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Variability of chlorophyll-a in the Southwestern Atlantic from satellite images: Seasonal cycle and ENSO influences

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ABSTRACT

Seasonal and interannual satellite chlorophyll-a variability (CSAT) was assessed in the Southwestern Atlantic based on over 11 years (1997–2008) of Sea-Viewing Wide Field-of-View Sensor data. An Empirical Orthogonal Function analysis of the seasonal CSAT cycle showed strong variability and the spatial structure of the leading pattern revealed an opposite behavior over the continental shelf north and south of 37°S with low (high) biomass south (north) of 37°S during wintertime. This distribution is related to the lack of stratification of the water column in the southernmost region during winter due to heat loss to the atmosphere as well as wind induced and convective mixing, in contrast to a vertically stable water column north of 37°S induced by the fresh Río de la Plata discharge. High variability in CSAT between 47 and 51°S in the inner and outer shelves could be related to the southern Patagonian fronts. On interannual time scales the influence of El Niño-Southern Oscillation on CSAT during spring was estimated and related to wind stress, vertical velocities and Río de la Plata discharge. During El Niño events the continental shelf north of 45°S is characterized by high CSAT values (anomalies >0.5 mg m^{-3}) while low values are found to the south (anomalies <-0.5 mg m^{-3}), except for positive anomalies near to the Malvinas Islands. The opposite pattern occurred in La Niña years. Conversely, the Brazil–Malvinas confluence has a lower CSAT in El Niño years in comparison with La Niña years. The higher chlorophyll-a of some areas over the shelf north of 45°S during El Niño was supported by increased Río de la Plata discharges, northerly winds anomalies and upwelling generated in the shelf between 33 and 39°S. The winds tend to retain the patch of high chlorophyll-a off Río de la Plata in spring, but advect it toward the Brazilian coast in summer. This result indicates the extreme importance of wind variability for the spreading or retention of phytoplankton in this area. No support was found for a mechanism linking Ekman pumping and CSAT variability over the continental shelf south of 45°S and in the Malvinas–Brazil confluence.

1. Introduction

Global ocean studies using ocean color satellite images have shown high chlorophyll-a concentration structures in the Southwestern Atlantic (SWA) (Yoder and Kennelly, 2003), a region that makes an important contribution to the global atmospheric CO_2 uptake by the ocean (Gregg and Conkright, 2002; Bianchi et al., 2009; Takahashi et al., 2009). Regional and international fishing fleets are attracted to the SWA by important fish and squid's populations inhabiting this area (Podestá, 1990; Jiménez et al., 2010).

The processes governing ecosystem functioning and variability in the SWA are still scarcely known despite the importance of the region. Limited space-time studies provided in situ data on phytoplankton biomass and productivity, mainly in the Rio de la Plata (RDP), Brazilian coast and in the Argentinean shelf break zone (Carreto et al., 1986; 1995; Ciotti et al., 1995; Brandini et al., 2000; Calliari et al., 2008; Lutz et al., 2010). More recently, availability of remote sensing technology allowed the identification of synoptic physical and biological patterns over that large area, and the analysis of their variability. Most studies have focused on the analysis of chlorophyll-a seasonal variability, while interannual variability remains less well understood because longer time series are needed (Saraceno et al., 2005;

Abbreviations: CSAT, satellite-derived chlorophyll-a; SWA, Southwestern Atlantic; RDP, Río de la Plata

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Romero et al., 2006; Garcia et al., 2008; Garcia and Garcia, 2008; Lutz et al., 2010).

Hydrographic and ocean color satellite data indicated the correspondence between certain high average chlorophyll-a concentration areas in the SWA and nutrient-rich waters, fronts and river plumes (Carreto et al., 1995; Brandini et al., 2000; Bianchi et al., 2005; Saraceno et al., 2005; Romero et al., 2006; Calliari et al., 2008). In the open ocean, the strong thermal fronts resulting from the convergence of Malvinas and Brazil Currents (Fig. 1) frequently show high chlorophyll-a areas as a result of the stability provided by warm but nutrient-poor subtropical waters and the enrichment by subantartic waters in the transition zone (Gayoso and Podestá, 1996; Brandini et al., 2000; Garcia et al., 2004; Saraceno et al., 2005). Over the northern continental shelf high chlorophyll-a is related to RDP discharge, the subtropical shelf front, and areas where subantartic waters reach the euphotic zone (Ciotti et al., 1995; Calliari et al., 2008; Garcia and Garcia, 2008). On the southern shelf, high phytoplankton biomass is associated with the stratified side of the midshelf front and the Patagonian shelf break front (Fig. 1) (Carreto et al., 1995; Romero et al., 2006; Garcia et al., 2008). In situ studies confirmed elevated primary production in these areas (Garcia et al., 2008; Bianchi et al., 2005; Lutz et al., 2010).

