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Phytoplankton pigment distribution in the northwestern Alboran Sea and meteorological forcing: A remote sensing study

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ABSTRACT

A set of weekly-composite SeaWiFS (Sea-viewing Wide Field of view Sensor) imagery (from 1998 to 2004) has been used to asses the temporal and spatial variability of the surface chlorophyll distribution in the Northwestern Alboran Sea. Empirical Orthogonal Function (EOF) analysis of the images series shows the existence of three different regions in which surface chlorophyll presents a homogeneous temporal behavior in the neighborhood of the Strait of Gibraltar.

The temporal patterns of surface chlorophyll concentrations in each region have been characterized by studying the role of several forcing factors, mainly the zonal component of the wind field.

The first identified region occupies the coastal area in front of Estepona and Málaga and shows the highest chlorophyll concentration in the entire region of study in absence of easterly winds. A second region is located far offshore, in the zone usually occupied by the Atlantic jet entering the Alboran Sea, showing high concentrations of chlorophyll when the easterlies blow. Finally, a third region has been situated in the normal location of the Western Alboran Gyre (WAG).

The zonal wind field arises as a main forcing function in the modulation of the intensity and location of the upwelling processes in the area, while the entrance of the Atlantic jet seems to be the main agent feeding of all these processes.

1. Introduction

The Northwestern (NW) sector of the Alboran Sea is a highly dynamic area featuring a number of different processes with strong mesoscale variability (Tintoré *et al.*, 1991; Viúdez *et al.*, 1996; Gomís *et al.*, 1997) as fronts, cyclonic and anticyclonic gyres and upwellings (Minas *et al.,* 1987; Gleizón *et al.,* 1996) involving water masses of diverse composition and origin (Gascard and Richez, 1985).

The main forcing agent of the hydrodynamic processes in this area and in the entire

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Alboran Sea is the Atlantic jet coming through the Strait of Gibraltar (Bormans and Garrett, 1989; Benzohra and Millot, 1995; García Lafuente *et al.*, 1998) and feeding the two main anticyclonic gyres characteristic of the general Alboran Sea circulation (Lacombe, 1971; Lanoix, 1974; Arnone *et al.*, 1990; La Violette, 1984; Kinder and Parrilla, 1987; Vázquez-Cuervo *et al.*, 1996).

Frontal areas present a high temporal and spatial variability (Zakardjian and Prieur, 1998) making necessary a high resolution sampling for a correct interpretation of the data sets. Sampling aboard a research vessel is expensive and time-consuming and, frequently, it does not give the necessary resolution to study the short time scale processes in such dynamic areas. The use of remote sensors onboard satellites is a good alternative or, at least, a convenient complementary technique in these cases. This method has the advantage of spatio-temporal synopticity but, on the other hand, it has the disadvantage of retrieving information from only the upper layer of the water column and cannot discern what happens in deeper waters.

In this work the surface chlorophyll concentrations derived from the SeaWiFS sensor imagery from the Northwestern (NW) Alboran Sea are analyzed. This platform was launched in 1997 with the aim of analyzing biogeochemical factors in the ocean which could play a role in global climate change (Hooker *et al.*, 1992).

Remote sensing data have been applied previously to the study of the hydrology of the Alboran Sea as a whole (e.g. Tintoré *et al.*, 1988; Folkard *et al.*, 1997; Parada and Cantón, 1998). In these works SST (Sea Surface Temperature) imagery of all the Alboran Sea and the Gulf of Cádiz was used to characterize the main hydrological structures in the basin, i.e. the two anticyclonic gyres and the Atlantic jet.

However, the use of thermal images to identify processes as upwellings and fronts in the vicinity of the Strait of Gibraltar is not ideal due to the range of different temperatures shown by the Mediterranean and Atlantic waters during the year (Folkard *et al.*, 1997; Parada and Cantón, 1998; Baldacci *et al.*, 2001). Thereby, the existence of a number of surface waters with different temperature in the region are able to mask the phenomena characterized by changes in SST, as coastal upwellings and fronts (Álvarez *et al.*, 2000).

For these reasons, studying this system using chlorophyll imagery may better characterize the observed phenomena. In this vein, García-Gorriz and Carr (1999) used nine years of CZCS (Coastal Zone Color Scanner), OCTS and SeaWiFS data of all the Alboran Sea in order to determine the climatologic tendencies of the circulation and upwelling processes in the basin. Similarly, Baldacci *et al.* (2001) made a study of the NW region of the Alboran Sea outlining the main structures and processes in the area together with its intra-annual variability by using one-year series of SST and SeaWiFS images. These works demonstrated the importance of the coastal upwelling in the Spanish shore as the main source of chlorophyll to the region throughout the year.

In the present work the temporal and spatial resolution is increased, which allows a more detailed analysis of the processes taking part in the NW Alboran Sea. A temporal series (1998 to 2004) of high resolution SeaWiFS imagery is used to characterize the main hydrodynamic structures and their dynamics. The role of forcing functions (such as the intensity and direction of winds) in the modulation of variability is also studied.

