Chlorophyll concentration along the northwestern coast of the Iberian Peninsula vs. atmosphere-ocean-land conditions

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ABSTRACT

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The aim of this work is to investigate the relationship between the atmosphere-ocean-land conditions and chlorophyll *a* (Chl-*a*) formation along the northwestern coast of the Iberian Peninsula. Spatial and temporal distribution of Chl-*a* concentration, sea surface temperature, surface winds and rivers discharge were analyzed from 1998 to 2007, using remote sensing data. Generally, the Chl-*a* concentrations are higher near the coast showing a seasonal variability. In fact, along the coast there are higher Chl-*a* concentrations during the dry season (April to September) which can be associated to the upwelling favorable conditions (southward winds). These favorable conditions are related to the presence of cold nutrient-rich water which upwells towards the surface layers enhancing the primary production. During winter months, the wind pattern is usually upwelling unfavorable (northward winds); however high Chl-*a* concentration also occurs near the coast. These high values could be related to the inland nutrients input through rivers discharge and winter upwelling events. Afterwards, correlation coefficients were computed between Chl-*a* and upwelling index, SST and rivers discharges. Between June to September chlorophyll and upwelling index are positively correlated, increasing southward (0.58 to the south of the study area). During winter, the correlation coefficient between chlorophyll and rivers discharge is 0.75 in the northern region of the study area. Therefore, during summer months the chlorophyll variations could be explained mainly by the frequent upwelling events, whereas during winter months, high chlorophyll concentration near coast depends on rivers discharges.

ADDITIONAL INDEX WORDS: *Rivers discharge, SST, Ekman transport, upwelling*

INTRODUCTION

The knowledge of physical processes at global or regional scales in the ocean is fundamental to study the oceanic biogeochemical processes, particularly those linked to primary production. Primary production in marine environment is the result of the water masses movement coupled to nutrient and light availability. The most productive areas worldwide are the upwelling regions. The rising of deep cold water makes nutrients available for primary production in the euphotic zone where mass and energy are transferred through trophic webs. Phytoplankton productivity is also enhanced by riverine nutrients input.

The chlorophyll-*a* concentration is an important biogeochemical quantity monitored by satellites, since it is a present pigment in all phytoplankton species and, for this reason, commonly used as an index of phytoplankton biomass.

Therefore, the spatial and temporal patterns of Chl-*a* concentration, water temperature and wind are important oceanographic characteristics with important implications for sustainable management of fisheries and aquaculture.

The use of remote sensing imagery constitutes an efficient way to improve the knowledge of the environmental conditions of an ecosystem, being used to characterize the behavior of primary production over vast areas.

The northwestern coast of the Iberian Peninsula (IP) is the northernmost limit of the Eastern North Atlantic Upwelling System (Wooster *et al.*, 1976), being a region characterized by great hydrologic and biogeochemical activity. Coastal upwelling has important biological implications since primary production is controlled by this phenomenon (Shannon *et al.*, 2003).

The region under study (see Figure 1) is characterized by active and persistent coastal upwelling events, prevailing from June to September (Wooster *et al.*, 1976), promoting important primary production related to the presence of Eastern North Atlantic Central Water (ENACW) near the coast (Fiuza, 1984). The predominantly southward winds observed in summer at the northwestern coast of the Iberian Peninsula, drive an offshore Ekman Transport and force the upwelling of colder, nutrient laden, subsurface waters along coast. In this region coastal upwelling can also occur during autumn-winter months (Peliz and Fiuza, 1999; Alvarez *et al.*, 2003; Alvarez *et al.*, 2009). In fact, over the last decades, Borges *et al.* (2003) have reported an increase in frequency and intensity of winter upwelling events.