Earlier studies of phytoplankton in the SWA showed a strong seasonal cycle, wider over the shelf (sd > 4 mg m^{-3}) than in the open ocean (sd < 1.5 mg m^{-3}) (Saraceno et al., 2005; Romero et al., 2006). A region of relatively high chlorophyll-a is found during winter associated with warm subtropical and coastal waters (Romero et al., 2006). On the other hand, the lack of stratification during the colder months caused by heat loss toward the atmosphere and by wind induced mixing limits the primary production and phytoplankton biomass during winter south of 37°S (Carreto et al., 1995; Rivas and Piola, 2002; Bianchi et al., 2005). A pronounced bloom occurs in the spring over the continental shelf associated with the stratification of subantartic waters and enhanced light availability (Saraceno et al., 2005; Rivas et al., 2006; Romero et al., 2006; Garcia et al., 2008; Garcia and Garcia, 2008).

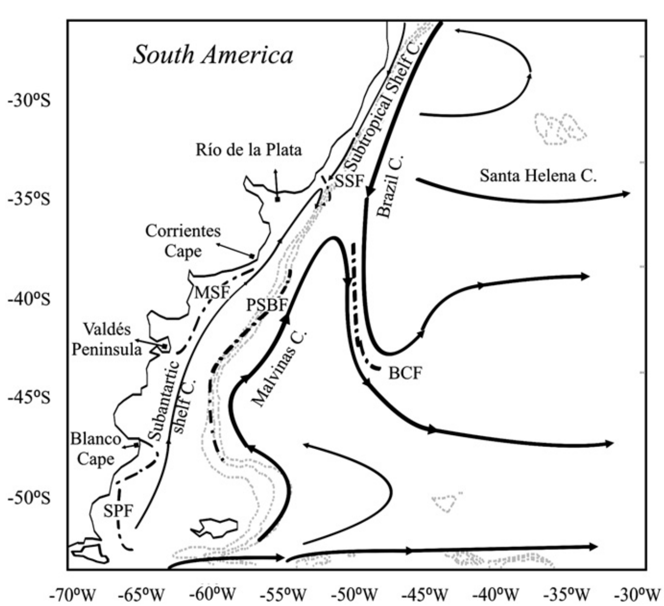

Fig. 1. Schematic surface circulation (black arrows) in the Southwestern Atlantic and geographical locations referred to in the text. The 500, 1000 and 1500 m isobaths are included in the figure (grey dotted lines). Also the fronts are indicated (black dotted lines): Brazil/Malvinas Front (BCF), Subtropical Shelf front (SSF), Midshelf Front (MSF), Patagonian Shelf-Break Front (PSBF), and Southern Patagonian Front (SPF).

Year to year chlorophyll-a variability has also been reported over large areas. Hypothesis such as wind anomalies leading to upwelling events and changes in the positions of fronts, as well as anomalies in the discharges of large rivers have been put forward to explain the observed anomalies (Saraceno et al., 2005; Romero et al., 2006; Garcia and Garcia, 2008).

El Niño-Southern Oscillation (ENSO) has a strong effect on the precipitation in Southeastern South America, particularly in spring (Grimm et al., 2000). Consequently, the freshwater discharges to the ocean from large point sources such as RDP and Lagoa dos Patos increase during El Niño events-with an historic high ca. $\sim$82000 m^3 s^{-1} in RDP flow during the winter of 1983- and decrease during La Niña events with values smaller than 5000 m^3 s^{-1} (Mechoso and Pérez Iribarren, 1992; Barros et al., 2002; Borus et al., 2006; Piola et al., 2008). Chlorophyll-a was observed to increase in shelf waters adjacent to the RDP during the moderate 1987 and the strong 1997 El Niño events, presumably resulting from a higher extent of the river plume and nutrient fluxes to the shelf (Carreto et al., 1995; Garcia and Garcia, 2008). In addition, ENSO has global effects on winds (Li and Clarke, 2004) which could potentially affect the chlorophyll-a distribution in the SWA.

Previous studies that focused in chlorophyll-a variability in the SWA had restricted time coverage because of limitations in the length record of satellite imagery, especially important to analyse the ENSO influence. Moreover, most studies have addressed the impact of El Niño (Ciotti et al., 1995; Garcia and Garcia, 2008) and little is known about that of La Niña events.

In this work we focus on a large area in the SWA to evaluate an 11-year record of satellite derived chlorophyll-a (CSAT) variability and its connection to regional processes and ENSO dynamics. Based on earlier evidence reviewed above, we expected to find significant CSAT variability at different time-scales associated to seasonal cycles, RDP freshwater flows and wind forcing. Changes in chlorophyll-a during opposite ENSO phases are analyzed using composite analysis. To summarize, the objective of this paper is threefold (1) to describe the seasonal CSAT variability in the Southwestern Atlantic over the period 1997–2008; (2) to determine the influence of El Niño/La Niña in chlorophyll-a distribution; (3) to evaluate the relative importance of river outflow and Ekman pumping on chlorophyll-a variability during ENSO events.

