 5 than in Area 4.

In winter, Areas 6 and 7 (but mainly Area 7, as we discussed below) receive a coastal water mass originated from the south portion of Brazil, with nutrients from the outflows of both Rio de la Plata and Lagoa dos Patos (Piola & Romero 2004, Pimenta *et al.* 2005). Indeed, the relative contribution of Colored Dissolved Organic Mater (CDOM) has been showed to be higher in winter in Area 6 (Ciotti unpublished data) which may imply that the Chl values could be overestimated due to presence of CDOM. Note that the goodness for the fit to the annual model in Area 6 is about the same of that observed in Area 5, suggesting important interannual forcing in Area 6 as well.

Area 7 comprises the southernmost portion of Brazilian continental shelf waters. The influence of both La Plata River and Pato's Lagoon discharges on ocean color imagery has been recently reported (Garcia & Garcia 2008, Piola *et al.* 2008). The extent of the La Plata plume over the Brazilian shelf is associated with both surface winds and river discharge (Piola *et al.* 2008, Garcia & Garcia 2008). During winter, the La Plata plume extension is associated with more intense and persistent

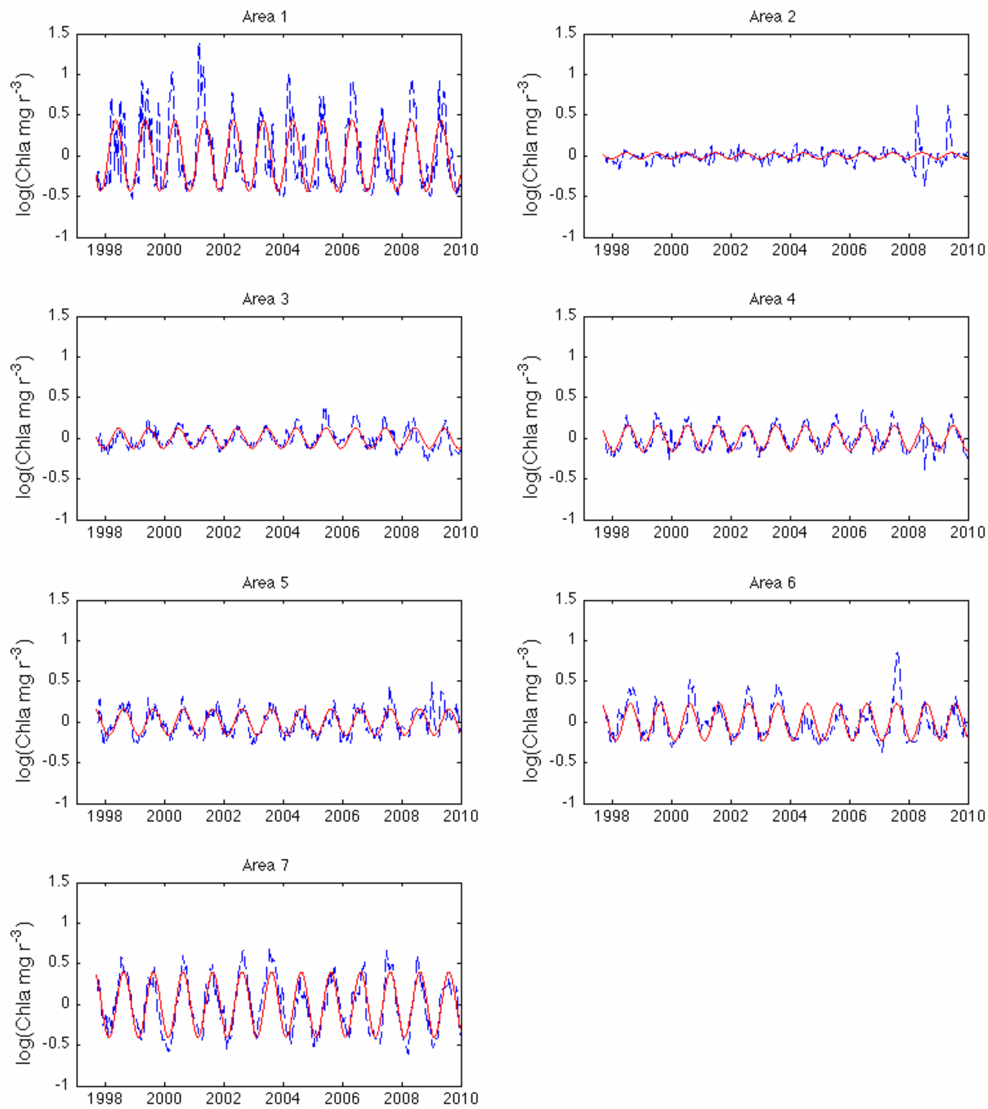


**Figure 5.** Annual cycles of chlorophyll concentration (Chl, mg.m$^{-3}$) adjusted for each subarea (red solid line) versus observed Chl values in each 8-Day period (blue doted line).

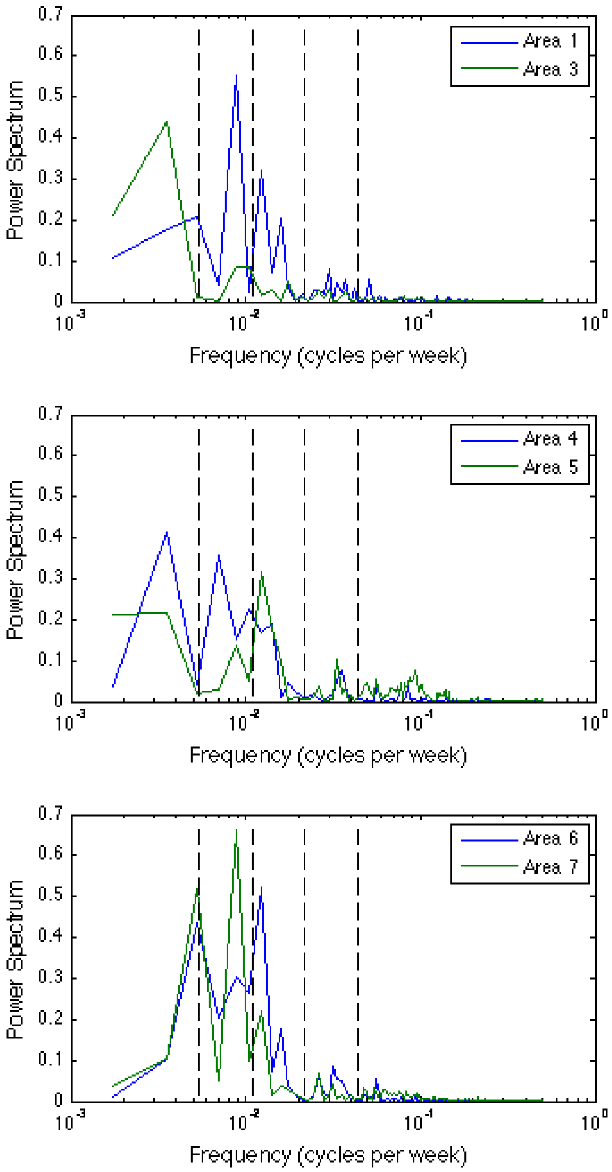


**Figure 6.** A variance-preserving plot of power energy (in mg2 m-6) for the normalized deseasoned chlorophyll time series from Areas 1 and 3 (above), Areas 4 and 5 (middle), and Areas 6 and 7 (below). The vertical dashed lines stand for ½ year, 1 year, 2 year and 4 years cycles, from right to left, respectively.

