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Quantitative estimation of the influence of surface thermal fronts over chlorophyll concentration at the Patagonian shelf

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Abstract

Eighteen-year (1985–2002) mean monthly SST Pathfinder data with 9 km spatial resolution have been used to estimate surface gradients by finite differences. Then the seasonal climatological means have been calculated from the intensity of these gradients, and surface thermal fronts present in the Patagonian Continental Shelf (PCS) have been located. Moreover, 6 years (1998–2003) of SeaWiFS data with approximately 4 km spatial resolution have been used to estimate monthly composite images of surface chlorophyll concentration, after which seasonal climatological means distributions have been generated. Both seasonal distributions have been analyzed together and by combining the knowledge of oceanographic processes and phytoplankton responses to light and nutrient availability, regions where the presence of a thermal front affects photosynthetic activity have been identified. Subjective criteria have been applied to define eighteen areas where phytoplankton biomass is influenced by the presence of a thermal front. In these areas, the surface chlorophyll (spatial mean and total), its relationship with the surface chlorophyll of the whole region, and the seasonal evolution of this relationship have been calculated. All frontal areas cover less than 15% of the total surface, but they contribute with over 23% of the phytoplankton annual mean biomass. Considered as a group, during summer they show high chlorophyll values very similar to those in spring. During the cold period, when the water column is vertically mixed in practically the whole of PCS, the influence of physical fronts over the biological production is minimum. The frontal zone image remains clearly defined during summer, when approximately 85% of the area will have a determined mean chlorophyll concentration, while the other 15% has a 2.45 times larger value. While three pattern trends have been identified in the frontal areas, only two of them condition the pattern of the group, due to their horizontal extension.

Keywords: Fronts; Patagonian Shelf; Satellite; Physical–biological influences

1. Introduction

Richardson et al. (1985) claimed that there is a natural tendency to publish those cases in which a front is associated with high values of chlorophyll, and that the cases where high values of chlorophyll are not found near a frontal zone, are less diffused. Perhaps for this reason ocean frontal zones are in general associated with major biological activity and high productivity levels. Quantitative verification of this assertion is not simple. It requires, for example, an adequate definition of the term "frontal zone", a demarcation of the area where the presence of a front affects biological activity and the definition of the variables that allow to follow the process.

An oceanic front is a region where a sudden change of any property occurs and where the horizontal gradient

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of this property achieves higher values. Fronts are not necessarily exclusive of the surface, nevertheless, if the aim is to localize all fronts present in a specific moment in a vast region, the need for synoptic data places satellite observations in a privileged position, although these only allow the identification of surface fronts.

The temperature in the Patagonian Continental Shelf (PCS) is regulated mainly by the surface heat flux, which has a very marked annual cycle, shifting horizontal advection to a secondary level (Rivas, 1994; Rivas and Piola, 2002). This is why in almost all the region the temperature shows a clear annual signal (Podestá et al., 1991; Rivas, 1994) and regulates the development and erosion of the seasonal thermocline that conditions the stability of the water column. Surface temperature fronts identified with satellite imaging (SST) are, in general, more numerous and more intense during the warm austral season (October–March), when the surface heat flux is from the atmosphere to the ocean (Fig. 1). They are located at the boundary between a strongly stratified zone with high surface temperature, and a colder and more homogenous vertical one. While atmospheric heat flux is used exclusively for heating a shallow surface layer when the water column is strongly stratified, the same amount of energy makes the temperature rise in a deeper water layer in a weakly stratified column. This is reflected in the horizontal surface temperature gradient. There are chiefly three mechanisms that allow the proximity of water masses with different stability degree: i. all along the continental shelf-break, shallow subantarctic shelf waters meet the cooler, more saline and vertically highly mixed waters of the Malvinas current, ii. in coastal zones the vertical shear induced by strong tidal currents at particular topographic shoals, generates areas that are vertically well mixed even during the warm season, and iii. in zones near a significant continental inflow of fresh water, salinity may be important in the regulation of vertical stratification. In this case, as stratification of the water column is caused by salinity differences, it might continue in the surface cooling period, allowing the identification of surface temperature gradients in the cold season.

