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Seasonal variability in satellite-measured surface chlorophyll in the Patagonian Shelf

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Abstract

Six years (January 1998—December 2003) of SeaWiFS ocean color satellite data are used to estimate monthly climatological means and to present the near-surface chlorophyll-a seasonal evolution in the Patagonian Shelf. The southern part of the shelf presents elevated chlorophyll concentrations from spring through autumn, while the northern part shows three regions with particular characteristics. The external region, bordering the 200 m isobath, presents elevated concentrations from spring through autumn supported by the nutrient-rich waters from the Malvinas (Falkland) Current. The central region presents a typical pattern of temperate regions, characterized by two well-defined maxima, a stronger spring bloom and a weaker fall bloom, and low chlorophyll values throughout summer (scarce availability of nutrients) and winter (light being the limiting factor). Even though the displacement direction of the spring and fall blooms do not agree with previous information reported in the literature, they are interpreted based on the heat exchange in the air–sea interface that controls the development and erosion of the seasonal thermocline. Finally, the coastal region presents less-marked seasonal variability and isolated small areas with elevated concentrations associated with frontal areas are observed. The spatial mean chlorophyll evolution, averaged over the whole shelf (less than 200 m depth), shows a marked annual cycle with high values from spring to autumn, supporting the importance of frontal regions as a fertilization mechanism. An increasing trend in chlorophyll concentrations, within the 6 years analyzed here (in the order of 23%), is apparent based on an increasing of the maximum annual values. From the comparison with in situ data it can be concluded that satellite information reproduces the spatial patterns of chlorophyll fields obtained from more classical data, while differences exist in absolute values obtained from both methodologies.

Keywords: Phytoplankton; Patagonian Shelf; Satellite ocean color; Seasonal variability

1. Introduction

Chlorophyll-*a* in situ data, collected by oceanographic cruises provide either non-synoptic, coarse resolution realizations of global processes or detailed, but time and site specific views of localized features and processes. On the other hand, satellite information provides quasi-synoptic, comprehensive coverage and excellent spatial/time resolution data. One of its limitations is the confidence of the estimated values based on global algorithms not validated or calibrated with in situ observations,

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which is essential to ensure the optimal quality of the data. Another limitation is that satellite-derived chlorophyll-*a* concentrations estimates phytoplankton biomass content of the upper layer of the ocean only, the first attenuation depth, while its distribution throughout the entire euphotic zone is not taken into account. This is important in many ecological studies and in the estimation of primary productivity of the water column. And even a more important limitation is cloud cover that limits its spatial and temporal coverage, especially at high latitudes. The Patagonian Continental Shelf (Fig. 1) is a relatively poorly studied region far away from the main navigation routes. Consequently, the sparse availability of in situ data makes the use of satellite information especially attractive.

The Patagonian Continental Shelf (PCS) is identified in general terms as an area of high primary productivity. It appears in the satellite images as a region with high values of surface chlorophyll-*a* concentrations (Longhurst et al., 1995; Podestá, 1997; Reta and Carreto, 2000). Oceanic fronts present in the PCS control the distribution and intensity of the biological production observed in the area. In the entire Patagonian Shelf, the mixing induced by the tidal currents brings about high levels of dissipation and it can inhibit the development of seasonal thermocline, particularly in zones of topographic shoals. This creates thermal fronts in spring and summer that defines the border between stratified and vertically mixed waters (Glorioso, 1987; Martos and Piccolo, 1988; Glorioso and Flather, 1995; Piola and Rivas, 1997). Tidal fronts have been identified in the study area (see Fig. 1) in the San Matías Gulf's mouth, to the SE of the Valdés Peninsula, in the San Jorge Gulf's mouth, along most of the coast south of 47°S, and around the NW of Malvinas (Falkland) Islands (Carreto et al., 1981a, 1986; Glorioso, 1987; Lutz and Carreto, 1991; Glorioso and Flather, 1995; Rivas and Dell'Arciprete, 2000; Bava et al., 2002; Sabatini and Martos, 2002; Acha et al., 2004; Bogazzi et al., 2005). Another type of oceanic front in the region is clearly distinguished south of 38°S coincident with the external shelf border (approximately 200 m isobath) and it is denominated shelf-break front (Fig. 1) (Brown and Podestá, 1997; Podestá, 1997; Bava et al., 2002; Bogazzi et al., 2005). The shelf-break front is a quasi-permanent thermohaline boundary between shelf subantartic waters and colder, saltier and nutrient-rich waters of the Malvinas (Falkland) Current flowing northward along the shelf-break.

The annual evolution of chlorophyll's content, on the Patagonian Shelf, has been documented using in situ data from different oceanographic cruises (Brandhorst and Castello, 1971; Carreto et al., 1981b). In particular, the North-Patagonian gulfs have been thoroughly surveyed (Carreto and Verona, 1974; Carreto et al., 1974; Verona and Carreto., 1974; Charpy and Charpy-Roubaud, 1980a, b; Charpy et al., 1982, 1983; Sastre et al., 1997; Gayoso, 2001). In addition, Podestá (1997) shows a first approach of seasonal chlorophyll-*a* content in the shelf using Coastal Zone Color Scanner (CZCS) satellite data.

In an early work Brandhorst and Castello (1971) present two charts of the spatial distribution of surface chlorophyll-*a* concentration in the Argentine Sea, one for austral summer (February and March) and one for austral winter (June and July). They were made with data obtained during surveys Pesquería III and IV (Proyecto de Desarrollo Pesquero, 1968a, b) and complemented with information published in the Texas A. & M. University (1963, 1964a, b). In spite of the limited number of stations used and the coarse spatial resolution, the authors identify in summer a chlorophyll-*a* maximum with values up to 5 mg m^{-3} next to the shelf-break area, west of the Malvinas (Falkland) Current axis; some isolated small areas with values around 1 mg m^{-3}, and over the continental shelf, south of 48°S, values higher than 1 mg m^{-3}. Furthermore, they point out the strong relation existing between chlorophyll-*a* and nutrient distributions. During winter period, they show the presence of a highly productive tongue extending over the central shelf from the mouth of the Río de la Plata to 43°S, with values higher than 2 mg m^{-3}, and a considerable decreasing of the observable values next to the slope and also in the southern part of the shelf (at latitudes higher than 45°S). This decline was attributed to the attenuation of the solar radiation and the homogeneous vertical distribution of phytoplankton due to the absence of a thermocline.

Carreto et al. (1981b) analyze the distribution of nutrients, phytoplanktonic pigments, cell number and phytoplanctonic composition in early austral winter (June 17–July 18, 1978) in the northern area of the shelf (between 43 and 36°S), and in early austral spring (September 21–October 12, 1978) in the coastal zone, where bottom depth is less than 100 m (between 47 and 37°S). In the winter cruise,

