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Chlorophyll-*a* variability within Basque coastal waters and the Bay of Biscay, between 2005 and 2010, using MODIS imagery

Stéfani Novoa[1*], Guillem Chust[1*], Yolanda Sagarminaga[1], Marta Revilla[1], Javier Franco[1], Victoriano Valencia[1], Ángel Borja[1]

Abstract

Understanding the response of chlorophyll-*a* (as a proxy for phytoplankton biomass) to both anthropogenic pressures and natural factors is important for water quality assessment purposes and for the management of biological resources. In the Basque coastal area, discharges produced by the Adour and Nervión rivers (south-eastern part of the Bay of Biscay) have been proven to reach up to 15-20 km off the coast. The first objective of this study was to describe the spatial and temporal variability of chlorophyll-*a* in the Basque coast and the Bay of Biscay, in relation to river discharges at a daily, seasonal and inter-annual scale using MODIS images acquired between 2005 and 2010. The second objective was to offer a synoptic description of the spatio-temporal variability of chlorophyll-*a* in the entire Bay of Biscay, using multivariate statistical methods and satellite imagery. The results indicate that seasonal chlorophyll-*a* cycle is slightly different in coastal areas affected by the Adour and the Nervión river waters, compared to offshore waters. The spring chlorophyll-*a* peak in March in offshore waters shifts to May in the Adour nearby area Nervión. The multivariate statistical analysis highlights the influence of river discharges in the spatial variability of chlorophyll-*a* in coastal areas of the bay. The Spanish and French Basque coastal waters are differentiated in terms of chlorophyll-*a* concentrations levels reached, river regimes and morphology of the continental shelf. Statistical and indicator maps have been created to represent the main components of chlorophyll-*a* variability in the area of study. They confirm that, at present, phytoplankton is at good status and eutrophication risk is low in the Basque coastal waters. These maps may provide water quality indicators in a continuous spatial distribution in the area and may be used for the selection of water quality stations as a function of the dynamics of the water masses characterised.

Keywords: Chlorophyll, satellite, MODIS, intra and interanual variability, river plumes, Bay of Biscay, Basque Country

Introduction

Primary production in temperate areas is subject to a high spatio-temporal variability (Cebrián and Valiela 1999; Bode *et al*. 2005, Muylaert *et al*. 2006, Gameiro *et al*. 2010). Phytoplankton blooms are events of rapid production and accumulation of phytoplankton biomass that are usually responses to changing physical driving forces originating in the ocean (e.g., upwelling), the atmosphere (wind), or in land (precipitation and river runoff). These drivers have different timescales of variability; thus, phytoplankton blooms can be short-term episodic events, recurrent seasonal phenomena, or sporadic events associated with extraordinary climatic or hydrologic conditions (Cloern 1996, Cloern 2001). Several studies have reported the high variability present in oceanic, continental shelf and coastal areas of the Bay of Biscay (Tréguer *et al*. 1979, García-Soto and Pingree 1998, Lampert 2001, Gohin *et al*. 2003, Loyer *et al*. 2006).

River discharges into coastal waters are an important element in the dynamics of the continental shelf in the Bay of Biscay (Puillat 2004, Guillaud *et al*. 2008, Prego *et al*. 2008). The plume regions off the river mouths play an important role in the shelf's physical, biogeochemical and ecological functioning, as the river discharge includes nutrient, sendiments, pollutants and other consitutents in addition to freshwater (Arnau *et al*. 2004, Wysocki *et al*. 2006, Weston *et al*. 2008, Petus *et al*. 2010). In the presence of a river plume, light and circulation patterns, stratification and nutrient pathways are significantly altered. Hence, the ecological processes taking place in the plume area are influenced by this exchange between the continental shelf and the river water (Sierra *et al*. 2002). The extent of the influence of the river discharge depends mainly on the river flow regime and on the volume of the discharges (Cravo *et al*. 2006), at seasonal and annual scales (Signoret *et al*. 2006). Also, the exchange dynamics between river discharges and coastal waters is affected by atmospheric and

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marine factors, such as wind and waves (Stumpf *et al*. 1993; Gonzalez *et al*. 2004). The changing levels of river discharges and the dynamics taking place on the coast affect phytoplankton productivity and growth, since nutrients play an important role in primary production (Harding 1994, Lavín *et al*. 2006, Domingues *et al*. 2008).

Understanding the dynamics of chlorophyll-*a* (chl-*a*) in relation to both anthropogenic pressures (e.g. urban waste water inputs) and natural nutrient inputs is important for water quality assessment purposes (Gohin *et al*. 2008), and also to determine the influence of those inputs on coastal activities such as fisheries. Hence, the first objective of this investigation was to examine and describe the variability of chl-*a* concentration in surface waters of the Basque coastal area, using satellite imagery and its possible relationship with river discharge. The hypothesis is that rain events and river discharge act as fertilization factors, enhancing phytoplankton growth and leading to increased biomass (i.e. chl-a) in the Basque coast. To perform this study, three approaches to analyse rainfall, river discharges and chl-*a* patterns were followed: (i) daily, (ii) seasonal, and (iii) inter-annual variability. The second objective was to offer a synoptic description of chl-*a* spatio-temporal variability in the entire Bay of Biscay, using multivariate statistical methods.

Materials and methods

In situ dataset

A time series of daily data at inland stations of two rivers, the Adour (France) and the Nervión (Spain) were acquired for the 2005-2010 period. In the case of the Nervión River, rainfall (mm), river discharge ($m^3.s^{-1}$), turbidity (NTU) and suspended and dissolved matter ($mg.m^{-3}$) were measured at a station located on the river. The station selected was the nearest station to the river mouth without influence of the marine tides; its name is Abusu. The data was downloaded from the "Diputación Foral de Bizkaia" web site (www.bizkaia.net/). In the case of the Adour, only daily river discharge data was available and the data was downloaded from the DIREN web site (Directions Régionales de l'Environnement; www.hydro.eaufrance.fr/). The total river discharge was computed by combining the contributions from the 6 main streams of the Adour basin (Figure 1; Petus, 2009).

Satellite data

A total of 1672 OC5 products for the 2005-2010 period were downloaded from Ifremer's ftp server (ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/ocean-color). The OC5 is an empirical algorithm, developed and validated by Gohin *et al*. (2002, 2008) and Gohin (2011). This algorithm derives chl-a, turbidity and suspended matter products with look-up tables applied to standard MODIS/Aqua Level-2 reflectance products (processed with SeaDAS).