The former simplified explanation of thermal fronts found in the PCS allows us to infer the importance of these systems in biological activity. If these surface fronts are

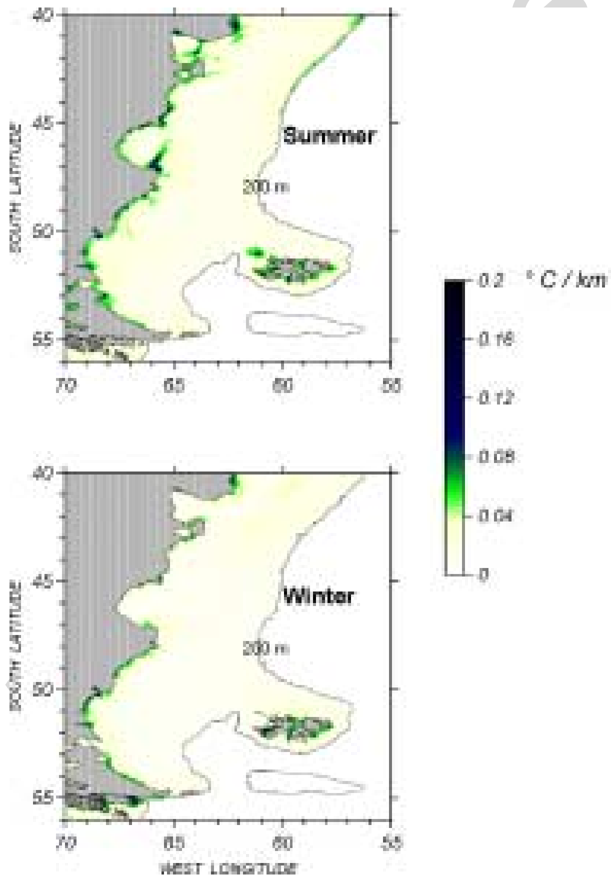

Fig. 1. Mean seasonal SST gradient magnitude (in °C km^{-1}) in the PCS (depth < 200 m) for summer (January–February–March), autumn (April–May–June), winter (July–August–September), and spring (October–November–December), for the 1985–2002 period. Frontal pixels are those with gradient magnitude > 0.045 °C km^{-1}.