Due to this important primary production several studies regarding the characterization of Chl-*a* concentration (Bode *et al.*, 2009; Alvarez *et al.*, 2012), sea surface temperature (Torres *et al.*,

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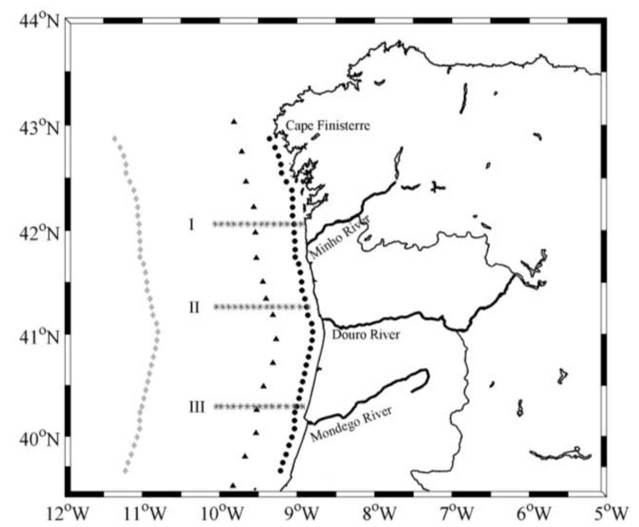

Figure 1. Map of the Iberian Peninsula western coast. Near coast black dots and asterisks represents the points where SST and Chl-*a* data were retrieved. Offshore grey diamonds represents the reference points for SST upwelling index calculus. Black triangles represent the location where wind data was retrieved.

2003; Relvas *et al.*, 2007) and wind (Torres *et al.*, 2003; Alvarez *et al.*, 2008) have been carried out along the western coast of IP.

The area under study includes the Galician western shelf (Spain) and northern Portugal, from 39.5º N to 43.0º N (Figure 1) and it is characterized by the presence of low surface salinity (Oliveira *et al.*, 2004). In fact, the western IP coastal zone is influenced by many terrestrial freshwater sources being the most important the Mondego, Douro and Minho Rivers (Figure 1). They originate an alongshore low salinity water lens. The freshwater input is more intense during the winter, but low salinity values persist during all year as a buoyant plume, called Western Iberian Buoyant Plume (WIBP) (Peliz *et al.*, 2002). The extension and depth of this plume has high variability, being very dependent on the wind regime. It stretches offshore in upwelling favourable winds remaining in the inner shelf during non-upwelling conditions.

Taking advantage of remote sensing data, this work aims to investigate the relationship between the atmosphere-ocean-land conditions and Chl-*a* formation along the northwestern coast of the Iberian Peninsula (Figure 1).

DATA SOURCES AND METHODS

In the present work, remote sensed Chl-*a* concentration, sea surface temperature and wind data is used to investigate Chl-*a* formation along the northwestern coast of the IP (Figure 1).

Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (http://oceancolor.gsfc.nasa.gov/SeaWiFS/) provides the first continuous, long term observations of global ocean chlorophyll from space. The responses of ocean biology to seasonal, regional and interannual events have been comprehensively observed for the first time using SeaWiFS chlorophyll imagery. In the present work SeaWiFS Chl-*a* concentration data for the western IP, with a spatial resolution of 9 km, was considered.

A global comparison between the SeaWiFS chlorophyll with *in situ* data from NASA and NOAA was accomplished by Gregg and Casey (2004), reveling that the offshore subregion located between the United Kingdom and the central Iberian Peninsula does not have major discrepancies between both data sets. In fact, for this sub-region a root mean square error (RMS) of 19.7% and a correlation of 0.65 were determined.

The SST data were obtained from the Advanced Very High Resolution Radiometer (AVHRR) sensor, onboard NOAA satellites, with a spatial resolution of 4 km. Data from this sensor is the most used in the estimation of SST for scientific and operational applications in oceanography and fisheries.

Both, Chl-*a* and SST satellite data have a temporal resolution of 8 days and are available from 1998 to 2007.

Surface wind data were provided by the QuikSCAT (http://podaac.jpl.nasa.gov/DATA_CATALOG/quikscatinfo.html) satellite available from July 1999 to December 2007. The QuikSCAT dataset consists of global grid values (0.25º×0.25º) of meridional and zonal components of wind measured twice a day. It should be noted that satellite measurements are not available near coast (~25 km).

According to a recent study performed by Sousa *et al.* (2012), QuikSCAT data is a valuable tool to obtain representative wind data near the northwestern IP coast, showing good results when compared with *in situ* wind observations. In fact, a RMS error of 1.4 ms^{-1} was found between satellite and *in situ* data measured in a station located 44 km offshore from the Minho River.

