A CLASSIFICATION OF THE SOUTH ATLANTIC BY THE SEAWIFS CHLOROPHYLL CONCENTRATION VARIABILITY IN ECOLOGICAL PROVINCES

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September, 2013

Abstract: This work proposes a subclassification of the South Atlantic Ocean based on the Empirical Orthogonal Function methodology applied to chlorophyll concentration. Other parameters (such as the temperature of the sea surface, wind speed and sea level anomalies) are also analyzed, correlating the results to physical processes occurring in the ecological provinces. The analysis, which is based on remote sensor data correlation, between NOAA, SeaWIFS and the TOPEX/Poseidon satellite, indicates a strong relationship with upwelling events and coastal discharges in some of the regions.

Key words: Ecological provinces, remote sensing, multivariate analysis, physical processes.

1 Introduction

The South Atlantic Ocean (SAO)(Fig. 1) presents a large degree of spatial and temporal variability. Its system of ocean currents and the distribution of solar radiation generate specific ranges for many variables such as the

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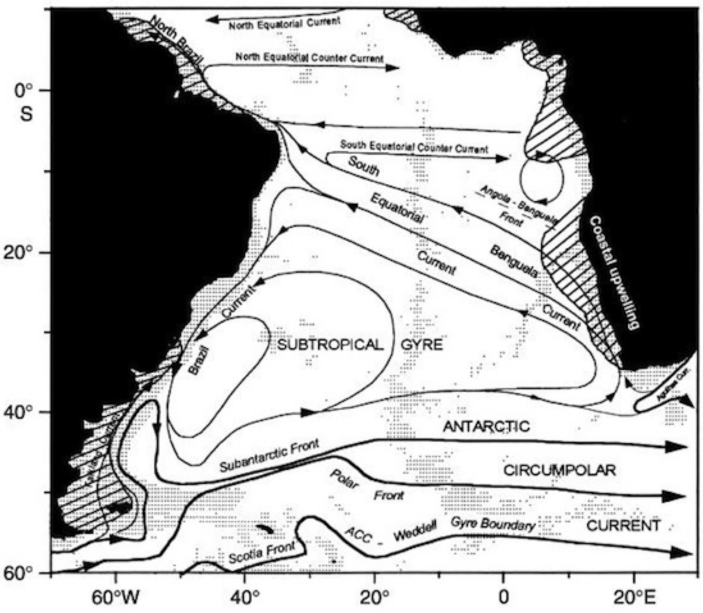

Figure 1: From [33], modified according to chlorophyll distribution as seen in satellite images.

sea surface temperature (SST), which can fluctuate between 15°C and 30°C, and chlorophyll concentration (CHL), ranging from 0 to 6 mg/m^3. Crossing the SAO basin, the South Equatorial Current (SEC) flows westward of the subtropical gyre, guided by trade winds [42] [40]. At a latitude of about 12°S, it reaches the Brazilian coast and divides itself onto two new currents: the North Brazil Current (NBC), which flows to the Gulf of Mexico [35] and the Brazil Current (BC), flowing southward with the continental shelf [40]. Part of the SEC and the NBC suffer a retroflection toward the African coast, which will form a front system and feed the equatorial trade winds [18]. Flowing northward, the Falklands Current (FC) covers the entire coast of Argentina, Uruguay and parts of Brazil. Is a branch of the Antarctic Circumpolar Current (ACC) and flows northward in the opposite direction of the CB, charged with nutrients [30] (Fig. 1). The physical processes that occur throughout the region (such as upwelling events, gyres systems and vorticities, as coastal discharges) might influence the differences between the characteristics of each current.

We aim to define Ecological Provinces (EP) as oceanic regions that cover relatively large areas characterized by different biological and physical features and atmospheric influences. Our definition of EP is based on the analysis of CHL measured by satellite sensors that cover the SAO. The joint analysis of the sea surface temperature (SST), sea level anomaly (SLA) and wind speed (W) will point out which physical processes are influenced. However, several classifications of the SAO have already been proposed by different authors [22] [23] [38] based on oceanographic parameters. A detailed classification that includes two other provinces i.e. the ETRA - Eastern Tropical Atlantic and the BENGA - Benguela Current can be found in [44].