2. Data and methods

2.1. Satellite data

Analyses are based on CSAT time series in the SWA region [25–55°S, 70–30°W] estimated by the OC4v4 Sea-viewing Wide Field-of-view Sensor (SeaWiFs) retrieval algorithm (Fig. 1). Given the extension of the area considered and the focus on large scale processes, we considered images of monthly average CSAT with a 100×100 km spatial resolution obtained from 〈http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.seawifs.2.shtml〉. The RDP proper was excluded from the analysis because chlorophyll-a could be overestimated due to the large amount of sediments within the estuary (Armstrong et al., 2004; Martinez et al., 2005).

2.2. Reanalysis data

To characterize the mechanical forcing of the ocean by the atmospheric circulation anomalies monthly surface winds and wind stress from the NCEP Reanalysis CDAS-1 were used (Kalnay et al., 1996) during the same period as the CSAT data. These data were obtained from 〈www.cdc.noaa.gov/data/gridded/data.ncep.reanalysis.html〉.

2.3. Seasonal variability

The spatial and temporal seasonal variability patterns of CSAT fields in the SWA were determined using empirical orthogonal functions (EOFs) based on the monthly CSAT time series from September 1997 to August 2008. The method expresses the total variability of a particular field in terms of spatial patterns (that maximize the explained variance) each one having an associated time series that determines its evolution. By construction, EOFs do not necessarily correspond to physical variability modes, but in certain cases it is possible to make such link. We computed the EOFs using the covariance matrix and in order to obtain simpler spatial structures that allow easier interpretation the original EOFs were rotated using the Varimax procedure (Wilks, 2006). Several studies have successfully used the EOF method to interpret spatial and temporal features in chlorophyll-a imagery (Yoder and Kennelly, 2003; Garcia and Garcia, 2008).

2.4. ENSO influence

CSAT pattern anomalies related to El Niño and La Niña events were evaluated by composite analysis. For that purpose, we considered the three-month period (trimester) October to December (OND) in moderate and strong El Niño (1997 and 2002) and La Niña (1998, 1999, and 2007) as classified by the Oceanic Niño Index (http://ggweather.com/enso/oni.htm). OND is the season of strongest rainfall over Southeastern South America and it agrees well with the peak of the El Niño/La Niña events (Grimm et al., 2000). Moreover, these months coincide with the timing of the phytoplankton bloom in the region of study. The significance of the composite (El Niño-La Niña) was evaluated at the 10% level using a two-sided Student t-test. Analogous maps were constructed for surface wind anomalies and Ekman pumping during OND, the latter calculated using the wind stress and assuming a constant density value of 1025 kg m^{-3}.

2.5. Interannual variability in continental shelf off RDP

The effects of RDP discharges on the CSAT in the adjacent area [29–37°S, 57–49°W] were explored using the monthly discharge data from September 1997 to August 2008 obtained from Borus et al. (2006). The OND anomalies in river discharge were calculated and correlated with NDJ, DJF and JFM CSAT fields in the adjacent area. The effect of the wind stress on the plume distribution was analysed with linear regression between OND river discharge anomalies and NDJ, DJF, JFM surface wind within [30–37.2°S, 57.5–47.5°W]. Monthly wind data from September 1997 to August 2008 were used in the analysis. Statistical significance at the 10% level was assessed with a two-sided Student t-test.

3. Results

3.1. Seasonal variability

The first mode of the EOF analysis used to evaluate the spatial and temporal patterns of CSAT explained 59% of the total variance and is shown in Fig. 2A. Highest CSAT concentration and strongest variability was found in the continental shelf with opposite behavior north and south of 37°S. The associated time series (Fig. 2B) represents the evolution of the grid points in the spatial pattern. The value of the field at any time is the product between the value in the spatial pattern and the time series at that time. Thus, the EOF analysis showed a clear annual cycle, with positive CSAT anomalies in winter north of 37°S. The annual changes in CSAT associated with EOF1 depend on the region considered but have typical values of about 2.5 mg m^{-3}. The pattern shows a region of large negative CSAT anomalies off the coast between Corrientes Cape and Valdés Peninsula. On the other hand, strong positive CSAT anomalies are present between 47°S and 51°S near the coast (off Grande Bay), and in the outer shelf and shelf break at the same latitude during spring (Fig. 2).

3.2. ENSO influence

During El Niño events anomalously high CSAT concentration was observed over the continental shelf north of 45°S (anomalies $>$ 0.5 mg m^{-3}) and low concentration to the south (anomalies $<$ -0.5 mg m^{-3}), except for a positive anomaly near Malvinas Islands. The opposite pattern occurred during La Niña years (Fig. 3A and B). The region delimited by 35–55°W and 39–41°S, near the Brazil–Malvinas convergence and the Brazil return flow (Fig. 1) had a lower phytoplankton biomass in El Niño years in comparison to La Niña years (Fig. 3A and B). The CSAT composite of El Niño vs La Niña is very patchy due to the small number of events considered. Nonetheless there are regions where variability is statistically significant ($p<0.10$, $n=5$), with higher CSAT during El Niño (Fig. 3C, red color). These regions are: i) off RDP, in the Uruguayan and Brazilian coasts, ii) south of Corrientes Cape (~40°S), iii) on the outer continental shelf and shelf-break off Valdés Peninsula (42–43°S), iv) midshelf off Blanco Cape (~48°S). Significantly ($p<0.10$, $n=5$) higher CSAT during La Niña was found in the Brazil-Malvinas Currents convergence zone (Fig. 3C, in blue color).