River discharge data from the Mondego, Douro and Minho Rivers were also evaluated. Mondego and Douro discharges were provided by Instituto Nacional da Água (http://www.snirh.pt/) and Minho discharges by Confederación Hidrográfica del Miño-Sil (http://www.chminosil.es/).

In the present work, 41 points (from south of Mondego River to Cape Finisterre – black dots in Figure 1) near coast and three sections (I, II and III) were considered to study the meridional and zonal variability of SST and Chl-*a* concentration, respectively. Black dots (Figure 1) are located at 0.15º from the coast and both dots and asterisks are spaced in a way that each point coincides with different AVHHR or SeaWIFS cells.

To evaluate the relation between Chl-*a* and upwelling occurrence, the Upwelling Index (UI_{ET}) was calculated through the Ekman Transport, that is defined in terms of wind speed, W, (Alvarez *et al.*, 2012) from the QuikCAT satellite, by:

$$Q_x = \frac{\rho_a C_d}{\rho_w f} \left(W_x^2 + W_y^2\right)^{1/2} W_y \qquad (1)$$

$$Q_y = -\frac{\rho_a C_d}{\rho_w f} \left(W_x^2 + W_y^2\right)^{1/2} W_x \qquad (2)$$

where air density ρ_a=1.22 Kg m^{-3}, sea water density ρ_w=1025 Kg m^{-3},C_d=1.4×10^{-3} is a dimensionless drag coefficient, and f is the Coriolis parameter, defined as twice the vertical component of Earth's angular velocity, Ω. The subscript x corresponds to the zonal component and the subscript y to the meridional one.

Once wind data are not available near coast, the Ekman Transport was calculated for the offshore triangles (Figure 1), located at 0.64º from the coast.

Upwelling Index (UI_{SST}) was also determined through the SST difference between coastal (black dots near coast) and oceanic (gray diamonds) points at the same latitude.

Finally, the correlation coefficients between Chl-*a* and SST, *UI* and rivers discharge were computed through the equation:

$$r_{x,y} = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y} \qquad (3)$$

where cov(x,y) is the covariance between data and σ is the standard deviation. The significance level is also computed through a matrix of p-values. P-value is the probability of getting a correlation as large as the observed value random chance, assuming that the null hypothesis is true. If p-value is small (less than 0.05) then the correlation will be significant.

RESULTS

Chl-*a* and SST variability

Along the western IP, Chl-*a* concentration is higher near the coast (Alvarez *et al.*, 2012). Therefore, mean annual evolution of Chl-*a* concentration from SeaWiFS for the 41 near coast points was computed (black dots in Figure 1). Results are illustrated in Figure 2.

According to the results of Figure 2, Chl-*a* concentration shows seasonal and spatial variability along the northwest IP coast. Indeed, in spring-summer months high Chl-*a* concentrations are detected, reaching maxima values during August.

Between July and September maxima Chl-*a* concentrations are observed along all the IP coast, highlighting three of these maxima: one between Mondego and Douro rivers, other in front of Minho river and the last in front of Galician Rias (with values ranging from 4 – 6 mg m^{-3}).

In autumn-winter months, high Chl-*a* concentration is found along the western IP coast, although with lower values than in summer. These high values are not uniform along the coast, being the most significant values located at latitudes 40.50º N, 41.50º N and 42.40º N. For instance, relative maxima of 2.5 – 3.0 mg m^{-3} at 40.50º N, of 3.0 – 3.5 mg m^{-3} at 41.50º N and 3.5 – 4.0 mg m^{-3} at 42.40ºN were detected (Figure 2). This high Chl-*a* concentration could be related to the nutrients input from land through rivers discharge. Otherwise, winter upwelling events can also occur along the IP west coast, bringing nutrient rich water from lower depths (deCastro *et al.*, 2006; Alvarez *et al.*, 2009).