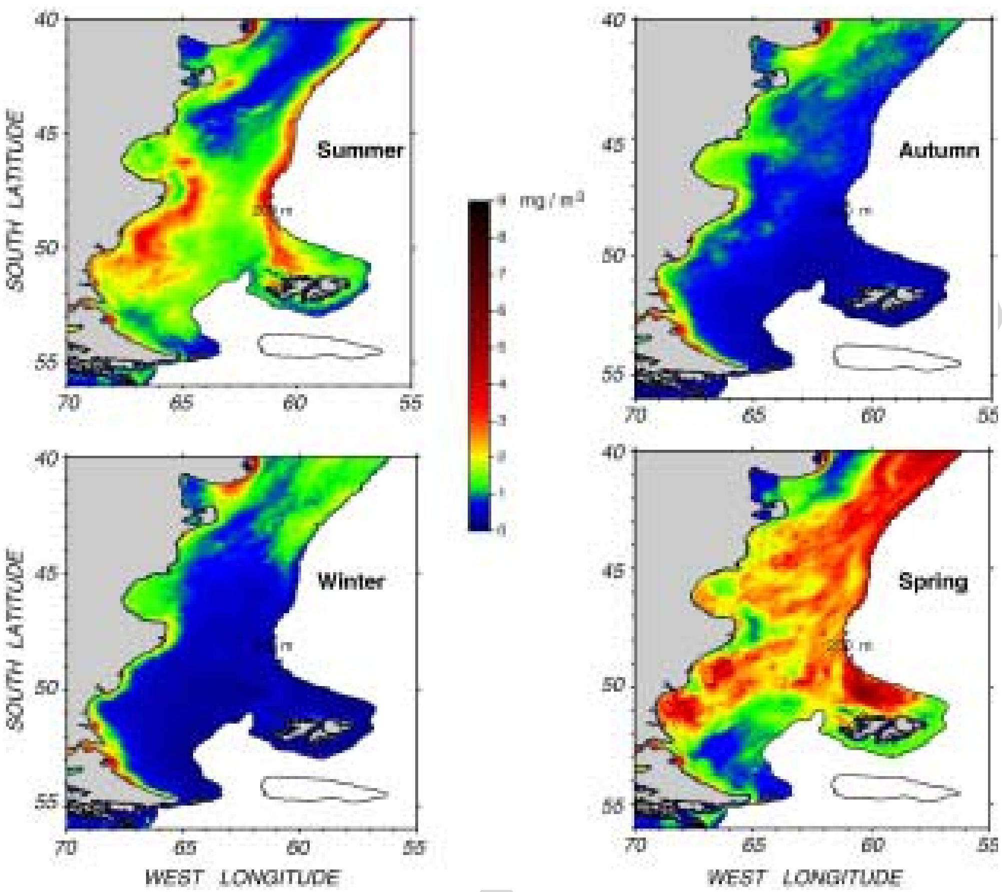

Fig. 2. Seasonal mean chlorophyll maps derived from SeaWiFS data, for the period 1998–2003.

indicators of coexistence of a stratified zone receiving adequate light levels at the surface, and a more vertically mixed zone with better access to nutrients generated at the bottom, it is expected that a horizontal exchange between both generates the optimal conditions to increase the growth of marine phytoplankton.

The development of the seasonal thermocline and the subsequent vertical stratification is not present in all PCS. At points south of 51° S, Krepper and Rivas (1979) have observed that the water column remains homogenous even in December. Sabatini et al. (2004) mention, for the same zone, the presence of salinity fronts and their associated upwelling processes, which cannot be detected with SST satellite data. Therefore, it is necessary to consider that surface front identification only from SST data is incomplete.

Identification of an adequate variable representing biological activity could be a difficult process. Taking into account that the aim is to register the "simultaneous" occurrence of physical and biological processes in large regions, the advantages of variables obtained through sensors onboard Earth-monitoring satellites are unsurpassed. These variables allow a synoptic coverage of physical and biological properties as well as a consistent methodology. In addition, Romero et al. (2006) say that although all regions present substantial inter-annual variations, the bloom locations are stable and all the high chlorophyll-*a* regions in the PCS are associated with well-defined fronts. This is why, in the present work, we will use surface chlorophyll concentration obtained from SeaWiFS data as biological variable.

Several studies have shown that different organisms (phyto- and zooplankton, nekton and marine birds) increase their concentrations exactly over the fronts, while other studies show that the concentration is higher only on one side of the front. As regards the phytoplankton, it is accepted that chlorophyll concentration increases only on one side of the front. In consequence, a frontal zone could be interpreted as an area that separates higher concentrations from lower ones. The limit of influence of the frontal zone on the higher chlorophyll concentration region is not a simple question to examine.

The present work aims to quantify the influence of the identified temperature fronts in the PCS on its biological activity. The main aim is the numerical assessment of the importance of thermal fronts in surface chlorophyll distribution.

2. Methods and data

Eighteen-year (1985–2002) mean monthly SST Pathfinder data with 9 km spatial resolution were used to estimate monthly surface gradients by finite differences. A cumulative histogram was constructed with the intensity of SST gradient for each of the 216 months, and, using the criteria described by Saraceno et al. (2004), the magnitude of the gradient threshold was identified (which was used for the classification of each pixel as frontal or not frontal). Then mean climatological austral seasons (January, February, March — summer; April, May, June — autumn; July, August, September — winter and October, November, December — spring) were calculated from the intensity of these gradients. In Fig. 1, intensity of the surface gradients is shown for each season. Pixels where intensity is higher than 0.045 °C km^{-1} can be considered as frontal.

Monthly composite images of surface chlorophyll concentration were constructed with 6 years (1998–2003) of SeaWiFS data, with a spatial resolution of approximately 4 km. Then, mean climatological season distributions were calculated (Fig. 2) with the same temporal intervals as those used with the SST data. The error of the satellite estimations of the surface chlorophyll concentration is difficult to evaluate. A more detailed analysis of the trustworthiness of the satellite data used in this paper can be found in Rivas et al. (2006). 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.