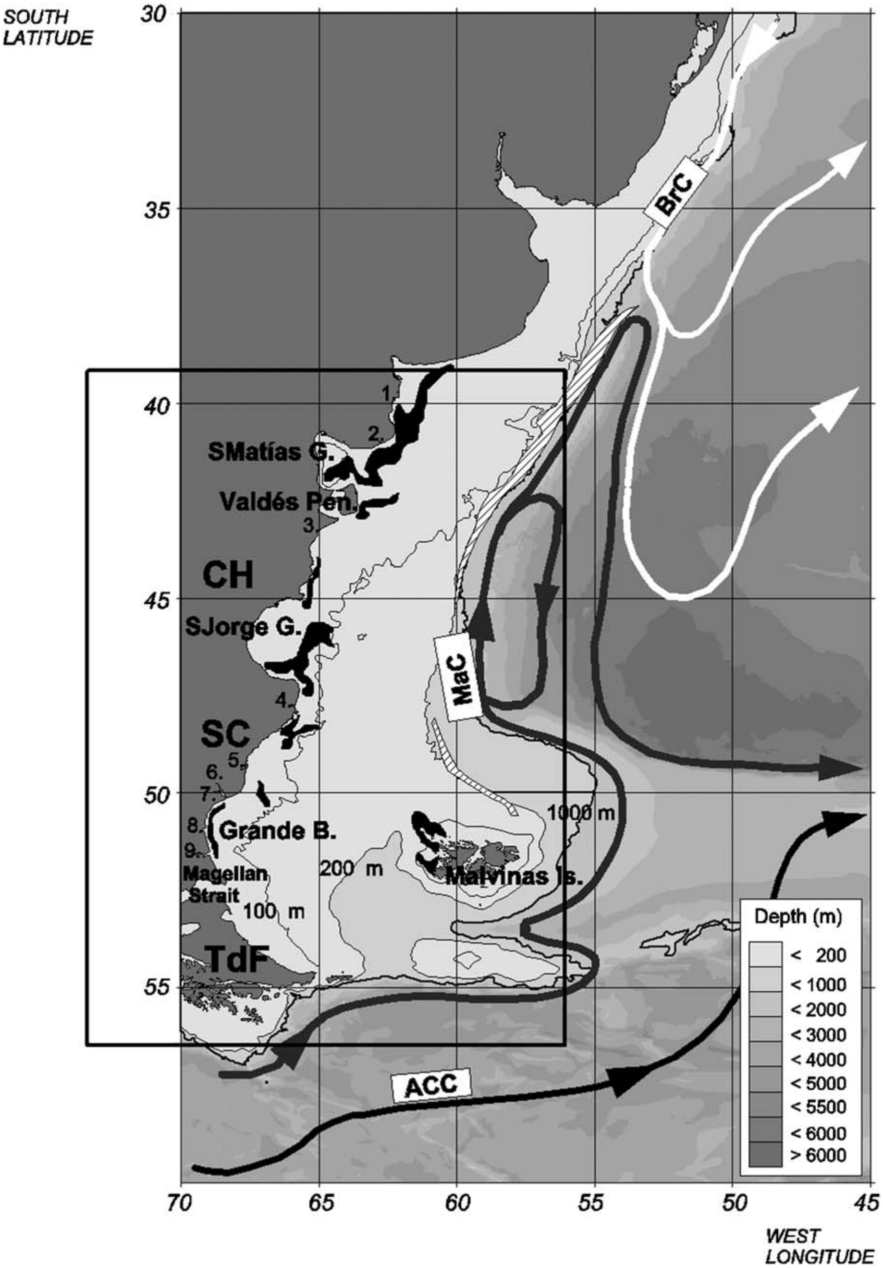

Fig. 1. Southwestern Atlantic Shelf schematic circulation, showing the Malvinas/Fakland (MaC), Antarctic Circumpolar (ACC) and Brazil Currents (BrC) (adapted from Piola and Rivas, 1997). Shown in gray tones is the bathymetry and in black lines the 100, 200 and 1000 m isobaths. Inside the black line rectangle is the Patagonian Continental Shelf (PCS), the study area, and local names used in the text are indicated. **CH:** Chubut, **SC:** Santa Cruz, and **TdF:** Tierra del Fuego provinces. January mean surface thermal fronts, based on sea surface temperature satellite imagery (surface thermal gradient $>0.05\,^{\circ}\mathrm{C\,km^{-1}}$), are shown over de PCS; the Shelf-break Frontal System is represented by the white striped zones and the Tidal coastal fronts by the black zones (adapted from Rivas and Dell′Arciprete, 2000). Patagonian rivers are also indicated: 1. Colorado, 2. Negro, 3. Chubut, 4. Deseado, 5. San Julián, 6. Chico, 7. Santa Cruz, 8. Coig and 9. Gallegos.

two centers of relative abundance were observed in the intermediate shelf (with values up to $2\,\mathrm{mg\,m^{-3}}$). In the spring cruise, the concentration of phytoplanktonic pigments ranged from 0.28 to more than $10\,\mathrm{mg\,m^{-3}}$, and an intense peak to the north of San Jorge Gulf was observed. They conclude that the temporary displacement of the spring blooming shows two well-determined directions; west to east and north to south, in agreement with the progressive development of the seasonal thermocline.

Podestá (1997) presents a preliminary description of phytoplanktonic pigment distribution in the Argentinean Sea based on the first years, between October 1978 and May 1980, of CZCS data, the first satellite sensor to monitor ocean color launched by NASA in 1978. In the northern region of the shelf (north of 45°S), the blooming pattern is typical of temperate regions, characterized by two well-defined maxima, a main peak during spring with values ranging between 3 and $5\,mg\,m^{-3}$, and a secondary peak during autumn with values between 0.5 and $1\,mg\,m^{-3}$. Both blooms develop in opposite direction, the spring bloom progresses towards the outer region while the autumn bloom advances from the slope towards the coast, with high values throughout the summer. South of 45°S relatively high chlorophyll-*a* values remain during summer after the spring bloom. This first analysis, using CZCS data in the SW Atlantic, reveals a strong enhancement of pigment concentration along the slope in a 35–45 km wide band that persists from spring through autumn and, even though it shows interannual variability, it presents a marked spatial and temporal continuity.

More recently, some works using ocean color data have been published that provide valuable information on the shelf and shelf-break regions, even though they were focused on the open ocean area. Garcia et al. (2004) analyze the annual cycle of chlorophyll-*a* concentration in the region delimited by 30–50°S and 30–70°W using 5 years of weekly averaged Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images. They use a nonlinear model to fit the annual harmonic of the chlorophyll-*a* concentration time series, quantify the goodness of the model for different locations and find mesoscale activities (with periods of about 9–12 weeks) associated with the Brazil–Malvinas Confluence dynamics. Saraceno et al. (2005) using chlorophyll-*a* and sea surface temperature (SST) satellite data identify eight biophysical regions in the South Western Atlantic. On the Patagonian Shelf-break region, coastal-trapped waves are suggested as a possible mechanism leading to the intraseasonal frequencies observed in SST and chlorophyll-*a* fields, whereas the meridional wind speed may partly explain the interannual variability. Finally, Barré et al. (in press) analyze 2 years of simultaneous SST and chlorophyll-*a* data provided by Aqua/MODIS. With these high spatial (1.1 km) and temporal (1 day) resolution images they distinguish a double thermal front in the Confluence region and it is suggested that a substantial part of the chlorophyll-*a* local maximum in the Malvinas return flow is of continental-shelf origin.

In the present work, 6 years of SeaWiFS ocean color data (January 1998–December 2003) are used to analyze the phytoplanktonic pigments distribution and seasonal variability in the PCS between 40 and 55°S. This data presents higher spatial and temporal resolution than traditional in situ observations. On the other hand, this second generation water color sensor offers better spectral resolution, improved calibrations, and higher signal-to-noise ratio that results in an improved atmospheric correction scheme and a more accurate determination of phytoplankton concentration compared to CZCS.

Monthly climatic means are built and patterns of chlorophyll-*a* concentration and its seasonal evolution are compared to the ones presented in the previously mentioned works. They are interpreted, when possible, with available hydrographic and atmospheric data within the present understanding of Patagonian shelf marine ecosystem. In Section 2, data sets and processing methodology used are described and in the following section results of the seasonal variability are presented. Finally, in Section 4 the confidence of the values used is analyzed and conclusions are provided.