2. Material and methods

a. SeaWiFS imagery processing

We used daily SeaWiFS local area coverage (LAC) data received by the satellite reception ground station at the University of Las Palmas de Gran Canaria (HCAN) at 1.1 km spatial resolution. These images, high-resolution level 1 SeaWiFS ocean color radiances, were atmospherically corrected and processed to level 2 using SeaDAS version 4 (http://seadas.gsfc.nasa.gov), SeaDAS was also used to remap (Mercator projection) level 2 chlorophyll concentration and PAR (Photosynthetically Active Radiation) estimates. Each image was navigated (i.e., adjusting to the real coastline), if necessary, by co-registering the image with the outline of the coast. In SeaDAS, chlorophyll concentration (in mg m^{-3}) is derived from the OC4 ocean color algorithm (O'Reilly *et al.*, 1998; 2000), The accuracy of water-leaving radiances measured by SeaWiFS is within 5%, and chlorophyll-*a* derived from the data is within 35% for case I waters (McClain *et al.*, 1995).

In the analysis performed, weekly composites have been used instead of daily images due to the high cloud coverage showed by the latter. To compute this composite, the mean of every daily image in a week is calculated pixel by pixel. Thereby, the weekly composite keeps the spatial resolution of the original images (1.1 km). The images used cover the time period from January 1998 to December 2004 (363 weekly composite).

b. Meteorological data

For our analysis we used wind data recorded at the Tarifa station of the "Instituto Español de Meteorología" (Spanish Institute of Meteorology). These data consist of wind speed and direction at four times every day (00, 07, 13 and 18 hours). Using the complete dataset, the zonal component of the mean daily wind is calculated, being the positive values westerlies and negative easterlies. A possible source of error using this data set could be caused by local wind anomalies, as in the location of Tarifa the easterlies are known to occur with a higher frequency than expected for the rest of the study area. However, comparison with wind data from other meteorological stations (Ceuta and Algeciras) showed that, in spite of a slight underestimation of the mean zonal wind, the data set used is representative and suitable for the analysis of zonal wind dynamics in the whole area.

The zonal component of the wind is considered because of its impact on the transports through the Strait of Gibraltar (Candela *et al.*, 1989; Dorman *et al.*, 1995; Folkard *et al.*, 1997). This is due to wind magnitude and to the topography of the Strait which extends mainly in an east-west direction (Fig. 1). Moreover, a detailed analysis of both zonal and meridional component of the wind field has revealed that the former is, in average, five times greater than the latter for all the studied period.

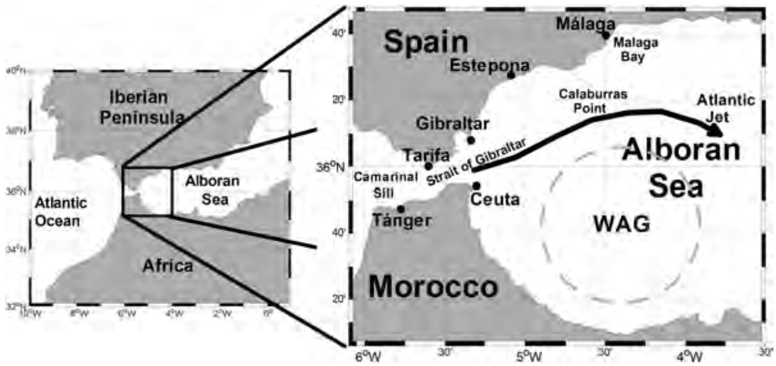

Figure 1. Region of interest (ROI).

c. Empirical Orthogonal Function (EOF) analysis

EOF analysis was used to examine the spatio-temporal variation of surface chlorophyll in the Region of Interest (ROI) (Fig. 1). EOF analysis provides a description of the spatial and temporal variability of a time series in terms of orthogonal functions called empirical modes (Emery and Thompson, 1998).

In order to enhance the variation of temporal patterns, the temporal mean was removed in the EOF analysis (as in the so-called temporal EOF described by Lagerloef and Bernstein, 1988). We use SVD (Singular Values Decomposition) methods performing a similar analysis to that of Navarro and Ruiz (2006).

To examine if the modes calculated are statistically significant, the distance-error concept (**$\delta\lambda$**; North *et al.*, 1982) was used. Following these authors, **$\delta\lambda$** is calculated as

$$\delta\lambda = \lambda\sqrt{\frac{2}{N}} \qquad (1)$$

where λ is the eigenvalue and N is the number of images used in the EOF analysis (N = 363 weekly composites in the present study). A mode is considered significant only if the distance (difference) between its associated eigenvalue and the next is bigger than $\delta\lambda$.

d. Spectral analysis of the time-series

The spectral analysis of a time-series gives crucial information to describe, understand and forecast the climatologic variability of that series (Ghil *et al.*, 2002).Thus, the time series of the weekly chlorophyll concentration is decomposed in its singular eigenvalues (Vatvard *et al.*, 2001), using a Singular Spectral Analysis (SSA).