Daily data analysis

First, the relationship between chl-*a* concentration derived from satellite images and rainfall events and river discharge were studied. For this purpose, two OC5 chl-*a* products corresponding to two days before and one day after a rainfall event were downloaded. The rainfall event occurred on the 13th of January 2009 (a time of the year with high precipitation levels), but no images were available on that day due to the cloud cover, hence, chl-*a* products corresponding to the 11th and the 14th of January 2009 are presented here. Satellite chl-*a* concentrations extracted from a 3 x 3 pixel window near the river mouth was compared to river discharge data. Secondly, the response of variables measured *in situ* and variables derived from satellite images in relation to the rainfall event was studied. The *in situ* variables measured (rainfall, river discharge, turbidity and organic matter) were averaged, between days -1 and 7, being -1, one day before the rainfall

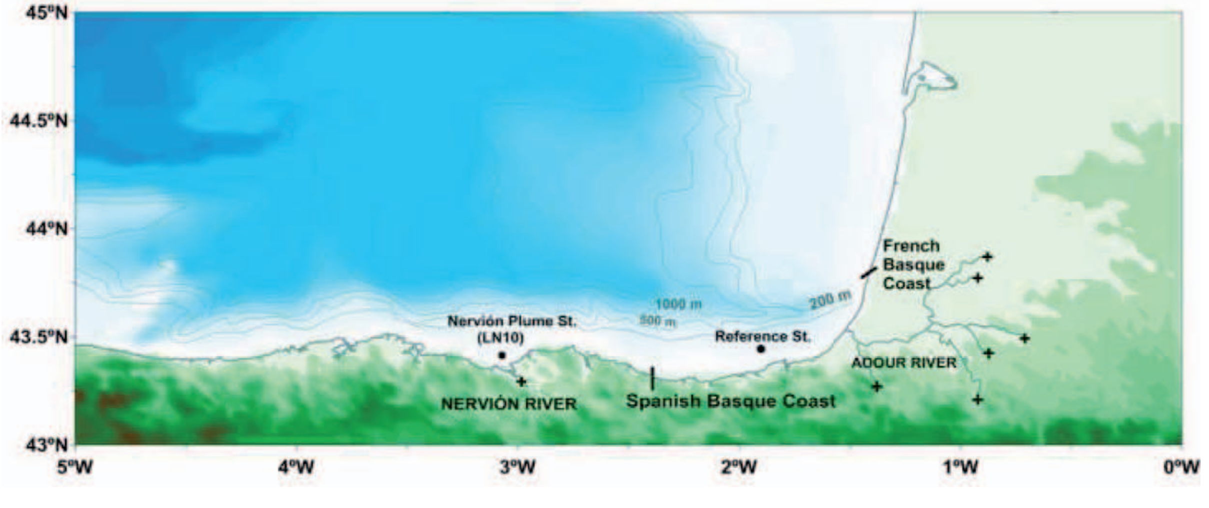

Figure 1. Study area in the southeastern corner of the Bay of Biscay. The crosses (+) represent river stations, the black circles (•) represent the marine stations.

event, 0 the day of the event, 1 the day after the event, and so on. Chl-a, turbidity and suspended matter data, within surface waters of the river plume area, were acquired using satellite imagery. Values of the three variables were extracted using the averaged 3 x 3 pixel window located near the river mouths. The distance from the river mouth was approximately 1.5 pixels (or 0.9 nautical miles); this distance was necessary to avoid the effect of the land pixels. The analysis could not be performed for the Adour due to the lack of rainfall data.

Then, cross-correlation analyses with daily lags were performed with the different *in situ* variables obtained for the Nervión River, i.e. rainfall versus river discharge, organic matter and turbidity.

Seasonal analysis

Chl-*a* 90th percentile (P90) and average maps were produced for the 2005-2010 period (see Novoa *et al*. 2012, for more details). This was performed by initially selecting all cloud-free images available for the study area during the 2005-2010 period. Subsequently, the P90 and average values were calculated for each pixel of all images selected for that period using IDL programming. As such, the IDL program calculated for each pixel the average chl-*a* value and, for P90 maps, the value where 90% of the observations were equal or below. This approach resulted in two types of products, monthly P90 and mean chl-*a* maps for the 2005-2010 period. Results obtained with P90 and mean chl-*a* maps were compared for coastal and offshore waters. This comparison was performed between chl-*a* concentration values extracted using a 3 x 3 pixel window positioned near the Adour and Nervión river mouths and at the offshore reference station.

Spatial analysis

Figure 2. Polygons used to extract mean chl-*a* concentrations at different distances from the river Nervión and Adour mouths (MODIS Terra, 17/05/2004).

The evolution of chl-*a* concentration in the river plume areas with increasing distance from the coast, was examined using the monthly P90 chl-*a* maps calculated with images downloaded between 2005 and 2010. As such, mean values of chl-*a* at different distances from the coast were extracted in the form of polygons, as shown in Figure 2.

Inter-annual analysis

The long-term trends (years 2005-2010) of sea surface (0-1 m) chl-*a*, suspended particulate matter and turbidity in river plume areas, were analysed along with the variability of rainfall and river discharge of the rivers at the inland stations. *In situ* data from the Littoral Water Quality Monitoring and Control Network (LQM) of the Basque Country, managed by the Basque Water Agency, used previously in Revilla *et al*. (2009) and in Novoa *et al*. (2012), was used to perform a time series analysis of the 2005-2010 period, and was compared to the same analysis performed with satellite data. The locations of the Nervión (LN10) and the reference stations are shown in Figure 1. The 3 x 3 pixel window positioned at those locations was used to extract the chl-*a* concentrations.

Time series analysis of several variables measured *in situ* and with satellite images was performed. In the case of the satellite-derived variables, 2-week means were used to avoid missing values. In the case of *in situ* data, daily measurements of river discharge and rainfall were employed for the analysis, while chl-*a in situ* measurements used in this analysis were performed once per trimester. The variability of each variable was examined by means of the "*decompose*" procedure in R language, which extracts the seasonal component of the time series, and outputs the trend followed by each variable without this component. Subsequently, the trend values were linearly regressed against the years, and the significance of the trend-line was measured with the p-value returned by the regression. A permutation resampling method was performed to test the significance of the trend-lines. The time series was permuted 1000 times, and the observed slope from the regression between the trend and the time series was then compared to the permuted slopes. The null hypothesis established that the observed slope did not show a significant change over the years. If the observed value is found to be outside 95% quantile range of the histogram, then the null hypothesis is refuted. For more information on this procedure see Davison and Hinkley (1997).

Cluster and Principal Component Analysis

Two multivariate statistical analyses were performed over the entire Bay of Biscay, an unsupervised classification and a Principal Component Analysis (PCA), to synoptically describe the variability of chl-*a* concentration throughout the seasons and from coasts to open waters. The entire bay was considered for these analyses to examine the spatial variability of the Basque coast area in relation to the entire bay.

The unsupervised cluster classification of the chl-*a* OC5 products was performed with the k-means routine from the ENVI program. All the products available for the 2005-2010 period were included in this analysis. This routine initially computes class means evenly distributed in the data space. Three classes were selected for this classification. Then, it iteratively clusters the pixels into the nearest class using a minimum distance technique. Every single iteration recalculates class means and reclassifies pixels with respect to the new means. This process continues until the maximum number of iterations is reached. For more information see Tou and Gonzalez (1974).

The PCA was performed using the ENVI program as well. All the OC5 chl-*a* products available for the 2005-2010 period for the entire Bay of Biscay were used for this purpose. The PCA produces uncorrelated output bands, to segregate noise components, and to reduce the dimensionality of data sets. This routine finds several sets of orthogonal axes that have their origin at the data mean and that are rotated so the data variance is maximized. It produces principal component bands that are linear combinations of the original spectral bands and are uncorrelated. The first PC band contains the largest percentage of data variance and the second PC band contains the second largest data variance, and so on. The percent of total variance can be determined from the eigenvalues, which are the measure of variance in a PCA. The set of weights applied to band values to obtain a principal component are called eigenvectors. To obtain more information on this procedure see Richards and Jia (2006).