2. Data and methods

Daily level-2 Global Area Coverage (GAC) SeaWiFS chlorophyll-*a* data, corresponding to the period January 1998–December 2003 (6 years), were retrieved from the Distributed Active Archive Center (DAAC) at Goddard Space Flight Center. It is a nominal 4 km resolution product processed with the OC4 algorithm (reprocessing #4). These data were sub-sampled over the study area (40–57°S and 70–55°W) and re-gridded to a Cylindrical Equidistant projection at $0.0333^\circ \times 0.0333^\circ$ resolution. Thumbnail images were examined to determine whether at least 20% (approximately) of the study area was cloud free. Multiple orbits from the same day were composited into a single image to produce a time series of daily scenes. Land and cloudy pixels were flagged to zero and were not taken into account for the computations carried out

Table 1
Number of images used in calculating the climathological means for the period 1998–2003 and the theoretical number of possible images for each month

	Used	Possible
January	127	186
February	107	169
March	99	186
April	108	180
May	79	186
June	77	180
July	87	186
August	105	186
September	90	180
October	107	186
November	95	180
December	121	186
Total	1202	2191

in this work. In order to avoid anomalous chlorophyll-*a* retrievals found adjacent to clouds and land edges, masked areas (i.e. clouds and land) were enlarged in every direction by one pixel. Variability is examined by forming monthly composites from the daily images, resulting in 12 scenes per year. Further averaging by calendar month over the 6 years produced a climatological monthly seasonal cycle and their corresponding standard deviations were calculated. The number of cloud-free pixels contributing to each monthly composite is spatially and temporally variable and is a limitation to the interpretation of the data in the study area. Table 1 presents the total number of images used to calculate the statistics mentioned before and maps of the number of cloud-free pixels for each calendar month for the entire period (January 1998–December 2003) were generated to illustrate the spatial distribution of observation on a pixel-by-pixel basis (Fig. 2). Cloud coverage increases with latitude and is highest in winter (May–July). For example in June, less than 6 data existed in some pixels of the southeastern region of the study area for the 6-year period although 77 images out of 180 possible images were available.

3. Analysis

3.1. Annual cycle

Fig. 3 presents the annual cycle of chlorophyll-*a* concentration as a monthly climatological series. South of approximately 47°S elevated concentrations are observed in austral spring and summer (October or November–March) with maximum values higher than $8\,\mathrm{mg\,m^{-3}}$ in the southern region of the slope zone (associated to the shelf-break front, see Fig. 1), in the Grande Bay area and to the north of the Malvinas (Falkland) Islands (both associated with tidal fronts identified in those areas, see Fig. 1). In autumn and winter chlorophyll-*a* concentrations decrease progressively in the whole region and appreciable values persist only along the coast of Tierra del Fuego and southern Santa Cruz provinces, with concentrations higher than $1\,\mathrm{mg\,m^{-3}}$. These high values are probably spurious due to the presence of suspended inorganic matter (sediment load) and dissolved organic matter along the coast of the southern Patagonian region. This coastal region has a strong influence of continental discharge like the drainage of Deseado, San Julián, Chico, Santa Cruz, Coig and Gallegos rivers and the inflow of diluted and fine sediment-loaded waters from the Magellan Strait (see Fig. 1). In this coastal and optically complex case-2 waters, as defined by Morel and Prieur (1977), standard algorithms currently used to retrieve chlorophyll-*a* concentration from satellite data break down. Elevated concentrations found in places far from frontal areas during summer, when stratification inhibits the vertical flux of nutrients, are not easy to explain unless some other mechanisms exist that prevent the depletion of nutrients in the upper layer. Krepper and Rivas (1979) found that the stratification of the water column in the austral region of the shelf is controlled by temperature while salinity remains vertically homogeneous and that this stratification extends southward (in December and January) reaching 51°S approximately, being almost negligible south of that latitude. In addition, Glorioso and Flather (1995), with a barotropic model, show that local wind and the bathymetric depression that exists between the Malvinas (Falkland) Islands and the Tierra del Fuego Island generates a large anticyclonic gyre in southern Grande Bay. The model predicts that the divergence of the flow should be compensated with an upwelling of nutrient-rich waters, as was observed by Sánchez et al. (1995). More recently, Sabatini et al. (2004), using hydrographic data collected in the southern Patagonian Shelf during six austral summers (1994–2000), agree in pointing out that the density structure of the water column becomes nearly homogeneous south of 51°S. The mentioned

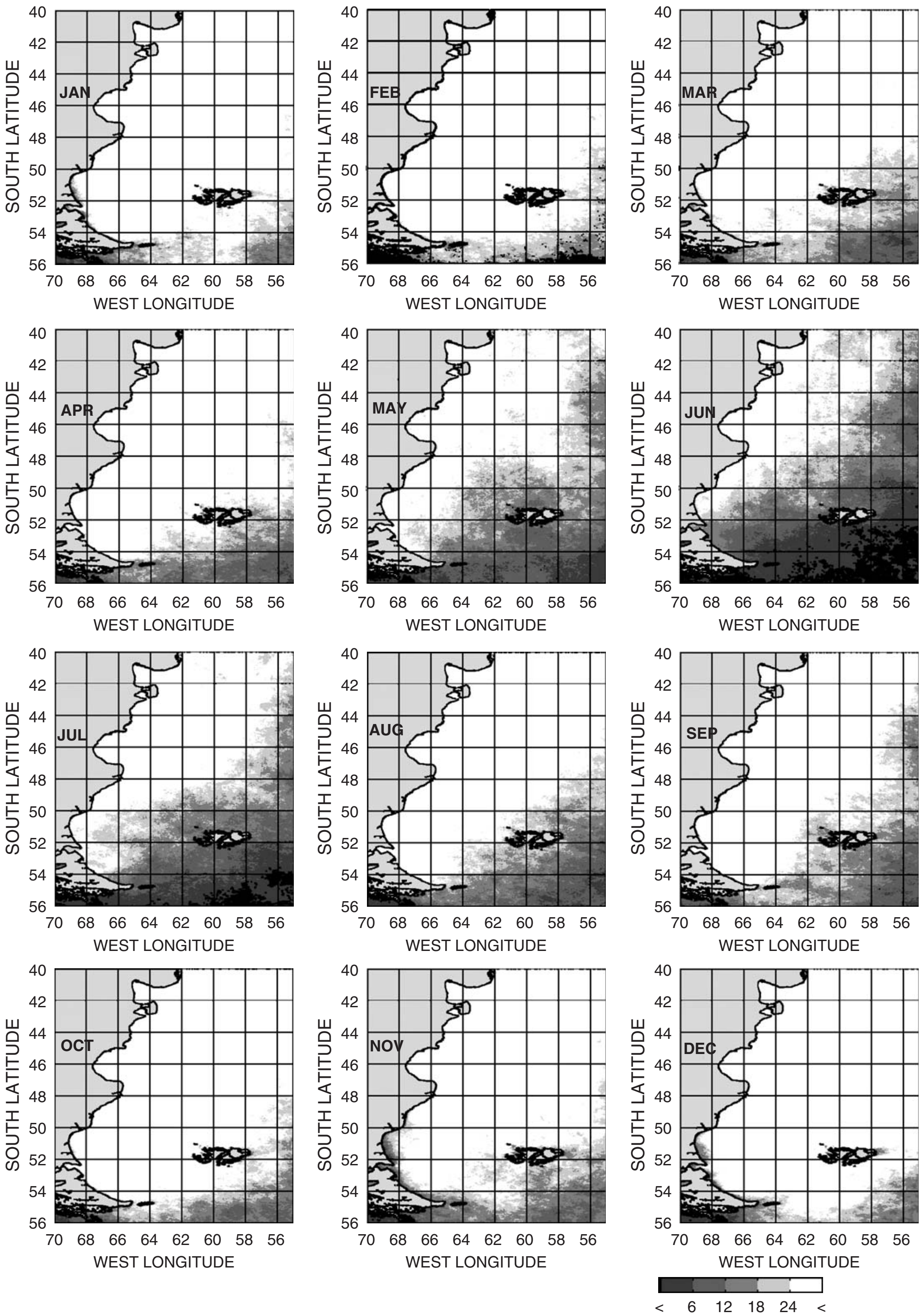

Fig. 2. Number of cloud-free pixels for each calendar month along the entire period (January 1998–December 2003). Table 1 shows the maximum theoretical number of possible images for each month.

