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Chlorophyll variability and eddies in the Brazil–Malvinas Confluence region

Carlos A.E. Garcia[a,*], Y.V.B. Sarma[a], Mauricio M. Mata[a], Virginia M.T. Garcia[b]

[a] *Department of Physics, Fundação Universidade Federal do Rio Grande, Av. Itália, km 8, Rio Grande RS 96201-900, Brazil*
[b] *Department of Oceanography, Fundação Universidade Federal do Rio Grande, Av. Itália, km 8, Rio Grande RS 96201-900 Brazil*

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Abstract

Ocean-color data from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) have been used to investigate temporal and spatial variability of chlorophyll-*a* concentration in the Brazil–Malvinas Confluence (BMC) region (30–50°S and 30–70°W). Our analysis is based on 60 monthly averaged and 230 weekly averaged images ($9 \times 9\,\mathrm{km}^2$ resolution) that span from October 1997 to September 2002 in the Southwestern Atlantic Ocean. A nonlinear model was used to fit the annual harmonic of the chlorophyll concentration anomalies in the region. Analysis of the spatial variability of model parameters has shown the existence of a marked annual cycle at several locations in the study region. We also have observed shorter-period oscillating features on smaller spatial scale, associated with the BMC dynamics. These mesoscale features have periods of about 9–12 weeks and have a marked northward propagation with higher chlorophyll values relative to the surrounding waters.

Further investigation of these mesoscale features with an advanced very high-resolution radiometer thermal infrared and TOPEX/POSEIDON (T/P) altimeter data has unveiled interesting eddy-like surface structures in the BMC region. These multiple eddies are clearly visible on both thermal and color imagery off southern Brazil. Furthermore, the SeaWiFS images have shown a decrease in chlorophyll-*a* concentration as these eddies propagate northward, due to mixing with chlorophyll-poor tropical waters carried southward by the Brazil Current. Several rings along the shelf region, which are probably generated by shear instabilities, also have been detected by the ocean-color images.

1. Introduction

The Brazil Current and the Malvinas (also known as Falkland) Current converge along the continental margin of South America within the latitude band 35–45°S, where both currents flow seaward in a complex pattern of meanders and eddies (e.g., Olson et al., 1988). This frontal zone is known as the Brazil–Malvinas Confluence (BMC) and is recognized as one of the most energetic regions of the world oceans (Gordon, 1989). The strong mixing causes rapid cooling of subtropical waters brought by the Brazil Current, making this area very important for understanding circulation and heat transport processes (Wainer et al., 2000).

The typical position of BMC is at approximately 38°S (Gordon and Greengrove, 1986), but several

*Corresponding author. Tel.: +55-53-233-6643; fax: +55-53-233-6652.

E-mail address: dfsgar@furg.br (C.A.E. Garcia).

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studies have demonstrated remarkable variability of this position. For instance, Provost et al. (1992) studied the dominant periodic variations of sea-surface temperature (SST) in the BMC region (32–52°S and 50–70°W) from 202 advanced very high-resolution radiometer (AVHRR) SST images with $4 \times 4\,\mathrm{km}^2$ resolution. Although the annual signal dominates the SST time series, strong departures from this signal also are found in the BMC frontal region. The authors further showed that a semi-annual frequency is present in the region, associated with Southern Hemisphere atmospheric forcing. Garzoli and Giulivi (1994) studied the BMC frontal position and its variability through modeling experiments forced by climatological winds. They concluded that the main source for the BMC frontal variability is a local wind forcing associated with the seasonal cycle in the Southern Hemisphere. No apparent correlation was found between wind-forcing events in the Antarctic Circumpolar Current and observed anomalous northward penetration of the Malvinas Current.

Relevant biological processes take place in the BMC region, where photosynthetic uptake of carbon is enhanced by the nutrient-rich subantarctic waters (SAW) of the Malvinas Current, contributing significantly with the global carbon budget (Moore and Abbott, 2000). This area is considered an important region of ocean CO_2 uptake, due to high biological utilization of carbon in spring and summer (Feely et al., 2001). In addition to the SAW, other sources of nutrients in the region are the freshwater runoffs from both La Plata River (approximately 36°S) and Patos Lagoon (approximately 32°S), which also produce water-column stratification over the continental shelf (Brandhorst and Castello, 1971). In general, phosphate levels in the low-salinity coastal waters are similar to SAW ranges (0.4–1.0 μM), while silicate is usually higher, reaching 45 μM (Carreto et al., 1986; Niencheski and Fillmann, 1997; Ciotti et al., 1995). On the other hand, nitrate levels can be very low in the freshwater plumes (<1 μM), contrasting with variable and high values (<1–20 μM) in the shelf break or deeper waters under SAW influence (Carreto et al., 1995; Ciotti et al., 1995).

Surface chlorophyll-*a* concentration over the shelf in the northern part of the area (31–34°S) has been reported to be high in coastal waters south of Patos Lagoon ($>5\,\mu\mathrm{g\,l^{-1}}$) and much lower ($<0.5\,\mu\mathrm{g\,l^{-1}}$) near the shelf break in early spring (Ciotti et al., 1995). Farther south (approximately 38–39°S), between the coast and the shelf break, chlorophyll-*a* is highest in early spring ($\sim$4–10 $\mu\mathrm{g\,l^{-1}}$), associated with the coastal front and the development of water-column stability (Carreto et al., 1995). This nucleus moves toward the shelf break during spring, where SAW provide a rich nutrient source. Lowest values have been measured in winter ($<1\,\mu\mathrm{g\,l^{-1}}$), while in summer chlorophyll is generally low in the shelf, except for a few sites under influence of SAW (Carreto et al., 1995). The region between approximately 39–46°S, along approximately 56°W was sampled during four cruises of the Atlantic Meridional Transect (AMT, April 1996–October 1997), and total chlorophyll (chlorophyll-*a* + divinyl chlorophyll-*a*) was in the range 0.2–1.2 $\mu\mathrm{g\,l^{-1}}$ (Gibb et al., 2000).