From this decomposition and using the Root-MUSIC (MUltiple SIgnal Classification) method it is possible to get the signal with pure frequencies which are within the original time-series (Rao and Hari, 1989). The SSA method has been used previously in the study of SST patterns in the Alboran Sea (see Alvarez *et al.*, 2000).

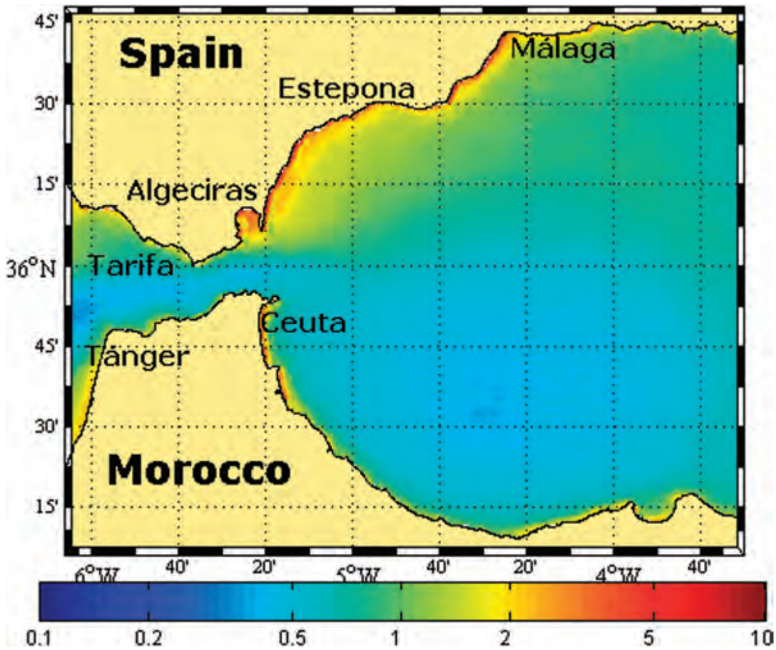

Figure 2. Climatologic spatial distribution of superficial chlorophyll during the 7 years.

3. Results

The climatologic distribution of the surface chlorophyll concentration during the whole period (7 years) in the ROI (Region Of Interest) shows the main typical hydrological structures in the area (Fig. 2). These structures include the upwelling zone along the Spanish coast (Gil, 1985; Minas *et al.*, 1987; Rubín *et al.*, 1992; Gil and Gomís, 1994; Rubín *et al.*, 1997; Parada and Cantón, 1998; Rodríguez *et al.*, 1998; Prieto *et al.*, 1999) and an oligotrophic gyre in the south (Minas *et al.*, 1987; García Lafuente and Cano, 1994; García Lafuente *et al.*, 2000), called the Western Alboran Gyre (WAG).

The highest levels of surface chlorophyll in the ROI (2 – 9 mg m^{-3}) are located in a coastal band in front of Málaga Bay and in the eastern side of the Strait of Gibraltar. Another band of high chlorophyll concentration (2 – 3 mg m^{-3}) is found in the Moroccan coast of the Cádiz Gulf. The lowest mean chlorophyll concentrations (0.2 – 0.5 mg m^{-3}) are found in the central channel of the Strait of Gibraltar and within the WAG.

The monthly climatologic values of the average surface chlorophyll concentration in the ROI and the monthly climatologic zonal wind intensity during the seven-year period are shown in Figure 3a. There is an intense chlorophyll bloom in the beginning of the spring (March-April) reaching an average concentration over 0.9 mg m^{-3} (Fig. 3a), a sharp decrease until 0.5 mg m^{-3} during the summer months (June through September) and a gentle increase up to 0.8 mg m^{-3} during autumn (from September to December); an annual cycle similar to the one described for the whole Alboran Sea by Garcia-Gorriz and Carr