Taking into account the previous subclassification of the SAO proposed by [10], a dynamic method is now developed in this paper, to define the boundaries of the EPs based on the statistical analysis of physical and biological data. The contribution of this study consists of a new and more accurately and objective zonation of the SAO in terms of EPs from remote sensing data. In addition, the methodology is fully based on advanced multivariate techniques applied on remote sensing data sets.

2 Methodology

The data used in the study encompasses monthly global fields provided by sensors such as the AVHRR from the NOAA satellite (Pathfinder - Version 5) for the SST at 4 Km resolution data, the SeaWiFS for the CHL data (Version 3, at 9 Km resolution) [17], the TOPEX/Poseidon radar altimeter for the SLA at 25 Km resolution, and the Quikscat scatterometer for the W data at 25 km resolution. The sample size of these four parameters spans a 10 year period from January 1998 to December 2008. A new methodology is now developed to define the boundaries of the EPs. A new layer of complexity was added in the Lempel-Ziv (LZ) analysis [19] of the CHL data in order to find troubled areas. What follows is a multivariate method based on the modes of variability.

The covariance matrices were used to extract the oscillatory modes by means of Empirical Orthgonal Function (EOF), which defined the relevant regions. The EOF was used to classify areas, generating clusters with similar patterns. The variability analysis was then performed using Singular Value Decomposition methods, in order to calculate the temporal variability, the spatial oscillatory modes and their corresponding eigenvalues [48]. This procedure allowed the analysis of anomalies in the SAO. The time series associated with temporal patterns of each mode are dimensionless and represent the evolution of spatial modes in time [49]. The SAO area is therefore divided into sub-regions, statistically confirmed by the two-sample significance

Kolmogorov-Smirnov test [25]. We have also calculated the spatial mean of the four variables, and the basic statistics were applied in each EP. This analysis will observe the rate of change in these variables and compare the results with those in the bibliography.

3 Results

3.1 Analysis of Variability Modes: EOF

As previously stated, the EOF allows the decomposition of a field into spatial and temporal components. Given that the first analysis is based purely on biological factors, the EOF was only applied to the monthly CHL fields. The first mode represents 68.7 % of the variance and corresponds to the annual mean seasonal cycle (Fig. 2A). Its spatial pattern also shows that the region of strong seasonal variability is mainly concentrated within the coastal regions and the Eastern Equatorial Atlantic (EEA). The second mode (Fig. 2B) explains 5.63% of the total variance. The temporal amplitude corresponds to an interannual variability of the seasonal cycle, identifying regions with the highest rate of change in the spatial mode.

These regions are centered in the South and Southwest shelf zone and in the Eastern side of the study area, probably influenced by the Equatorial Upwelling Zone. The peaks during the austral winter in the southwest suggest upwelling events which could even help to identify different masses of water. The third mode (Fig. 2C), with a percentage of variance explained of 2.39% shows some variability in the southern platform. Regarding its temporal amplitude, semi-annual intervals may be observed, with minor cycles corresponding to specific events in the southern and southeastern Brazilian shelves. All together explains about 77% of the total variance. The linear correlation analysis between the fields of mean CHL concentration and the first EOF mode was also conducted to ensure the last one to the evolution of the annual cycle (Fig. 3).

Some periods were found, one of few months and the annual and semi-annual identified above. In [15] it was observed that highest pigment concentration values (greater than 0.06 mg/m^3) appears below a frontal region beginning at approximately 30°S, which coincides with the northern limit of the Subtropical Convergence Zone [2]. They proposed a classification of the SAO by means of a PCA of the chlorophyll-a.