One possible cause of the CSAT anomalies is the wind change that results from the atmospheric adjustment to the SST changes in the equatorial Pacific. To investigate this possibility changes in surface winds and Ekman pumping were analysed. In the subtropics there was an anomalous high pressure circulation that induces southwestward wind anomalies during El Niño; a tendency for opposite anomalies occurred during La Niña (Fig. 4). Such wind pattern during El Niño periods induced vertical velocities at the bottom of the Ekman layer between 33 and 39°S as is shown in Fig. 5, while the opposite is true during La Niña periods. In the southern region over the shelf, westward (onshore) wind anomalies were evident during El Niño and eastward (offshore) during La Niña. Note the similarity of the spatial pattern but of opposite sign in the wind stress and vertical velocities anomalies during El Niño and La Niña events (Figs. 4 and 5).

3.3. Interannual variability in continental shelf off RDP

The correlation of CSAT with RDP river discharges showed significantly increased ($p<0.10$) phytoplankton biomass in the Uruguayan and south Brazilian coasts associated with positive anomalies in the OND RDP discharges (Fig. 6A–C). Moreover, the positive phytoplankton biomass anomalies showed different spatial distribution depending on the trimester considered (Fig. 6). During NDJ the higher CSAT area is located close to RDP mouth (Fig. 6A), while in the following trimesters (DJF and JFM) the strongest CSAT anomalies extend northeastward (Fig. 6B and C). The linear regression of surface winds with respect to RDP river discharge suggests that winds tend to retain waters near RDP mouth during OND, but tend to drive the flow northeastward in the following trimesters (Fig. 6D–F).

4. Discussion and conclusion

4.1. Seasonal variability

The results suggest a strong signal in the seasonal cycle with opposite behavior north and south of 37°S. During winter the

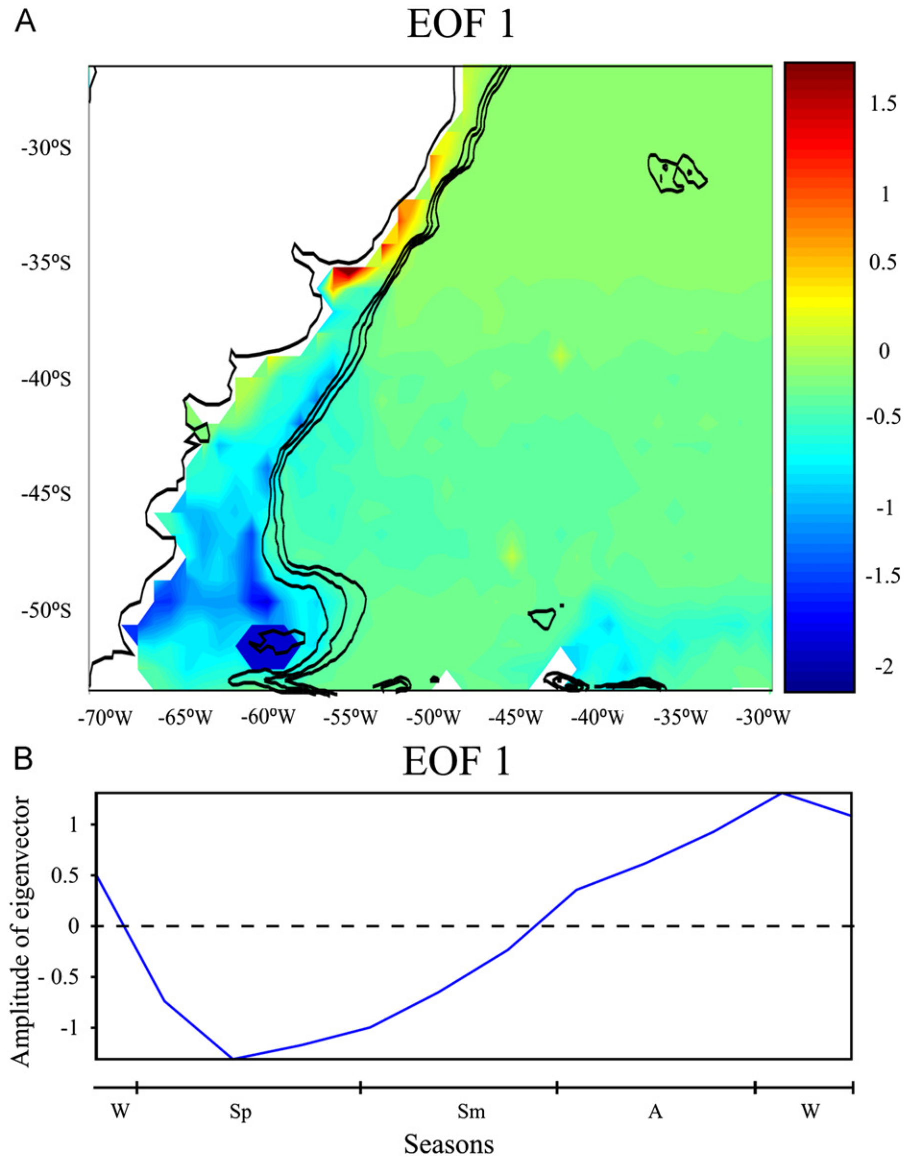

Fig. 2. Results of the EOF analysis showing the spatial (A) and temporal (B) pattern of mode 1. The 500, 1000, and 1500 m isobaths are included in the figure. The amplitude of eigenvector was standardized (value/standard deviation). CSAT anomalies are calculated by multiplying the eigenvector amplitude by the spatial pattern.