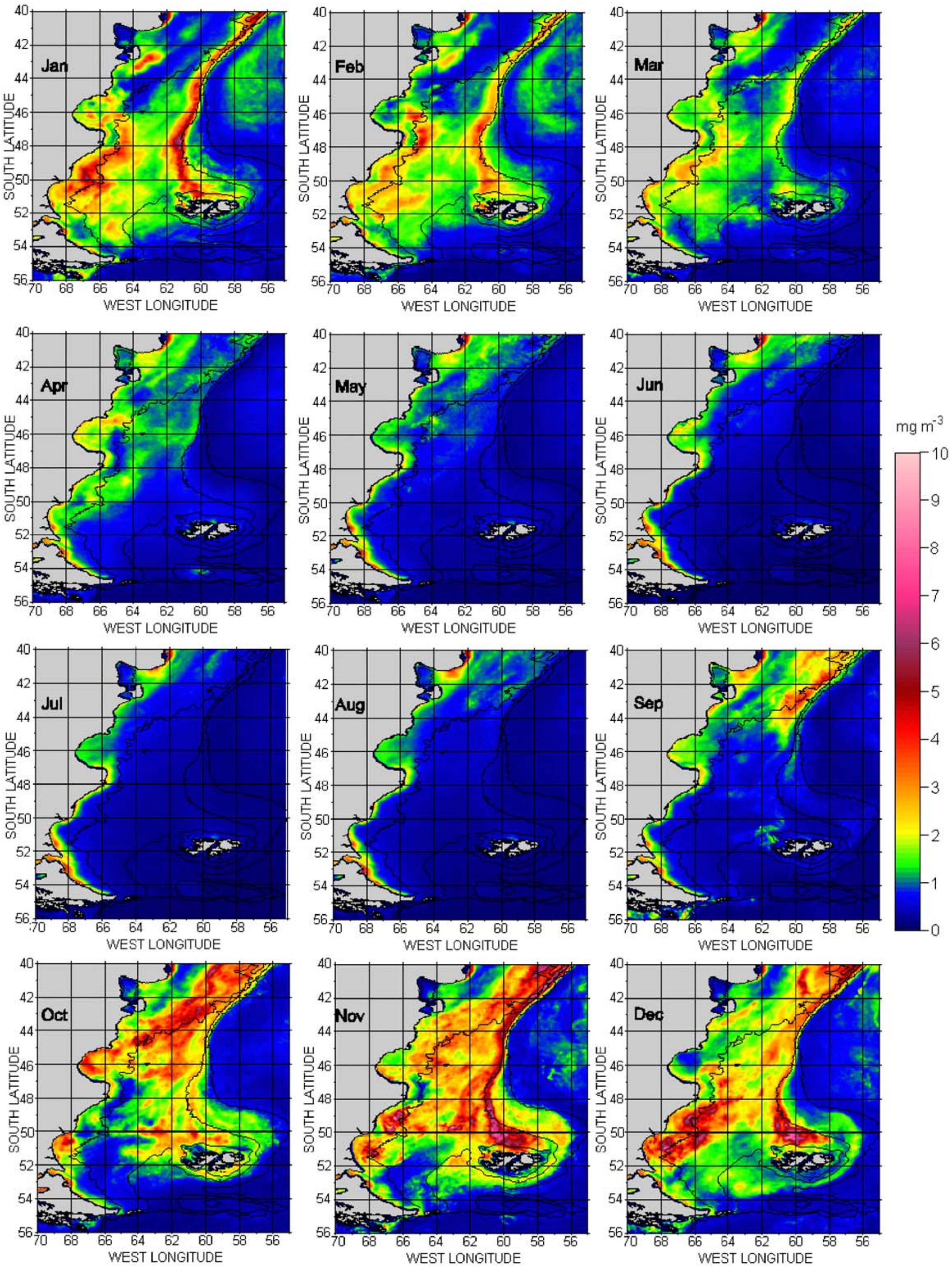

Fig. 3. Monthly climatological chlorophyll-*a* concentrations ($mg\,m^{-3}$) maps derived from monthly averaged SeaWiFS data for the January 1998–December 2003 period.

authors identified, in a cross-shelf section off Grande Bay at 51°S, the presence of three frontal areas (haline fronts) and the associated circulation, which led them to suggest the existence of an upwelling zone 300 km off the coast. In that case, the homogeneous zone could provide the nutrients and the predominant mean flow towards NNE (Piola and Rivas, 1997) the advective mechanisms needed to keep the elevated concentrations observed in the whole region. All the available observations (Brandhorst and Castello, 1971; Podestá, 1997) indicate that the southern region of the shelf presents elevated chlorophyll-*a* concentrations from spring through autumn and the mechanism responsible for providing the nutrients remains to be explained. High nitrate and phosphate concentrations during this period have been found by Brandhorst and Castello (1971) and more recently by Paparazzo (2003).

Three regions can be distinguished north of 47°S:

The *external shelf*, bordering the 200 m isobath, presents elevated concentrations in September, during spring bloom, until autumn (March). In the proximity of the slope subantarctic shelf waters meet the colder, more saline and nutrient-rich waters of the Malvinas (Falkland) Current, producing a thermohaline front known as the shelf-break front (Fig. 1). In the nutrient-rich, but strongly turbulent, Malvinas (Falkland) Current waters the phytoplankton production is limited by the deep mixing layer (Brandini et al., 2000). Two processes let us interpret the observed values: (1) the development of the seasonal thermocline over the shelf, which keeps the surface layer adequately illuminated and (2) the nutrient supply of the shelf-break front to the shelf waters. Given that the strip of elevated planktonic concentrations never extends further north than Malvinas (Falkland) Current's end (~39°S, see Fig. 1), Podestá (1997) relates this phenomena to the nutrient-rich waters of that current. Acha et al. (2004) mention previously published works (Hubold, 1980a, b; Lutz and Carreto, 1991 and Carreto et al. 1995) that, based on sampled in situ measurements, show the high productivity of that zone.

In the *mid-shelf* and San Jorge Gulf, chlorophyll-*a* concentrations increase during a spring bloom. They start increasing in September, peak in October and decrease in November. During austral summer, from December to March, concentrations are low and this can be explained considering the depletion of nutrients in the mixing layer. In April and May concentration increases again during a fall bloom, but it appears weaker than the spring bloom. The spring bloom seems to progress from north to south, while the fall bloom progresses in the opposite direction, from south to north.

The *coastal region* presents moderately high chlorophyll-*a* concentrations throughout the year. In summer, local peak values are evident south of San Jorge Gulf entrance and off southeast Valdés Peninsula, which are most likely related to tidal fronts present in these areas (Fig. 1). Furthermore, freshwater discharges by Negro and Colorado rivers strongly influence the chlorophyll signal in the northern coastal margin of the images analyzed. The relative maximum found in this zone throughout the year might be generated by a local supply of nutrients or spurious values originated by the presence of suspended sediment and/or colored dissolved organic matter, which can confound the radiative signal reaching the sensor. In the northern side of the San Matías Gulf entrance, the high concentrations observed in winter images (June–August) were attributed to resuspended sediments (due to shallow depths in the gulf entrance and the mixing action of tides and wind) by Podestá (1997). The northwestern end of San Matías Gulf did not show this general pattern. Low concentrations are found from October or November–March and from May to August, which could be related with nutrient depletion in the euphotic layer. This different pattern found between the northern and southern side of the gulf is another expression of the frontal system previously mentioned for that region (Carreto et al., 1974; Piola and Scasso, 1988; Rivas and Beier, 1990; Gagliardini and Rivas, 2004). The origin of this front is attributed to the inflow of shelf waters through the southern side of the gulf entrance. The relatively high values present in the coastal area during winter are not in agreement with vertical mixing of the water column, which would limit the light availability. Nevertheless, in July and August peak values of chlorophyll-*a* concentrations are found in the northern mid-shelf. This is in agreement with previous in situ field measurements (Pesquería IV surveys, Proyecto de Desarrollo Pesquero, 1968b; Carreto et al., 1981b), even though it is not compatible with the expected light availability.

