SPATIO-TEMPORAL VARIATIONS IN CHLOROPHYLL-A CONCENTRATION IN THE PATAGONIC CONTINENTAL SHELF: AN EXAMPLE OF SATELLITE TIME SERIES PROCESSING WITH GRASS GIS TEMPORAL MODULES

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ABSTRACT

We studied the spatio-temporal variations of chlorophyll-a concentration and phytoplankton blooms in the continental shelf and shelf break of the Argentinean patagonic region by means of a time series of 11-years of MODIS/Aqua level 3 (L3) chlorophyll product. We aggregated data according to different granularities and estimated annual and monthly anomalies. We also studied the phenology of phytoplankton blooms determining bloom starting date and date of maximum concentration. Finally, we estimated and described statistical indexes such as minimum and maximum bloom areas, their occurrence date and bloom occurrence frequency. All the temporal processing of this raster dataset was done with the recently implemented temporal modules of GRASS GIS 7. This Free and Open Source Software provides the advantage of automating all (or most of) the processing, allowing the application of the same methodology to analyze satellite time series of different variables, like sea surface temperature.

Index Terms— Chlorophyll-a, MODIS, Argentina, time series analysis, GRASS GIS 7

1. INTRODUCTION

The planktonic microscopic and photosynthesizing organisms inhabiting oceans, globally called phytoplankton, constitute the basis of all oceanic food webs and play a fundamental role in carbon cycling and biogeochemical cycles [1]. Changes in phytoplankton biomass have significant impacts on all the biological, physical and geochemical processes occurring in the aquatic system. Therefore, there has been a rising interest in studying, monitoring, and understanding these variations and their phenology at the regional and global scales [2].

Since algae have photosynthetic pigments, such as chlorophyll-a, that absorb and reflect sun light mainly in the visible part of the electromagnetic spectrum, phytoplankton is capable of changing the optical properties of surrounding water, that is the *ocean color*. This principle allows to estimate chlorophyll-a concentration (proxy for phytoplankton biomass) through measurements of the reflected radiation from the upper ocean layer by means of remote sensing.

Phytoplankton blooms are a rapid increase in phytoplankton biomass, in terms of number of cells per volume unit or chlorophyll concentration. These blooms may occupy large extensions and are normally seen from space. Their occurrence and phenology are key for the maintenance of ocean food webs and carbon cycling [1].

The Argentinian continental shelf is one of the richest areas of the world oceans both in terms of phytoplankton biomass but also for the great abundance of economically important fish and mollusc species. However, the ecosystem dynamics is not completely understood. Therefore, the objective of this study was to analyze the spatio-temporal variations of satellite chlorophyll-a concentration (chl-a) and phytoplankton blooms in the continental shelf and shelf break of the Argentinian patagonic region using the newly implemented temporal modules of GRASS GIS 7 [3].

2. MATERIALS AND METHODS

We used a time series of 11 years (2003-2013) of MODIS-Aqua L3 chl-a (OC3Mv6 algorithm) images of 4.6 km and 8 days of spatial and temporal resolution, respectively. Data was imported into GRASS GIS [4], time-stamped and registered as a spatio-temporal raster data set (strds) in a temporal database. We first analyzed the availability of valid data over the study region (patagonian shelf and shelf break, from 38° S to 55° S and from 55° W to the coastline) and characterized its monthly and annual variability. Then, we studied the spatio-temporal variability of satellite chlorophyll-a concentration aggregating data with different temporal granularities. We aggregated data for the whole study period, annually, seasonally, and monthly using different descriptive statistics, such as the mean, median, standard deviation, minimum and maximum values. We also built monthly and seasonal climatologies for the whole period analyzed (2003-2013), and estimated monthly and annual anomalies. Next, we described and analyzed the spatial variability of temporal or phenological indexes, such as bloom starting date (estimated by 2 methods: the maximum rate of change and a threshold of 5% above the median) and date of maximum concentration. Finally, we estimated and described statistical indexes such as minimum and maximum bloom areas, their occurrence date and bloom occurrence frequency.