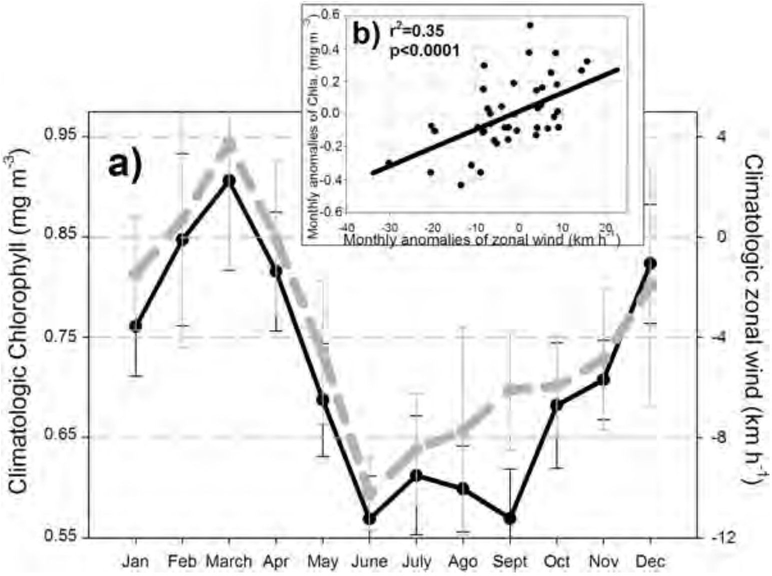

Figure 3. (a) Climatologic monthly values of chlorophyll (black line) and zonal wind field (gray dashed line) positive values state for westerlies and negative for easterlies. Errors bars correspond to the range within 95% of data are located. (b) Chlorophyll anomalies vs. wind anomalies.

(1999). The zonal wind intensity shows also an annual cycle with more westerly winds during the winter months and easterlies in summer as previously reported by Dorman *et al.* (1995). There is a significant correlation ($r^2 = 0.9$, $p < 0.01$, $n = 12$) between the climatologic zonal wind intensity and the average chlorophyll concentration, with a trend to increase the average surface chlorophyll concentration when the wind blows from the west.

However, the existence of concordant annual cycles does not imply that a relationship between both variables exists. So, these annual cycles have subtracted form wind and surface chlorophyll data and still a significant correlation between them is present ($r^2 = 0.35$, $p < 0.001$, $n = 84$; Fig. 3b) for the monthly average data. No significant correlation was found between meridional constituent of the wind field and surface chlorophyll concentration so in the following analyses only zonal wind will be considered.

It is also possible to create a composite image of chlorophyll anomalies corresponding to a typical situation of westerlies (positive zonal wind, Fig. 4a) and of easterlies (negative zonal wind, Fig. 4b). Each composite has been calculated subtracting the climatologic pattern showed in Figure 1 to the mean distribution of surface chlorophyll during each wind regime. These images show that the distribution of chlorophyll concentration changes according to the dominant wind regime. Under the effects of westerlies, the chlorophyll appears concentrated in the Spanish coastal region (positive anomalies values in Fig. 4a) with a frontal area far offshore indicating the presence of the Atlantic jet. It is also possible

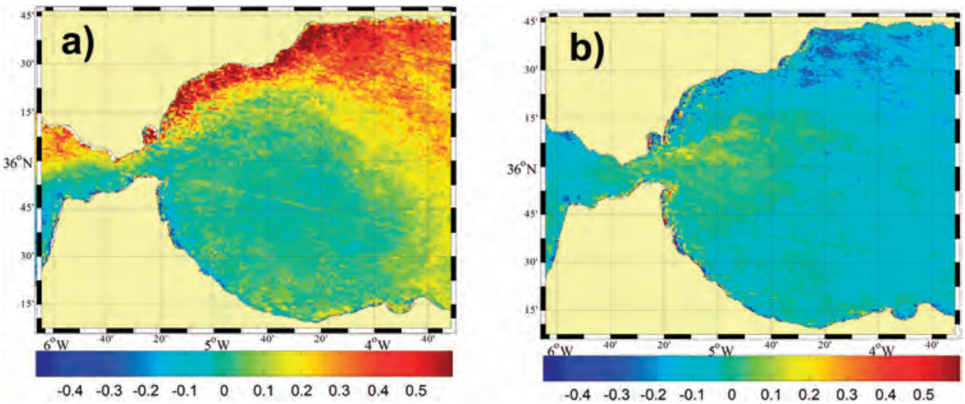

Figure 4. Distribution of chlorophyll anomalies with (a) westerlies and (b) easterlies winds.

to distinguish the southward turn of that jet to create the WAG. On the other hand, when easterlies blow, the maximum chlorophyll anomalies move southward invading the area usually occupied by the Atlantic jet in the westerlies situation.

The time series of the average chlorophyll concentration in the ROI (Fig. 5a) has been analyzed by means of the SSA, obtaining the eigenvalues and their associated energy (variance) (Fig. 5b).The eigenvalues 1 and 2 defined a pure signal with a periodicity of 52 weeks (nearly 1 year), as is shown by the Root-MUSIC method, which represent about 20% of the total variance of the series. The third eigenvalue is representative of a long-term tendency with a periodicity of 7 years, with the 7% of the total variance. Eigenvalues 4 and 5 define a signal with two years periodicity representing 6% of the variance.

Using these three signals (defined by the first five eigenvalues) it is possible to reconstruct the chlorophyll temporal series (Fig. 5c). The annual signal shows the maximum values (0.8 - 0.9 mg m^{-3}) during February and March and the minimal (0.5 - 0.6 mg m^{-3}) in September, very similar to the climatologic annual cycle (Fig. 3a). The next signal in terms of energy is the long-term tendency, which shows the maximum around year 2001 and minimum at the end of the studied period. Finally, the biannual signal shows bigger amplitude during the first half of the period, with a decrease throughout the last three years. From the EOF analysis of the complete satellite images series and using the error-distance criterion defined by Eq. (1), only the three first modes could be considered significant. These three modes represent around 40% of the total variance of the series.