In order to identify areas where chlorophyll concentration could be influenced by the presence of a thermal front, seasonal distribution of chlorophyll and thermal gradient were analyzed jointly. During autumn and winter, SST fronts and major pigment concentration areas show certain coincidence. The area of high chlorophyll concentration can be found in the vicinity of the coast and zones with higher intensity are associated with fresh water discharge. At this time of the year they are limited to very small areas, in consequence their concentration rarely has a significant influence on the total concentration. It is probable that the presence of suspended sediments brought by the fresh water flow contaminates the satellite signal. To sum up, during cold

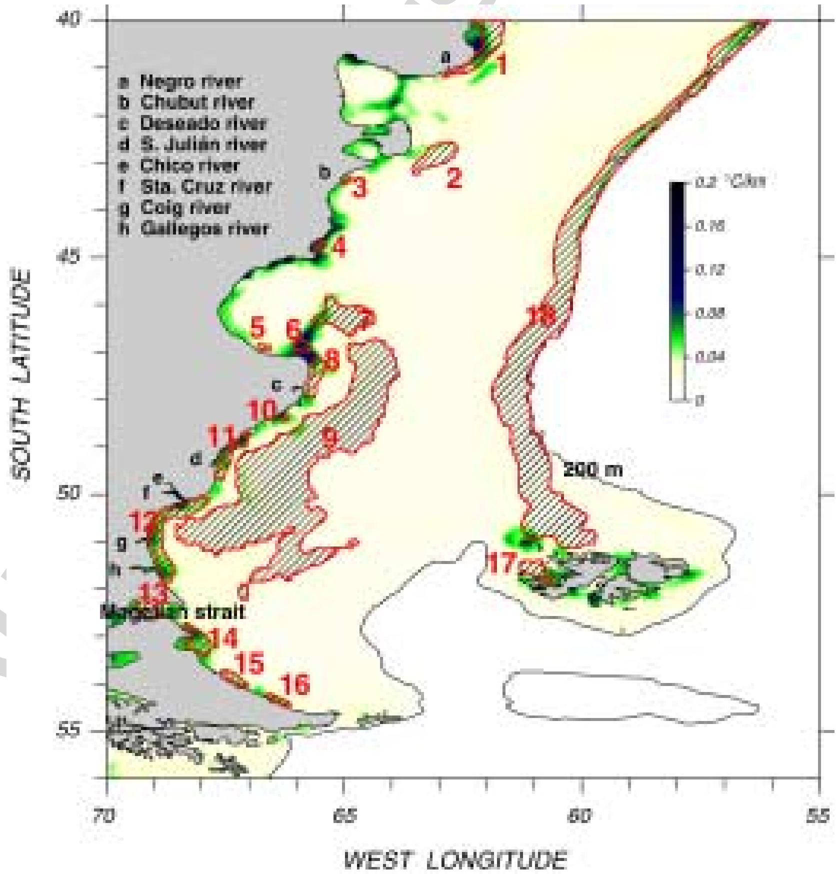

Fig. 3. Summer SST gradient magnitude and the location of the 18 regions where the surface chlorophyll is greater than 2.24 mg m^{-3} in summer or chlorophyll frontal areas (red hatched areas). The location of the main fresh water inflow (rivers and the Magellan strait) is indicated.

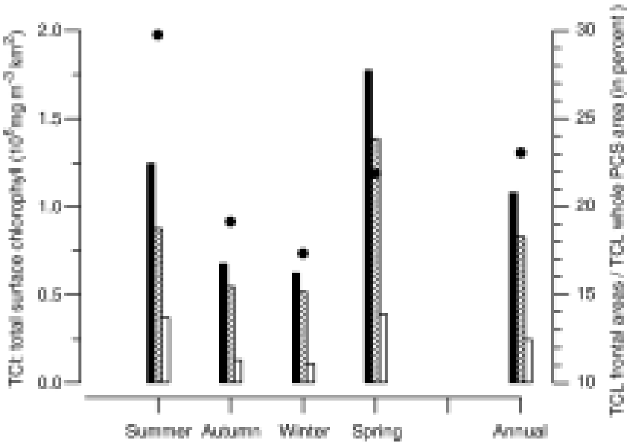

Fig. 4. Seasonal and annual mean total surface chlorophyll integrated over the whole PCS area (black bars), no frontal or residual area (dashed bars) and the 18 frontal areas considered as a group (white bars). Dots (right axis) indicate the total surface chlorophyll frontal areas/total surface chlorophyll whole PCS area ratio in percentage.