All the raster processing was done in GRASS GIS 7 [4], taking advantage of and testing the new temporal modules [3]. GRASS is a multi-purpose Free and Open Source GIS which can be used for geospatial data production, analysis and mapping. The software was chosen because it allows full control from Python, Perl, UNIX shell scripts, and DOS batch files that can combine several modules together in a workflow [5] and can be run fully automated and embedded into service chains as the GIS backend for Web Services. Besides, it integrates well with other software packages for geostatistical analysis, cartographic output, and Web GIS applications and it runs on various computer operating systems.

3. RESULTS

The results showed that mean chl-a concentration changes spatially during the cycle of a year and among years, both in values attained and in the distribution and extension of high concentration areas. However, a certain constancy was observed in the location and timing of phytoplankton maxima (bloom) occurrence. Figure 1 depicts the monthly mean climatology in chl-a concentration for the study area.

The greatest bloom extension was normally observed in austral spring (Oct, Nov, Dec), and covered the shelf break front (located along the 200 m isobath), the coastal tidal fronts and midshelf up to 52° S, with a latitudinal north-south progression direction that starts in September. On the other hand, during the austral summer months (Jan, Feb, Mar), on the other hand, the extension of bloom areas was reduced, and the highest values (chl-a $\approx$ 3.0-5.0 mg/m^3) remained along the shelf break, in the coastal tidal fronts, and over midshelf south of 46° S. In autumn (Apr, May, Jun), there were still high concentration areas (chl-a $\approx$ 2.0-3.0 mg/m^3) in the inner shelf north of 42° S and middle shelf between 44° and 46° S; while in winter months (Jul, Aug, Sep), the whole area showed low chl-a concentrations, with the lowest values (chl-a $<$ 0.5 mg/m^3) south of 46° S. Temporally, the spatial aggregates showed a marked annual cycle with high values in spring (that persist over the summer) and a decline through autumn-winter time. Besides, there seemed to be a secondary bloom in autumn, generally smaller than the spring (primary) bloom.

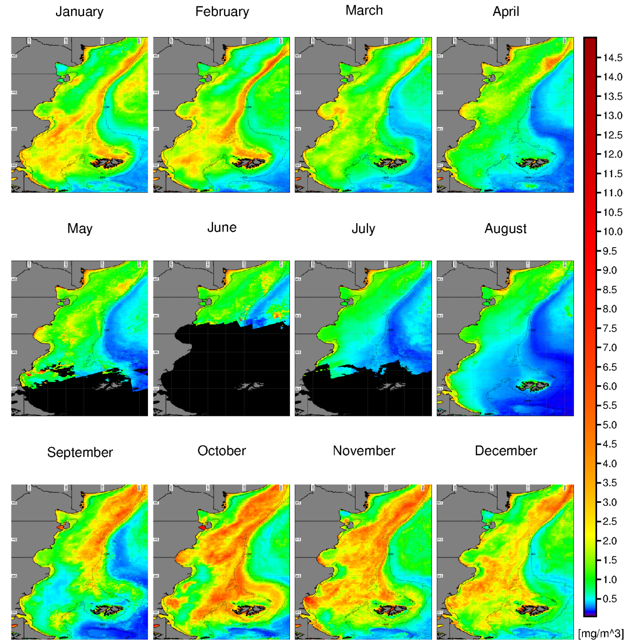

Fig. 1. Climatological monthly mean chl-a maps (mg/m^3) obtained from MODIS/Aqua L3 over the period 2003-2013. Black areas represent areas with no valid data and contours correspond to the 200 and 1000 m isobaths.

Both monthly and annual anomalies showed extensive variation in the average, minimum and maximum chl-a concentrations attained, with years (and months) of large areas of positive anomalies and years (and months) of dominant negative anomalies. Figure 2 shows mean annual anomalies. The largest areas of positive anomalies were observed in 2003, 2010 and 2011, while the largest areas of negative anomalies were observed in 2004, 2005 and 2006.

The highest chl-a concentration in most of the shelf ($\approx$ 36%) occurs during October. However, in some areas of the mid- and outer shelf south of 46° S the annual maximum values occur later, in December (Fig. 3.a). Bloom starting date in more than 60% of the shelf occurred between early September and late October (Fig. 3.b and c).