The spatial distribution of the three significant modes is shown in Figure 6. The first mode marks a region in a narrow-coastal band along the Spanish coast with highly positive values and almost null values in the rest of the ROI (Fig. 6a). The second mode presents positive values in a region separated from the coast, in a zone that frequently is occupied by the Atlantic jet (Fig. 6b). The third mode shows values slightly over zero only in the region of the WAG (Fig. 6c). Using these three modes it is possible to define three different regions in the ROI: Region 1 (R1) determined by a value of the first mode over 0.6; Region

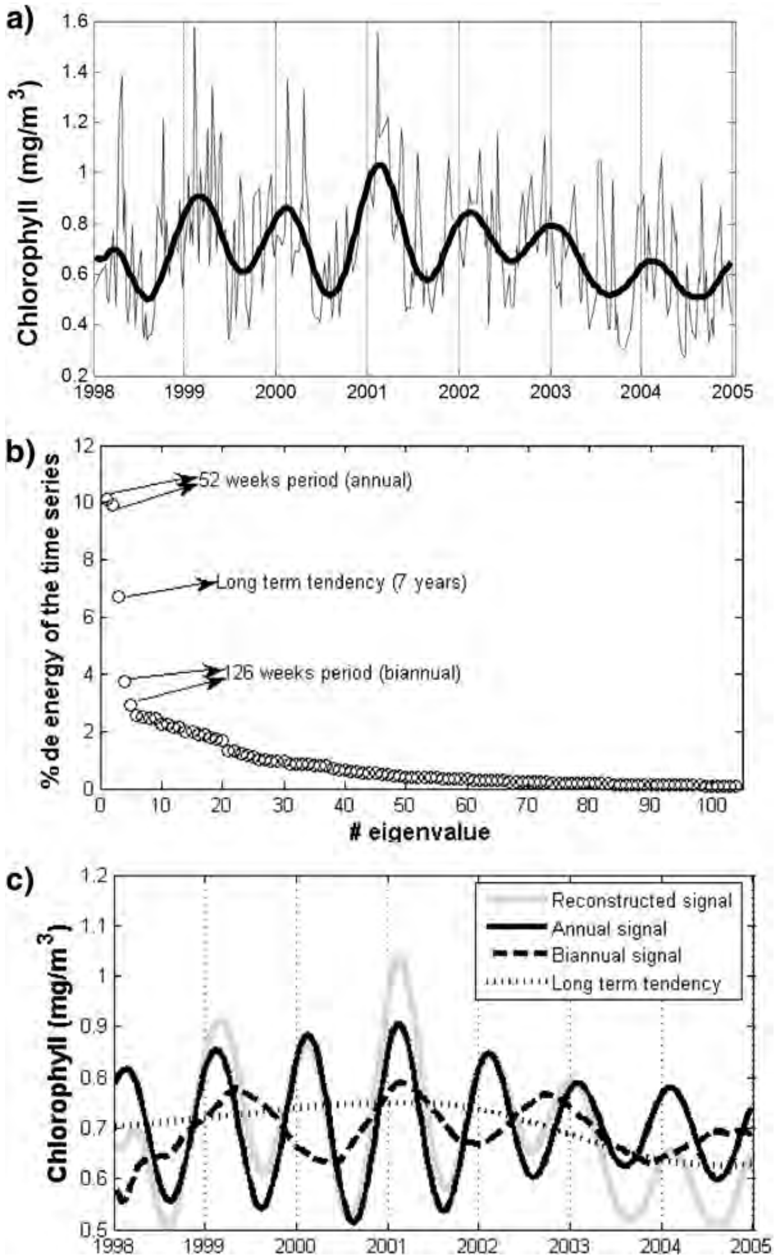

Figure 5. (a) Time series of the mean chlorophyll concentration in the ROI (thin line) and reconstruction using SSA (thick line). (b) Eigenvalues of the time series of chlorophyll. (c) Reconstruction of the chlorophyll time series using the root-MUSIC analysis (gray line) and individual signal detected.