seasons the areas of major surface chlorophyll concentration are very reduced and data retrieved from satellite observation may possibly not be completely reliable. During spring practically the whole region shows high chlorophyll level caused by the seasonal bloom typical of temperate regions, which complicates the association of productive areas with thermal fronts. During summer temperature gradients are higher and thermal front areas are better defined (Fig. 1), with areas of high chlorophyll values observed in their vicinity (Fig. 2). Once the spring bloom has consumed available nutrients in the photic layer, the influence of thermal fronts on chlorophyll records becomes more tangible. The proximity of mixed and stratified water in fronts brings about adequate illumination conditions as well as the availability of nutrients to maintain high production values. Thus it may be inferred that regions with high chlorophyll concentration during summer are regions where physical fronts influence biological activity. In order to delimit these high productivity zones, mean spatial chlorophyll concentration during summer (1.51 mg m^{-3}) and its standard deviation (0.73 mg m^{-3}) were calculated. A graph was developed showing the chlorophyll concentration isoline equivalent to the mean value plus one standard deviation (2.24 mg m^{-3}). Fig. 3 shows the curve with summer SST gradient intensity. In general, main productivity zones (chlorophyll concentration higher than 2.24 mg m^{-3}) do not exactly coincide with the adjacent front zones.

Eighteen zones with a chlorophyll concentration during summer higher than 2.24 mg m^{-3} were delimited and defined as areas where the presence of a physical front affects photosynthetic activity (see Fig. 3), or biological fronts. Defined with these subjective criteria, the zones where biological activity is altered by the presence of a thermal front, the surface chlorophyll in these areas, its relationship with the surface chlorophyll of the whole region, and the seasonal evolution of this relationship were calculated.

In each zone, and in the whole PCS, the total surface chlorophyll concentration was calculated for each season of the year with the following surface integral:

$$\mathrm{ClT}_i = \int_{\mathrm{Ai}} \mathrm{Cl}\ \mathrm{d}A_{\mathrm{i}}$$

where C1 is the surface chlorophyll concentration (mg m^{-3}) and A_{i} is the area of the frontal region under consideration. This variable is used for estimating the importance of each frontal region in each season of the year in the chlorophyll concentration of the entire PCS. Units are 10^6 mg m^{-3} km^2.

To have an idea of how intensely a specific region is affected in its biological activity, the total surface chlorophyll per area unit was used, or its equivalent, i.e. mean spatial chlorophyll observed in the area:

$$\mathrm{MCL}_{\mathrm{i}} = \mathrm{ClT}_{\mathrm{i}}/A_i$$

3. Results

Fig. 4 and Table 1 show, for each season of the year and the annual mean, the total surface chlorophyll for

Table 1
Total surface chlorophyll (TCL) and mean spatial chlorophyll (MCL), estimated for each season and the annual mean, in all the PCS, the no frontal or residual zone and the 18 frontal areas considered as a group

	TCL: Total surface chlorophyll (10^6 mg m^{-3} km^2)			MCL: Mean spatial chlorophyll (mg m^{-3})		
	All PCS Area=0.823 10^6 km^2	No frontal Area=0.7021 10^6 km^2	Frontal area=0.1209 10^6 km^2	All PCS	No frontal	Frontal
Summer	1.2464	0.8755	0.3709	1.51	1.25	3.07
Autumn	0.6774	0.5476	0.1298	0.82	0.78	1.07
Winter	0.6255	0.5170	0.1085	0.76	0.74	0.90
Spring	1.7714	1.3837	0.3877	2.15	1.97	3.21
Annual	1.0802	0.8310	0.2492	1.31	1.18	2.06