Ocean-color data have seldom been used to investigate the temporal and spatial scales of dynamical processes in the South Atlantic Ocean. However, previous works from other areas have shown that chlorophyll from ocean-color sensors can be used as a good tracer of water masses (e.g., Ginzburg et al., 2002) and surface currents (e.g., Garcia and Robinson, 1989). Spatial and time coverage by previous ocean-color sensors (e.g., Coastal Zone Color Scanner) did not allow such analysis to be made in the past. Signorini et al. (1999) investigated the variability of sea-surface chlorophyll using first-year Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data, in conjunction with an ocean circulation model, TOPEX/POSEIDON (T/P) altimetry and wind-stress data sets, in the tropical and subtropical Atlantic Ocean during 1997–1998 El Niño event. They concluded that the regions of high-chlorophyll concentration are correlated with mesoscale and large-scale physical phenomena. In the eastern tropical Atlantic, for instance, the absence of fall blooms was correlated with SST anomalies and El Niño Southern Oscillation (ENSO) whereas the Ekman pumping was responsible for spreading surface blooms over the region (Signorini et al., 1999).

In this study, we first investigate the spatial and temporal variability of chlorophyll-*a* concentration in the BMC region. Then, we explore the possibility of using the pigment concentration as a passive tracer to study surface dynamics in the Southwestern Atlantic Ocean. We also present a case study of the evolution of eddies in the area during January 2001. The importance of ocean-color data in this context is highlighted by close examination of temporally coincident SeaWiFS, AVHRR and T/P satellite data.

2. Data and methods

2.1. Satellite data

2.1.1. Sea-viewing Wide Field-of-view Sensor images

We used 60 monthly averaged and 230 weekly averaged SeaWiFS Level-3 Standard Mapped Images (SMI) with $9 \times 9\,\mathrm{km}^2$ resolution to study the variability of chlorophyll-*a* concentration (in logarithm scale)—log[C]—in the BMC region. The data set corresponds to the period from October 1997 to September 2002 (5 years) that were available by NASA after reprocessing #4. The original SMI, which have dimensions of 4096 (longitude) $\times$ 2048 (latitude) pixels, were converted into subsamples of an area corresponding to 30–50°S and 30–70°W. Then, the original SMI data of $0.089 \times 0.089^\circ$ spatial grid were re-binned to $0.52 \times 0.52^\circ$ grid. The mean images were calculated from the weekly averaged re-binned images. Weekly image anomalies, relative to the total period of 5 years, were calculated by subtracting the mean image from each image to examine periodic signals for time-series analysis. Land and cloudy pixels were flagged to zero and were not taken into account for computations carried out in this work.

Local area coverage (LAC) SeaWiFS scenes, received at Rio Grande ground receiving station (Brazil), were processed with SeaWiFS Data Analysis System (SeaDAS). Images for January 2001 were selected to study the eddy fields and other instabilities observed off southern Brazil coast. Raw images (HRPT) were processed to level L1A, and subscenes of 900 pixels by 2100 lines from these full-resolution ($1 \times 1\,\mathrm{km}^2$) images were selected for further processing. Each subscene covers the geographical region between 27–50°S and 37–58°W in the South Atlantic Ocean. The subscenes were then processed to Level L2 using OC2 algorithm provided in SEADAS (version 4.1) software. The Level-2 images have a spatial resolution of 1 km.

2.1.2. Advanced very high-resolution radiometer images

AVHRR images, also received at Rio Grande station, were processed to generate SST fields (Kidwell, 1995). Both the AVHRR and SeaWiFS images from January 12, 2001 were analyzed in combination to study the mesoscale eddy-structure field in the BMC.

2.1.3. Altimetry data

Along-track sea-level anomalies (SLA) from the T/P Merged Geophysical Data records (AVISO, 1998) were used to estimate the dynamic height signal associated to the mesoscale features observed by the SeaWiFS sensor. The along-track SLA used here refers to ascending track 239 on the January 12, 2001 (cycle 306). The corrections needed to minimize the environmental effects on the altimeter signal (tides, water vapor, ionosphere, etc.) were applied according to the AVISO (1998) standards.

2.2. Empirical model of the annual cycle

The method employed to model the annual cycle is based on a nonlinear least-squares procedure to model the weekly averaged log[C] anomalies. We used log chlorophyll values because they were nearly normally distributed, which is a pre-condition for time-series and spectral analyses. Mean values of weekly averaged log[C] were computed for each pixel and were subsequently removed from the corresponding time series to obtain the anomalies. The model is based on the following equation: $Y_{ij} = \bar{Y}_j + \widetilde{Y}_{ij}$, where Y_{ij} stands for the observed weekly averaged log[C]

at time i (week) and location j, $\bar{Y}_j$ is the mean and $\widetilde{Y}_{ij}$ is the fluctuation (anomaly). The last term is a sum of the two terms, $\widetilde{Y}_{ij} = \widetilde{Y}_{ij}^m + \varepsilon_{ij}$, or

$$\widetilde{Y}_{ij} = a_j \cos[(2\pi/T)(t_i - \phi_j)] + \varepsilon_{ij}.$$

The term $\widetilde{Y}_{ij}^m$ stands for model fluctuations, a_j is the amplitude of the periodic function, ϕ_j is the phase and ε_{ij} is the residual. T is period (46 weeks) and t_i varies from 1 to 230 weeks (October 1997–September 2002). We used a nonlinear fitting procedure to model the periodical signal, and for each time-series we minimized the quantity $\sum\varepsilon_{ij}^2$. The root mean square (rms) of residuals of the annual model for each location was then estimated. We also calculated the ratio of the variance explained by the model to the total variance (coefficient of determination, r^2) for each time series to verify the goodness of the model.