northeast winds rather than with increases in discharge by the La Plata River. Garcia and Garcia (2008) demonstrated the annual cycle as the most dominant mode of variability over the southern Brazilian continental shelf, and the associated high amplitude in the annual cycle (see Table IV) is mainly controlled by the seasonal variation in the incursion of La Plata plume. The northward La Plata River plume extension varies from year to year (Piola *et al.* 2008) leading to a strong interannual variability in Chl is also expected in the region. The few observations also show larger in situ chlorophyll concentration during spring and winter in Area 7 (Ciotti *et al.* 1995). The meridional gradient of Chl from Area 7 to Area 3 during winter (Table III) that is probably related to the seasonal migration of La Plata River plume reflected in the amplitudes for the annual fits up to Area 3 (Table IV).

**Comparison Between SeaWiFS and MODIS/ Aqua Chl and Data Coverage**

Because of the inconsistencies for both CSZC and OCTS data acquisition over the BCS, our seasonal comparisons over the seven Areas were performed only for SeaWiFS and for MODIS/Aqua (Table III), during periods when the 8-Day composite images were available for both sensors. The non-parametric statistical tests to access significant differences between sensors for the same sample size (Table V) show statistically comparable Chl for the two sensors in most, but not in all Areas. Significant differences were mainly related to data coverage, especially during winter and fall, when SeaWiFS data coverage was higher in Area 1 but MODIS/Aqua data coverage was higher in the remaining Areas. Differences in Chl were detected in Areas 1, 2 and 3, with no apparent seasonal patterns. Note that we used data from MODIS/Aqua reprocessing 1.1, performed in August 2005.

**Long-term variability of chlorophyll based on SeaWiFS 12-years period**

The analyses of the interannual variability in Chl fields given by SeaWiFS dataset (Sept. 1997 to Dec. 2009) show clear seasonal cycles all regions, except in Area 2 (Table IV). In addition, the amount of energy contained in Chl anomalies derived spectra was an order of magnitude higher in Areas 1 and 7 (Fig. 6) due to the presence of Amazonas River (Area 1) and La Plata River (Area 7). Except for Area 2, the results suggest long term variation (> 2 years) in most of BCS. Note that the vertical axis in Figure 6 represent the total energy, given in [chla]2, where the signal variance is preserved within the frequency spectrum. A 4-years signal was observed in Areas 4 to 7 a pattern already detected in southern BCS (Garcia & Garcia 2008), who associated this signal with both cycles of La Plata river discharge and alongshore winds. In the remaining areas, the cycles may be associated with long-term changes on the Trade winds regime and mesoscale features.

## Complementary information

It is outside the scope of this work to detail other variables than Chl and data coverage by the four ocean color sensors. However, the presence of a south to north gradient of Chl values in the winter that may be related to the seasonal meridional excursion of the La Plata river plume, lead us to investigate the general patterns observed in two additional ocean color products that may complement and aid the interpretation of Chl patterns (Fig. 7). The hypothesis to test is that the south-north Chl gradient observed in winter reflects partially the influence of continental outflows on over-estimatives for Chl due to the presence of CDOM.

As mentioned before, MODIS/Aqua provides data on sea surface temperature (SST) and chlorophyll fluorescence line height (FLH) that can complement Chl, and a new ocean color product (available for SeaWiFS and MODIS/Aqua) - the CDOM-index – can illustrate the relative importance of this component over phytoplankton. In a first approximation, FLH appears to confirm the trends shown by Chl:i) Area 3 showed the lowest FLH and CDOM-index, while the maximum were observed in both Areas 1 and 7. However, Area 2 is no longer the least variable, being replaced by Area 3 for both FLH and CDOM-index, which suggest that the seasonal variability on Area 3 may be a seasonal contribution of CDOM by changes in wind field. There is a contrast between Area 1 and 7 regarding the CDOM-index, much more evident in the south. Note also that Areas 5 and 6 have different mean FLH but similar Chl, with an apparent larger contribution of CDOM in Area 6 that may explain this divergence. A discussion in depth of these differences among products would require validation programs and the development of semi-analytical regional models. Our goal here is to point out that data are already available for scientific interests in physical and biological processes in the BCS. Although these products are not free of some fundamental errors, they may be used to ask scientific questions and design better surveys.