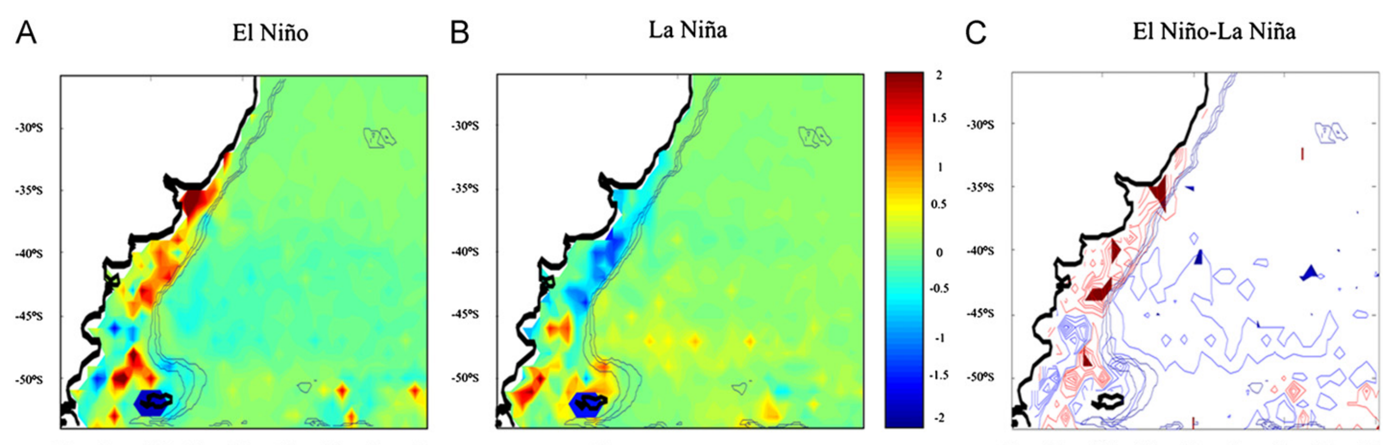

Fig. 3. (grayscale version). Sea surface CSAT anomalies in (A) El Niño events and (B) La Niña events. In (C) the composite El Niño- La Niña shows positive (gray) and negative (black) statistical differences (Student, $p < 0.10$) between periods. The 500, 1000 and 1500 m isobaths are included in the figures. (color version). Sea surface CSAT anomalies in (A) El Niño events and (B) La Niña events. In (C) the composite El Niño- La Niña shows positive (red) and negative (blue) statistical differences (Student, $p < 0.10$) between periods. The 500, 1000 and 1500 m isobaths are included in the figures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

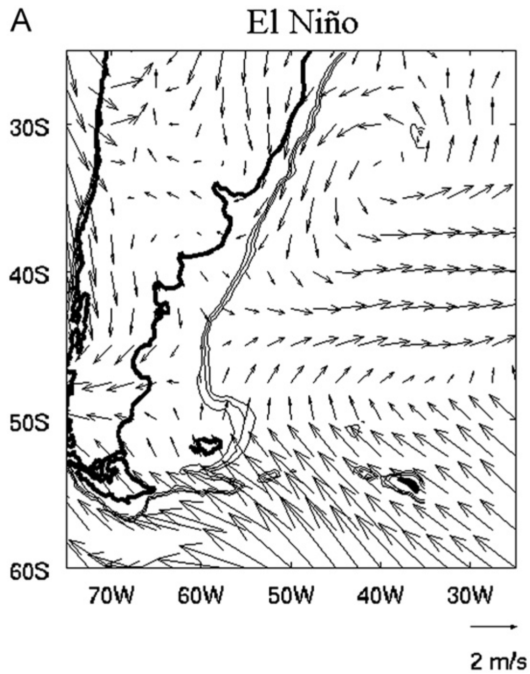

Fig. 4. OND surface winds (m s^{-1}) anomalies during (A) El Niño and (B) La Niña events. The 500, 1000, and 1500 m isobaths are included in the figure.