3. Results and discussion

3.1. Simple statistics

The mean and standard deviation weekly averaged log[C] images for the entire period can be seen in Figs. 1A and B. The minimum and maximum values for mean weekly averaged log[C] were -1.85 (0.014 mg m^{-3}) and 1.09 (12.3 mg m^{-3}), respectively. The standard deviation of weekly averaged of log[C] varied from 0.02 to 1.58. The number of cloudless pixels is relatively high (Fig. 1C), with mean and standard deviation values of 179.5 and 26.8, respectively. We also computed the simple statistics of monthly averaged SeaWiFS data, and similar results were obtained (not shown here). As seen in Fig. 1A, higher mean values are observed over the Brazilian and Argentinean continental shelves, as compared to open-ocean waters. The lower values of chlorophyll offshore in the northern regions are due to the oligotrophic waters of the South Atlantic Ocean gyre. The transport of surface chlorophyll eastward into the interior of the ocean also can be clearly seen on the mean image as part of the BMC extension and the flow of the South Atlantic Current (SAC). Based on the mean image for the period (Figs. 1A and 3), the mean position where continental shelf waters with relatively high-chlorophyll content are advected by the western boundary current system toward open areas is at 39.5°S–54.25°W. We consider this as a mean position of the encounter of the two currents, where chlorophyll levels are around log[C] = -0.2 ($C = 0.63$ mg m^{-3}) at the crossing of the 1000 m isobath. Those waters then flow seaward in a complex pattern of menders and eddies carrying chlorophyll-rich shelf waters. In situ observations along a transect from 30° to 62°S showed higher values of chlorophyll, associated with the BMC zone, as compared with Brazil Current or Malvinas Current waters, in three consecutive years (Brandini et al., 2000).

Along the Argentinean continental shelf, the chlorophyll signal is particularly strong. The peak values for chlorophyll concentration are found at the entrance of La Plata estuary, spreading northward along the Uruguayan and the Brazilian coastlines. Freshwater discharges by La Plata River and Patos Lagoon (32°S–52°W) strongly influence the backscattering of radiation in visible band over the inner continental shelf, as these waters carry large quantities of suspended matter. Chlorophyll concentration values given by SeaWiFS algorithm in these case-2 waters are reported to be non-valid (Gonzalez et al., 2000; Omachi and Garcia, 2000).

Another striking feature is the strong signal along the Argentinean shelfbreak, with higher values over the continental shelf and BMC regions (Fig. 1A). These high-reflectance streaks are regularly observed along the Argentinean shelfbreak, associated with coccolithophore blooms, which produce large quantities of calcite carbon (Brown and Podestá, 1997). The southward Brazil Current shows lower chlorophyll values, associated with the low-nutrient waters of tropical origin. The northward Malvinas Current also showed a tongue of relatively low chlorophyll values (south of approximately 42°S). This is in agreement with results in Brandini et al. (2000), who found consistently low chlorophyll values (<0.4 mg m^{-3}) in the Malvinas Current during November of three consecutive years. Those low values were attributed to excessive turbulence and,

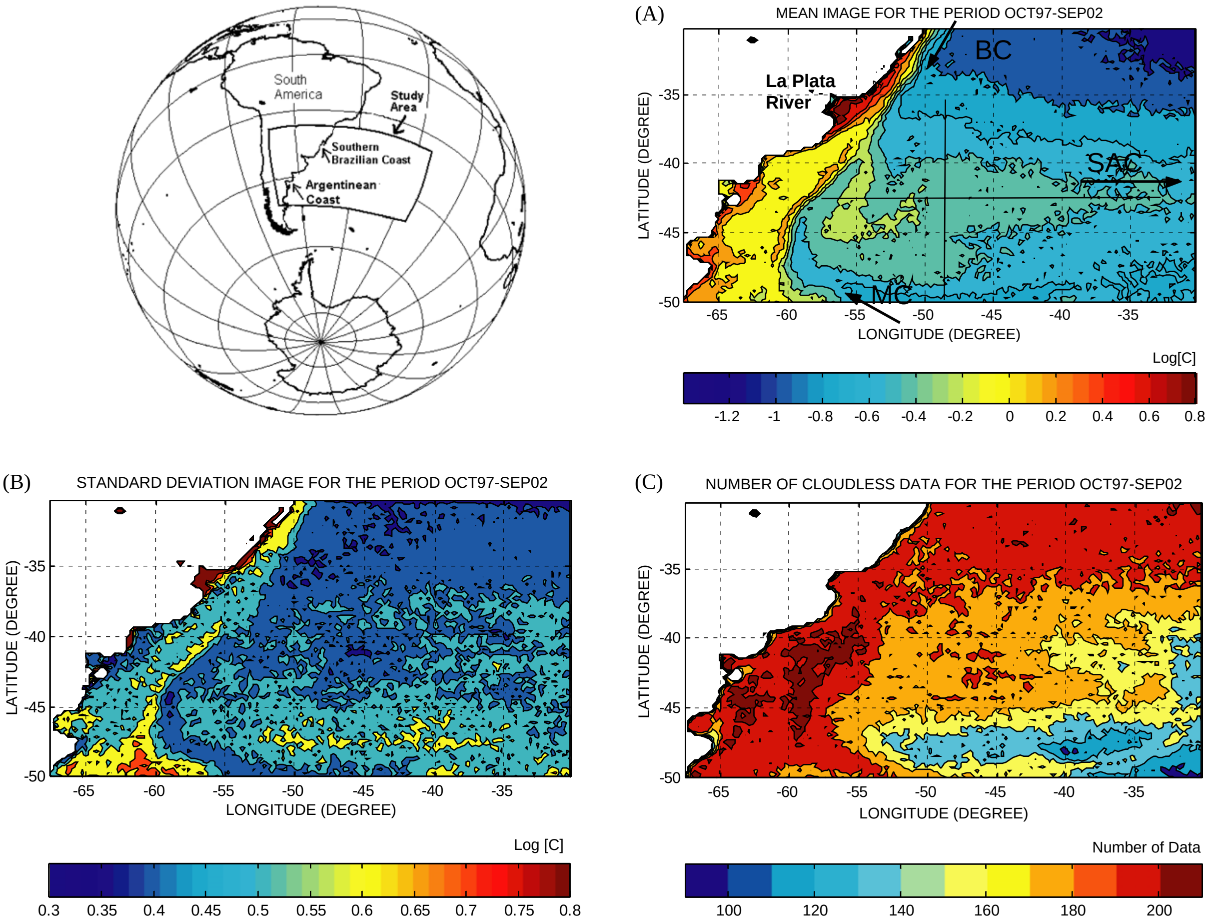

Fig. 1. (A) Mean chlorophyll concentration, (B) standard deviation and (C) number of cloudless pixels obtained from the weekly averaged SeaWiFS images for period October 1997–September 2002. The main current systems in the Southwestern Atlantic Ocean (BC, Brazil Current; MC, Malvinas Current; SAC, South Atlantic Current) also are shown in (A). The two black lines are transects used to extract chlorophyll anomalies (see Fig. 2) from the mean monthly chlorophyll field over the period October 1997–September 2002. The insert indicates the study area.

therefore, instability in the upper layers, particularly in the euphotic zone.