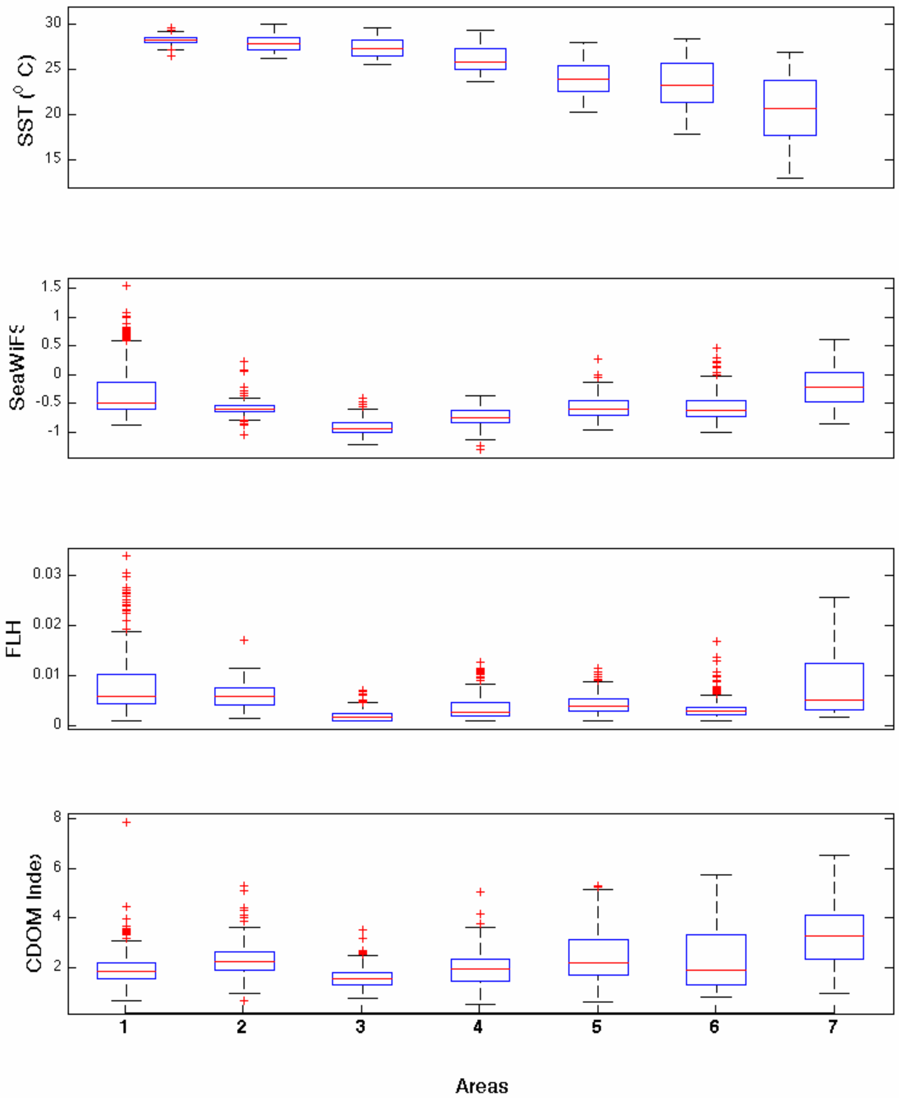


**Figure 7.** Statistical distributions for all available data per Area for Sea Surface Temperature (SST, MODIS/Aqua), Chlorophyll concentration (log scale; Chla SeaWiFS), Fluorescence Line Height (FLH, MODIS/Aqua) and the CDOM index (SeaWiFS).

