Seasonal and Interannual Variability of Coccolithophore Blooms in the Vicinity of the Patagonian Shelf Break (38°S – 52°S)

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Abstract. Previous studies have shown that the Patagonian shelf is a region of high phytoplankton productivity (very intense ocean blooms) and strong uptake of atmospheric CO₂. The timing and duration of coccolithophore blooms, whose members are armored with miniature plates of calcite, and other phytoplankton groups blooms along the Patagonian shelf break, were analyzed using satellite-derived time series of chlorophyll, calcite, and sea-surface temperature, and historic hydrographic data. The primary mechanisms responsible for the seasonal variability and succession of phytoplankton groups along the edge of the continental shelf are changes in light intensity and nutrient supply within the mixed layer.
Introduction

The Patagonian shelf off Argentina shows complex dynamic processes influenced by tides, the confluence of Brazil and Malvinas (Falkland) Currents, and the transition zone between the shelf water of various origins and the Malvinas Current waters. The Patagonian Shelf tides constitute one of the strongest regimes in the world, where a significant amount of global tidal energy is dissipated by the effect of bottom friction (1). Strong vertical mixing is promoted by very energetic tidal currents, which in turn create shelf fronts associated with high chlorophyll concentrations visible by ocean color satellites (2, 3). The Brazil/Malvinas Confluence (BMC) near 39°S results from the collision of the southward Brazil Current (BC) with the Malvinas Current (MC), which is a northward branch of the Antarctic Circumpolar Current (ACC). The MC transports cold and relatively fresh sub-Antarctic waters equatorward, and the BMC generates one of the most energetic regions of the world ocean (4). The MC is steered by the topography of the shelf break forming a distinct oceanographic front. High phytoplankton biomass associated with the shelf-break front is attributed to nutrient input by upwelling processes (5). The frontal areas in the shelf and shelf-break are associated with intense CO₂ uptake in summer, with estimated mean seasonal fluxes of up to -5.7 mmol CO₂ m⁻² d⁻¹ (6). Model studies do suggest that this area has a significant biogenic carbon export rate (7), with an important contribution from biological productivity (8).

Previous remote sensing studies associated the Patagonian shelf-break front with occurrence of coccolithophorids (9). Early phytoplankton samplings in the area reported
the presence of the species *Emiliania huxleyi* (10). The key environmental and ecological factors controlling the blooms of these organisms are particularly illumination, mixed layer depth, and photoadaptation. Blooms of *Emiliania huxleyi* have been reported from many regions around the globe, especially in the North Atlantic (11-14). A review of the literature on the occurrence of *E. huxleyi* and environmental factors (15) reveals that they are associated with highly stratified water, with mixed layers almost always ≤30m, indicating a high light requirement. Concerning nutrients, this species seems to tolerate and grow well under low levels of phosphate (high N:P ratios) (16, 17), presumably due to their ability to use dissolved organic phosphorus. Silicate levels can also be low during *E. huxleyi* blooms, as many times they follow diatom blooms (12, 14, 18). Oceanic strains of this species have also been shown to tolerate low concentrations of iron (Brand, 1991).

In this paper we offer an analysis of the timing and duration of both coccolithophore and other groups of phytoplankton blooms along the Patagonian shelf break (Figure 1), as well as insights on the mechanisms that drive and maintain these blooms. Our analysis is based on time series of chlorophyll and calcite concentrations derived from satellite ocean color data, historical hydrographic data, and other ancillary satellite data.
Data Sources and Methodology

The calcite images were processed from daily time series of 4-km SeaWiFS GAC L1A cut-outs for the region using the two-band algorithm for suspended calcium carbonate (also known as particulate inorganic carbon (PIC)), based on normalized water-leaving radiance ($nLw$) at 440 and 550 nm (19, 20). The Chl $a$ was obtained from GAC L1A $nLws$ (443, 490, 510, and 555 nm) using the OC4v4 chlorophyll algorithm (21). The SeaWiFS time series covers the period of September 1997 – October 2005, while the AVHRR SST data spans from January 1997 to December 2004. The monthly composites of the L2 cut-outs for Chl $a$ were obtained under separate processing using revised thresholds for coccolithophore masking (Christopher Brown personal communication), which provide more accurate detection of coccolithophore presence.