In order to show the differential seasonal evolution of chlorophyll-*a* in the different regions previously identified, the temporal evolution of the monthly mean values of seven sites were drawn,

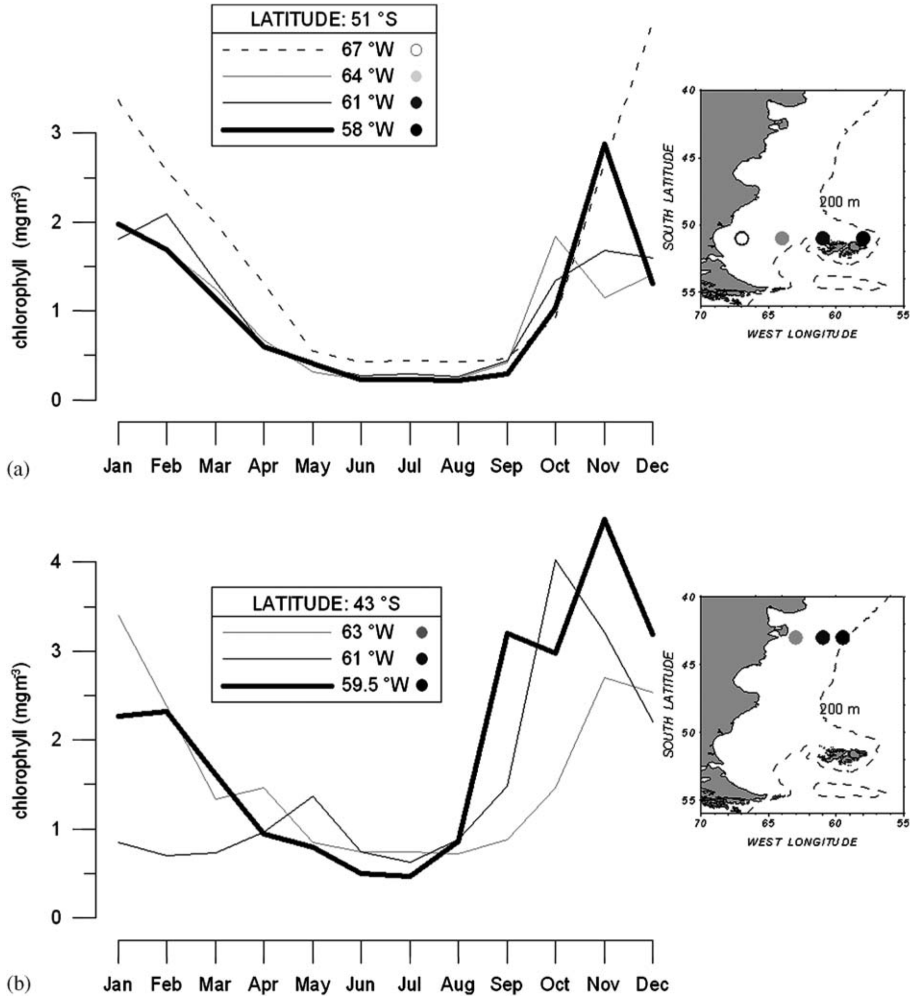

Fig. 4. Time series of mean monthly SeaWiFS chlorophyll-*a* concentration (mg m^{-3}) at seven sites over the PCS (see insets for location). (a) Sites representative of the southern region (at 51°S) and (b) sites representative of the northern region (at 43°S).

four along a representative transect of the southern region at 51°S and three along a representative transect of the northern region at 43°S (Fig. 4). Even though differences exists in the amplitude of the four sites of the southern region (Fig. 4a), they show a similar behavior, high values from October to April and very low values the rest of the year, when light is the limiting factor. In order to support high chlorophyll-*a* concentrations during summer, nutrient should be available. In the coastal zone and to the northwest of Malvinas (Falkland) Islands tidal fronts have been identified (Fig. 1). In the northeast of the mentioned islands the subantarctic Malvinas (Falkland) current supply the nutrients. And in the mid-shelf the circulation associated with the haline front identified by Sabatini et al. (2004) could be responsible for a high-nutrient upwelling area.

The temporal series of the northern transect (Fig. 4b) show the differential behavior of the three regions identified before. The coastal zone show less-marked seasonal amplitude and the highest values corresponds to the spring–summer period, probably due to the influence of the tidal front located to the southeast of Valdés Peninsula. Also a weak autumn bloom (April) can be identified in the coastal zone. In the mid-shelf zone spring (stronger) and autumn (weaker) blooms can be observed and low concentrations in summer (nutrients limited) and winter (light limited) are apparent. The site next to the 200 m isobath show the mentioned behavior described for the external shelf zone, high values from September to March. This figure also shows that the spring bloom propagates from the external shelf to the coast

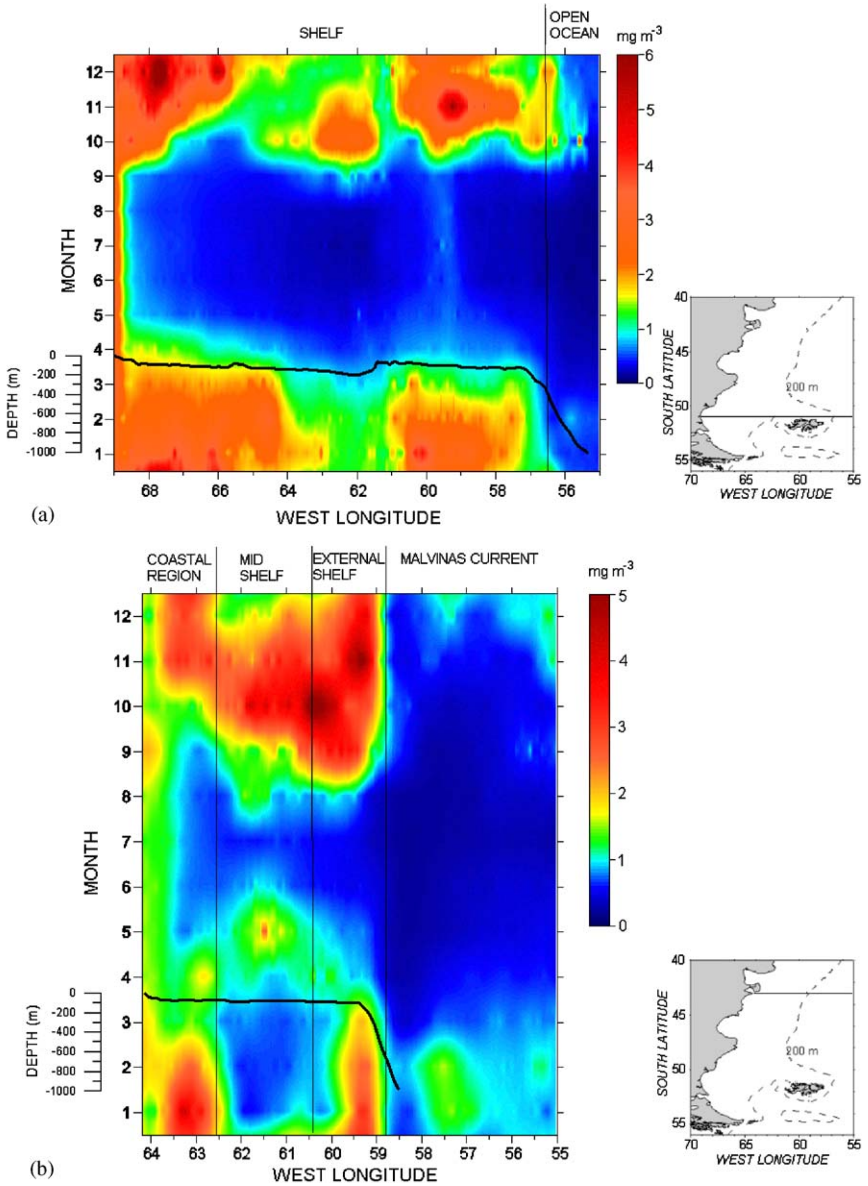

Fig. 5. Climatological SeaWiFS chlorophyll-*a* concentration (mg m^{-3}) for two zonal transects for the January 1998–December 2003 period. (a) Southern cross-shelf section (51°S) and (b) Northern cross-shelf section (43°S), contoured as a function of West longitude and time. The temporal resolution of the time series is 1 month and the spatial resolution cross-shelf is 4 km. The bathymetry is displayed as a black line.

while autumn bloom propagates in the opposite direction.