In this study, the results provided by the PCA offer a visualization of the similarities and differences among pixels in relation to the temporal evolution of the chl-*a* concentration averages. This analysis also provides a visualization of the global connections between the chl-*a* pixels of the entire Bay of Biscay. In this case, the PCA variables are the averaged chl-*a* months, which are 70 in total and the number of observations used in the analysis are the total number of pixels in the area of study, hence 244097 points of observation (the land is not included). Monthly composites were chosen for this analysis because the PCA principles state that missing values should be avoided. Some areas show missing values during large periods of time (more than 10 days in some cases), due to clouds or image artifacts. The 70 monthly averaged composites rarely provided missing values for the Bay of Biscay area.

Results

Daily variability

Images before and after the rainfall event, which occurred on the 13th of January 2009, showed an increase of chl-*a* in the coastal area one day after the event (Figure 3). In the case of the Nervión River, there was an increase of river discharge on the same day of the rainfall event and the maximum river discharge was reached after one day (Figure 3).

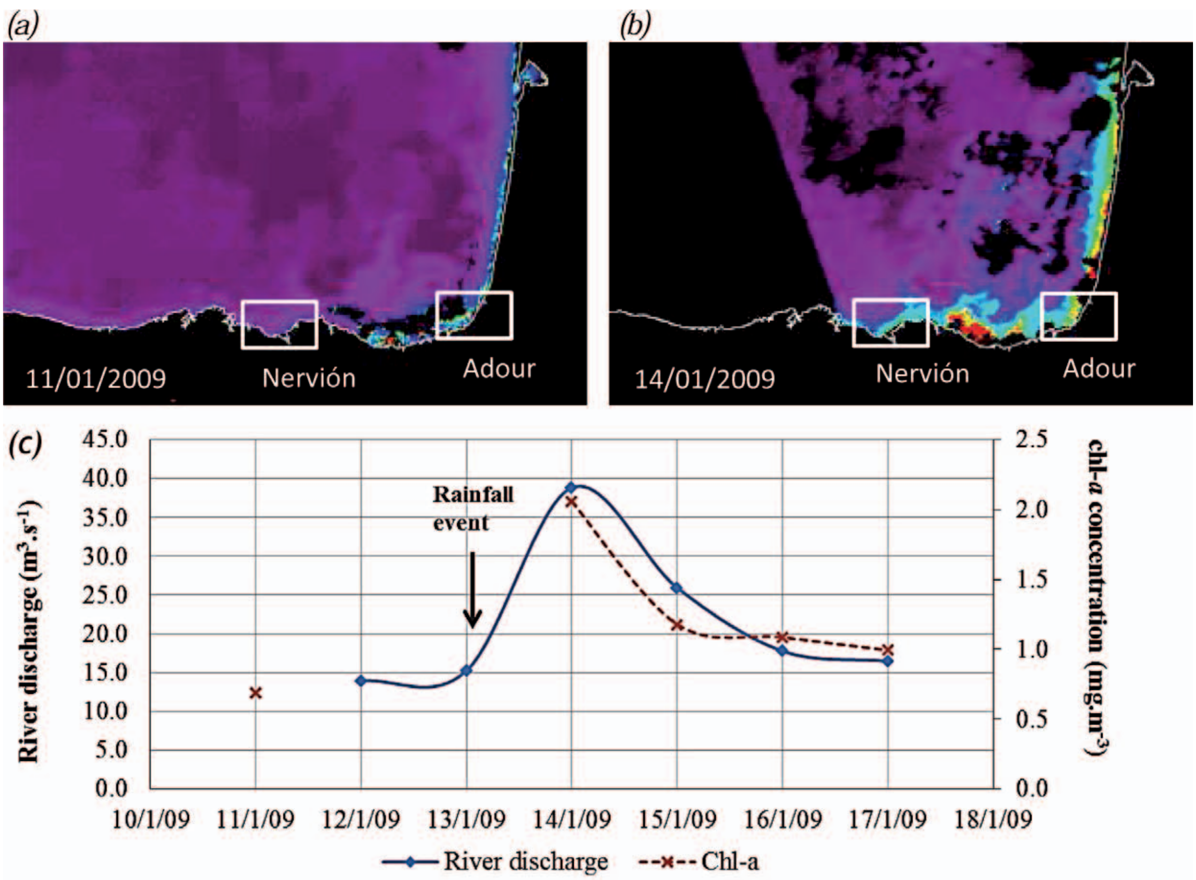

Figure 3. MODIS daily image showing chl-*a* distribution (estimated with the OC5 algorithm) before *(a)* and after *(b)* a rainfall and discharge event occurred on the 13th of January 2009. *(c)* High chl-*a* concentration (dashed lines) was observed one day after the rainfall event, and on the same day of the river discharge increase was recorded at the Nervión river station.

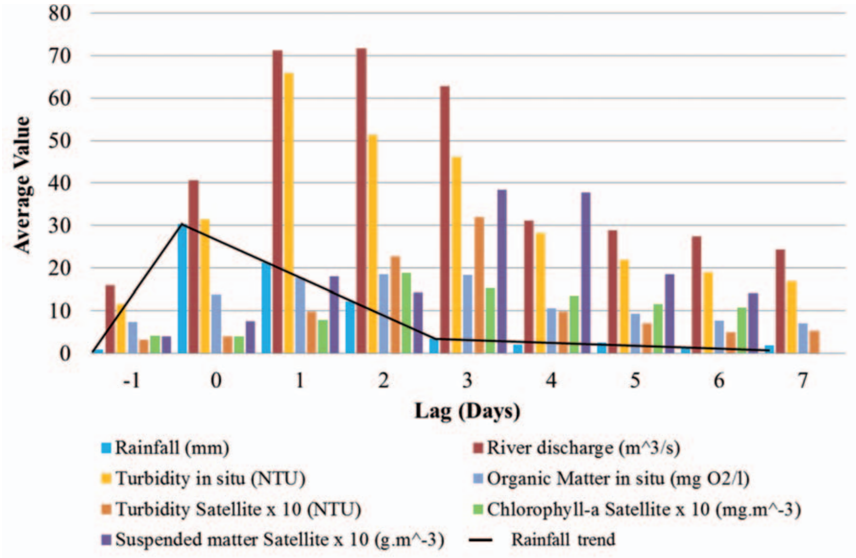

Figure 4. Diagram showing the evolution of the different variables measured *in situ* (rainfall, river discharge, organic matter, and turbidity) at the river Nervión station and with satellite imagery at the river plume (chl-*a*, suspended matter and turbidty). The values shown are an average of 13 rainfall events. Some parameter values are transformed for display purposes.