Time series of photosynthetic available radiation (PAR) were obtained using the PAR SeaWiFS algorithm (22, 23), and sea-surface temperature (SST) was obtained from monthly 4-km AVHRR Pathfinder grids from the Jet Propulsion Laboratory PODAAC. Seasonal climatologies of SST, sea-surface salinity (SSS), and nutrients (NO$_3$, PO$_4$, and SiO$_2$) were obtained from the World Ocean Atlas 2001 (24). Seasonal mixed layer depth (MLD) climatology was obtained from the Climatological Atlas of the World Ocean (25). Monthly climatologies of Chl $a$, PIC, PAR, and SST were made from the available satellite products.
Discussion and Results

Figure 2 shows monthly composites of calcite and Chl a for November and December 2004, and January 2005. The white polygon delimits the portion of the Patagonian shelf break from which the data were extracted for analyses. As shown in Figure 2, there are phytoplankton blooms (including calcite-producing species) that occur over the shelf at depths less than 100m but they are not as spatially coherent nor locked to the bathymetry as the shelf break blooms, thus our choice of regional domain for analyses. Note that the Chl a concentrations are high (> 4 mg m\(^{-3}\)) during November but are much lower (< 0.5 mg m\(^{-3}\) on average) during December and January. Conversely, almost no calcite was detected within the study region in November, but significant concentrations (6 to 10 mmol C m\(^{-3}\)) were detected by the calcite algorithm during December and January. This result from ocean color data analyses was verified with *in situ* data. In November 2004 we carried out a cruise along the high chlorophyll band in the Patagonian shelf-break, to determine the phytoplankton species composition, primary production rates and the main oceanographic and optical features associated with the bloom in spring. Based on preliminary analyses of these data, the distribution of phytoplankton groups across the shelf-break front showed a transition between diatom and dinoflagellate-dominated community in the front to a small size phyto-flagellate dominance east of the shelf-break front. Only a few cells of the species *Emiliania huxleyi* were detected in the shelf-break plankton samples, which represent the inoculum for the subsequent bloom development observed by satellite data.
To demonstrate the environmental conditions conducive to phytoplankton blooms and species succession along the Patagonian shelf break, the seasonal cycle of relevant parameters is shown in Figure 3. The relevant parameters shown in Figure 2 are monthly means of SST, SSS, MLD, NO$_3$, PO$_4$, SiO$_2$, Chl $a$, PIC, and PAR for the regional polygon shown in Figure 2. The MLD is derived from temperature stratification alone (25), but salinity has little effect on the calculation of the MLD as it changes very little (0.3%) throughout the year along the shelf break (see Table 1). The actual monthly values for each parameter are summarized in Table 1. Note that the time scale spans from June to May to place the peak PIC and Chl $a$ in the center of the plot for convenience.

Inspection of Figure 3 and Table 1 reveals the following seasonal progression for the physical and biogeochemical parameters. The classical spring bloom behavior starts in September when there is an increase in SST and PAR, a sharp reduction of the MLD, a subsequent reduction in nutrient concentration due to uptake by photosynthesis, and a quick rise in chlorophyll concentration. The mean Chl $a$ concentration peaks in November and stays above 1.0 mg m$^{-3}$ until March when surface PAR begins to decrease below 100 Watts/m$^2$ and the MLD begins to increase above 40 m. However, the calcite concentration starts to increase later in November and peaks in January when the mixed layer is shallowest (17.6m), PAR is near a peak (161.6 Watts/m$^2$), and all nutrients are at their lowest concentrations and phosphate reaches its minimum value (0.68 µM). These environmental and ecological conditions, which are conducive to growth of $E. huxleyi$ and were identified in our analyses, closely match the conditions described in the literature (see introduction), which explains the phasing and duration of different phytoplankton blooms along the Patagonian shelf break. A community dominated by
diatoms and dinoflagellates are replaced by lower biomass coccolithophorids dominance as predicted in phytoplankton succession models (26).