Finally, we estimated and described statistical indexes such as bloom area and bloom occurrence frequency. We classified pixels as bloom and non-bloom using 5% above the median of the series in each pixel as threshold. Then, with the time series of classified maps, we estimated total and yearly frequency of bloom occurrence and percentage of occurrence (as a proxy for bloom duration). Figure 4 shows the inter-

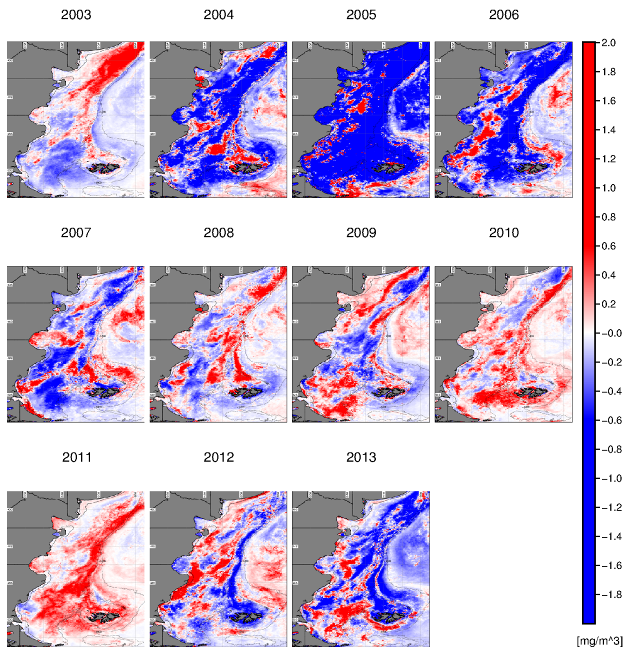

Fig. 2. Annual anomalies in mean chl-a concentration (mg/m^3) from MODIS/Aqua L3 images over the period 2003-2013.

annual variation in percentage of bloom occurrence. Years that showed positive anomalies in previous analysis, also showed a higher percentage of bloom occurrence, i.e.: they showed bloom level concentrations for a "longer" period.

4. DISCUSSION AND CONCLUSION

This is the first study using L3 (8-day and 4.6 km) MODIS-Aqua time series to characterize the spatio-temporal variability of chl-a concentration and phytoplankton blooms in the Patagonian continental shelf and shelf break region for a period reaching present (2003-2013). Besides, this is also the first time that bloom phenology indexes are estimated and their spatio-temporal variability is analyzed. In general, results demonstrated consistency with previous studies and variations observed in former periods, both satellite-derived and measured *in situ* [6, 7]. Therefore, regarding known issues in ocean color radiometry (atmospheric correction, over-estimation in coastal areas, global vs regional models, lack of valid data in higher latitudes, etc.), satellite chl-a was capable of reproducing the spatio-temporal patterns of phytoplankton variability. This work set the basis to continue studying more effective methods to study algal blooms (and their variability) in the Argentinian sea, with the final goal of including these kind of products in models that allow to predict the occurrence of harmful algal blooms, the dynamics of marine system (under extractive pressure) and the effects