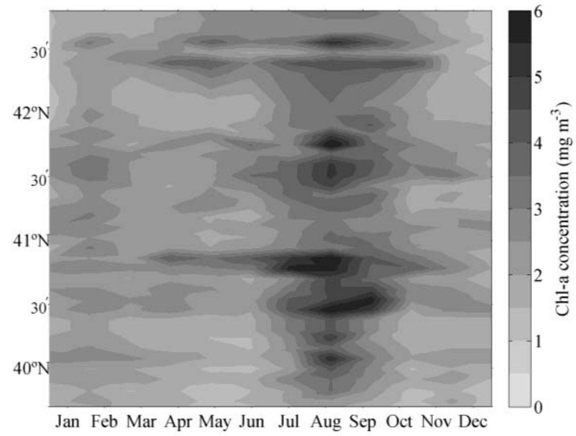

Figure 2. Mean annual evolution of Chl-*a* concentration (1998-2007) along the IP west coast.

The mean annual evolution of Chl-*a* concentration and sea surface temperature were also computed for the sections I, II and III being the results represented in Figure 3. Results confirm that the Chl-*a* concentration is higher near the coast and during spring-summer months. The highest values (6-7 mg m^{-3}) were found for the zonal section I, which is located northern of the Minho River mouth. For all sections the spring-summer maxima are confined to the coast (~6 km), while winter maxima spread offshore (Figure 3a).

According to the results (Figure 3b), near coastal sea surface

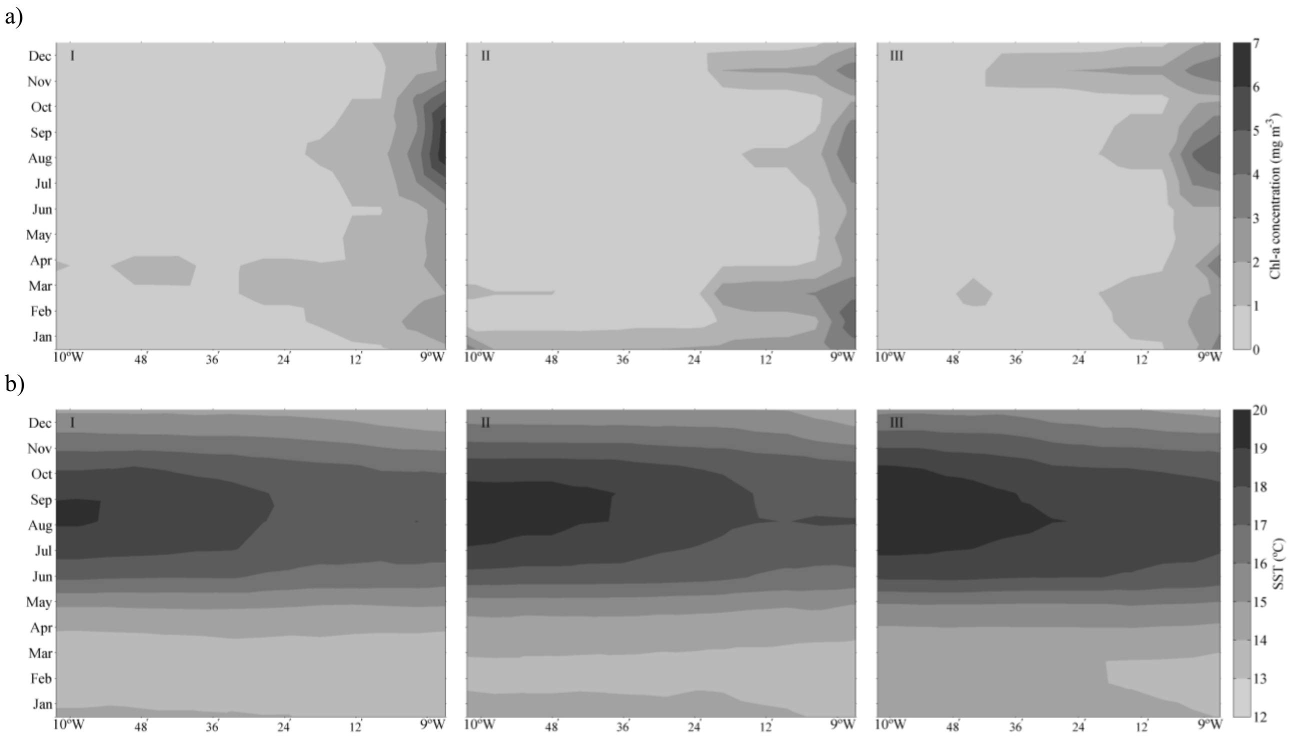

Figure 3. Mean annual evolution of a) Chl-*a* concentration (mg m^{-3}) and b) SST (º C) in the sections I, II and III represented by the asterisks points in Figure 1 (1998-2007).

temperature is colder than offshore, which is probably related to upwelling events during summer months and to the WIBP fed by the rivers runoff during winter months. Indeed, plume waters have lower temperatures than surrounding offshore waters and they may even be colder than the waters beneath (Santos *et al.*, 2004). This fast cooling is due to plume high buoyancy, which allow heat exchange between surface waters and atmosphere in a different way from the surrounding waters as the thermally driven convection is limited to a thinner layer (Santos *et al.*, 2004).