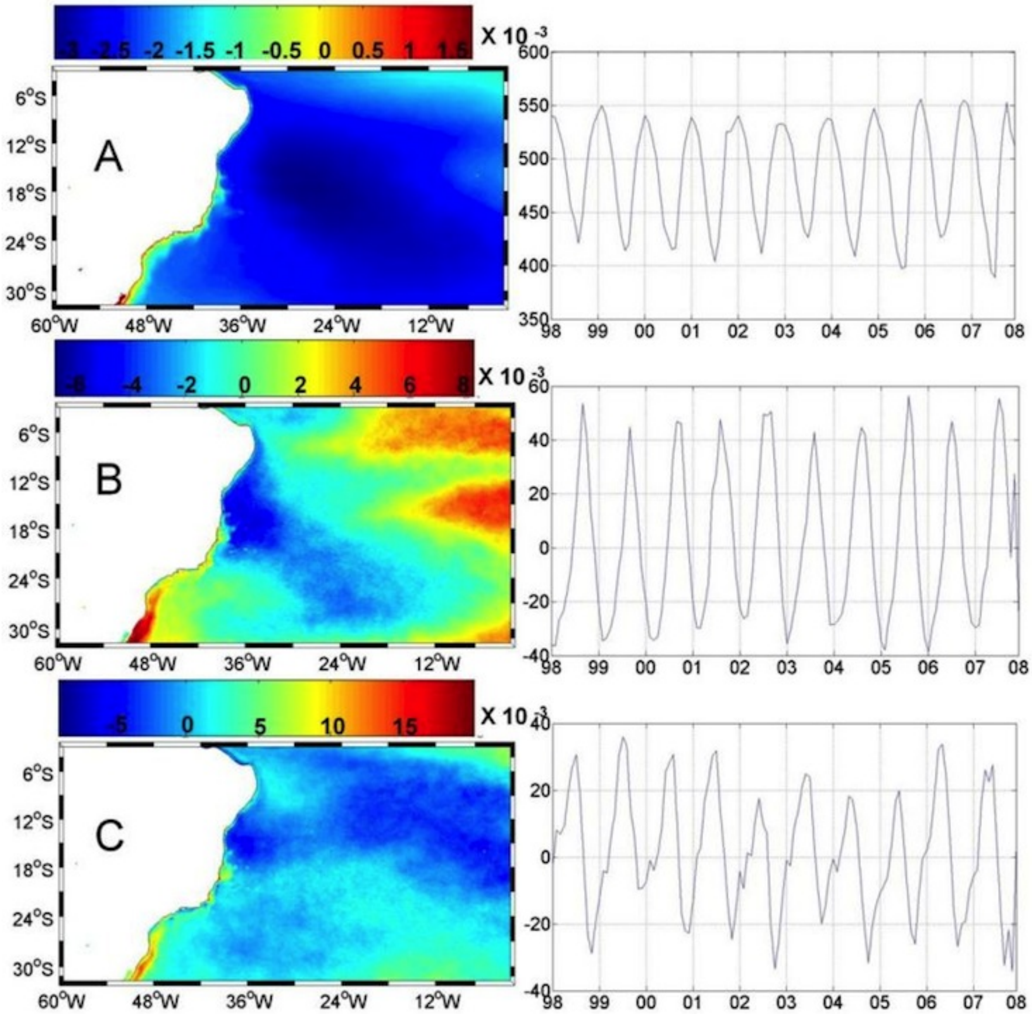

Figure 2: Oscillation modes originated from the EOF applied to the CHL dataset; Temporal amplitude graphs are represented by time in years; spatial patterns in Log10 units - final values must be exponent in base 10. Scale units are in mg/m^3.