3.2. *Time–space diagrams of the anomalies*

The time history of monthly averaged log[C] anomalies was examined along two zonal transects (see Fig. 1A) in order to depict latitudinal- and longitudinal-variability of the chlorophyll signal. The transect along 43°S was from 58°W to 33°W (25° wide), while the transect along 48°W extended from 35°S to 50°S (15° wide). Both transects were chosen so as to cover the tongue-like structure associated with the BMC, observed on the mean chlorophyll image (Fig. 1A). The zonal Hovmöller diagram unveils strong and clear annual signal, which has a bandwidth of 5–6 months over the whole area (Fig. 2A). Furthermore, near the western boundary the diagram shows a well-defined westward propagating signal, which resembles intraseasonal Rossby wave-like structures, which have been already observed in the area (Campos and Olson, 1991). The same signal is not clearly observed further east, probably as a result of the marked decay in chlorophyll concentration seaward from the BMC zone.

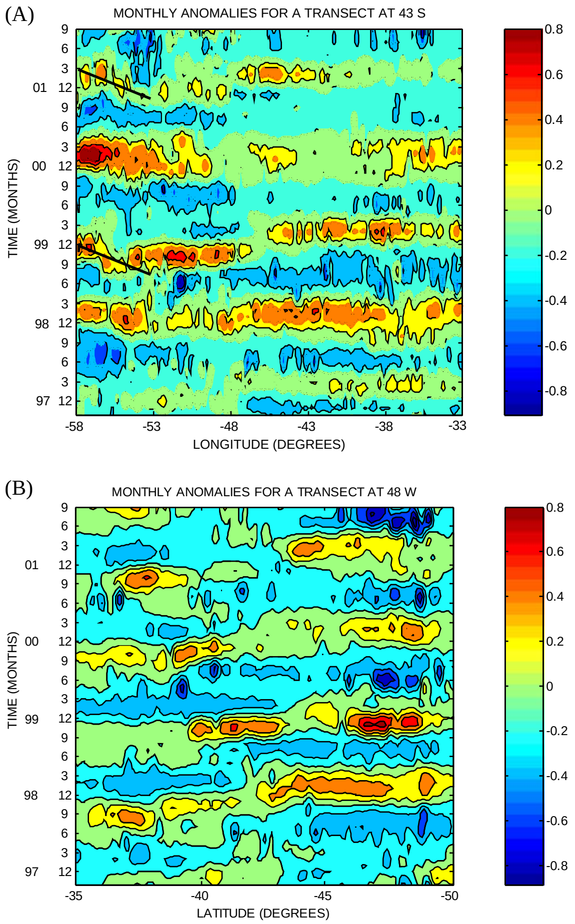

Fig. 2. Chlorophyll concentration anomalies (in log scale) for the (A) zonal (at 43°S) and (B) meridional (at 48°W) transects for the period October 1997–September 2002. The log[C] anomalies were obtained from the monthly averaged images. The exact positions of transects can be seen in Fig. 1A. In Fig. 2A, the black lines show intraseasonal Rossby wave-like structures propagating westward.

The meridional Hovmöller of monthly anomalies (Fig. 2B) shows evidence of propagation of chlorophyll signal as low-frequency wave from north to south. As this transect was taken over the 48°W meridian, the signal is not associated with the poleward advection of the Brazil Current itself. One possible explanation for the observed feature is the natural time lag in the annual increase of chlorophyll concentration following the seasons, as the classical spring bloom process (Sverdrup, 1953). As spring approaches, phytoplankton blooms tend to occur first in subtropical zones, where marked increases in SST result in thermal stratification and thus in water-column stability. Toward higher latitudes, those crucial factors need some more time to turn the environmental conditions from winter to the spring/summer regime. This is clearly seen in the annual cycle plots of northern sites, as compared to southern sites (Fig. 4).

3.3. The annual cycle

In order to understand the role of periodical signals in the chlorophyll concentration, we computed the variance preserving spectra for six selected sites in the study region as seen in Fig. 3. A strong annual signal is present in the Argentinean continental (site 1) and shelf-break waters (site2) and Brazilian shelf waters (site 3) (Figs. 4A–C). In Fig. 4C a positive outlier is seen in June 1998, which may be related to interannual signals, such as ENSO, which the model is unable to solve. Thus, the spuriously high-chlorophyll signal ($>50\,\mathrm{mg\,m^{-3}}$) over the southern Brazilian shelf at this occasion is probably caused by the strong reflectance signal of suspended matter from the

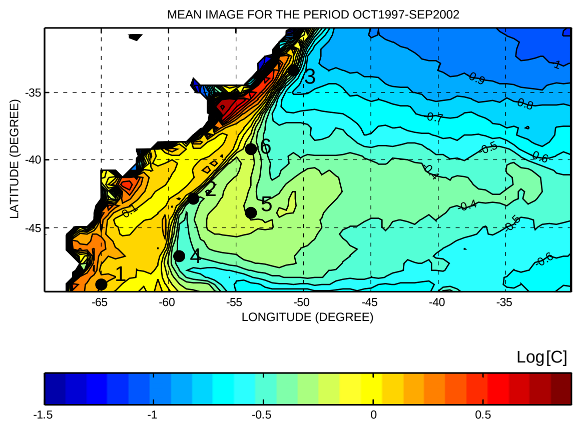

Fig. 3. Mean log[C] image for the October 1997–September 2002 period. Modeled and observed log[C] anomaly, in conjunction with variance preserving spectra, are discussed for six sites shown in this figure: (1) Argentinean Continental Shelf, (2) Argentinean shelfbreak, (3) Brazilian shelf, (4) Malvinas Current, (5) Confluence Zone and (6) Shed Eddy Zone.