**Table III.** Seasonal chl cycles and proportion of data coverage (i.e., 0 would represent no data while 1 would represent that all pixels had valid data) per region (Seawifs MODIS). Values represent the overall means for all 8-Day median values of Chl observed in each area. These means were computed for periods with concurrent data acquired by both sensors, up to 31 December 2009.

| SeaWiFS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Season | Fall | | Winter | | Spring | | Summer | |
| Area and latitudinal range | CHL Mean (Std) | COVER Mean (Std) | CHL Mean (Std) | COVER Mean (Std) | CHL Mean (Std) | COVER Mean (Std) | CHL Mean (Std) | COVER Mean (Std) |
| 1 - 4N-1S | 2.17 (2.05) | 0.27 (0.20) | 0.54 (0.57) | 0.53 (0.17) | 0.25 (0.07) | 0.41 (0.12) | 0.91 (1.72) | 0.18 (0.13) |
| 2- 1S-5S | 0.32 (0.23) | 0.44 (0.23) | 0.27 (0.03) | 0.71 (0.15) | 0.25 (0.03) | 0.58 (0.12) | 0.25 (0.07) | 0.29 (0.17) |
| 3- 5S-15S | 0.16 (0.05) | 0.62 (0.18) | 0.15 (0.04) | 0.70 (0.15) | 0.10 (0.02) | 0.73 (0.18) | 0.11 (0.02) | 0.62 (0.24) |
| 4- 15S-21S | 0.23 (0.07) | 0.74 (0.21) | 0.26 (0.07) | 0.73 (0.20) | 0.16 (0.05) | 0.52 (0.30) | 0.15 (0.03) | 0.58 (0.27) |
| 5- 21S-24S | 0.28 (0.11) | 0.86 (0.20) | 0.38 (0.12) | 0.86 (0.21) | 0.28 (0.11) | 0.57 (0.30) | 0.23 (0.21) | 0.69 (0.29) |
| 6- 24S-28S | 0.27 (0.11) | 0.79 (0.21) | 0.55 (0.43) | 0.75 (0.24) | 0.25 (0.11) | 0.48 (0.28) | 0.18 (0.04) | 0.65 (0.28) |
| 7- 28S-34S | 0.66 (0.42) | 0.72 (0.24) | 1.61 (0.79) | 0.77 (0.20) | 0.78 (0.52) | 0.74 (0.25) | 0.30 (0.13) | 0.78 (0.18) |

| MODIS/Aqua | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Season | Fall | | Winter | | Spring | | Summer | |
| Area and latitudinal range | CHL Mean (Std) | COVER Mean (Std) | CHL Mean (Std) | COVER Mean (Std) | CHL Mean (Std) | COVER Mean (Std) | CHL Mean (Std) | COVER Mean (Std) |
| 1 - 4N-1S | 1.72 (1.83) | 0.23 (0.17) | 0.50 (0.69 | 0.46 (0.14) | 0.29 (0.56) | 0.28 (0.11) | 0.57 (0.85) | 0.13 (0.10) |
| 2- 1S-5S | 0.36 (0.24) | 0.53 (0.23) | 0.26 (0.03 | 0.78 (0.10) | 0.26 (0.03) | 0.57 (0.11) | 0.28 (0.07) | 0.34 (0.16) |
| 3- 5S-15S | 0.18 (0.06) | 0.67 (0.17) | 0.17 (0.06 | 0.73 (0.14) | 0.11 (0.02) | 0.71 (0.15) | 0.13 (0.06) | 0.65 (0.21) |
| 4- 15S-21S | 0.24 (0.09) | 0.83 (0.16) | 0.28 (0.07 | 0.83 (0.15) | 0.17 (0.05) | 0.61 (0.27) | 0.15 (0.02) | 0.69 (0.24) |
| 5- 21S-24S | 0.27 (0.09) | 0.93 (0.10) | 0.36 (0.12) | 0.91 (0.16) | 0.26 (0.11) | 0.62 (0.30) | 0.20 (0.05) | 0.77 (0.23) |
| 6- 24S-28S | 0.25 (0.10) | 0.87 (0.16) | 0.46 (0.32) | 0.83 (0.22) | 0.24 (0.08) | 0.54 (0.25) | 0.19 (0.06) | 0.70 (0.25) |
| 7- 28S-34S | 0.59 (0.32) | 0.82 (0.19) | 1.47 (0.82) | 0.82 (0.17) | 0.76 (0.54) | 0.77 (0.18) | 0.31 (0.11) | 0.80 (0.15) |