In summer, coastal sea surface temperature ranges from 16 to 18º C, while offshore it ranges from 19 to 20º C. During winter, sea surface temperature is lower ranging from 12º C near coast to 14º C offshore.

Upwelling indices vs. river outflow

To understand the upwelling implications in Chl-a formation along the IP west coast, atmospheric and oceanic conditions were analyzed in terms of upwelling indices. The mean annual upwelling index was determined in two ways: one through the Ekman Transport (UI_{ET}) and other through the sea surface temperature (UI_{SST}) (Figure 4).

The UI_{ET} is defined as the Ekman Transport normal component to the shoreline (Bakun, 1973; Nykjaer and Vancamp, 1994; Gomez-Gesteira *et al.*, 2006) and was computed from QuikSCAT winds. Positive (negative) UI_{ET} values means upwelling favorable (unfavorable) conditions.

Conversely, the UI_{SST} is computed through the SST difference between coastal (black dots near coast – Figure 1) and oceanic (gray diamonds – Figure 1) points at the same latitude. Thus, from the UI_{SST} is possible to identify the presence of upwelled water in surface, i.e. when near coast SST is colder than the offshore SST. In this case, negative (positive) UI_{SST} values means upwelling favorable (unfavorable) conditions.

Analyzing the UI_{ET} corresponding results (Figure 4a), strong favorable upwelling conditions are detected from April to September, with the upwelling index UI_{ET} ranging from 400 to 900 m^3s^{-1} km^{-1}. The highest mean value is found during July at latitudes between 40.0 and 40.5º N (Figure 4a). In February and November favorable conditions are also detected, although with less intensity. In fact, the upwelling index for these months is approximately 500 m^3 s^{-1} km^{-1}. Although the UI_{ET} during these months is lower than during summer months, the values are not negligible and may be related to winter upwelling events that deliver nutrient rich water to the coast (deCastro *et al.*, 2008a; Varela *et al.*, 2010) generating an increase of Chl-*a* concentration.

For the remaining months, negative values of UI_{ET} are observed, meaning upwelling unfavorable conditions. For instance, in October and December the upwelling index values reach -200 m^3 s^{-1} km^{-1}.

The general UI_{SST} pattern is similar to the UI_{ET} i.e., the upwelling favorable conditions are detected in spring-summer months and unfavorable conditions are observed in autumn-winter months. However, the most upwelling favorable conditions occur with 1-2 months difference between UI_{SST} and UI_{ET}. Indeed, through the UI_{SST} results, upwelling favorable conditions occurs between June and November with the strongest negative values observed in September (-2.5º C), while according to UI_{ET} it occurs in July. The referred difference was also detected in previous studies (Nykjaer and Vancamp, 1994; deCastro *et al.*, 2008b).

Generally, through the joint analysis of both upwelling indices it can be concluded that upwelling events occurs mainly during summer months (between June and September). Thus, the cold and nutrient-rich upwelled water together with solar radiation leads to the development of phytoplankton, web food and consequently leads to an increase of Chl-*a* concentration (see Figure 2).