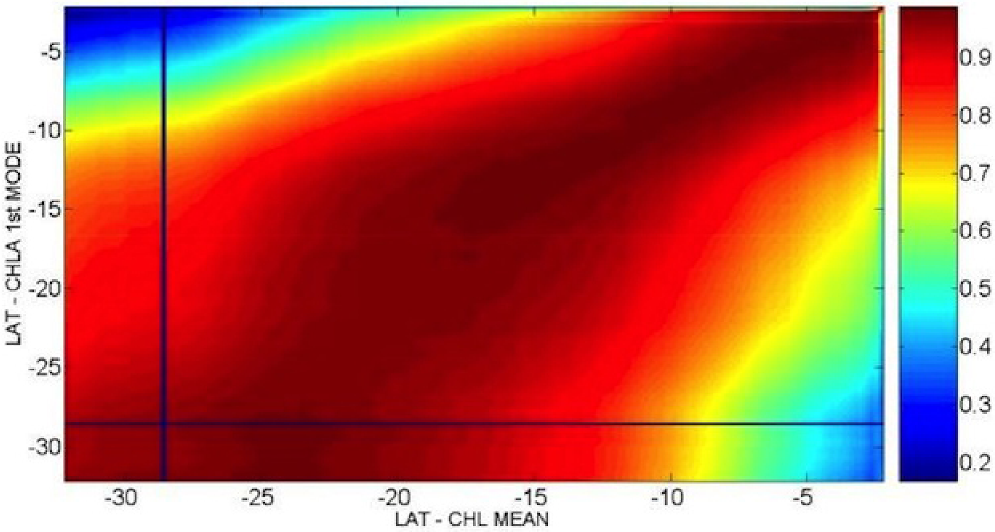

Figure 3: Correlation between CHL mean field and EOF 1st mode. Black lines are the valueless coastal area.

Same sign values of the EOF in the second mode (Fig. 2B) are located in four different areas: the brazilian coastal zone from the south of the study area up to the Abrolhos region (17°23' S - 18°10' S and 38°33' W - 39°06' W), the Equatorial zone, and two other regions, probably influenced by the Benguela current and the African coast. Opposite values are associated to the subtropical gyre, and the Eastern Brazilian coast. The time series from this mode appears to be related to interannual oscillations, with austral spring and summer peaks. As is the case with the second one, the third spatial mode (Fig. 2C) presents highest magnitudes coming from the southeast of the studied area and some upwelling zones. This amplitude can be correlated with a few months of intra-seasonal variability, as showed by two different peaks in the time series oscillation.

3.2 Complexity Coefficient

The Lempel-Ziv's complexity index gives an idea of how complex is a binary chain. After the isolation of the time series of values for each pixel, these were transformed onto binary time series, computing then the complexity index.The spatial pattern of the Lempel-Ziv's complexity index is shown in (Fig. 4). It shows that the center of the SAO (where the subtropical gyre is) has low complexity, with mean values around. The highest complexity is