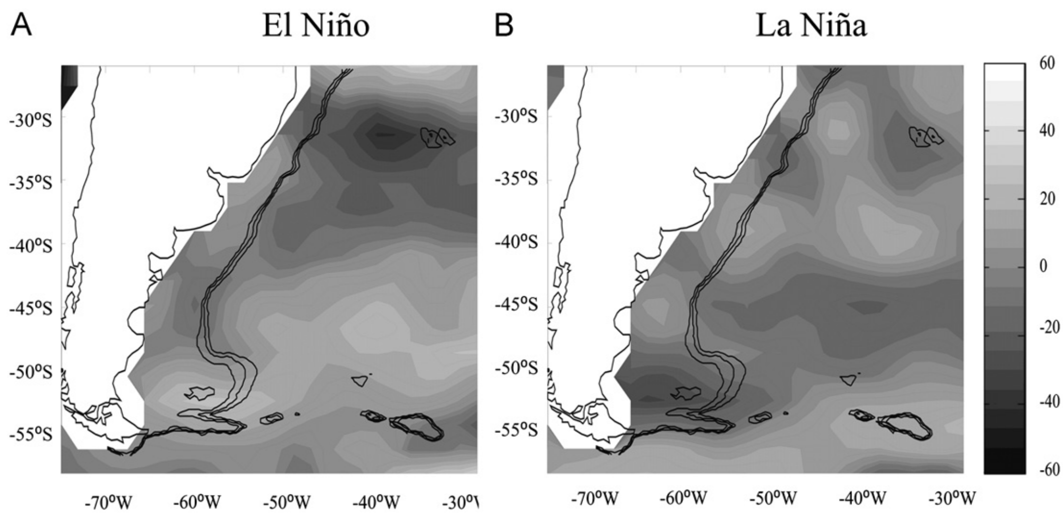

Fig. 5. OND vertical velocity (w, m yr^{-1}) anomalies during (A) El Niño and (B) La Niña events. Contours of w with an interval of 3 m yr^{-1}. White and black shading correspond to upward and downward velocities, respectively. The 500, 1000, and 1500 m isobaths are included in the figure.

stratification south of 37°S in the Argentinean Shelf vanishes due to mixing driven by heat fluxes to the atmosphere and wind stirring (Rivas and Piola, 2002; Bianchi et al., 2005), which could be the reason for limited primary production and chlorophyll-a concentration in the southern region (Carreto et al., 1995; Bianchi et al., 2009).

The low CSAT in coastal waters between Corrientes Cape and Valdés Peninsula seems to coincide with the well-mixed side of the Midshelf Front (Fig. 1). It has been suggested that the wind provides a substantial part of the energy required to vertically mix the water column in shallow, near coastal waters, and as a consequence accumulation of phytoplankton biomass is prevented (Carreto et al., 1995; Romero et al., 2006).

In agreement with Romero et al. (2006) the amplitude of the seasonal cycle was found to be largest south of 45°S (Fig. 2A). Studies based on SST climatology (1985–1997) and numerical simulations confirm the existence of the South Patagonia Front in the southern region (SPF, Fig. 1) from October through April (Bianchi et al., 2005; Romero et al., 2006). In the inner and well-mixed waters of this front, the existence of two regions of high tidal energy (Palma et al., 2004) could act as a nutrient supply to the euphotic zone and support the development of phytoplankton blooms on the stratified side, consistent with a high CSAT band between 48 and 51°S in Fig. 2. Moderate to high primary production values and CO_2 atmospheric sinks have been reported in this area (Bianchi et al., 2005; Lutz et al., 2010). Moreover, a recirculation cell in the Grande Bay Coast (Palma et al., 2004) may contribute to generate a "zooplankton hot spot" in this region probably related to nutrient enrichment and organism retention (Sabatini et al., 2004).

The high CSAT band in the outer South Patagonian shelf and shelf break could be related to the moderate temperature and salinity gradients across the Patagonian Shelf Break Front (PSBF, Fig. 1). This front is a transition between shelf and Malvinas