The temporal evolution of monthly averaged chlorophyll-*a* values was examined along two zonal transects (Fig. 5) in order to depict the differential longitudinal variability of the chlorophyll-*a* signal. The transect along 51°S was from 69°W to 55°W, while the transect along 43°S extended from 64°W to 55°W. The southern region shows (Fig. 5a), excluding coastal pixels, which present a homogeneous distribution of chlorophyll-*a* with high values all along the year, a similar seasonal variability in the whole shelf area with high values from spring through autumn and low values from April through September. Even though between 63°W and 61°W relatively high concentrations (with values higher than 1 mg m^{-3}) are discernible, they are lower than the surrounding shelf waters and a relative maximum is evident in October–November (spring bloom). This phenomenon could be showing that nutrient supply in the mid-shelf during summer months is less intense than in surrounding regions, where coastal and Malvinas tidal fronts exist. Conversely, in the northern transect it is possible to identify the three previously described zones (Fig. 5b). The diagram of the northern zonal transect, along 43°S (Fig. 5b), shows evidence of the propagation of the spring bloom from the external shelf (beginning in September) to the coastal area (beginning in November). Meanwhile, the autumn bloom seems to start first in the coastal and external zone (April) and latter in the mid-shelf (May). These results disagree with previous reports (Carreto et al., 1981b; Podestá, 1997) that described the propagation of the spring bloom from the coastal zone to the shelf-break region. Estimates of surface heat flux in the air-sea interface from the NCEP reanalysis (Kalnay et al., 1996) from 1989 to 2001 in 21 nodes distributed over the shelf were used to generate Fig. 6. In each of the 21 nodes (dots in Fig. 6) a mean value plus an annual cosine signal were fitted by least-squares to the surface net heat flux extracted from NCEP reanalysis. The fit, which explained 56–72% of the variance depending on the node, was used to estimate the date in which the surface heat flux change its direction, thus indicating the beginning of the sea surface warming (stratification, Fig. 6a) or the sea surface cooling (beginning of vertical convection, Fig. 6b). They show that while spring stratification starts in the first days of August in the northeastern region, in the southwestern region it begins in mid-September and that the water column mixing, due to sea surface cooling, begins first in the southwest (first days of March) and arrives to the northeast a month later. Therefore, the propagation of the spring and, to a less extent, the autumn bloom found in the present work is consistent with the sense of displacement that could be expected regarding the development and erosion of the seasonal thermocline, even though is not in agreement with the previously mentioned works.

Taking into consideration the region as a whole (Fig. 3), it can be observed that higher concentrations are found to the north in September–October and in November–December to the south. This shows that the spring maximum propagates, as was previously mentioned by Carreto et al. (1981b), in a southward direction. This sense of propagation is also in accordance with the estimated progress of the water column stratification in the meridional direction (Fig. 6a).

3.2. *Temporal evolution of the mean chlorophyll-a fields*

In order to analyze the interannual variability, the spatial mean chlorophyll-*a* values averaged over the whole region under study (40–56°S and from 55°W to the coast) and over the continental shelf (40–56°S and from the coast to the 200 m isobath) for each of the 72 month was calculated. The temporal

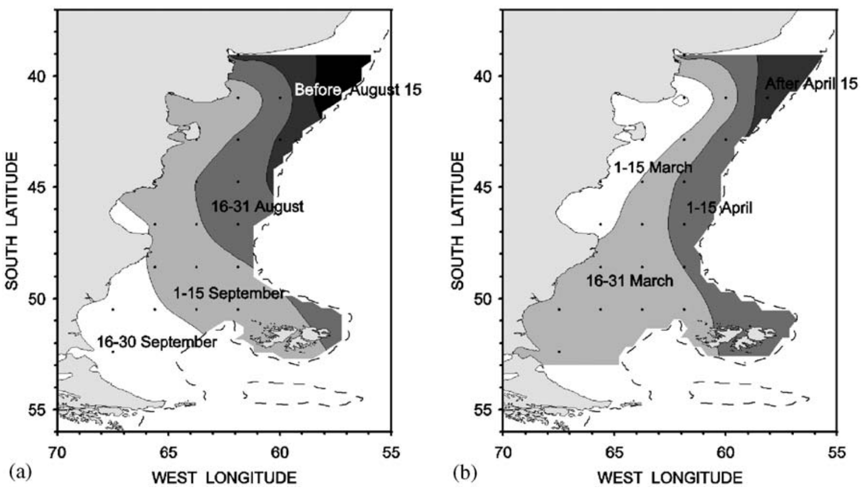

Fig. 6. Time of the year that marks the beginning of (a) surface warming and (b) surface cooling. The figure was made using de NCEP derived surface heat flux at 21 nodes (black points) for the period 1989–2000.

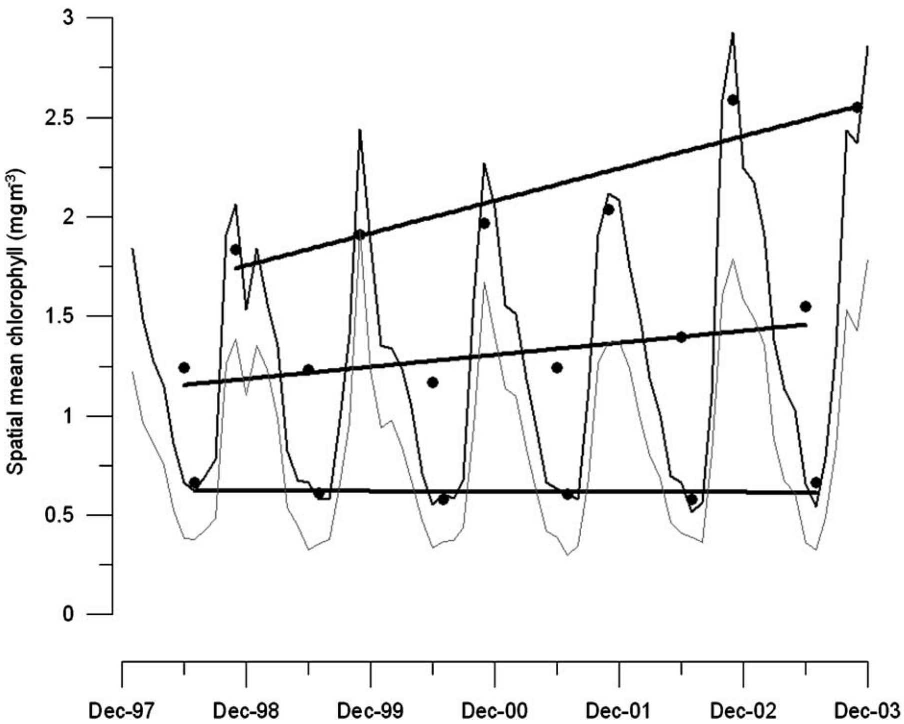

Fig. 7. Temporal evolution of spatial mean chlorophyll-*a* averaged over the whole study area (gray curve) and the shelf basin (black curve). Linear trends of chlorophyll-*a* annual concentrations for the shelf basin (black lines): maximum (October–December means), upper line, minimum (June–August means), lower line, and mean (12 months average), in-between.

evolution of the spatial monthly means (black and gray curves in Fig. 7) clearly shows that including the open ocean region the temporal evolution does not change much and only a decrease in the mean chlorophyll-*a* concentrations, compared to the shelf values, is apparent (gray line in Fig. 7). This indicates that the shallow region of the shelf is the main responsible of the high surface chlorophyll-*a* concentrations usually found in the region. The mean chlorophyll-*a* values show a typical annual cycle with high values from spring to autumn.