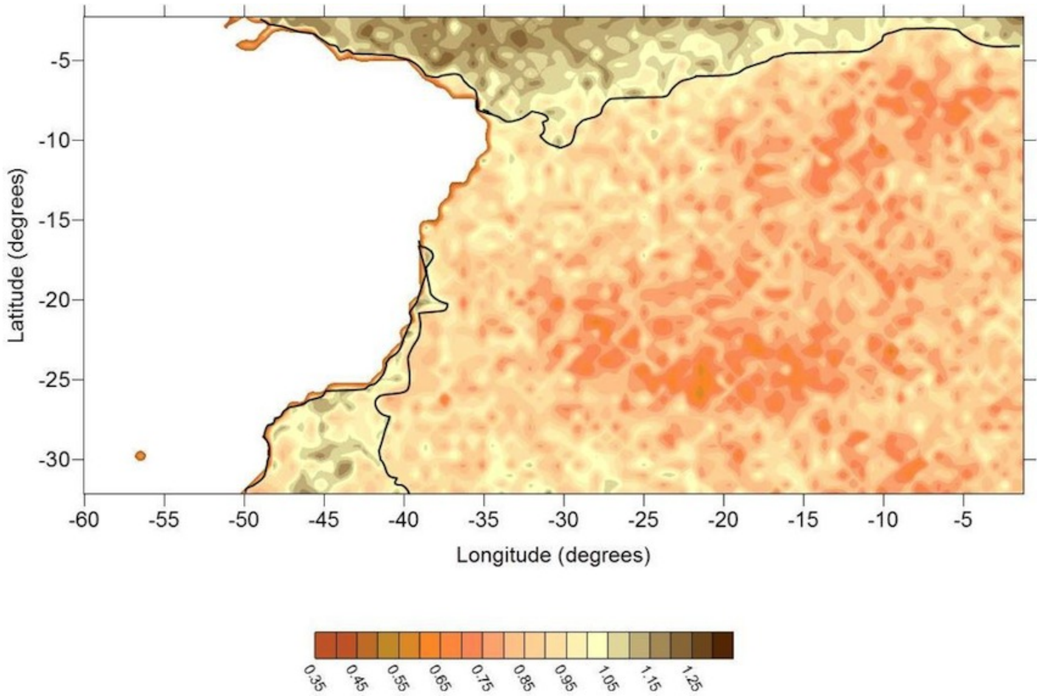

Figure 4: Lempel-Ziv complexity graph.

located in the equatorial Atlantic and smaller areas near the coast.

Combining the results from the Lempel-Ziv complexity index and those from the EOF analysis, it is possible to propose a preliminary classification of the SAO into four EPs, with different regimes of variability. There is a separation between the northern and southeastern Brazilian coast and the South Eastern Atlantic region (SEA).

3.3 Pertinence of the Ecological Provinces

The belonging of the different pixels to a EP has been estimated by simple basic statistical techniques applied to spatial averages of chlorophyll in each EP. First the mean and standard deviation of each proposed EP was computed (Table 1) to be a basis of the distribution of CHL in each region. The first EP shows the highest values (see Fig. 5). Regarding the size of chlorophyll concentration, the most equatorial regions (i.e, 2 and 3) become relevant zones for their oceanographic features. The fourth province has extremely low values of variance, considered insignificant for the study. The area covered by the EP 5 corresponds to the Atlantic Subtropical Gyre

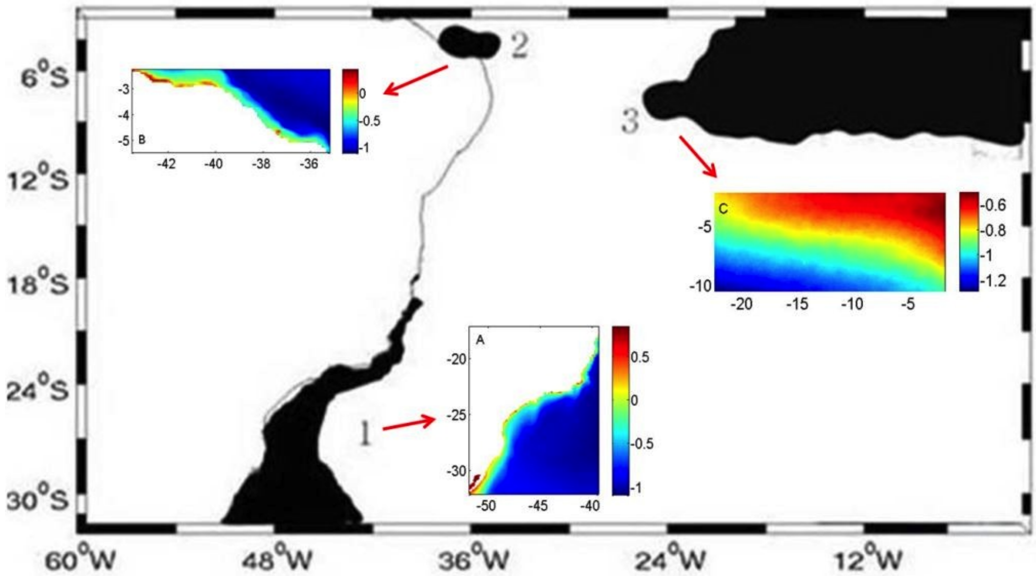

Figure 5: Annual mean of the chlorophyll data in the first (A), second (B) and third (C) EPs considered; In big is the hipotetical representation of all regions in the SAO; Spatial patterns are represented in Log10 units - final values must be exponent in base 10; Scale unit is in mg/m^3.