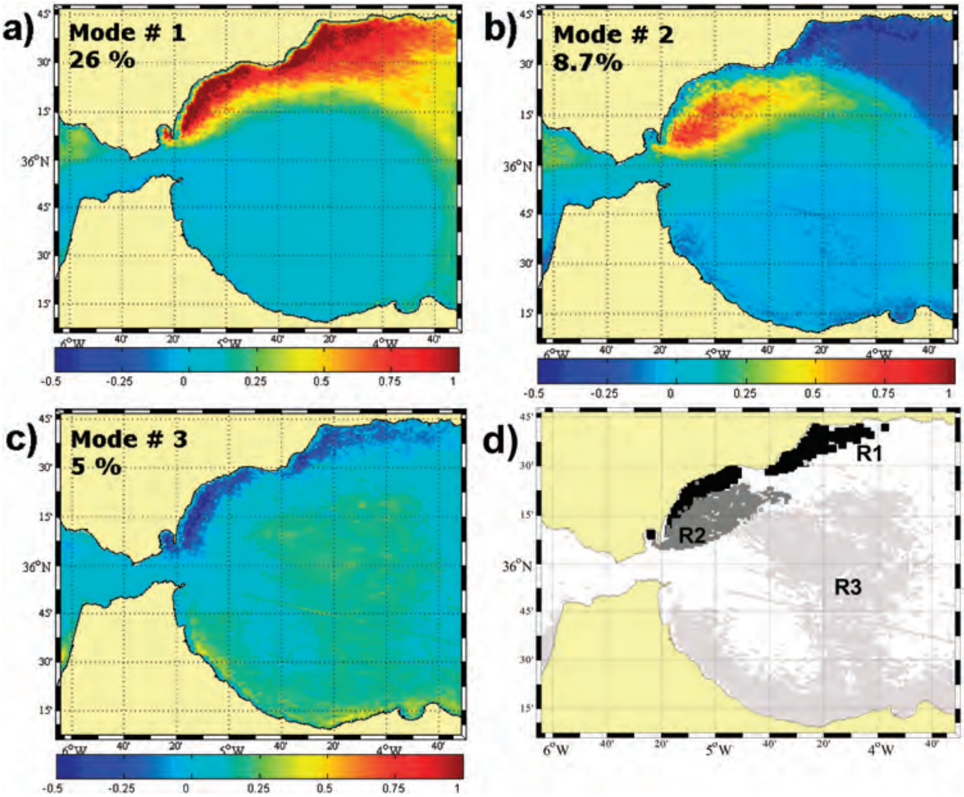

Figure 6. (a), (b) and (c) spatial distribution of the 3 first modes of the EOF. (d) Homogeneous regions defined as expressed in the text.

2 (R2), with values of the second mode higher than 0.4; and Region 3 (R3) occupying the zone where mode three is higher than 0.3 (Fig. 6d); these limits are chosen because they divide the ROI in three regions spatially separated.

The temporal evolution of the three modes is shown as black bars in Figure 7. This figure also shows the reconstructed signal of these evolutions (gray line) obtained following the same procedure previously described for the chlorophyll temporal evolution (Fig. 5).

The reconstruction of mode 1 (Fig. 7a) is made with four different signals (not shown). The more intense signal (accounting for the 40 % of the total variability) has an annual periodicity, with a maximum in April-May and a minimum in September, very similar to that found in the chlorophyll evolution. For the second mode (Fig. 7b), two significant signals are found, being the more energetic (24 % of the total energy) an annual signal with the maximum values during the end of the summer (September) and the minimum around April. This signal seems to be complementary of that found for the first mode. Finally, the third temporal mode presents two main different signals (Fig. 7c). One has an annual

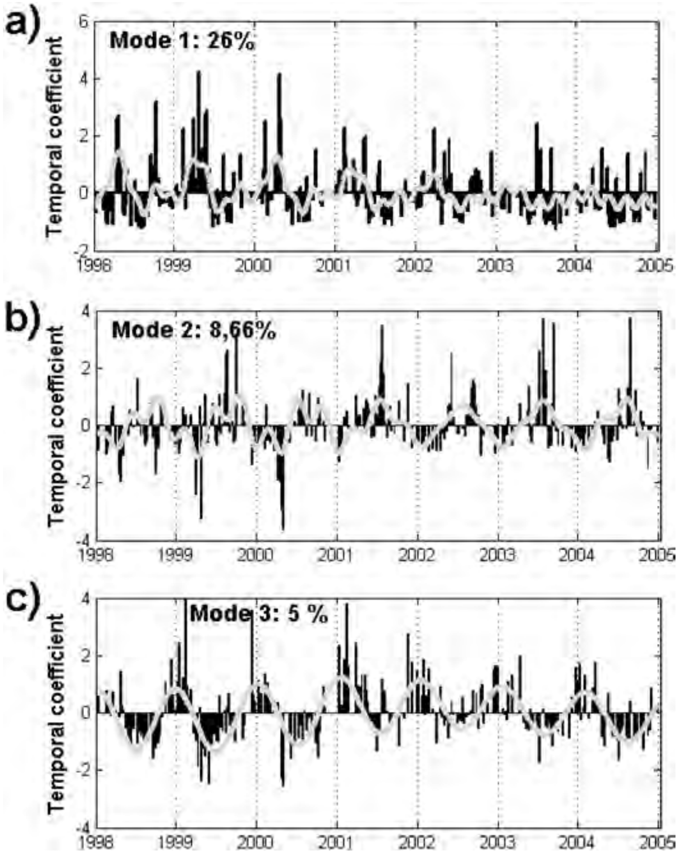

Figure 7. Temporal evolution of each mode (black bar) and reconstructed signal using SSA (gray line).

periodicity with maximum values in January and minimum in July. The second signal is a long-term tendency with a minimum in 1999 and a maximum in 2002.