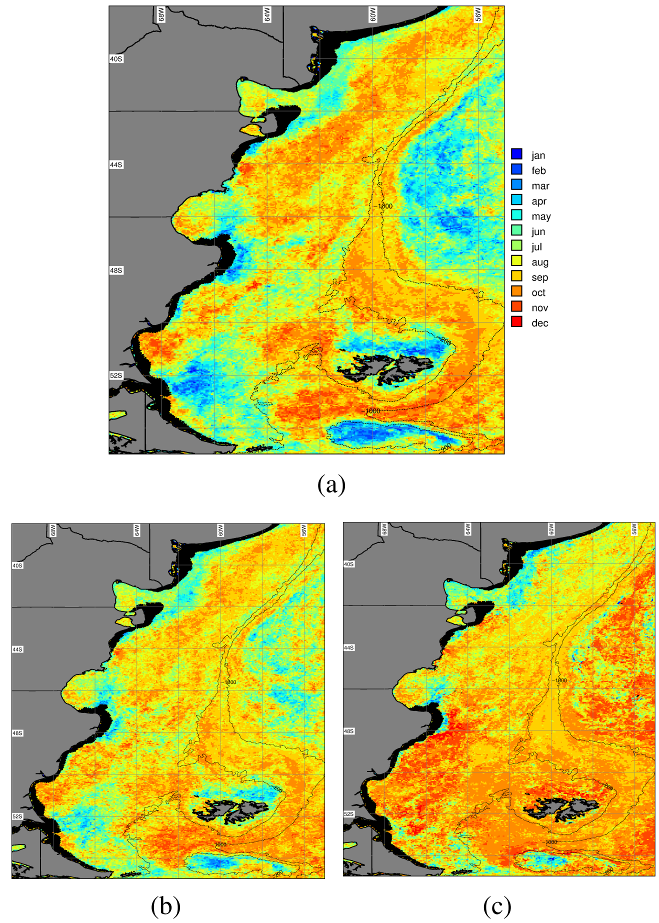

Fig. 3. (a) Month of maximum chl-a concentration (mg/m^3) from MODIS/Aqua L3 images over the period 2003-2013. (b) Month of bloom start estimated as maximum rate of change and (c) based on a threshold of 5% above the median.

of global changes over climatic and biogeochemical cycles.

The spatial variability observed at each moment, or for the aggregation of a certain period, is likely to be dependent on the environmental differences among diverse areas and the particular dynamics associated to the geographic location. On the other hand, the temporal variability can be related to seasonal regular cycles in lightning conditions, nutrient flux and vertical stratification, among others. Moreover, the inter-annual variability and anomalies observed in chlorophyll-a concentration and phenological indexes considered in this study might be explained by wind anomalies that change front's positions and anomalies in rivers discharges as a consequence of higher precipitations because external or extrinsic forces associated with global phenomena such as El Niño Southern Oscillation (ENSO) [8]. The mechanism by which these phenomena operate is still under study. Some authors suggest that global effects of ENSO upon winds (as a consequence of changes in sea surface temperature) may

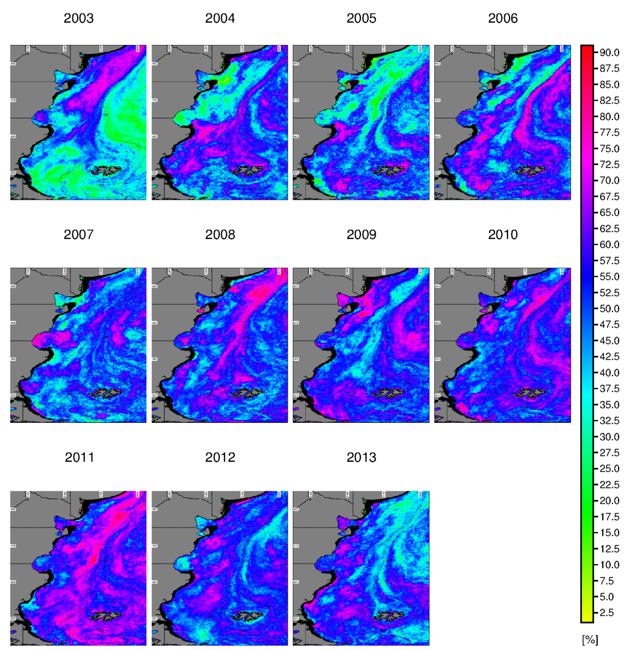

Fig. 4. Inter-annual variations in the percentage of bloom occurrence (2003-2013). Pixels with chl-a concentrations a 5% above the median of the series were classified as bloom.

affect phytoplankton distribution [8]. Some others sustain that what changes is phytoplankton community composition and/or bloom starting date [9, 10]. In Southern Southamerica, ENSO has strong effects on rainfall, especially on spring rainfall. This increases the discharges of great rivers such as Rio de la Plata (RDP) located at $\approx 35°$ S. In fact, high concentrations of chlorophyll-a were detected over the shelf off RDP discharges during El Niño events, probably because of the larger extension of the plume and the higher nutrient supply [8]. It is well-known that phytoplankton variability and changes in their phenology (bloom starting date, bloom duration, etc.) may have deep effects upon biogeochemical cycles, climatic patterns, fisheries and the general structure and functioning of marine ecosystems. These global effects are a strong motivation to study phytoplankton changes under global warming [1, 11], and particularly in the Patagonian shelf and shelf-break where *in situ* measures are particularly scarce.

Aside from the results *per se* in terms of gained knowledge regarding satellite chl-a concentration in the Argentinian Sea, the relevance of this work is also related to the use of a novel free and open source tool that provides the advantage of automating all (or most of) the processing, and which allows the application of the same methodology to analyze satellite time series of different variables, like sea surface temperature.

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