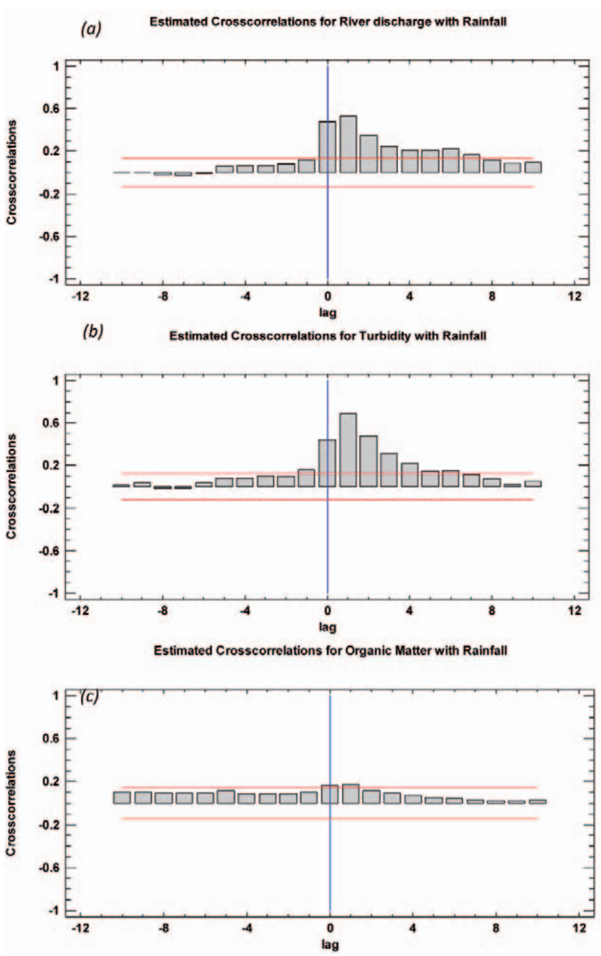

Figure 5. Cross-correlations between *in situ* parameters. *(a)* River discharge with rainfall, *(b)* Turbidity with rainfall and *(c)* Organic matter with rainfall.

Figure 4 shows that, in the case of the Nervión river, the averaged turbidity and organic matter measured *in situ*, present a maximum increase one day after the event. This analysis showed that chl-*a*, suspended matter and turbidity estimated with satellite imagery reached a maximum concentration 2 days (on average) after a rainfall event i.e. average of 13 rainfall events.

The cross-correlation between rainfall and river discharge is significant on the same day of the event and on the seven following days. Rainfall and turbidity measured *in situ* are also significantly correlated at day lags between 0 and 7, while organic matter is significatively correlated with rainfall only on the day of the event (Figure 5).

Seasonal variability

The monthly P90 and mean images for the 2005-2010 period showed similar seasonal patterns for both the offshore and the coastal areas, with some exceptions (Figures 6, 7, 8). In offshore waters, two main chl-*a* concentration peaks are observed, one of them is observed during spring (March-April) and the other in November. However, the P90 and the mean values extracted from the images show different magnitudes. The P90 chl-*a* levels are greater in November than in March, while the mean data shows the opposite, higher chl-*a* concentrations in March compared to November (Figure 8). The summer months in offshore areas show the lowest levels of chl-*a* concentration.

In coastal waters, seasonal differences are observed in different areas (Figures 6 and 7). In the area of the Adour river plume, the maximum chl-*a* concentration is observed in May, for both the P90 and the mean products (Figures 6, 7, 8). A peak is observed with the P90 chl-*a* values in February that is observed with less magnitude on the chl-*a* mean figure (Figure 8). In the area of the Nervión plume (Figure 8), there are two

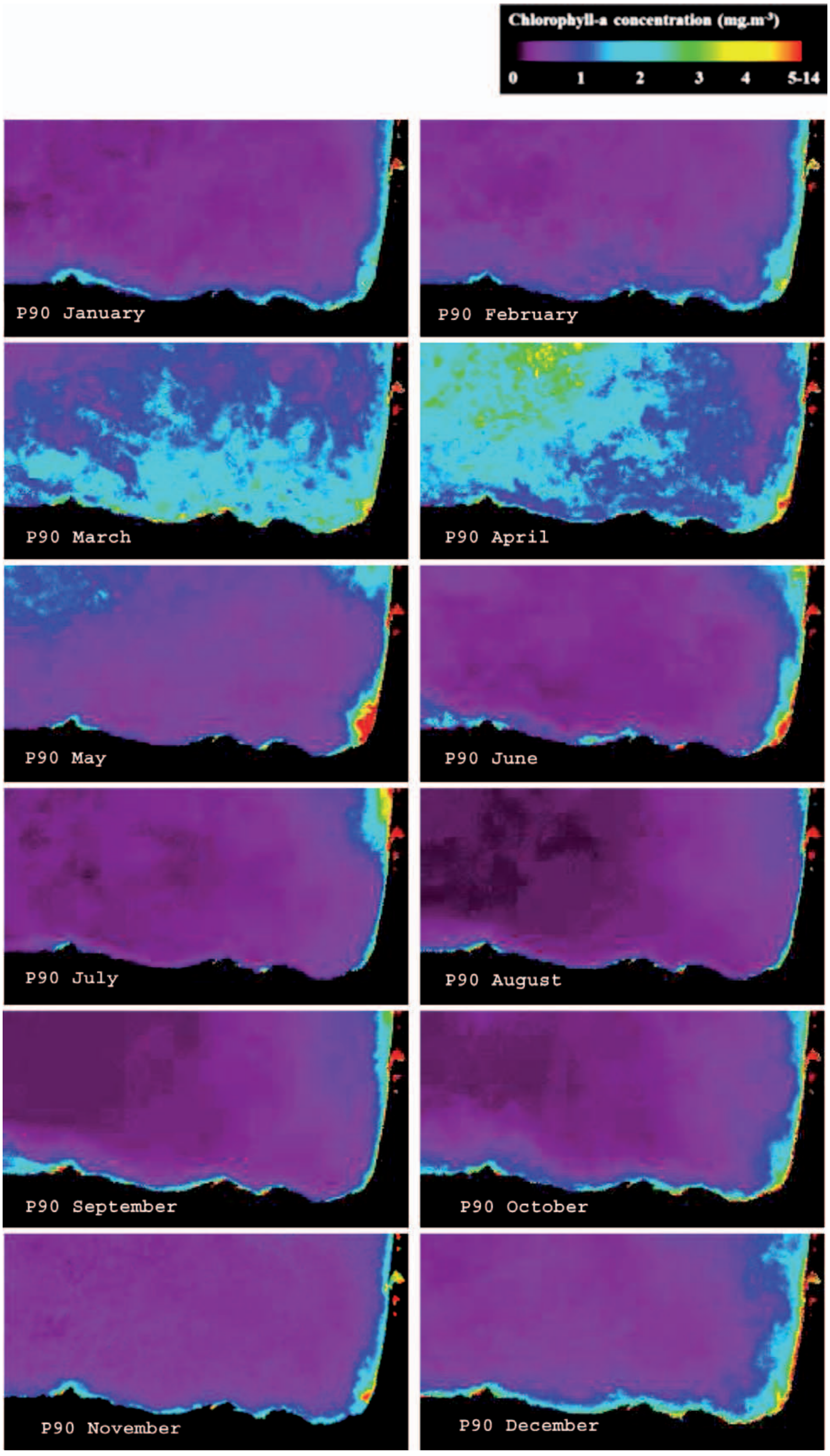

Figure 6. Monthly P90 chl-*a* maps for the 2005-2010 period.