## Recommendations and Conclusions

We have shown that the ocean color data are adequate for time series studies but they are currently only a decade-long and quantification of long-term trends is not feasible at present time for the BCS. Our simple analyses have shown however, the presence of long-term and interannual variability that must be taken into account in future studies on BCS. Systematic ocean color measurements from multi-instrument, multi-platform and multi-year observations are needed to understand how annual and decadal-scale climate variability affects the growth of phytoplankton on the continental shelves. It is important to have satellite ocean color data available for the scientific community to access changes in phytoplankton biomass, dissolved material and other derived products. However, SeaWiFS, MODIS, and MERIS sensors are either well beyond or nearing the end of their design lives (Mc Clain 2009). The continuity for these products will only be achieved over the next decades if an effort is made to launch new ocean color sensors.

The data from new sensors have also to be open to all ocean *color* researchers, including the pre-launch characterization and on-orbit calibration

**Table IV.** Correlation values of the annual model for each region and their respective amplitudes. All values are statistically significant (>99% level) except for region 2.

| Area and latitudinal range | $R^2$ to the Annual fit | Amplitude $mg.m^{-3}$ |
|---|---|---|
| 1 - 4N-1S | 0.524 | 0.44 |
| 2- 1S-5S | 0.083 | 0.04 |
| 3- 5S-15S | 0.567 | 0.12 |
| 4- 15S-21S | 0.640 | 0.16 |
| 5- 21S-24S | 0.542 | 0.16 |
| 6- 24S-28S | 0.576 | 0.23 |
| 7- 28S-34S | 0.783 | 0.40 |

data, so a critical and constructive discussion is set in place to guarantee the quality of the products and the preservation of the experience from past programs. Among the new planned sensors are the Ocean Color Monitor (OCM-2, India) and the Visible-Infrared Imaging Radiometer Suite (VIIRS, United States). Brazilian and Argentinean governments will also launch an ocean color sensor (SABIA-MAR) and at present the design of potential instruments is under discussion.

For studying the BCS in the future, we must be aware of the necessity of both improving existing ocean color algorithms and validate ocean color products. Regional algorithms may also be needed in certain areas. Recent improvements in field observation capabilities and the increase in number of experts in bio-optical algorithms (empirical and semi-analytical) will definitely push this line of research forward, but programs must be designed and conducted in long term. However, the Brazilian ocean color community is concentrated in few institutions in the South and Southwest Brazilian (*e.g.*, Garcia *et al.* 2005, Kampel *et al.* 2009). Products and models will improve with time, if a long-term program is established for all the necessary steps and not only for data acquisition.

The experience of countries like UK and USA has shown that it is crucial to complement remote sensing programs with a net of observational key locations over the continental shelves where systematic and repeatable surveys are executed for many years. Besides acquiring and validating remote sensing data, we have also to be concerned with the processing and distribution of these data and products to the scientific community. Results of our simple comparison among Chl, FLH and CDOM-index fields are encouraging, but the interpretation of biological and physical mechanisms associated with spatial distributions of these products must be improved. There is also a need to incorporate ecological modeling as part of ocean color data interpretation, and the ocean color groups must invest in this line, or better the different groups should work together.

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