(ASG), i.e., a high pressure zone strongly influenced by the wind action. The biological productivity of such an oligotrophic region is certainly small, but its immense size makes its contribution to the total biological content significant [27].

In terms of variability, the ASG pattern, suggested by the altimeter sea level trend analysis, is slowly migrating southward and has been growing in amplitude between 1994 and 2006 [46]. That is coherent with the growing phase of a bidecadal oscillation found from tide gauges. On interanual time scales the sea level in the corridor fluctuates out of phase in the west and east revealing noticeable variations of 10 cm amplitude at 4 to 5 years period [16]. However, the classification presented here is focused in mesoscale processes. For this reason, EP 5 is not considered in this study. To ensure the reliability of the EPs, the Kolmogorov-Smirnov significance test was carried out. The null hypothesis is that the distributions come from similar regimes. This hypothesis can be rejected at a significance level of 5%, confirming the relevance of the selected regions. Therefore, EPs 1, 2 and 3 are considered the most representatives regions to study (Fig. 4).

Table 1: Mean, standard deviation and variance of Chlorophyll concentration (mg/m^3) in the four EP.

EP	Mean	Standard deviation	Variance
1	0.323	0.119	0.0200
2	0.268	0.063	0.0040
3	0.173	0.077	0.0060
4	0.068	0.027	0.0007

3.4 Description of the selected EPs

The mean annual field of chlorophyll for the different EPs is presented in Figure 5(A-C). The first region (Fig. 5A) is located between coordinates 20°S-32°S and 40°W-52°W and corresponds to the regions of strong coastal activities. The north of this region is characterized by the oceanographically important chain of submarine mountains Vitória-Trindade (near the Espírito Santo state). The break in the coastal line is located near the city of Cabo Frio (at 22°52'S), a well known upwelling region. The Santos Basin covers the entire continental southeastern zone, extending from the southern coast of the state of Rio de Janeiro (22°47'S and 43°12'W) to the north of the state of Santa Catarina (25°57'S and 48°19'W), passing through to the Paranaguá-Cananéia Estuary (25°00'S - 47°55'W). It is a complex region with micro-currents system and the presence of islands. Southward, the intrusion of the MC can be detected at the Cape of Santa Marta (at 28°36'S), the region of Florianópolis and, finally, at the Patos Lagoon, during the austral winter [5][11].

According to [41], there is an exchange of mass and heat along the western limits through the shedding of the warm core from the BC, which also sheds cold core rings in the shelf. Upwelling events are observed during the austral summer at the latitude of 23°S (the Cabo Frio region), with a strong relation to the wind action. It is plausible that those phenomena are driven by the cold winds over local warm currents leading to the detachment of eddies [24], which penetrate in coastal water forming exceptionally cold water zones charged with nutrients.

Due to its oceanographic location, EP 2 (Fig. 5B) is under the influence of the Equatorial South Atlantic (ESAC) region and the NBC. The seasonal action of winds from the Inter-Tropical Convergence Zone (ITCZ), and the discharges of the Jaguaribe and Parnaíba Rivers might describe the variability of the zone. The Jaguaribe's Basin lies almost entirely within the boundaries of the state of Ceará (Brazilian Northeast), extending southward to the state of Pernambuco. It is influenced by variations in rainfall and its peak discharges are observed during the rainy season from January to July [28]. The Parnaíba River is divided in two arms flowing to different directions and subdivided into numerous islands [31].