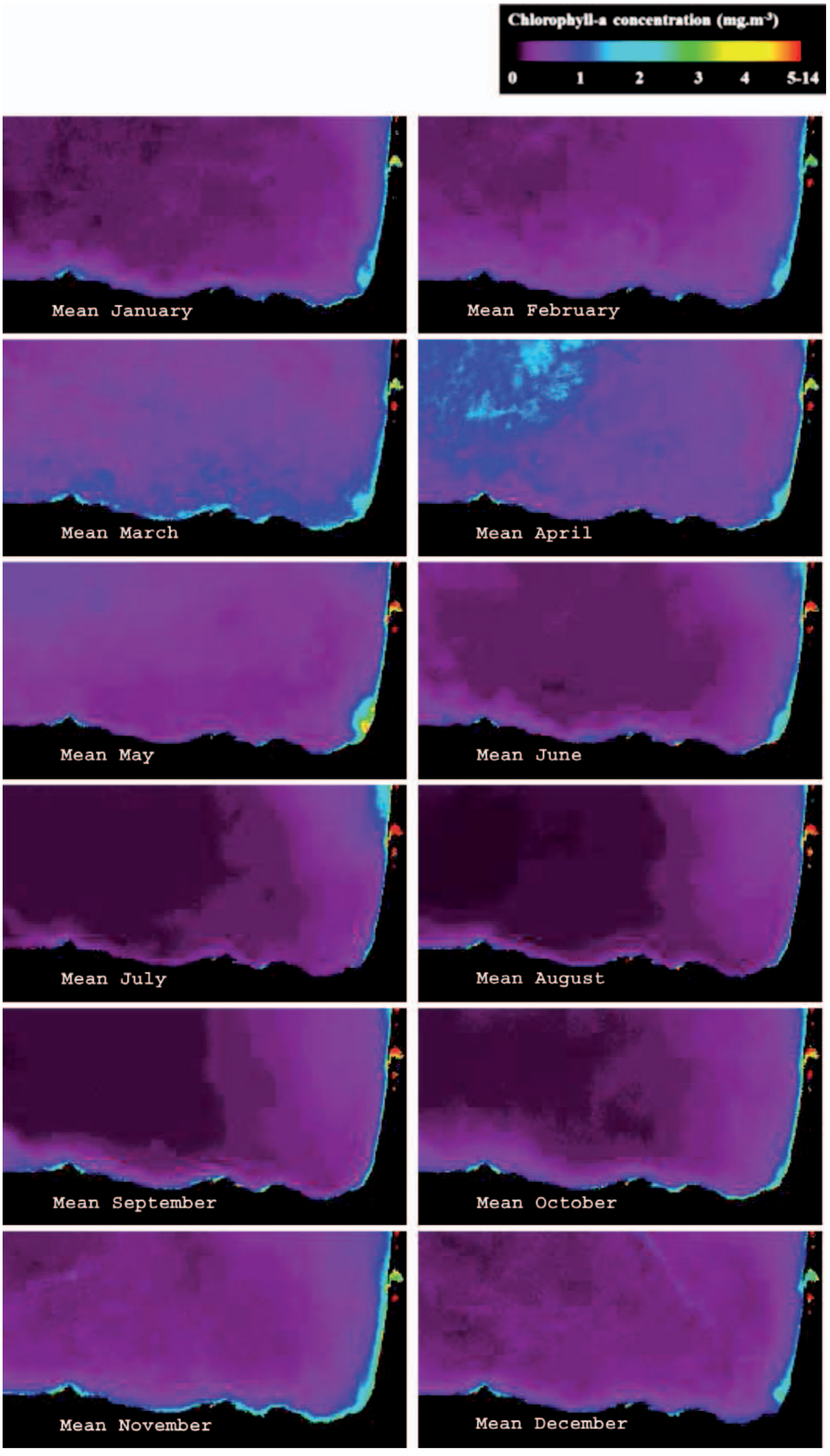

Figure 7. Monthly mean chl-*a* maps for the 2005-2010 period.

Figure 8. P90 Chl-*a* monthly values *(a)* and means *(b)* for the 2005-2010 period at 3 different locations: The Nervión river plume, the Adour river plume and the offshore reference station.

Figure 9. Monthly mean, maximum and minimum chl-*a* concentrations, and monthly mean river discharge and standard deviations, at the Nervión *(a)* and Adour *(b)* rivers, for the 2005-2010 period.

major chl-*a* peaks, one in March and one in November. Both the P90 and the mean values of the pixels located at the Nervión plume show this pattern and the chl-*a* concentrations are higher in November than in March. The patterns of the Nervión river discharges and chl-*a* levels observed in the river plume area coincide, except for the chl-*a* concentration increase observed in June (Figure 9). The variability of the river discharges is also greater during the spring and the autumn months. In the case of the Adour, the patterns are slightly different, as the highest river discharges occurred in April-May, and the highest mean chl-*a* concentration values at the Adour river plume area are observed in May (Figure 9). These are also the periods of greatest river discharge variability (Figure 9).

The chl-*a* seasonal pattern slightly changes with distance from the coast (Figure 10). Chl-*a* 90th percentile between 1.2 and 11 nautical miles from the Nervión river mouth, exhibits two major peaks, one in spring and another in November. The magnitude of the chl-*a* concentration decreases with increasing distance. However, two particularities can be observed. First, at 1.2 miles from the coast, there is a peak in June that is not observed at a farther distance. Second, the peak occurring in November is of greater magnitude compared to the peak occurring in March at 1.2 miles, but this is not observed at larger distances. In the case of the Adour, the month with the highest chl-*a* concentration is May, up until a distance of 11 nautical miles; at this distance, March is the month with the highest chl-*a* concentration.