Gregg et al. (2005) find that remotely sensed global ocean chlorophyll-*a* has increased 4.1% from 1998 to 2003, that most of the increased has occurred in shallow regions (10.4%), where bottom depth is less than 200 m, and they estimate that the Patagonian Shelf is one of the main contributors to the increase (67.8%). The black curve in Fig. 7 shows that the spatial mean chlorophyll-*a* estimated over the shelf have a positive trend, but it is difficult to differentiate this from the annual cycle. Besides, this positive trend does not seem to be the same for the minimum and maximum concentrations. Therefore, the annual mean (averaging the 12 monthly means of each year), the maximum annual mean (averaging October–December, see also Fig. 9), and the minimum annual mean (averaging June–August, see also Fig. 9) for the continental shelf were calculated and a linear trend using regression analysis was computed for each of the three means. The results (Fig. 7 and Table 2) indicate that the increase in percentage (estimated as the slope of the line times the temporal increment, i.e. 5 years, divided by the corresponding mean value) is smaller than Gregg et al. (2005) estimated, obtaining 23.2% for the annual mean, 37.9% for maximum values

Table 2
Trends in chlorophyll-*a* from SeaWiFS imagery over six years over the Patagonian shelf region (bottom depth less than 200 m)

	Slope	Error	Mean	Trend (%)
Annual mean	0.03916	0.0154	0.845	23.2
Maximum	0.10533	0.0241	1.390	37.9
Minimum	−0.00019	0.0067	0.399	−0.2

Slope and error for the linear regressions in Fig. 7 and the corresponding means for the spatial averaged values are shown.

and a relative negative trend (−0.2%) for the minimum concentrations. On the continental shelf, the minimum values of the annual cycle found in winter are due to limitation in light availability as a result of the vertical mixing, while the spring and summer maximums originates from the nutrient supply to the illuminated and stable zone of the water column. The present results show a positive trend, regulated by the increasing of the maximums, due to a higher nutrient supply during warmer periods when the water column is stratified. This is in agreement with Gregg et al. (2005), who associate the increase in chlorophyll-*a* with a significant decrease in the SST as a consequence of increasing upwelling of nutrient-rich waters.

4. Discussion and conclusions

As stated in the introduction, one of the limitations of satellite information is the confidence of the estimated values. The main difficulty in order to achieve this is the scarce availability of in situ data collected contemporaneously with the reception of the satellite imagery in the study region. A first approximation to validate SeaWiFS-derived chlorophyll-*a* estimations was done by Dogliotti et al. (2003) in the southern region of the Patagonian shelf, south of San Jorge Gulf (between 47°S and 54°S). Estimation of in situ chlorophyll-*a* concentration was made using in vivo fluorometry in a continuous sampling device during the cruise on board the R/V Capitán Oca Balda between 14–20 March, 1999. The chlorophyll-*a* concentrations thus estimated were compared to the values derived from daily high resolution SeaWiFS images coincident with the oceanographic cruise. This comparison showed a similar spatial distribution and a systematic overestimation of the satellite-derived values at low concentrations, in the order of $0.5\,\mathrm{mg\,m^{-3}}$, while comparisons at high concentrations could not be made due to cloud cover. However, it should be noted that previous experience with the calibration of in situ fluorescence sensors has shown that a high degree of variability exists between sensor readings and chlorophyll-*a* concentration over short and long time scales. Cucchi Colleoni and Carreto (2003) analyzed the space-time variability of phytoplankton biomass in San Jorge Gulf using field data obtained during five cruises over San Jorge Gulf in January, May, August, September and November 2000. The spatial chlorophyll-*a* distributions measured in situ shown by these authors and the monthly averaged concentrations estimated using Local Area Coverage (LAC) SeaWiFS images with 1.1 km nominal resolution mapped to 1-min resolution or 0.0166° (ca. $2\,\mathrm{km} \times 2\,\mathrm{km}$), show that satellite information reproduces the spatial patterns of chlorophyll-*a* fields contoured from more sparsely sampled in situ data, but differences in absolute values exist between both methodologies. These differences could be interpreted considering two factors. On one hand, the satellite information used were monthly composite images (year 2000) that smooth extreme values. On the other hand, sediment resuspension occurring in the tidal front located in the southern part of San Jorge Gulf entrance (see Fig. 1) could be confounding the standard algorithm. This area is usually flagged as turbid waters in the satellite images (high-scattering waters in the 555 nm radiances); therefore, satellite-derived concentration should not be reliable. As mentioned before, it is well recognized that the SeaWiFS standard algorithm break down in this case-2 waters, remaining in doubt the accuracy of chlorophyll-*a* concentrations thus retrieved (IOCCG, 2000). A more detailed analysis in this regard escapes the scope of this paper. In this sense, a comparison of exact time/space match-up analysis of the in situ and satellite data is required. In a recent work Garcia et al. (2005) evaluated SeaWiFS algorithms in the southwestern Atlantic and southern Ocean, mainly in open ocean waters adjacent to the present area of study. They generated a regional algorithm and compared their performances with NASA's operational algorithm OC4v4. They also performed a match-up analysis and found a good relationship between in situ and satellite-derived chlorophyll-*a* ($r^2 = 0.77$) and a positive bias of 32%, i.e. the satellite data overestimated the in situ chlorophyll-*a* concentrations. Even though they worked with open ocean waters, they also found that over La Plata river extremely turbid waters, where water reflectance values at 670 nm were very high, the satellite overestimated the in situ chlorophyll-*a* concentrations. Thomas et al. (2003) mentioned a similar comparison made in the Gulf of Maine (they obtained linear correlation coefficient of $r^2 = 0.55$ for 305 match-ups). They concluded that satellite data overestimate chlorophyll-*a* at low concentrations and underestimate it at high concentrations. If the same occurred in this area of study, it would limit our ability to interpret the estimated distributions, thus reducing the strength of space and time gradients. Nevertheless, in this