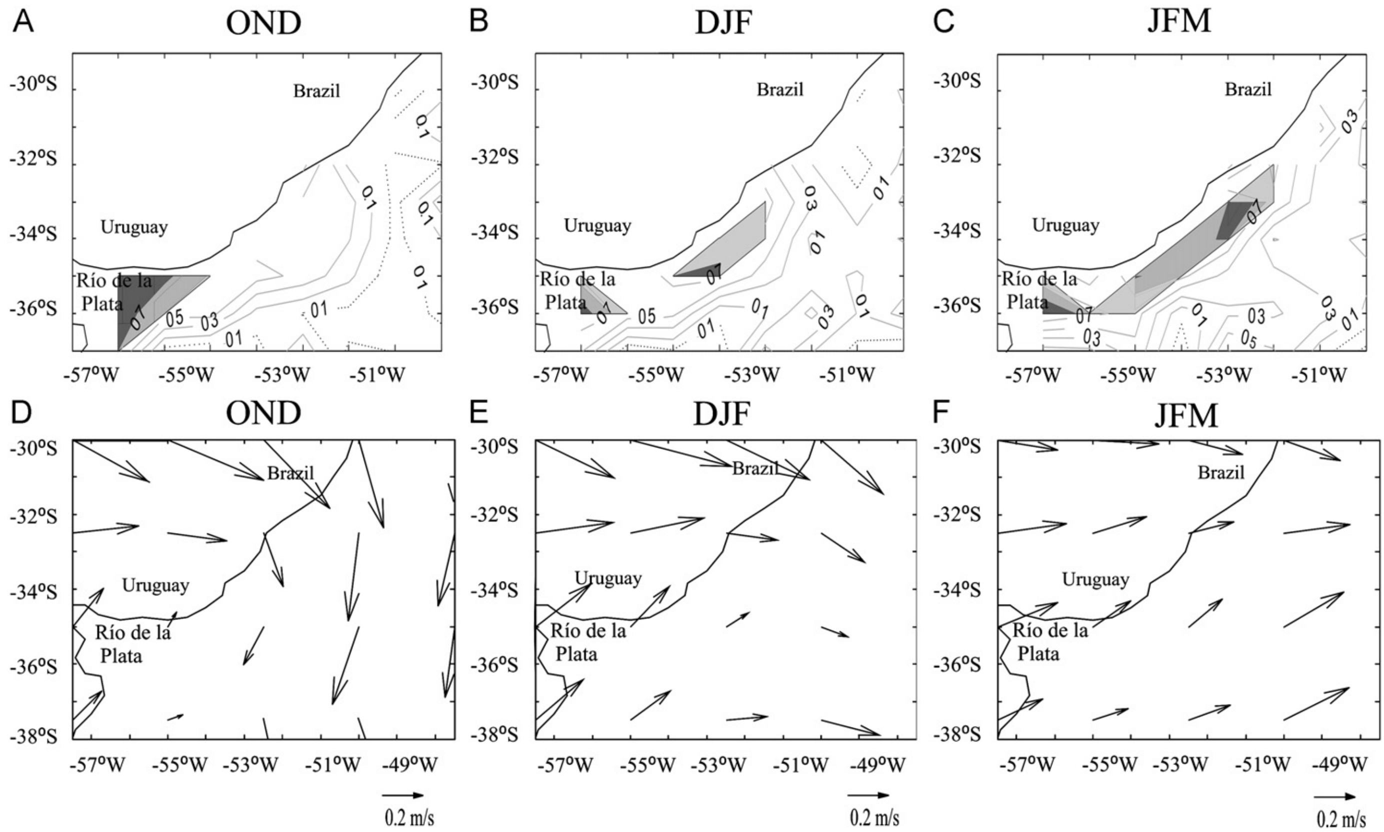

Fig. 6. Correlation ($p<0.10$) between Rio de la Plata OND discharge anomalies and the adjacent CSAT in OND, DJF, JFM (A)–(C). Contours with an interval of 0.1. Regression between Rio de la Plata OND discharge anomalies and wind anomalies (arrows) in OND, DJF, JFM (D)–(F).

Current waters, and some authors indicate that a nutrient enrichment mechanism such as upwelling of Malvinas Current waters (Palma et al., 2004; Garcia et al., 2008) maintain high primary production and phytoplankton biomass until summer (Carreto et al., 1995; Romero et al., 2006; Bianchi et al., 2005).

Present results indicate a remarkable influence of the RDP plume north of 37°S (Fig. 2A). This fresher surface layer could favor phytoplankton retention in the euphotic zone (Mann and Lazier, 2006). Its seasonal dynamics with a northern extension in winter under higher river discharge and predominant south-westerly winds (Piola et al., 2005, 2008; Möller et al., 2008) could explain the higher CSAT during colder months. In addition, the RDP plume is the main source of silicates (SiO_2 ~15 μM) in the region, and it can contribute with phosphates (Nagy et al., 2002; Calliari et al., 2005; Braga et al., 2008), thus fertilizing and inducing high chlorophyll-a concentrations in the adjacent shelf (Carreto et al., 1986; Calliari et al., 2008; Garcia et al., 2008; Garcia and Garcia, 2008). The presence of a subtropical front separating the warm Subtropical Coastal Current (with silicates and ammonia rich waters) and the cold Subantartic Costal Current (with nitrates enriched waters) could also influence seasonal chlorophyll variability (Ciotti et al., 1995; Piola et al., 2000).

Río de la Plata and offshore waters over the shelf have been reported as an important biogeographic barrier in the SWA limiting the distribution of several marine groups to either the south or the north of 34–36°S (Bisbal, 1995; Boltovskoy et al., 1999). As was mentioned above, that latitudinal range is located within the subtropical-temperate transition zone (Klein, 1997) and the presence of diluted seawater over the shelf (RDP plume) within a transition zone would contribute to further limit the dispersion of certain taxa (e.g., stenohaline). Our results suggest that differences in key aspects of ecosystem functioning north and south of 37°S, as indicated by opposing patterns of biomass time variability, could constitute another mechanism that reinforces the segregation of biological communities across that zone. This interpretation is also consistent with the definition of distinct Large Marine Ecosystems to the north (South Brazil LME♯15) and to the south of the RDP (Patagonian Shelf LME♯14) (Sherman et al., 1992; Sherman and Hempel, 2009).