the entire PCS, the sum of total surface chlorophyll in the 18 areas defined as affected by the thermal fronts, and the difference between the two, also regarded as the total surface chlorophyll of the residual zone or non frontal zone. The right axis in Fig. 4 shows the sum of the total surface chlorophyll in the 18 frontal zones as a percentage of the total surface chlorophyll for the entire PCS. It may be appreciated that areas regarded as affected by the thermal fronts correspond all together amount to 14.7% of the total area of the PCS (PCS total area: 0.8230 10^6 km^2, all frontal areas: 0.1209 10^6 km^2), contributing with more than 23% of the annual mean of total surface chlorophyll. This percentage reaches its peak during summer, with nearly 30%. During spring, although total surface chlorophyll in the frontal areas is higher than in summer (0.3877 vs. 0.3709 10^6 mg m^{-3} km^2), its influence on the total surface chlorophyll of the entire region is in fact lower than the annual mean (21.9%), probably due to the spring bloom that occurs in almost all the PCS. During autumn and winter, the total chlorophyll percentage (19.2% and 17.3% respectively) scarcely reaches the percentage of the whole area in question (14.7%). During the cold period, when the water column is vertically mixed in practically the whole PCS except for these regions where the inflow of continental fresh water exceeds the homogenizing effect of surface cooling and tide, the influence of physical fronts on the biological production is minimum.

In Fig. 5 (see also Table 1), for each season of the year as well as annual mean, the mean spatial chlorophyll concentration was graphed for the entire region, the non-frontal residual zone and the 18 frontal zones considered as a group. If we do not take the 18 frontal zones into consideration, chlorophyll mean does not vary very much.

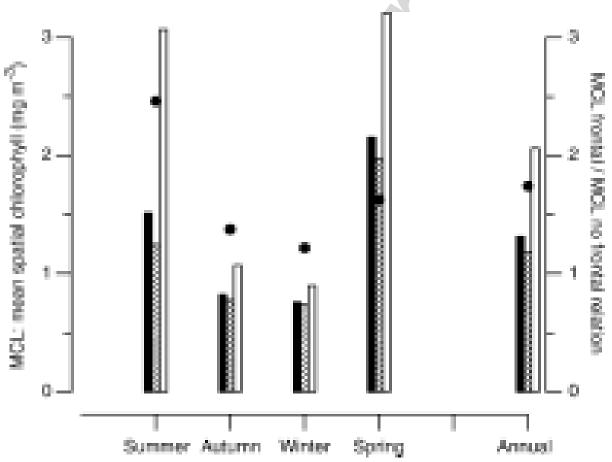

Fig. 5. Spatial mean seasonal and annual chlorophyll in the whole area (black bars), no frontal or residual area (dashed bars) and the 18 frontal areas considered as a group (white bars). Dots indicate the ratio frontal/no frontal mean spatial chlorophyll relation (right axis).

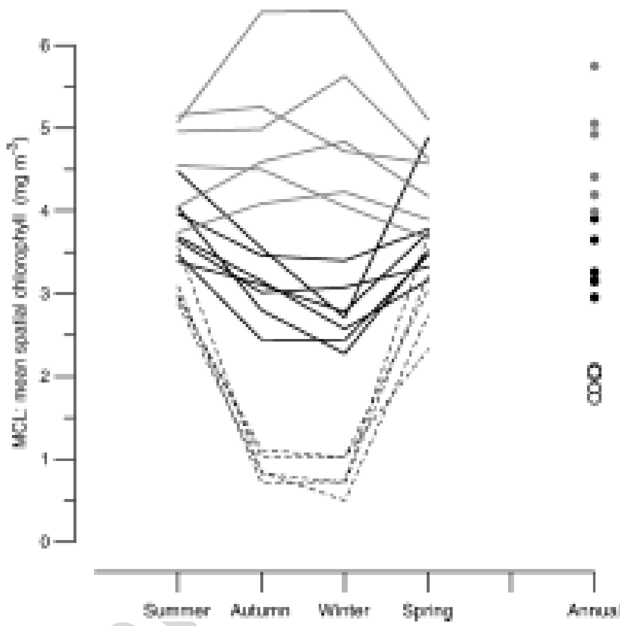

Fig. 6. Seasonal evolution and annual average of mean spatial chlorophyll in each frontal area. Areas identify with numbers 2, 7, 9, 17 and 18 in Fig. 3 (dashed lines), areas identify with numbers 4, 5, 6, 8, 11, 12 and 16 in Fig. 3 (black lines) and areas identify with numbers 1, 3, 10, 13, 14 and 15 in Fig. 3 (gray lines).