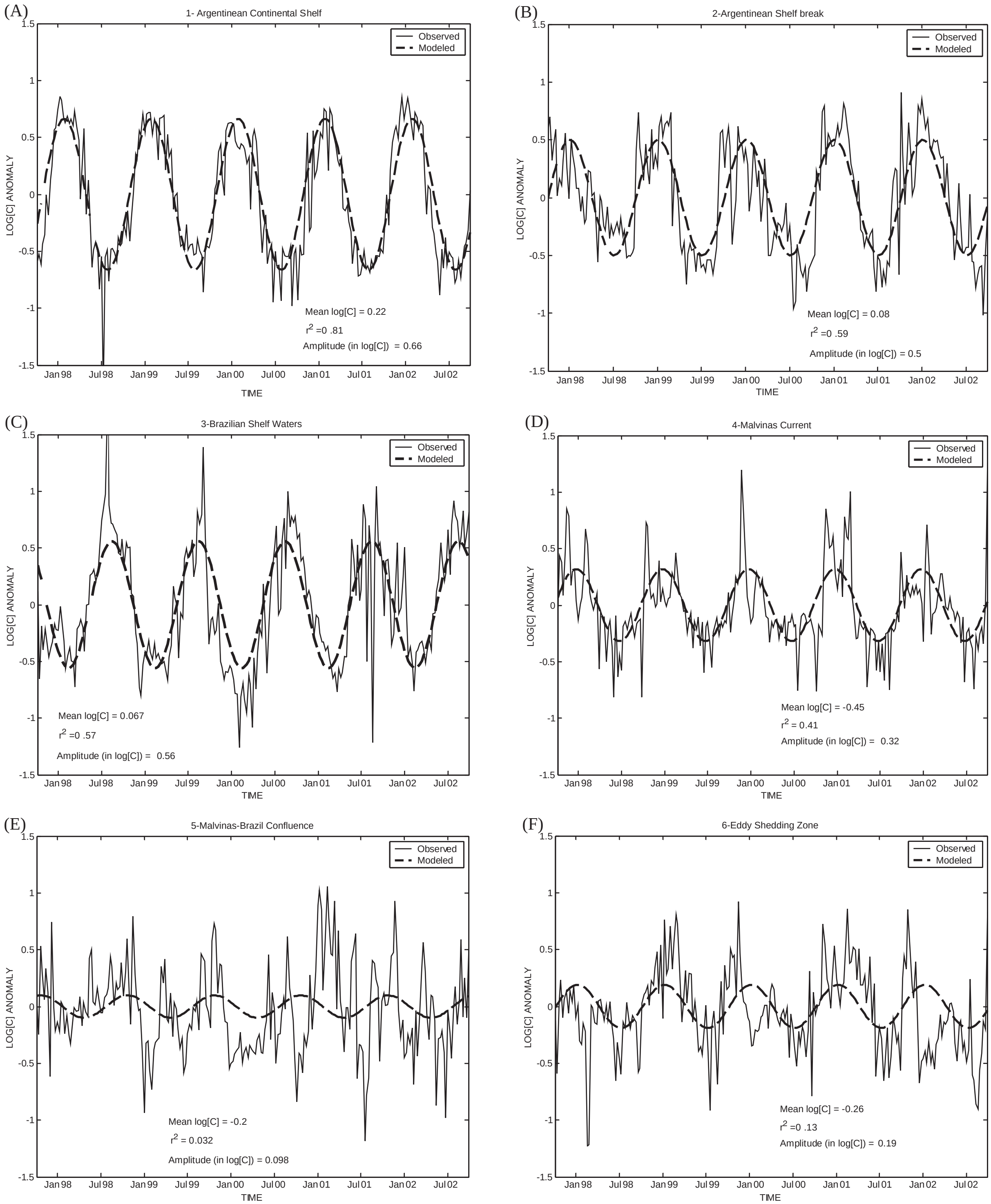

Fig. 4. Modeled and observed log[C] anomaly for the six sites shown in Fig. 3.

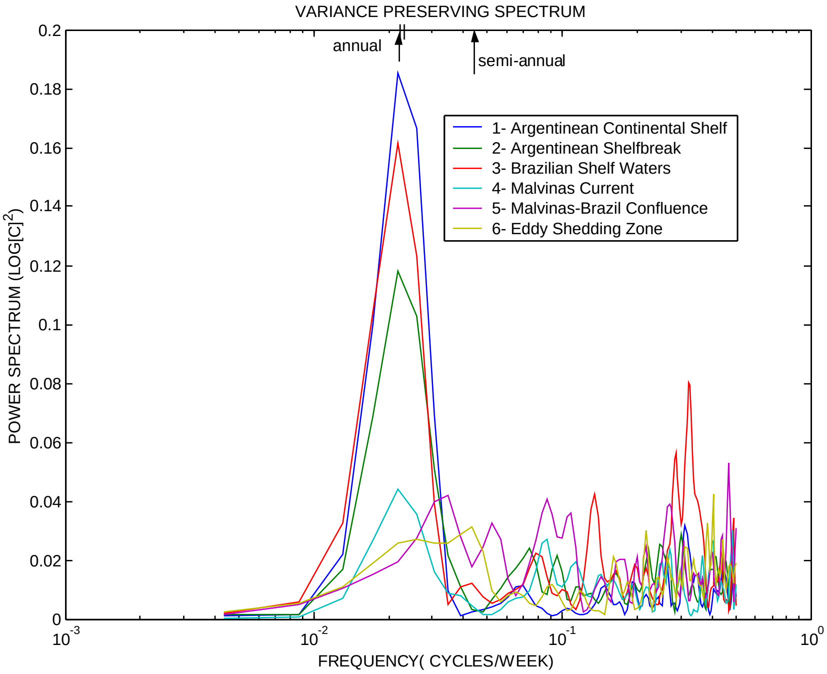

Fig. 5. Variance preserving spectra (log[C] squared) for the six sites shown in Fig. 3.

anomalously high La Plata River discharge following the 1997–1998 El Niño event.