Using the regionalization of the ROI based on the EOF analysis, the behavior of surface chlorophyll concentration can be studied for each differentiated region.

a. Region 1

The region R1 (Fig. 6a) occupies the area where the intense Estepona - Marbella upwelling has been described to be active under the combined influence of the westerly winds and the mean oceanic currents in the area (García-Lafuente *et al*., 1994 and 1998; Rodriguez *et al*., 1998). Throughout the seven years of study the average concentration of chlorophyll in this region seems to be positively correlated with the zonal component of the wind field ($r^2 = 0.37$, $p < 0.01$, $n = 84$; Fig. 8a).

However, in calculating this mean zonal component of the wind, different parameters

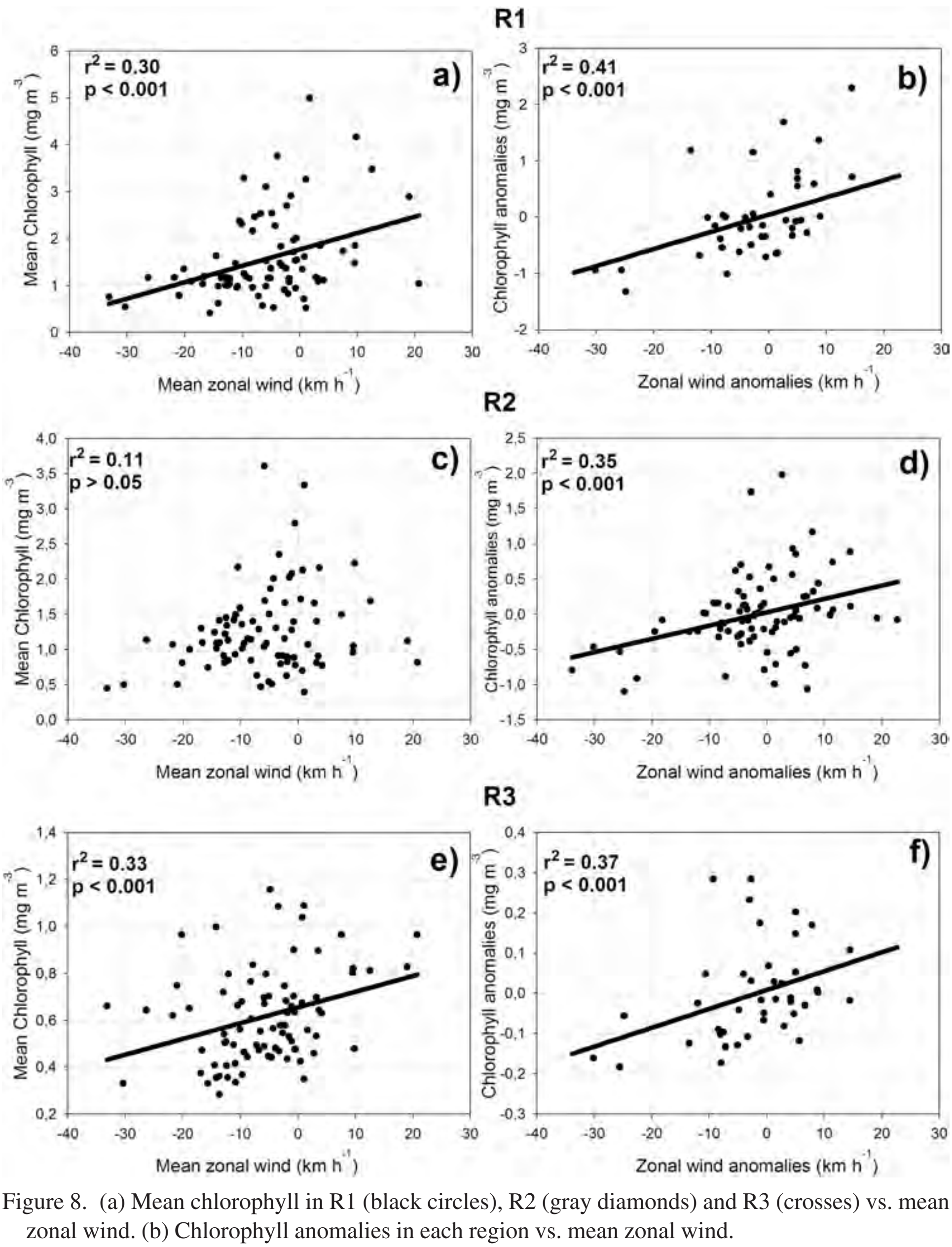

Figure 8. (a) Mean chlorophyll in R1 (black circles), R2 (gray diamonds) and R3 (crosses) vs. mean zonal wind. (b) Chlorophyll anomalies in each region vs. mean zonal wind.

such as the number of days in which each kind of wind (easterlies or westerlies) blow (monthly frequency) and the magnitude of these winds (monthly sum of wind modules) are taken into account. It is possible, then, to explore the relationship between the surface

Table 1. Statically values of the correlation between mean chlorophyll in R1 and R3 and the wind-series parameters. Frequency is the number of days per month that each zonal wind blew, Sum states for the monthly sum of intensity of easterlies and westerlies.