The difference observed between chlorophyll mean for the whole region and that of the non-frontal zone reaches 17.2% during summer (1.51 mg m^{-3} vs. 1.25 mg m^{-3}), and does not even reach 9% during the rest of the year. This is possibly due to the fact that non-frontal zones cover more than 85% of the total area. In contrast, during summer, chlorophyll spatial mean in the frontal zones as a whole is more than 145% larger than that observed in the non-frontal zone (3.07 mg m^{-3} vs. 1.25 mg m^{-3}). For the annual mean this percentage drops to 74.6%, reaching 62.9% in spring, 37.2% in autumn, and less than 22% in winter. These percentages make the frontal zone image remain clearly defined during summer, when approximately 85% of the area will have a determined chlorophyll concentration mean (1.25 mg m^{-3}), while the remaining 15% has a 2.45 times larger value (3.07 mg m^{-3}).

Mean chlorophyll for all frontal areas (Fig. 5) shows a very marked seasonal cycle with higher values during spring (due to the seasonal bloom that takes place in almost all PCS) and summer (caused by the influence of thermal fronts), and lower ones during autumn and winter. Mean chlorophyll values calculated for the frontal zones considered as a whole verify the proposed hypothesis for the definition of a frontal zone: the influence of a physical front allows it to extend until summer most of the activity registered during spring as a consequence of the establishment of the seasonal thermocline. Nevertheless, this seasonal trend is not uniform over all the 18 frontal

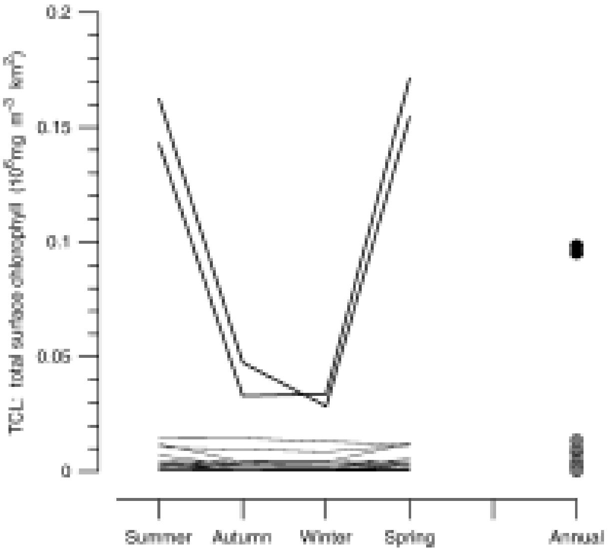

Fig. 7. Seasonal evolution and annual mean of total surface chlorophyll integrated over each frontal area. Black lines: areas identify with numbers 9 and 18 in Fig. 3, gray lines: areas identify with numbers 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16 and 17 in Fig. 3.

areas under consideration. When analyzing the trend of each frontal area separately, three patterns are found. Firstly, five areas are identified (numbers 2, 7, 9, 17 and 18 in Fig. 3), among which the larger ones are found, that show the marked seasonal behaviour described before: higher values during the warm season and lower ones during the cold season when the water column is more mixed. These areas are found on the stratified side of the surface thermal fronts (see Figs. 6 and 3). Secondly, there are seven more coastal areas that also show the same trend but with a less pronounced annual cycle and higher levels of chlorophyll (areas identified with numbers 4, 5, 6, 8, 11, 12 and 16 in Fig. 3). These are situated on the colder and shallower side of the surface thermal fronts. Thirdly, there are six areas adjacent to the coast, of reduced extension (numbers 1, 3, 10, 13, 14 and 15 in Fig. 3), those show even higher levels of chlorophyll and do not show a well defined seasonal variability, presenting higher values during the cold season. These areas are in general associated with continental fresh water inflow, where salinity unrelated to the surface heat flux could regulate stratification of the water column. On the other hand, suspended sediments that accompany the continental inflow contaminate the satellite signal and thus decrease data reliability. Within this group, an area situated near the outlet of the Chubut River, with extremely high chlorophyll values and reduced size, is observed (number 3 in Fig. 3). Another peculiarity noted is that certain coastal zones that show high chlorophyll levels in summer, and have been selected as possible candidates to be influenced by physical fronts, are situated in the vicinity of river outlets: the Deseado, the San Julián, the Chico-Santa Cruz, the Coig and/or the Gallegos (see Fig. 3 for location). These zones should be expected to behave according to the third pattern rather than the second one, with higher values during the warm season and annual lower signal, as they do.