4.2. ENSO influences

Even though it is known that the ENSO phenomenom has global effects on winds and ocean circulation (Li and Clarke, 2004) and in worldwide phytoplankton biomass distribution (Yoder and Kennelly, 2003), its impact on the SWA are less well understood. Our results revealed a clear ENSO influence in some local areas, with opposite effects during El Niño and La Niña as shown in Fig. 3. The areas particularly affected by ENSO tend to coincide with the high average CSAT areas related to the location of fronts and plumes (Bianchi et al., 2005; Saraceno et al., 2005; Romero et al., 2006). High CSAT in the midshelf region off Corrientes Cape has been related to the thermal midshelf front (Romero et al., 2006), which separates well-mixed, nitrate poor, coastal waters from seasonally stratified midshelf waters in spring and summer (Carreto et al., 1995). Probably changes in front location or in cross-front gradient intensity could be involved in the interannual CSAT variability (Carreto et al., 1995; Romero et al., 2006). Interannual variability also has been reported in the outer continental shelf and shelf-break off Valdés Peninsula (42–43°S), and off Blanco Cape (~48°S) (Brandini et al., 2000; Romero et al., 2006; Garcia et al., 2008). Saraceno et al. (2005) observed higher CSAT in the Patagonian Shelf Break in austral spring of 2002–2003 compared to previous years and suggested it may be related to enhanced northerly winds, which promote upwelling of subsurface waters supplying nutrients into the euphotic layer.

In oceanic waters, interannual CSAT variability indicated significantly lower phytoplankton biomass in El Niño years at the Brazil–Malvinas confluence and Brazil return flow zone, which is consistent with earlier observations indicating that interannual variability is larger compared to seasonal variability in such area (Saraceno et al., 2005).

According to the drivers of CSAT interannual variability described above, the northerly wind anomalies that occur over the northern shelf during El Niño could partially explain the higher CSAT concentration north of 45°S during this ENSO phase, particularly in the Patagonian Shelf Break. In this phase, the plume resulting from a higher-than-usual RDP discharge will spread offshore, increase nutrient export from the estuary to the continental shelf (Ciotti et al., 1995) and will be dragged southward by the northerly wind anomalies. Such processes could contribute to the higher CSAT anomalies in the northern Argentinean midshelf (e.g., off Corrientes Cape) associated with El Niño periods.

Higher phytoplankton production and hence biomass can be expected in the upwelling enrichment zones. In contrast, downwelling movement of the water masses deepens the pycnocline limiting the availability of essential nutrients to phytoplankton (Mann and Lazier, 2006). Higher CSAT concentration in coincidence with upward velocities during El Niño were found only off RDP, on the continental shelf and shelf break north of 45°S (Figs. 3 and 5). Thus, the wind effect on vertical velocity during opposite ENSO phases can only explain the variability in CSAT in some local areas. Other potential mechanisms such as column stability and SST gradients need to be further explored.

4.3. Interannual variability in continental shelf off RDP

Under normal conditions most nutrients and, particularly, dissolved nitrogen forms from the continental runoff are consumed by phytoplankton within the RDP estuary (Carreto et al., 1986; Nagy et al., 2002; Calliari et al., 2005). Present results support that higher RDP flow implies higher nutrient fluxes from RDP basin which then become available to continental shelf phytoplankton communities, as earlier suggested by Ciotti et al. (1995) for one event (the moderate 1987 El Niño). Similar results of an increased CSAT over the outer shelf have been reported by Garcia and Garcia (2008) in the 1997 and 2002 El Niño phase.

The evolution of positive CSAT anomalies from October to March can be explained by changes in surface wind anomalies that tend to retain the plume in NDJ, but advect it northward and offshore in the following seasons (Fig. 6D–F). This result agrees with Piola et al. (2005) who proposed surface winds and discharge level as the most important forcings for the extension and distribution of the RDP plume.

5. Conclusions

The analysis presented here revealed a strong annual cycle dominating the variability of CSAT in the studied region, particularly over the continental shelf. The leading pattern showed an opposite behavior to the north and south of 37°S. This distribution could reflect the contrasting behavior of water column stability north and south of such latitude. It seems reasonable to conclude that north of 37°S the buoyant RDP plume results in a highly stable column, which retains the phytoplankton cells in the euphotic zone allowing high chlorophyll-a concentration even during winter; in the southernmost region stability and sunlight requirements are only achieved during the spring and summer thermal stratification periods. Other forcings such as the existence of different water masses and fronts could also contribute to these differences. The high variability in CSAT in the inner and outer Patagonian shelf between 47 and 51°S seems to be related to the Southern Patagonian Front and the Shelf Break Front.

There are opposite patterns in the anomaly distribution of CSAT, wind and vertical velocities during spring at contrasting ENSO phases. The high CSAT in some areas north of 45°S during El Niño events are promoted by a combination of fertilizing processes resulting from increased RDP freshwater and nutrients fluxes, the northerly winds anomalies and the upwelling generated in the shelf between 33 and 39°S. The patch of high CSAT produced by RDP is carried by winds and moves from the Uruguayan coast in spring (OND) to the Brazilian coast in summer (JFM). Ekman pumping does not seem to play a significant role in the modulation of CSAT variability over the continental shelf south of 45°S and at the Brazil–Malvinas confluence.

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