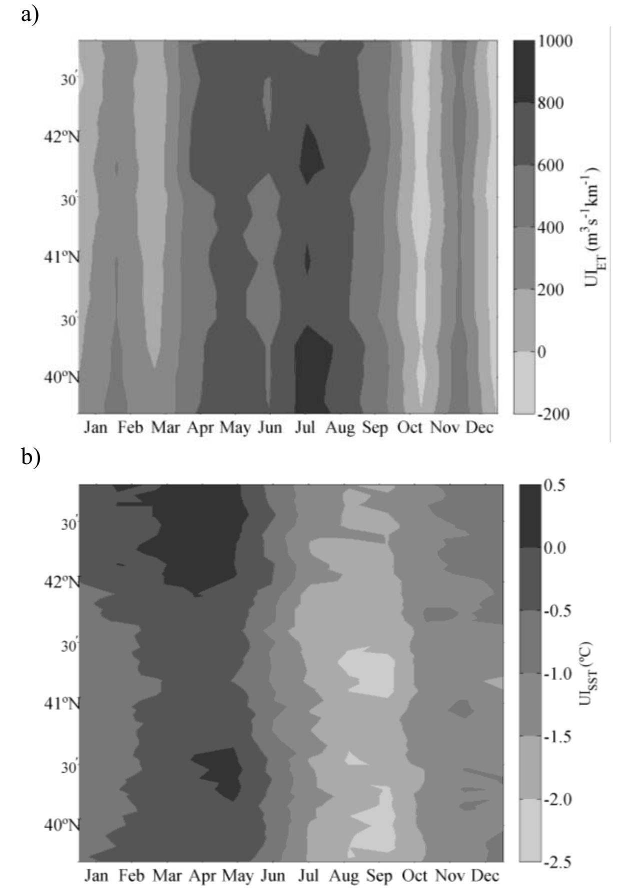

Figure 4. Mean annual evolution of Upwelling Index calculated from Ekman Transport (a) and SST (b) along the IP west coast (2000-2007).

To understand the most important forcing of Chl-*a* formation along the northwestern IP coast, the monthly mean river discharges from 1998 to 2007 of the Minho, Douro and Mondego rivers were computed. These results are then compared with the monthly mean UI_{ET} from 2000 to 2007 being the results presented in Figure 5. For the sake of clarity and taking into account that UI_{ET} and UI_{SST} (Figure 4) present its maxima/minima during the same seasons, only the UI_{ET} would be considered hereafter.

Rivers discharge showed typical patterns, with high values during winter and low values in summer, being the Douro River the most important freshwater source into the ocean. During typical non-upwelling winter conditions, plume waters are confined to the inner-shelf northward from Mondego River (Peliz *et al.*, 2002).

The Douro fluvial discharges range from 100 m^3 s^{-1} in August to 1100 m^3 s^{-1} in January, while Minho outflow ranges from 100 to 600 m^3 s^{-1}. Mondego River is the minor freshwater source, with values ranging from 15 m^3 s^{-1} in August to 180 m^3 s^{-1} in January.

The monthly mean upwelling index results (Figure 5) suggest that the most favorable upwelling conditions occur during summer months. For instance, the UI_{ET} has it maximum during July (~800 m^3 s^{-1} km^{-1}) and its minimum in December (-100 m^3 s^{-1} km^{-1}).

Although upwelling index during winter, are not so significant than in summer, the values found for February and November are

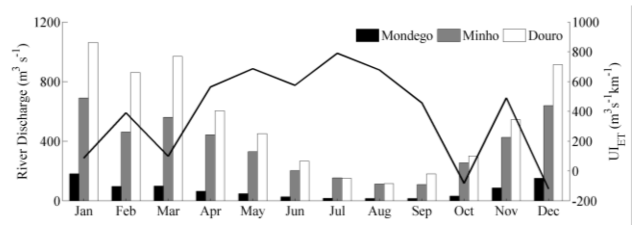

Figure 5. Monthly mean discharges ($m^3 s^{-1}$) from 1998 to 2007 (bars) and monthly mean Upwelling Index (m^3 s^{-1} km^{-1}) from 2000 to 2007 along the IP west coast.

not negligible, reflecting the existence of winter upwelling events that can turn the water more productive, even if to a lesser extent than during a summer upwelling event (Prego *et al.*, 2007).

Thereby, results suggest that in summer the most important forcing of Chl-*a* formation is the upwelling phenomenon. During winter conditions, phytoplankton blooms are often due to the interaction between the central waters that upwell when conditions are favorable, or through intrusions at the upper levels and the low salinity of the Western Iberian Buoyant Plume (Bode *et al.*, 2002; Peliz *et al.*, 2002; Santos *et al.*, 2004).