Mean spatial chlorophyll values allow to identify these three patterns, but on analyzing the seasonal evolution of the surface integral of chlorophyll in each frontal zone, two zones are noted which, due to their extension, practically control the production of the whole area considered to be affected by the fronts (Fig. 7). Indeed the 18 frontal areas as a group cover 14.7% of the entire study region (0.1209 10^6 km^2 of a total of 0.8230 10^6 km^2), but mainly two of them (areas identified with numbers 9 and 18 in Fig. 3) cover 12.5% of the whole area (0.1030 10^6 km^2), which represents more than 85% of the area considered as affected by physical fronts. These areas show higher total surface chlorophyll levels during the warmer season of spring and summer. Due to their extension, these two condition the trend of the whole frontal zone (see Fig. 7).

4. Discussion and conclusions

Richardson et al. (1998) have shown that in the stratified zone of the Northern Sea more than 70% of primary production takes place at the sub-surface maximum of chlorophyll during summer. Richardson and Bo Pedersen (1998) quote a series of works that establish that the distribution of this sub-surface maximum of chlorophyll is not uniform, and that peaks are more intense in the proximity to frontal zones. It would not be rare if something similar occurred in the PCS, but it is impossible to ascertain using only surface data. In consequence, the quantification of the influence of physical fronts over biological activity determined in the present work turns out to be an underestimate of the actual process.

Fronts, as hydrologic structures, influence the distribution of organisms in a broad range of ways that include taxonomic selection, transport and/or concentration, and the increase in productivity, among others. Particularly in the PCS, although frontal zones are comparatively small areas, they play a pivotal role in ecological processes, making high biological production possible; providing feeding and/or reproductive habitats for fishes, squids and birds; acting as retention areas for larvae of benthic species; and promoting establishment of benthic invertebrates that benefit from the organic production in the frontal area (Acha et al., 2004 and references therein). In the present work, only the influence of surface thermal fronts over the surface chlorophyll concentration in the PCS at a seasonal scale has been subjectively quantified.

In vertically homogenous water there is good nutrient availability, while stratified water obtains adequate light levels. This is why photosynthetic activity in the shelf is highly dependant on the stability of the water column. A superficial thermal front is an indicator of the confluence of stratified and mixed water. In non-frontal zones the co-existence of mixed and stratified water only takes place during spring (during the establishment of the seasonal thermocline) and, to a lesser degree, during autumn (when the seasonal thermocline breaks). This is the reason why higher concentrations of surface chlorophyll are found in the area of influence of thermal fronts. In the PCS this theory has been verified by recent analyses of the spatial-temporal distribution of surface chlorophyll (Romero et al., 2006; Rivas et al., 2006).

It is probable that surface chlorophyll distribution near the fronts has patchy behaviour, as Richardson et al. (1985) found. Some of these discontinuities are smoothed while using the seasonal surface chlorophyll distributions.

Using these criteria, 18 areas considered as affected by the presence of a physical front were distinguished. All areas cover less than 15% of the total surface, but contribute with more than 23% of the surface phytoplankton annual mean biomass. Considered as a group, during summer they show chlorophyll values very similar to those in spring. While three pattern trends were identified in the frontal areas, only two of them condition the pattern of the group, due to their horizontal extension. In both areas high nitrate and phosphate surface concentrations during the entire warm period (spring and summer) were found by Brandhorst and Castello (1971) and more recently by Paparazzo (2003). The mechanisms responsible for providing the illuminated layer with nutrients are related to the presence of the adjacent thermal fronts.

Surface thermal fronts in the PCS are relatively easy to identify and locate. They occupy reduced, relatively well defined areas, although it is not simple to associate them with clearly defined high productivity areas. Possibly due to advective and diffusive processes, the image of an arid landscape with very productive valleys or oasis associated with specific local conditions, does not adjust to the reality of the PCS. If the aim is to quantify the influence of frontal zones on biological activity, delimiting the area of influence is an obstacle to be overcome. The present work is a step in this direction.

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