The variance preserving spectra for the selected sites confirms the strong annual signal (Fig. 5), although differences in phase exist between locations. For instance, the peaks in chlorophyll anomaly values in site 1 (Fig. 4A) occur in austral summer (January–February) while in the Brazilian shelf (Fig. 4C) the peaks are observed at the end of the winter (August–September). As stated above, this time lag in pigment peaks probably reflects the onset time of phytoplankton blooms in both regions, driven by water-column stabilization. Indeed, in the south Brazilian waters ($\sim 32°$S) high chlorophyll and primary production rates are observed during late winter and spring, associated with stabilization of water column with concomitant nutrient enrichment from freshwater outflow and previous nearshore bottom turbulence (Odebrecht and Castello, 2001). On the other hand, on the Argentinean shelf, south of 45°S, phytoplankton biomass is mainly regulated by light availability, determined by water-column stability, since nutrient levels are high throughout the year (Bertolotti et al., 1996), and water-column stabilization must occur later (late spring–summer), as result of relaxation in southwestern winds.

The Malvinas Current (site 4) also presents a moderately strong annual chlorophyll anomaly signal (Figs. 4D and 5). Here, summer peaks are probably associated with lower water turbulence at this season, coupled with across-shelf mixture with high-chlorophyll shelf-break waters. In winter, chlorophyll values are generally low due to the high turbulence of these waters (Brandini et al., 2000). In the Confluence Zone (site 5), a broad-frequency signal that encompasses annual and semi-annual cycles is present (Figs. 4E and 5). Here, variations in chlorophyll levels are influenced by inter-annual changes in dynamics of both currents and therefore of the confluence itself. In this region, which is associated with the shelf-break front, Carreto et al. (1995) found high levels of nitrate supporting a high phytoplankton biomass throughout summer and autumn. However, they pointed out that the shelf-break system varies in time and space (either shoreward or seaward) depending on cyclical advance or reverse movements of the Malvinas Current. Thus, a considerable degree of variation departing from an annual signal can be expected at this site.

Based on 6-year time series of SST fields from AVHRR images, Lentini et al. (2002) evaluated the lifetime and average speed of warm-core rings shed by the Brazil Current. They found that ring lifetime ranges from 11 to 95 days, with a translational mean speed of 13.1 km day^{-1}. We also investigated the chlorophyll variability at the mean position of these eddies (site 6). In the Warm-Core Eddy Zone (Fig. 4F), the energy is distributed in a broader spectrum of frequencies; therefore, the annual cycle is not so clear (Fig. 5). This is due to the increase of the relatively higher frequency mesoscale energy available in the area, which acts like a noise input in the clean deterministic seasonal cycle.

As a synthesis of the annual cycle model performance for the whole study region, a spatial distribution of the model parameters is shown in Fig. 6. The amplitude a_j (Fig. 6A) and phase (Fig. 6B) of the annual cycle show a marked difference in some locations. The mosaic image of r^2 of fitting model to observed log[C] anomalies also was produced (Fig. 7) for each time series, which explains the goodness of the model for the whole study area.

In general, the amplitude of the anomalies is small in the inner shelf region all along the South American coast, especially in the La Plata estuary region. This signal of low anomaly amplitude continues across the shelf and into the interior of the ocean, along the BMC front. The outer shelf and slope regions along the South American coast show higher amplitude (0.4–0.6) except off La Plata estuary, where the continuity is broken by a cross-shelf signal of low anomaly amplitudes. The annual cycle seems to dominate in the outer shelf in the northern region, due to its proximity to the Brazil Current and to the seasonal role of stratification on phytoplankton production. In the inner shelf, the annual amplitude is small and strongly influenced by the La Plata and Patos Lagoon (32°S–52°W). The fresh and nutrient-rich outflow from these water bodies does not reveal a dominant annual cycle. This is probably partially due to persistent presence of suspended sediments,

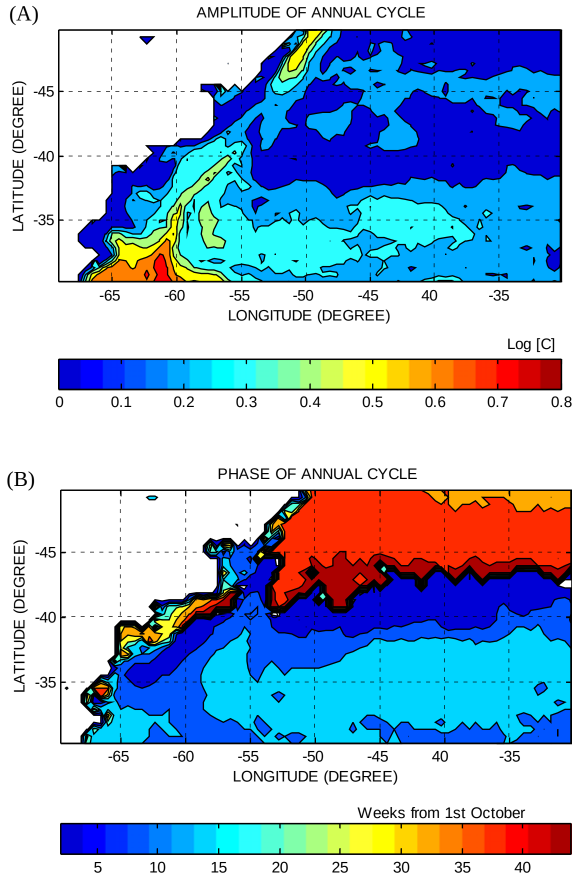

Fig. 6. Mosaic images of the estimates of amplitude (A) and phase (B) of the modeled log[C] annual cycle. In the case of phase values, day zero means 1 October.

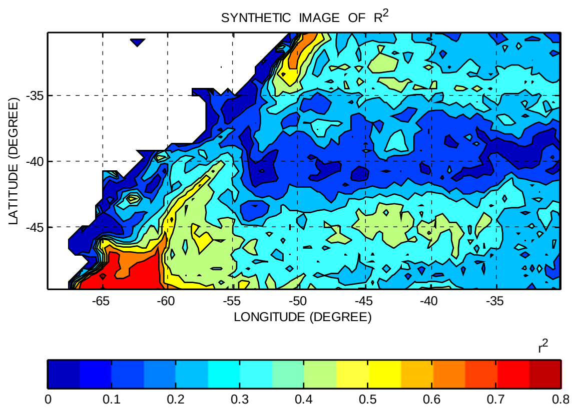

Fig. 7. Mosaic image of r^2 of fitting model to observed log[C] anomalies.

which result in high mean values ($>4\,\mathrm{mg\,m^{-3}}$) and standard deviation of computed log[C] compared to the surrounding shelf waters (Figs. 1A and B).