The EP 3 is located at the northeast of the SAO (Fig. 5C), at approximately 2°S-10.5°S and 2°W-23°W. Following [44], this area is under the influence of the biogeographical zone named Eastern Tropical Atlantic (ETRA) whereby it presents a strong relation with the Congo River discharge, which, in turn, might be linked to the seasonality of the African monsoons. The Equatorial Upwelling Zone and the wind activity are also probably correlated to it. The Eastern Equatorial Atlantic (EEA) collects a huge quantity of nutrients due to discharge from the Congo River that, alone, releases 1270 Km^3 of freshwater into the ocean every year [47]. This river is the second largest flow of water in the world, second only to the Amazon River. The annual cycle of the Congo discharge has two maxima, one in the austral summer (November - December - January) and one in late autumn (April - May

- June).

The Tropical Atlantic Variability (TAV), linked to the climate variability of North America and Europe [13], occurs at a seasonal time-scale and it is known as the West African Monsoon (WAM). It is a major wind system that affects West African regions and blows south-westernly during warmer months and north-easternly during boreal winter [43]. At interannual scales, WAM rainfall variability is modulated by both oceanic and continental convergence, variations in the position of ITCZ, and land-atmosphere interactions, respectively [12]. Some studies [45] [32] found a strong connection between this region and the El Niño phenomenon during austral winter, influenced by the formation of a cold-tongue due to the equatorial upwelling. Similarly, the associated sea surface cooling is correlated to the northward migration of the ITCZ.

3.5 Analysis of the oceanographic variables in the EP

The EPs were defined using the CHL concentration from satellite data. In this section, we jointly analyze the variability of CHL and the environmental parameters. The mean SST, CHL, SLA and WIND values, as well as its basic statistics, were computed for each month to analyze their variability within the EPs. Table 2 shows that the regions correspond to different physical and geographical environments: The further north and near the coast, the lower the SST and CHL variances. Together with higher CHL, such characteristics are proportional to their latitude location. These values are consistent with [34] which show the highest amplitude in the shelf. Concerning WIND and SLA values, they tend to be higher nearest to the coast. The correlation between the variables (Table 3) is based on their optimal combination in a time span. These associations allow us to understand the phenomena that better describe each EP.

Table 2: Variance of the SST, CHL, Wind and SLA in each ecological province (EP).

EP	SST	CHL	Wind	SLA
1	4.283	0.014	0.438	7.962
2	0.480	0.004	1.512	9.352
3	1.885	0.006	0.283	3.000

The first EP presents the highest temperatures and chlorophyll concentration values (Table Table 1). WIND and SLA data mean in EP 1 show intermediate values. Is the region with higher values of variance within SST and CHL (Table 2). Following the interpretation of [9], the correlation is highest in the combination of SST and CHL coefficients with WIND, suggesting upwelling events (Table 3).

Table 3: Correlation between the time series at all the studied ecological provinces.

EP	$\frac{SLA}{SST}$	$\frac{SLA}{CHL}$	$\frac{SLA}{WIND}$	$\frac{SST}{CHL}$	$\frac{SST}{WIND}$	$\frac{CHL}{WIND}$
1	0.50	0.45	0.46	0.77	0.63	0.47
2	0.46	0.14	0.66	0.06	0.58	0.33
3	0.68	0.57	0.36	0.77	0.41	0.48

The EP 2 is characterized by low SST and CHL values (Table 2). The Equatorial Atlantic region is characterized by SST between 26°C and 27.7°C. Concerning SLA, the area presents higher average and variance values. In the correlation analyses between variables, WIND leads together with SST and SLA parameters, illustrating the seasonality of winds in the ITCZ and coastal discharges regime (Table 3).

Variance is not so relevant in EP3, but CHL and SLA contribute to describe a relevant region. Also, the high correlation coefficients evidenced in this region (Table 3) represent a strong association between SLA, SST and CHL.

The higher chlorophyll concentration in EP 1 and 2 are probably related to coastal discharges. The characteristics of EP 3 might be linked to the African Coast upwelling, as well as to the African Monsoon periodicity.