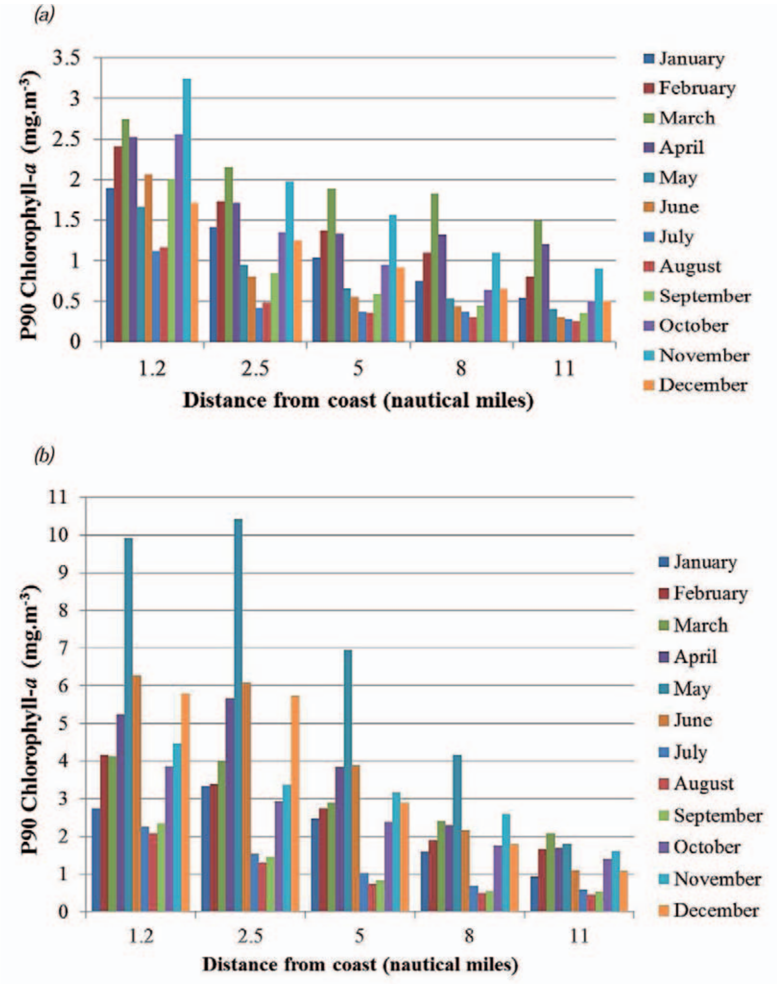

Figure 10. P90 Seasonal variation of chorophyll-a with increasing distance from the coast, from 1.2 nautical miles until 11 nautical miles, at the Nervión *(a)* and the Adour *(b)* river plumes

Inter-annual variability

Chl-*a* concentration calculated from monthly means show considerable inter-annual variation in magnitude and duration of peak events. In general, the chl-*a* variability coincided with the river discharge events during the 2005-2010 period. A peak in spring, followed by another peak of lower magnitude in autumn was observed, while the lowest values were observed during the summer months. Chl-*a* concentration is generally higher in plume waters than at the offshore station, which is not usually influenced by river discharges (Figure 11).

The variation of chl-*a* concentration in coastal water usually coincides with the long duration of river discharges (Figures 11, 12), and do not necessarily coincide with their magnitude. The highest mean chl-*a* concentration in the Adour plume area was 6.5 $mg.m^{-3}$ (June, 2007), followed by 4.6 $mg.m^{-3}$ (May, 2009). The lowest mean chl-*a* concentration in the Adour river plume was 0.5 $mg.m^{-3}$ and occurred in August 2008. The mean annual chl-*a* concentration reached 2.4 $mg.m^{-3}$ in 2007 and 1.3 $mg.m^{-3}$ in 2008. The levels of the other years varied between those two values.

The highest mean chl-*a* concentration in the Nervión plume area was 3.0 $mg.m^{-3}$ (November, 2008), followed by 2.9 $mg.m^{-3}$ (October, 2009). The lowest monthly mean chl-*a* concentration was 0.3 $mg.m^{-3}$ and occurred in July 2009. The annual mean chl-*a* concentration was the highest in 2005, with 1.3 $mg.m^{-3}$, while the lowest annual mean chl-a concentration was 1.0 $mg.m^{-3}$ and was observed in 2008. In general, the variability of river discharges coincided with the rainfall variability at the Nervión inland station (Figures 12 and 13).

The highest monthly mean chl-*a* concentration found at the offshore location was 1.5 $mg.m^{-3}$ (March, 2006), followed by 1.3 $mg.m^{-3}$ (April, 2008). The lowest mean chl-*a* concentration at the offshore location was of 0.2 and occurred in September 2006. The maximum annual chlorophyll mean value was reached in 2007 as well, and was of 0.7 $mg.m^{-3}$; the minimum mean value was observed in 2008, and was of 0.5 $mg.m^{-3}$.

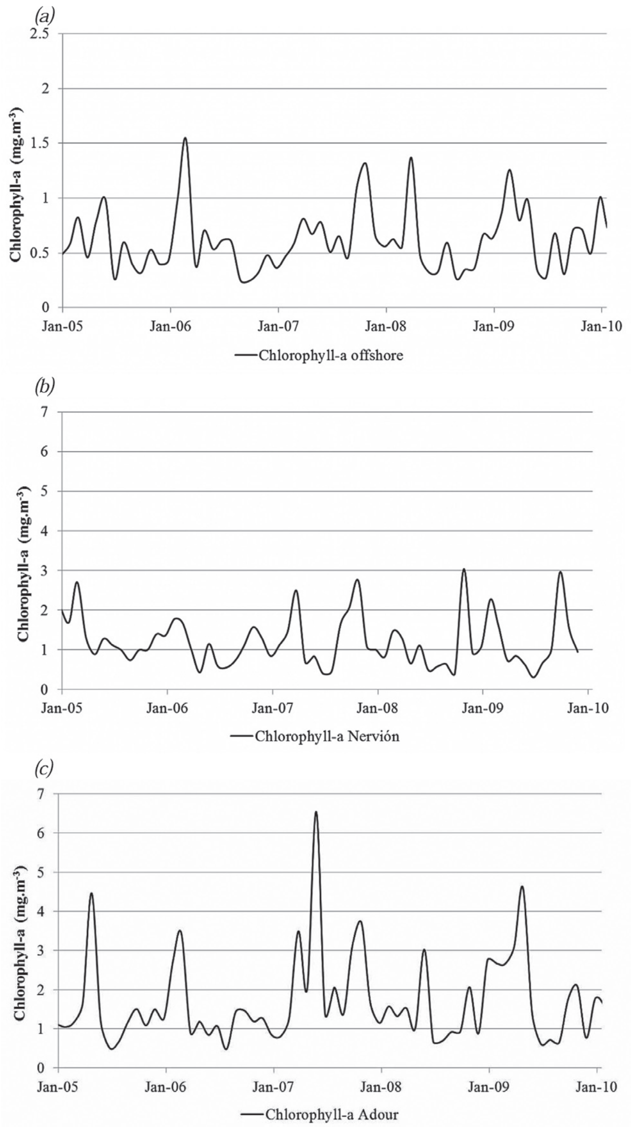

Figure 11. Time series of two-week mean chl-*a* concentration, at the offshore station *(a)*, the Nervión *(b)* and the Adour *(c)* river plumes.

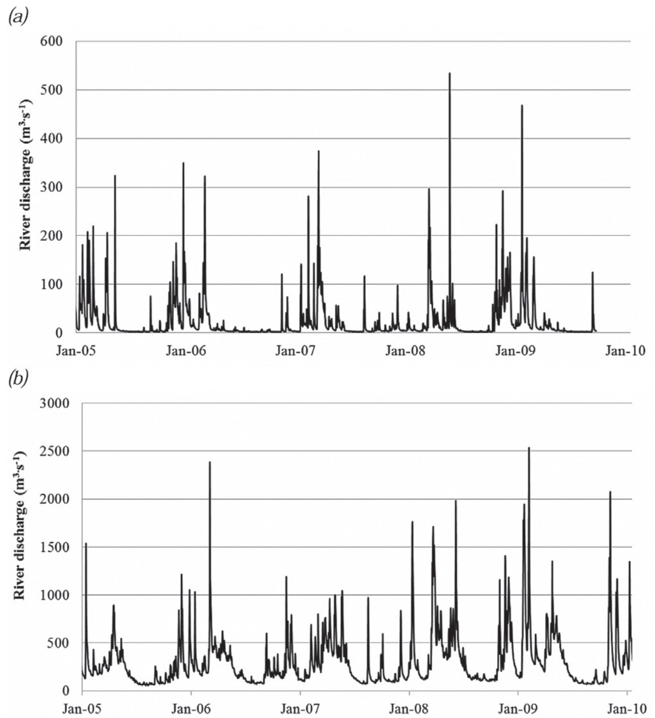

Figure 12. Time series of daily river discharges at the Nervión *(a)* and the Adour *(b)* river stations.