The long-wave structure associated with the western boundary current separation and therefore high mesoscale energy can be clearly recognized in Fig. 6A. Thus, the region has a small annual amplitude signal ($\sim 40°$W) with high relative errors (Fig. 7). These frontal motions and advection of chlorophyll from coastal areas by the Brazil Current produce intense mesoscale features at shorter time scales, which also are reflected in the log[C] anomaly signal. Therefore, an annual cycle would not be expected to dominate the chlorophyll signal in this area. Chlorophyll anomaly field in this region fluctuated at broader high-frequency values as will be described below. The model is unable to reproduce the annual cycle at several locations in the study region and, consequently, cannot explain the variance of observed fluctuations. We also have forced the model with other periodic signals such as semi-annual, but no significant improvement was achieved.

3.4. Shorter time-scale features

Several processes like the poleward migration of warm Brazil Current, generation of eddies and signatures of instability along continental shelf margin, as well as equatorward propagation of Malvinas Current, are clearly visible in the sequence of SeaWiFS images of January 2001 (not shown here). While the poleward movement with subsequent retroflection of the Brazil Current during summer is well known, the eddy-shedding nature is seldom observed in the ocean-color images. Fig. 8 shows the distribution of chlorophyll concentration on January 12, 2001 where the track of the T/P altimeter is also shown.

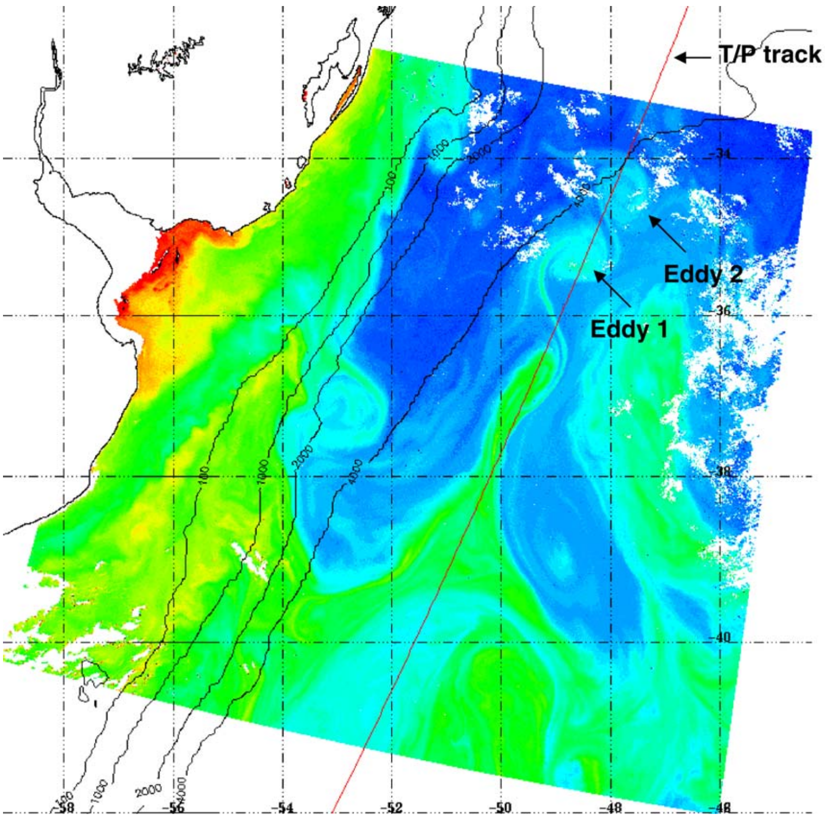

Fig. 8. SeaWiFS image (1 km resolution) of January 12, 2001.

Typically, eddy formation processes have been associated with the classical scenario observed in the Gulf Stream and the Kuroshio, where zonal instabilities generate meanders along the current path that grow, close upon themselves, and then shed eddies (or rings). However, the BMC eddies shown in Fig. 8 are illustrative of *retroflection* eddies; associated with currents that *retroflect* (i.e., turn back on itself) near their separation latitude (e.g., Olson, 1991). The retroflection eddies are generated close to the coast roughly at the same location, suggesting a geographically controlled formation (Richardson et al., 1994). Recently, Silveira et al. (1999) confirmed the models proposed by Ou and de Ruijter (1986) and Campos and Olson (1991), stating that the coastline tilt with respect to the north plays a major role in the type of separation of a particular western boundary current. When the coastline has westward tilt relative to the direction of the current a retroflection type of separation, typically observed in the Southern Hemisphere western boundary currents (Brazil Current, Agulhas Current, East Australian Current (EAC)), occurs. Conversely, when the coastline tilts eastward it results in a much smoother separation (Gulf Stream, Kuroshio).

The eddy-structure observed in the BMC region (Fig. 8) resembles the mechanism proposed by Nilsson and Cresswell (1981) for the formation of EAC warm-core (anticyclonic) eddies. Their model implies that the westward phase propagation of baroclinic Rossby waves along the Tasman front, associated with a strong poleward excursion of the EAC, is responsible for the eddy detachment from the main flow through the constriction of the EAC retroflection meander. In the same way, there could be constriction of the first cold meander (the first meander seaward from the retroflection) to form cold eddies in the warm (north) side, as observed in the BMC case studied here. In the sequence, these eddies may be advected toward the equator following the Brazil Current return flow. Furthermore, it is reasonable to assume that those eddies decay in size and strength as they travel away from the source region in a pattern similar to that shown in Fig. 8.