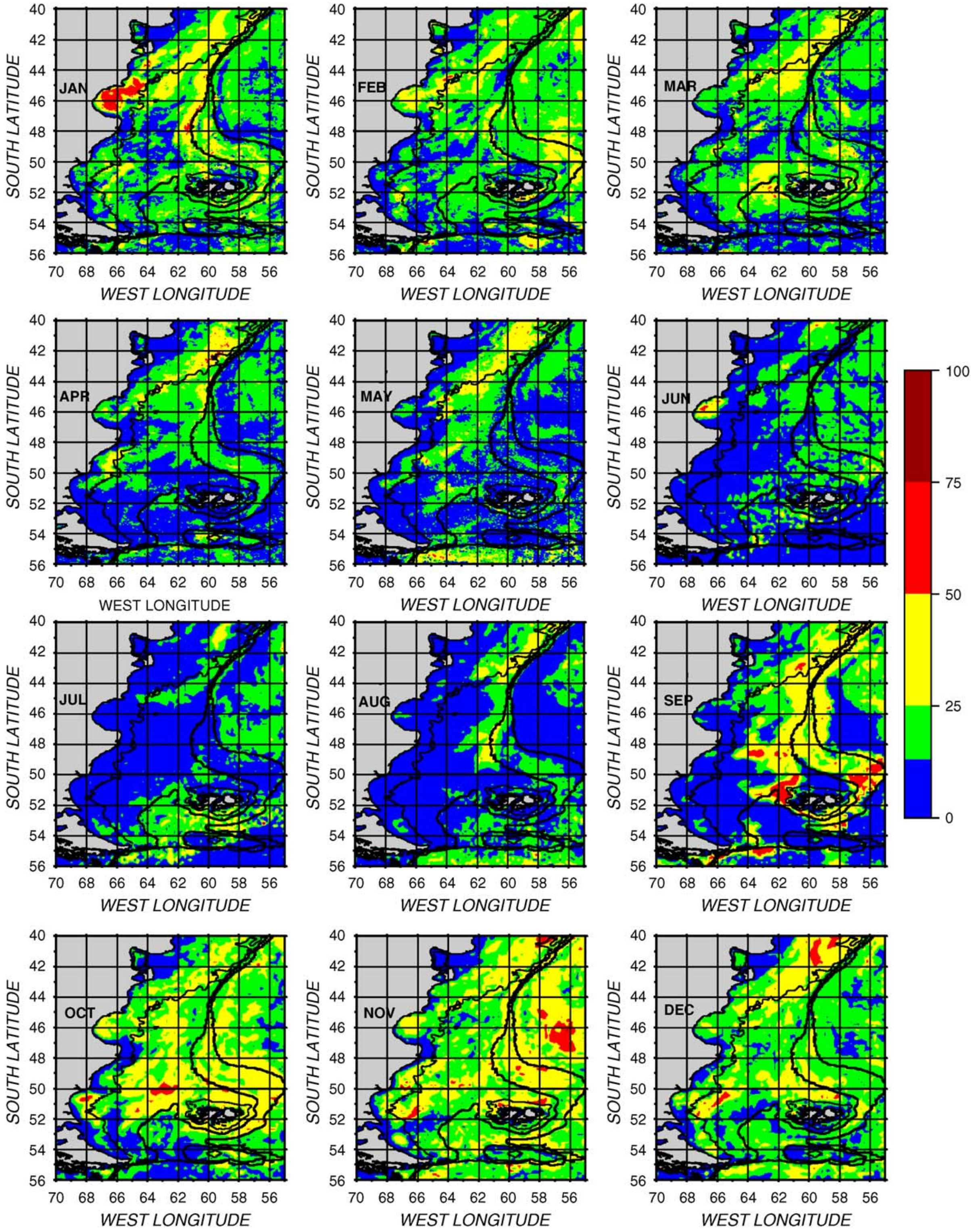

Fig. 8. Monthly climatological chlorophyll-*a* concentrations percentage error (see text for definition).

work the analysis has been restricted to the relative patterns that appear consistent with in situ fields found in the literature and the data presented provide a first synoptic view of the seasonal variability.

Another source of uncertainty in the data is associated with the representativity of the monthly climatological means used in this analysis. Cloud cover limits the number of data, for that reason in this work the average of all the available data for each month was used in order to obtain the corresponding monthly composite images. Composite images are not the real monthly mean value given that for each pixel a different number of data is used. Short-living blooms can either affect disproportionately the monthly mean value, showing extremely high values over part of the image or can be completely neglected in some other parts of the same image. Subsequently, monthly composites were averaged by calendar month over the 6 years producing climatological monthly images used in the present study and their corresponding standard deviations were also calculated. The standard deviations, which are relatively high comparing to the climatological mean values, were used to estimate the standard errors of the climatological means (dividing by the square root of the number of data) and the relative error (dividing again by the estimated mean value). Fig. 8 shows the estimated relative error of the climatological means used in the present analysis of the annual evolution. This figure shows that only in a few isolated pixels in some months the estimated error exceeds 75% and that only in some small regions it ranges from 50% to 75%. In a significant part of the area of study the error does not exceeds the 25%, giving confidence to the climatological means used.

The 6-year time series of SeaWiFS derived images analyzed here provides the most comprehensive and extensive view up to date of the seasonal variability of chlorophyll-*a* concentrations over the Patagonian shelf. The analyzed images permitted to identify a differential distribution pattern of pigment concentrations in the southern and the northern part of the shelf. The former is characterized by high concentrations that persist from spring through autumn, while in the latter three areas with particular characteristics can be distinguished. The external region, bordering the 200 m isobath, presents high concentrations from spring through autumn due to the input of nutrient-rich waters from the Malvinas (Falkland) Current. The central region presents a blooming pattern typical of temperate regions, characterized by two well-defined maxima, a stronger spring bloom and a weaker fall bloom, and low chlorophyll-*a* values throughout summer and winter, when the availability of nutrients is scarce and

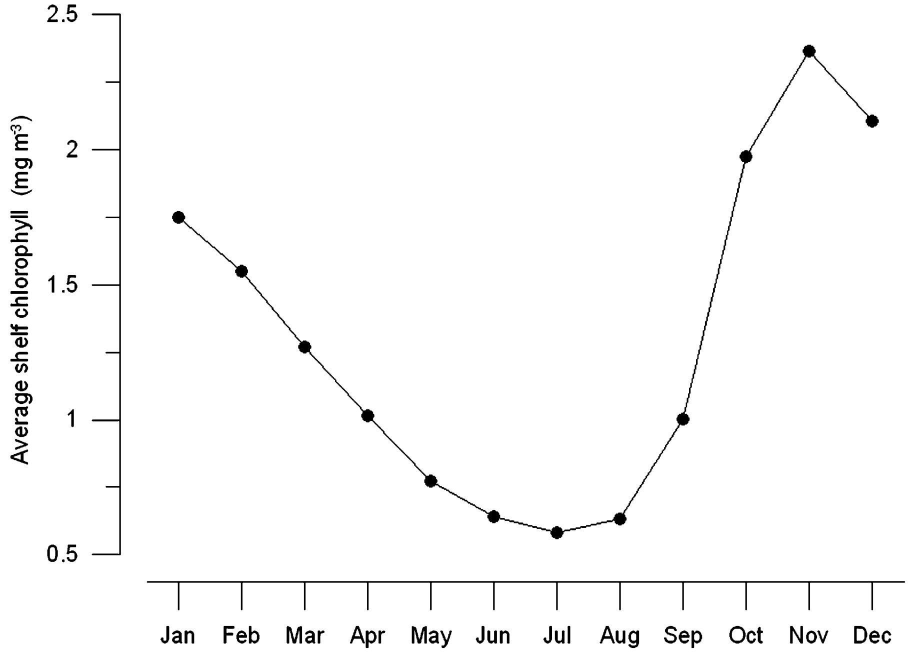

Fig. 9. Mean monthly climatological chlorophyll-*a* concentrations spatially averaged over the entire Patagonian Shelf (bottom depth less than 200 m).

when light the limiting factor, respectively. Finally, seasonal variations of chlorophyll-*a* concentrations in the coastal region present lower amplitudes and isolated small areas with high chlorophyll-*a* values can be found associated with frontal areas, where water column stability changes abruptly from one side of the front to the other.

This description is generally consistent with the patterns presented in previously published work (Brandhorst and Castello, 1971; Carreto et al., 1981a, b; Podestá, 1997), yet being more complete and detailed since it is based on data that provides a more comprehensive coverage and better spatial/time resolution. The more complete coverage given by SeaWiFS data, for example let us show that the sense of propagation of spring and fall blooms, though is not in agreement with Carreto et al. (1981a, b) and Podestá's (1997) suggestions, is associated with the heat exchange in the air–sea interface and the processes of development and erosion of the seasonal thermocline.

As previously mentioned, in the PCS relatively small frontal zones exists associated with an increased vertical mixing, which in terms keeps high levels of nutrients in the photic zone even after the spring bloom. As a consequence, the frontal zones are the main responsible of the high surface chlorophyll-*a* concentrations found in summer without which a general pattern typical of temperate regions, characterized by two well-defined maxima (a stronger peak in spring and a weaker peak in the fall), should be expected in the whole PCS. In order to evaluate the role of these frontal systems in the chlorophyll-*a* distribution over the PCS, monthly climatological data fields were averaged within the whole PCS (bottom depth less than 200 m) and the annual cycle of the chlorophyll-a concentrations can be seen in Fig. 9. A typical frontal zone regime, with high values from spring through autumn, can be observed showing the biological importance of these frontal zones, even though they are restricted to small regions.

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