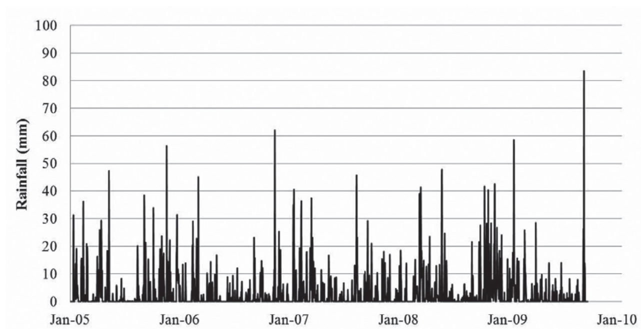

Figure 13. Time series of daily precipitation (rainfall) values at the Nervión river station.

Table 1. Time series analysis of several variables measured *in situ* and with satellite imagery. The values provided are the slopes of trend analysis. The asterisk (*) means that the bootstrap analysis proved the trend is significant.

slope	chl-a (*in situ*)	chl-a (satellite)	River discharge	Rainfall	Turbidity (satellite)
Nervión	-0.0220*	-0.0027*	0.0012*	0.0002*	0.0086*
Adour		-0.0020*	0.067*		0.0103
Offshore	-0.0010*	0.0017*			0.0141

The bootstrap analysis revealed a significant decrease in chl-*a* at the Nervión river plume region, measured with satellite and *in situ* data between 2005 and 2009 (Table 1). The *in situ* data resulted in a steeper slope than the satellite data (-0.0220 vs. -0.0027). The chl-*a* concentration measured in the Adour river plume showed as well, a significant decrease during the same period. The river discharge and rainfall measured at the inland river stations, increased significantly. The turbidity measured with satellite imagery significantly increased over the same period of time in plume and offshore waters.

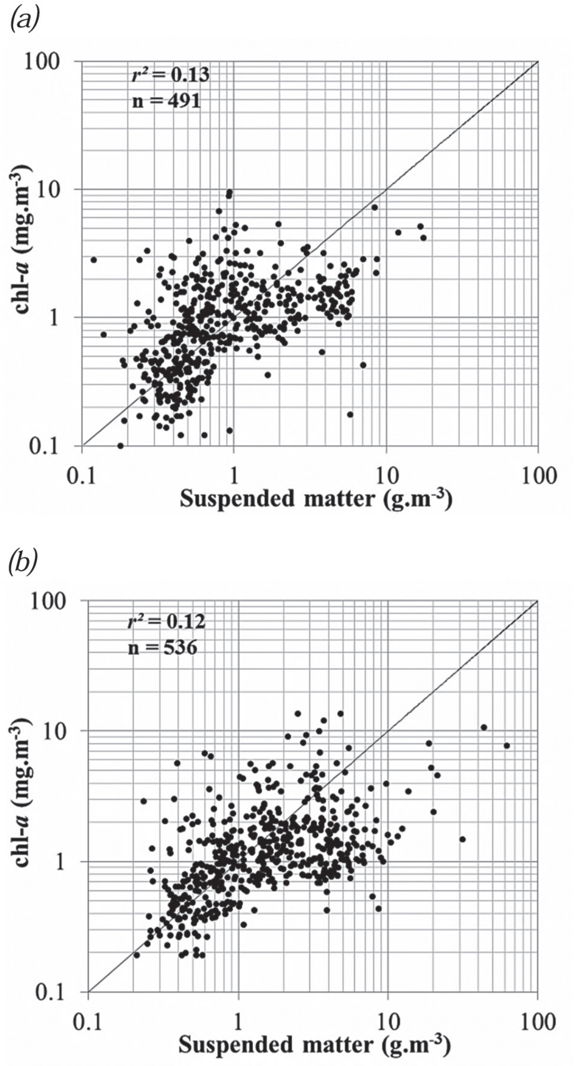

Figure 14. Linear regression between suspended matter and chl-*a* estimated with satellite imagery, for the Nervión *(a)* and the Adour *(b)* river plumes. The data are shown on a logarithmic scale for display purposes.

The logarithmic regression between the suspended matter and the chl-*a* concentrations (Figure 15) did not show a very high determination coefficients in both river plumes (Nervión r^2=0.13; Adour r^2=0.12).

Unsupervised classification and principal component analysis

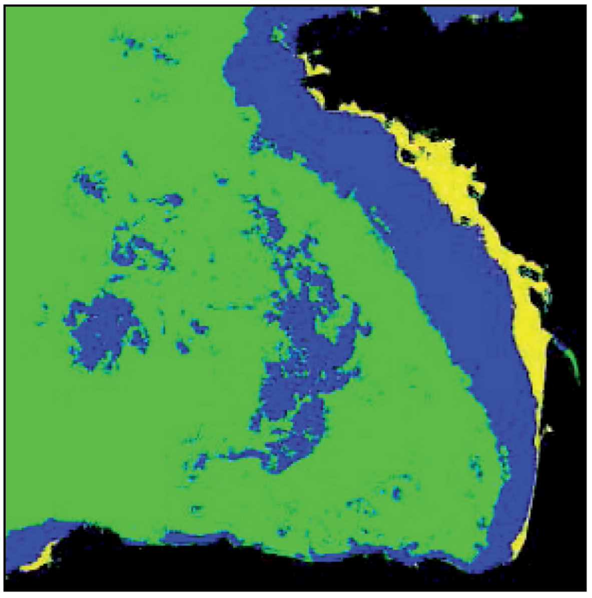

Figure 15. Unsupervised K-means classification performed with 1672 chl-*a* OC5 products. The black area is the land and was not considered in the classification. Class 1 is shown in yellow, class 2 in blue and class 3 in green.

The classification map showed three distinct surface water classes in the Bay of Biscay according to chl-*a* concentration (Figure 15). The first class (in yellow) includes the French part of the continental shelf influenced by river discharges, where chl-*a* concentrations are the highest. The Adour river plume area is included in this class. The second class (in blue) corresponds to an area of transition between river influenced areas and oceanic waters. This class has probably lower chl-*a* concentrations than the first class and it includes the region inside the continental shelf beyond the influenced areas by the French rivers. Northern Spain's coastal waters belong to the second classes well except for Galician waters. The third class (in green) would correspond to oceanic waters, where chl-*a* concentration is lower in general. This class includes the area beyond the continental shelf. However, some regions in the centre of the Bay located over deep water (>2000 m) and beyond the shelf, belong to class 2, indicated similar chl-*a* levels than transitional waters (Class 2, in blue). These higher concentrations are probably reached during bloom periods.

The first PCA band explained 57.3% of the total variance of the data and shows prevalent positive values in coastal areas, which are characterised by higher chl-*a* concentration (Figure 16).