The ocean-color images of January 2001 show continuous generation and northward migration of eddies from the BMC region. This process weakened after 26 January and the northward jet gradually disappeared thereafter. We noticed that the development of eddies occurred around beginning of January, at a period of 3–4 days. All the three eddies visible in Fig. 8 have developed and moved out from the generation area between 3 and 12 January. Later by 26 January, the first two eddies lost their identity and only a weak signature of the tertiary eddy appears in the northern region. During the course of their migration, these eddies are clearly recognizable by their corresponding core values in chlorophyll concentration. As they moved away from the generation region, chlorophyll concentration progressively reduced. The AVHRR image (Fig. 9) shows the cold-core eddies, and the temperature at the core gradually increases as they moved northward. Correspondingly, the altimeter sea-level height data along the path of these eddies also show fall in sea level at the centers of these eddies (Fig. 10). It may be noticed that the fall in sea-level height anomaly decreased as these eddies moved northward and gained heat.

Assuming that at the core of the eddy the chlorophyll-*a* concentration remains higher than in surrounding waters, we attempted to determine the velocity of these eddies by tracking the position of the peak value of chlorophyll-*a* at the core of these eddies. We found that they are being advected at an average velocity of $12\,\mathrm{km\,day^{-1}}$, which agrees with the observations in Lentini et al. (2002).

4. Conclusion

A time series of monthly and weekly averaged binned SeaWiFS images is closely examined in the Brazil–Malvinas Confluence region. Simple statistics performed on the images have shown that the mean position where continental shelf waters with relatively high-chlorophyll content are advected by the western boundary current system toward open areas is at 39.5°S–54.25°W. This high-chlorophyll signal is used here as a quasi-conservative tracer to verify time-spacing variability of the BMC. Analyses of zonal (at 43°S) and meridional (at 48°W)

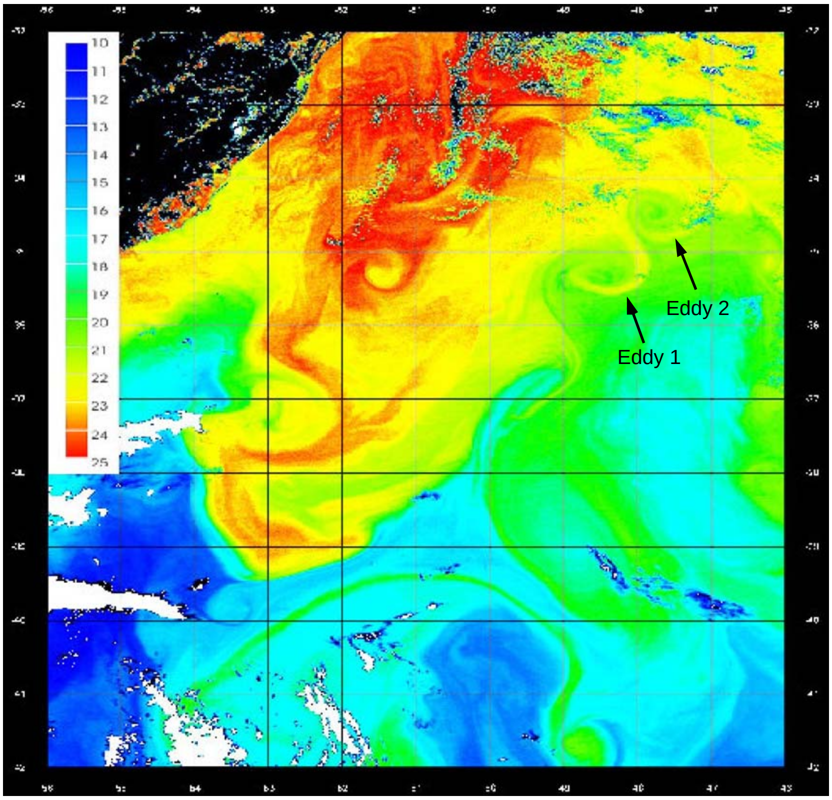

Fig. 9. AVHRR image (1 km resolution) of January 12, 2001.

transects of the log[C] anomalies have revealed a wave-like strong signal that oscillates approximately between 35°S and 50°S. The zonal Hovmöller diagram unveils a strong and clear annual signal that has a bandwidth of 5–6 months over the whole area. The annual cycle can be clearly seen on the time–spacing diagrams.

A simple sinusoidal model was produced to solve the annual signal from the log[C] anomaly time series. The model explained reasonably well the observed anomalies only in certain regions of the study area. Analysis of power spectrum in several zonal transects and at specific locations has confirmed that mesoscale activity dominates over the BMC zone, where periodic signals are about 9–12 weeks.

Ocean-color (SeaWiFS LAC) and infrared thermal images (AVHRR) together with T/P altimetry data were examined to verify mesoscale activities in the region. The eddy-like structures

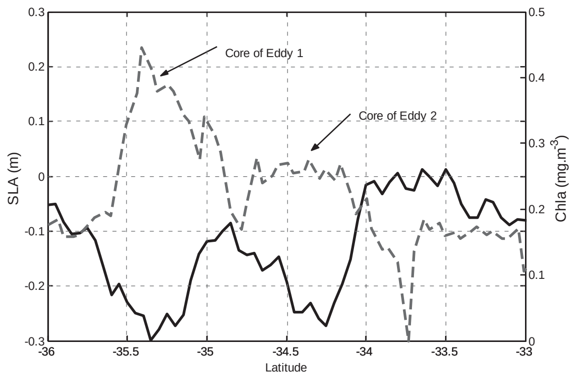

Fig. 10. Chlorophyll concentration (from SeaWiFS, right axis, dashed line) and sea-surface height (from T/P, left axis, solid line) along a track (red line) in the eddy propagation zone as shown in Fig. 8.

have shown that chlorophyll-a concentration reduces rather rapidly upon mixing with warmer northern waters. During mid-summer, the wind-driven boundary currents along the east coast of Brazil manifest several features of current–current interaction. The separation of eddies from the mean flow is rather rapid in this region. Zones of frontal instability also can be seen along the boundary between the western branch of Brazil Current and the continental shelf waters.

Despite the dynamics of this process being far from understood, this study shows that SeaWiFS images of surface chlorophyll concentration can be used as tracer to study the bio-physical dynamics in the Southwestern Atlantic and BMC region. Results in this work are in fairly good agreement between ocean-color and other physical data like sea-surface temperature and sea-level change. Furthermore, the ocean-color data provide substantial knowledge of signal variability at annual and other higher frequencies.

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