Figure 4 shows satellite-derived time series of Chl $a$, total calcite, SST, and PAR for September 1997- October 2005 (January 1997 – December 2004 for SST). The total calcite ($10^9$ gC m$^{-1}$) was obtained from the product of calcite concentration and the area of each pixel and then summed over the entire regional polygon (see Figure 2). Note that the Chl $a$ starts rising every year around September and peaks around November, with a few exceptions (2001 and 2003) where the increase in Chl $a$ started one or two months earlier. The calcite always reaches its peak after the maximum Chl $a$ concentration has been reached, in accordance with the analysis of Figure 3. Also note that PAR leads SST by about 2 months, implying that light becomes available for the spring bloom before the MLD reaches a minimum value. Even though the timing of the phytoplankton blooms is almost always predictable, their intensity and duration are highly variable from year to year. Variability in vertical stratification, MLD, and nutrient supply may play a major role in driving this variability.

**Summary and Conclusions**

We identified environmental and ecological processes that drive the timing and duration for the growth of the different phytoplankton groups along the Patagonian shelf break. The seasonal variability and succession of these groups respond to light intensity and nutrient supply changes within the mixed layer. The early spring bloom is presumably diatom-dominated and starts in September under nutrient-rich upwelled
Malvinas waters when the mixed layer begins to shallow (<80m), and peaks around November when the MLD is less than 40m. At this time the phytoplankton community is composed mainly of diatoms and dinoflagellates. After nutrients are depleted from the spring uptake, a coccolithophore bloom begins in November when the MLD is less than 40m, and peaks in January when the MLD reaches its minimum (18m) and PAR reaches its maximum intensity. This finding is consistent with earlier studies that identify maximum coccolithophore growth under well-illuminated shallow MLD and low phosphate concentrations, which are environmental conditions that limit the growth of diatoms and other groups.

Although the ocean color data shows that the timing and location of the Patagonian shelf break bloom is very predictable from year to year, significant interannual variability was identified on the intensity of the bloom. Further oceanographic cruises are planned to investigate the causes of this interannual variability. We anticipate that the degree of vertical stratification, and consequently the availability and proportion of nutrients within the euphotic layer, plays a role on driving the interannual changes.
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**References**


Table 1. Monthly means of SST (°C), SSS (psu), MLD (m), nitrate (µM), phosphate (µM), and silicate (µM) from seasonal climatology, and PAR (Watts/m²), Chl a (mg m⁻³), and PIC (mmol C m⁻³) derived from SeaWiFS data.

<table>
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<th>Mon/Parm</th>
<th>SST</th>
<th>SSS</th>
<th>MLD</th>
<th>PAR</th>
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<th>PO₄</th>
<th>SiO₂</th>
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**Figure Captions**

**Figure 1.** True color SeaWiFS image of 27 November 2001 showing a coccolithophore bloom along the Patagonian shelf break (bright light blue color). Superposed on the image are the approximate location of the Malvinas and Brazil currents and their confluence.

**Figure 2.** SeaWiFS-derived monthly composites of calcite (a, b, c, in mmol C/m$^3$) and chlorophyll (d, e, f, in mg/m$^3$) for November, December 2004, and January 2005 (top, middle, and bottom panels, respectively). The white polygon delimits the regional domain of study and the black contours correspond to the 200, 500, and 1000m isobaths.

**Figure 3.** Seasonal cycle of mean SST, SSS, MLD (a), nutrients (b), chlorophyll, PIC, and PAR (c) within the regional domain defined in Figure 1.

**Figure 4.** Time series of SeaWiFS-derived mean chlorophyll, PIC (a), PAR, and AVHRR SST (b) for the regional domain of Figure 1. The vertical red line in (a) corresponds to the time period of the Patagonian shelf-break cruise (November 2004).
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