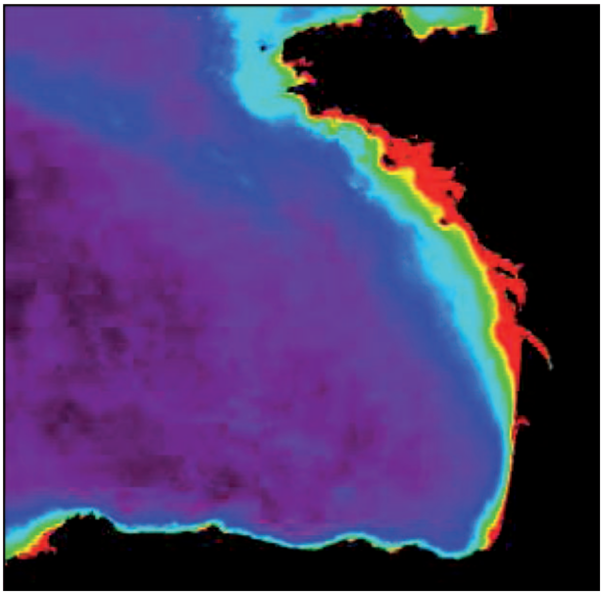

Figure 16. Spatial projection of the first Principal Component band. The lowest eigenvalues are shown in dark purple and the highest in red; the blue, green and yellow colours are used for the eigenvalues in between.

Discussion and conclusions

This study described the spatial and temporal variability of chl-*a* in the Basque coast and the SE Bay of Biscay. The main conclusions yielded by this study are that river discharges closely affect the variability of chl-*a* concentration levels in coastal areas at a daily, seasonal and inter-annual scale. In general, an increase of chl-*a* concentration was observed 1 or 2 days after a rainfall event, in Basque coastal areas near the Adour and the Nervión river plumes. Such a rapid increase of chl-*a* after an input of nutrients has not been reported previously in the area, where other studies found longer reactive periods. In particular García-Soto *et al*. (1990) reported an increase of primary productivity 4-5 days after a rainfall event in a coastal embayment near the Nervión estuary, and Alvarez *et al*. (2009) suggested a delay of 7 to 9 to detect primary productivity after an increase in nutrient concentrations from upwelling nutrients in the Cantabrian coast. Possible explanations for these differences that would need a more detailed study may be that the increase in chl-*a* concentration, observed with satellite images shortly after the rainfall event, is not produced by phytoplankton proliferation caused by nutrient inputs, but to an effect of the storms. Winds (turbulence) and waves (bottom shear stress), usually more intense during winter storms, have major effects on the particles in suspension and on the dynamics of coastal waters and the river plumes (Huret *et al*. 2007). These disturbances are producing a resuspension and an advection of particulate material (e.g. microalgae and sediments) of marine, benthic, or estuarine origin (Abreu *et al*. 2009). In fact, benthic diatoms were found in some water samples collected in coastal areas during the LQM survey (Borja *et al*. 2007-2010). Furthermore, the presence of higher levels of dissolved and suspended particulate inorganic material, due to resuspension or to river plume advection, could be also causing an overestimation of chl-*a* concentration by satellite imagery (Lahet *et al*. 2001, Bowers *et al*. 2009).

The seasonal variability patterns of chl-*a* concentration are different for the Adour and the Nervión river plumes, and differ as well from the pattern observed in offshore waters. In the case of the Adour, the highest chl-*a* concentration levels are observed during late autumn and spring, but mainly between April and June, the months of the greatest river floods driven by its pluvio-nival regime. In the case of the Nervión, the cycle is similar to offshore waters, where blooms are observed in spring and late autumn-early winter, except for a secondary peak detected in June. The increase of chl-*a* concentration during spring is due to the higher concentration of nutrients present produced by river discharges, but also to the increase of light availaibility during this season (Orive *et al*. 2004, Butrón *et al*. 2009)

Although the spatial influence of Nervión river is rather constrained (1.2 nautical miles from estuary), the Adour discharge has an influence up to 8 nm from coast, which derives in important phytoplankton growth in the marine areas under river discharge influence. These findings were also provided by other studies in the area (Retailleau *et al*. 2009, Lampert *et al*. 2002, Loyer *et al*. 2006).

The inter-annual analysis also shows a significant decrease of chl-*a* concentration (estimated with satellite data) between 2005 and 2010 in coastal areas (near the Nervión and the Adour river mouths) and a significant increase in offshore waters. The negative tendency in coastal waters, detected both by satellite and *in situ* data, could be related to the pollution control programmes set up in Nervión river in 1993 (García-Barcina *et al*. 2006), and from 1975 in the Adour river (Tudesque *et al*. 2008) that have considerably improved the water quality of these estuaries. Another reason for the chl-*a* decrease during the study period, could be the increase of suspended material related to the increase in river discharges, which could have caused a decrease of water clarity and thus, affected phytoplankton growth. In fact, other authors (Iriarte and Purdie 2004; Butrón *et al*. 2009) have addressed that light limitation due to turbidity and/or low residence time due to higher river flows, can limit the phytoplankton growth."

Nevertheless, in offshore waters the time series analysis performed with *in situ* and satellite chl-*a* estimates are contradictory: *in situ* measurements show a significant decrease of surface chl-*a* between 2005 and 2010, whilst satellite data estimate a significant increase, in the same location. Interestingly, although a negative chl-*a* tendency was found by Revilla *et al*. (2010a) in surface waters with *in situ* measurements, they also reported (Revilla *et al*. 2011) an increase in chl-*a* concentration at greater depths in the photic layer. Thus a possible explanation of this contradiction could lay on the fact than under clear water conditions, which is the case for this reference station, satellite estimates are integrating the part of the water column where an increase in chl-*a* occurs. In this case, chl-*a* satellite estimates would coincide with chl-*a in situ* estimates.

An unsupervised classification has resulted in three types of water bodies (Adour, Nervión and Oceanic) that converge in a relatively small area. The differences between these areas are mainly due to average chl-*a* concentrations, to the influence of river discharges and to the morphology of the coastal shelf and slope. Interestingly, the station used as reference of offshore waters, not affected by river discharges (Revilla *et al*. 2010a; b), belongs to the same class as the coastal areas of the Spanish Basque coastal waters. Therefore, this confirms that, at present, phytoplankton is at good status and eutrophication risk is low in the Basque coastal waters (Revilla *et al*. 2009; Garmendia *et al*. 2011).

The PCA resulted in a first band explaining 57% of chl-*a* variability located near coastal areas, where highest chl-*a* concentration levels are found, and which are related with river discharges areas and the morphology of the continental shelf, confirming the results found with the unsupervised classification.

The findings presented in this study reveal the value of remote sensing as a valuable tool for this type of studies, as it considerably improves the spatial and temporal sampling coverage needed to detect high frequency variability in primary production processes, which at present cannot be afforded by *in situ* monitoring programmes. Nevertheless, its applicability is limited to the study of upper ocean layers and estimations in turbid coastal waters may show inaccuracies if proper validated algorithms are not used. Thus, a complementation between both methodologies may at present largely improve the study and monitoring of primary production processes in coastal areas.

A next step for this study would be to deeper analyse the processes and factors affecting the variability of chl-a, and continue to improve the estimation of chl-*a* in coastal areas with satellite imagery.

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