4 Discussion

Physical processes are abundant at the South Atlantic Ocean covering several scales of space and time. Their main forces are considered tides, freshwater discharges, upwelling events, oceanic currents and the variability of some variables as the sea surface temperature, chlorophyll concentration, sea level anomalies and wind. Those parameters, interacting with geomorphological features such as bottom topography and coast bearing, produce several types of phenomena that can be arranged in specific zones according to their geographic locations, physical variables, seasonality, and enrichment mechanisms (Fig. 5).

These zones, named here as ecological provinces, cover all the biogeographical regions [22] of South Atlantic and we defined as regions that cover relatively large areas in the South Atlantic, containing differences in the characteristics of their biological and physical features, as geographically and atmospheric exogenous influences. It is clear that the ecological provinces play a paramount role in ecological processes of the ocean allowing for an exceptionally large primary production; contributing to the inputs of nutrients, providing appropriate physical conditions, breeding species need great quantities of nutrients concentrated near these areas.

At a continental scale, an important correlation exists between the distribution of coastal primary production and upwelling events in the Atlantic, which could constitute spots with high food availability. Moreover, the distribution of species and the structure of microorganisms assemblages are influenced by the presence of physical structure of the ocean [1]. Fishing activity is very high at the shelf break and depends on the interactions between microorganisms and the phytoplankton algae blooms. Coastal discharges are considered not only high productive zones, but also influence oceanographic and atmosphere parameters. The high rate discharge caused by some rivers directly influences some phenomena, which can become irrelevant factor in time to analyze and utilize certain area.

Our results show that some regions in the SAO are propense to suffer strong changes in physical and biological parameters. These changes might be provided by different sources as oceanographical phenomena and other mesoscale processes. The importance of understanding these processes can be directly linked to the human social development, not only in the study of the consequences of such phenomena and the environmental knowledge itself, but also in the use of these regions as commercial transit areas and fishing.

5 Conclusion

The ten years of CHL satellite data were used in an effort to classify the entire zone of the SAO into ecological provinces. Other variables such as SST, SLA and W, together with CHL, were analyzed to describe the obtained EPs. The classification of the region into biogeographic provinces is an undertaking that still requires more statistical analysis. However, the methodology have been used by other authors with the same purpose [15] [14] [36].

The correlation among the available variables is a valid procedure that reveals relevant information for better classification of previously reported provinces. The area under study could be generally classified as oligotrophic and associated with the Subtropical Gyre surrounded by more eutrophic provinces. From the joint analyses of data, the areas of upwelling and confluence of currents have been detected, in agreement with the literature [6] [27] [8] [26] [6]. According to the results, there is a constant and inversely proportional relation between the signals of SST and CHL.

The areas numbered as EP1, EP2 and EP3 are extremely influenced by external events which contribute to the exceptional pattern of variables:

- The first ecological province is the most influenced by upwelling events.
- The variability of EP 2 is directly linked to the discharges of the Jaguaribe and Parnaiba Rivers, as is the seasonality of winds in the ITCZ.
- Third region is influenced by the African coastal discharges, which, in turn,is associated to the TAV. The equatorial upwelling contributes to the strong phytoplankton bloom.

The joint analysis (with the use of multi-satellite data) utilized in this study, together with the precipitation and in situ data, might be useful for future works, correlating atmospheric and oceanographic processes. The spatial scale also allows analysis at regional level, potentially identifying mesoscale structures that might be associated to local events.

The fishing seasons are strongly associated with the spawning period and the growth of marine species, which in turn depend directly on primary production. Thus, a detailed knowledge about the areas of upwelling and phytoplankton booms can provide new insights for the food industry in coastal populations.

6 Acknowledgements

Orbital data were provided by AVISO (http://www.aviso.oceanobs.com/) and USA agencies:

- SeaWIFS: http://oceancolor.gsfc.nasa.gov/;
- QuikScat: http://podaac.jpl.nasa.gov/; and
- PathFinder: http://www.nodc.noaa.gov/.

Delcourt, F.T. was funded by the scholar fellowship from IFREMER.

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