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ORIGINAL RESEARCH ARTICLE

Spatio-temporal variability in the Brazil-Malvinas Confluence Zone (BMCZ), based on spectroradiometric MODIS-AQUA chlorophyll-*a* observations

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Summary The Brazil—Malvinas Confluence Zone (BMCZ) is characterized by high environmental variation, which could be reflected in several optical types of water, from one containing only phytoplankton and sea water to other optically more complex. In this paper, we analyze the spatio-temporal variability of the Chlorophyll-*a* detected by the ocean color sensor ($CHLA_{sat}$) in BMCZ in order to understand its environmental variability. We use the MODIS-Aqua $CHLA_{sat}$ monthly composites imagery from 2002 to 2015, and applied two statistical methods: the correlogram-based robust periodogram to identify, over a broad spectrum of temporal, the most significant periodicities, and the pixel gradient distribution to study the spatial-temporal gradients within the BMCZ and variations over the continental shelf and coastal waters. Our results point out to the predominance of the annual cycle over most of the investigated area, although an area from latitude 37°S in direction NE, alongshore of Uruguay to Brazil, evidences interannual periodicities, possibly related to variations in the discharge of the Rio de la Plata associated with the El Niño phenomena. The ocean color spectroradiometric signature in terms of

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pixel gradient presents a relatively high variability (~0.0 to 0.65 mg m^{-3}); in particular the high values of the pixel gradient correspond to saline front of the estuarine system of Rio de la Plata, and to the strip of the platform that extends along the isobaths of 80 m (coast of Uruguay), especially in the center and south of the study area.

1. Introduction

Ocean fronts over continental shelf are closely linked to bathymetric features. Besides these, other important fronts are associated with the discharge of large rivers: Rio de la Plata, for instance, represents a clear example over our study area (Brazil-Malvinas Confluence Zone). The discharge of this river is one of the largest in the southern hemisphere and the second largest after that of the Amazon River, contributing to an average of about 24,000 m^3 s^{-1} of fresh nutrient-rich water of the Atlantic Ocean. Furthermore, seasonal rainfalls, especially intense during El Niño periods, contribute to increase the discharge of Rio de la Plata up to about 80,000 m^3 s^{-1} (Acha et al., 2004; Depetris and Kempe, 1990; Guerrero et al., 1997; Huret et al., 2005; Mechoso and Iribarren, 1992). The fresh water plume travels over the continental shelf mainly responding to the bottom topography and seasonal characteristics of the main winds and can extend its influence to northern Uruguay — South Brazil or move south until reaching Mar del Plata city (Braga et al., 2008). The ocean waters are also influenced by contributions from warm waters of subtropical origin (Brazil Current) and cold waters of subantarctic origin (Malvinas current). These two water masses converge on the edge of the continental shelf, creating what is known as the Brazil-Malvinas confluence (BMCZ) (Gordon, 1989).

This region contrasts with the low phytoplankton concentrations of the Brazilian current (nutrient scarcity affects the growth of the primary producers) and the Malvinas current, although they are rich in nutrients, due to the presence of permanent winds, these vertically mix the water column and prevent the production of phytoplankton. Phytoplankton accumulation is observed only along narrow strips on the ocean surface, and its productivity is due to the fact that both currents provide elements that favor their growth and concentration. If the Malvinas Current brings nutrient-rich water, the Brazil Current makes phytoplankton growth quite stable and thanks to such stability of subtropical warm waters, the growth of phytoplankton is very significant (Carreto et al., 1995; Romero et al., 2006).

The frontal areas coincide with the geographical location of phytoplankton blooms. Marine phytoplankton abundance and productivity are subject to complex set of relationships between physical and biological patterns that appear to be different in physically distinct regions. Several ocean studies, in which ocean color satellite images were used, have shown high chlorophyll-*a* concentration structures in the BMCZ (Piola et al., 2000), but on the other hand, still few studies have been carried out on its space-time variability in such important area of the confluence (Machado et al., 2013).

The availability of remote sensing technology has enabled the identification of physical and biological synoptic patterns over the BMCZ. Most studies have been based on the analysis of the seasonal variability of in situ Chlorophyll-*a*, while the interannual variability remains still less approached due to the relatively short length of time series (Garcia and Garcia, 2008; Lutz et al., 2010; Machado et al., 2013; Romero et al., 2006).

Changes in ecosystems have already been reported by other authors, and the abrupt and nonlinear potential can again be more likely future changes (Machado et al., 2013). To understand these changes in marine ecosystems, with essential data sets with lots of information, thus, the satellite ocean color data are valuable assets. The global coverage provided by satellites provides a long time series of records of concentration of Chlorophyll-*a* detected by ocean color sensor ($CHLA_{sat}$), which is especially suited to identify patterns of temporal variability (Brandini et al., 2000; Piola et al., 2008), not only of phytoplankton biomass but also of all the optical components present in seawater, which absorb the same wavelengths as chlorophyll in optical complex water.

Argentina's continental shelf is a highly productive area; with values of phytoplankton abundance around three times the average for the rest of the oceans. Phytoplankton find not evenly distributed, but has a higher concentration in certain regions associated with ocean fronts (Marrari et al., 2016). In our study, we aim at describing quantitatively the temporal variations of the $CHLA_{sat}$ in the BMCZ by using two statistical approaches the robust periodogram and the pixel gradient distribution, never used to investigate the variability of the $CHLA_{sat}$, up to our knowledge.

2. Data analysis

The satellite data we used in our study are provided by the polar orbiting satellite AQUA, which carries the Moderate Resolution Imaging Spectrophotometer (MODIS). AQUA has a sun-synchronous circular orbit, overpasses any given location on Earth twice a day (one night time and one day time pass) and it orbits the Earth every 98.8 min, crossing the equator from south to north each day. Modis Aqua imagery were building at level 3 GLO (4 km resolution) in the Ocean color laboratory in the Facultad de Ciencias Marinas (Universidad Autonoma de Baja California). The level 1b data were obtained from the NASA Ocean Color Data web page (http://oceandata.sci.gsfc.nasa.gov/). The level 1b to level 2 conversion was made carried out using the SEADAS 6 using the specifically atmospherically data form each scene. The level 2 to level 3 monthly GLO imagery processing was made