Relation between Chl-*a* and atmosphere-ocean-land conditions

Since the main aim of the present work is to investigate the relationship between the atmosphere-ocean-land conditions and Chl-*a* formation along the Iberian Peninsula northwestern coast, correlations between Chl-*a*, upwelling index, rivers discharge and SST were also computed (Table 1). Following other studies (Alvarez *et al.*, 2008; Alvarez *et al.*, 2012), the upwelling index UI_{ET} was chosen to compute the correlations.

Correlations were computed by averaging each variable in the five surrounding points of the three main rivers, Minho, Douro and Mondego, for comparison with their discharges.

Based on the previously described results, correlations coefficients are computed for two distinct periods: one between June to September and other between November to February. Most of computed correlations have a significance level higher than 95% (Table 1).

The considered discharges results from averaging the river runoff from the 7 days previous to the Chl-*a* data. This methodology was previously adopted by Alvarez *et al.* (2003).

According to the results, between June and September Chl-*a* and UI_{ET} are positively correlated, increasing southward. In fact, near the Mondego River the correlation coefficient is approximately 0.58, while near the Minho River is 0.43. During this period, correlations between Chl-*a* and SST were negative, also with the highest coefficients found for Mondego River region (-0.42). Also, Chl-*a* and river discharges are negatively correlated between June and September, with values decreasing southward from -0.30 to -0.19.

These results indicate that high Chl-*a* concentrations in summer months (June-September) are related to upwelled cold, nutrient rich water, contributing to enhance the primary production.

Between November and February, chlorophyll concentration is positively correlated with Ekman transport upwelling index and with river discharges, being the latter more significant. Indeed, correlations between Chl-*a* and discharges ranges from 0.50 in Mondego River to 0.75 in Minho, while with UI_{ET} the correlation is approximately 0.30 for the three locations.

Conversely, Chl-*a* concentration is negatively correlated with SST for the period between November and February, with values ranging from -0.27 in Minho to -0.42 in Mondego River.

Therefore, correlations suggest that from November to February both upwelling index and rivers discharge have an important role in the Chl-*a* formation, however it seems that discharges are more significant. In fact, during winter, river discharges are strong and therefore transport large amounts of nutrients from inland to the coast.

In summary, according to the results, during summer months the high Chl-*a* concentrations could be explained by the frequent upwelling events that usually occur in the west IP coast, transporting water rich in nutrients from lower depths. Otherwise, during winter, high near coast Chl-*a* concentrations are probably linked to the rivers discharges and winter upwelling events.

CONCLUDING REMARKS

The present work evaluates the relationship between the atmosphere-ocean-land conditions and the coastal Chl-*a* formation along the Iberian Peninsula west coast, taking advantage of remote sensed data.

Generally, Chl-*a* concentrations are higher near coast, showing seasonal variability. Indeed, Chl-*a* concentrations are usually higher between June to September, which is associated to the observed high upwelling index. These upwelling favorable conditions were corroborated by the sea surface temperature, which reveals the presence of cold water near coast during this season. Therefore, the upwelled cold nutrient rich water enhances primary production and consequently Chl-*a* formation.

During winter, Chl-*a* blooms were also detected, and are probably related to the WIBP fed by the rivers runoff that transport nutrients to the ocean and to upwelling events.

From the correlation analysis, the decrease of SST with the increase of Chl-*a* concentration is visible during both analyzed periods. This decrease of SST is associated, in summer, to the upwelling events and during winter to both upwelling and rivers discharges. However, as Chl-*a vs*. discharges correlations are higher than the Chl-*a vs*. UI_{ET} during winter, the Chl-*a* variability depends mostly on the input of nutrients from land runoff.

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Table 1: Correlation coefficients between Chl-*a* and *UI*, SST and river discharges ([a] significance level < 95%, all the other values have a significance level > 95%).

	Chl-a vs. UI_{ET}		***Chl-a vs. SST***		***Chl-a vs. discharges***	
	June-September	November-February	June-September	November-February	June-September	November-February
Minho	0.43	0.32	-0.27[a]	-0.23[a]	-0.30	0.75
Douro	0.54	0.29	-0.35	-0.25[a]	-0.22	0.61
Mondego	0.58	0.31	-0.42	-0.20[a]	-0.19	0.50

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