	Easterlies Freq.	Sum Easterlies	Westerlies Freq.	Sum Westerlies
R1 Mean Chl.	**$r^2 = 0.36$***	$r^2 = 0.37$*	$r^2 = 0.12$**	$r^2 = 0.17$**
R3 Mean Chl.	**$r^2 = 0.28$***	$r^2 = 0.4$*	$r^2 = 0.003$**	$r^2 = 0.07$**

*$p < 0.01$, **$p > 0.05$, $n = 84$

chlorophyll and each one of these parameters by correlation analysis (table 1). Surprisingly, the average chlorophyll concentration is not correlated with frequency nor intensity of the westerlies, but shows a significant negative correlation with the easterlies ($r^2 = 0.36$, $p < 0.01$, $n = 84$; Table 1).

These relationships suggest that the activation of the coastal upwelling does not need the presence of westerlies; it only needs the absence of easterlies

b. Region 2

This second area extends from Gibraltar to Calaburras Point but is separated from the Spanish coast (Fig. 6b). The average concentration of chlorophyll in this R2 shows no significant correlation with the average zonal wind (Fig. 8c). However, there is a relationship between the anomalies of the chlorophyll in this region and the wind ($r^2 = 0.3$, $p < 0.05$, $n = 84$; Fig. 8d). As mentioned above, these chlorophyll anomalies are defined as the difference between the mean values of each month with respect to the climatologic value for this month.

Also, another significant negative correlation ($r^2 = 0.5$, $p = 0.01$, $n = 84$) has been

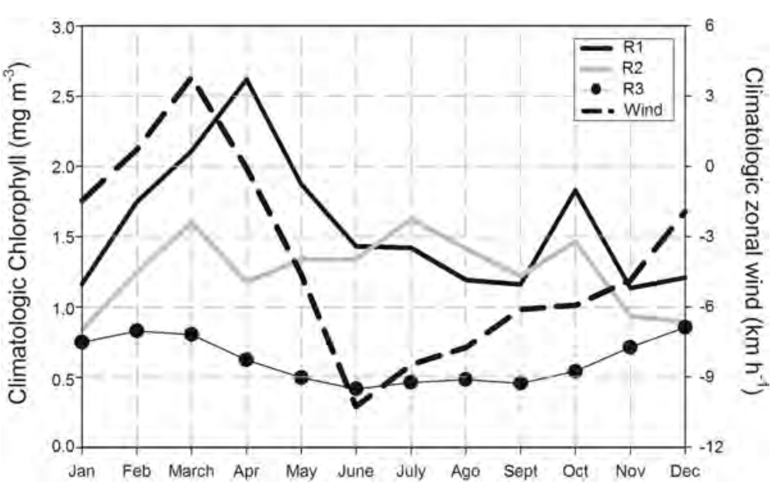

Figure 9. Monthly climatology of chlorophyll in each region along with zonal wind climatology.

found between the monthly climatologic value of the chlorophyll concentration and the monthly climatologic value of the monthly winds (see Fig. 9). This correlation reflects the increase of the climatologic values of the chlorophyll concentration in R2 in the presence of easterlies.

c. Region 3

This third region defined by the EOF analysis (Fig. 6d) includes an extensive area in which the WAG is usually located (Minas et al., 1987; Bormans and Garret, 1989). The mean value of the surface chlorophyll concentration in this R3 is, again, statistically correlated with the presence of westerlies ($r^2 = 0.31$, $p < 0.01$, $n = 84$; Fig. 8e) as happened in R1.

As with R1, the chlorophyll in R3 is well correlated with the absence of easterly winds, but shows no correlation with westerly winds frequency or intensity (Table 1).

4. Discussion

a. Interregional variations

The proposed regionalization of the ROI from the EOF modes could be explained in the framework of the existing information of the area. The distribution of planktonic organisms in the northwestern Alboran Sea usually shows a high concentration area in the northernmost band (the Spanish coast) coinciding with the R1; this zone also corresponds with a local coastal upwelling which has been evident for a long time as seen from surface (Lanoix, 1974) and even satellite studies (Tintoré *et al.*, 1988). On the other hand, a poor region is typically located in the south zone associated to the WAG, corresponding with the proposed R3 (e.g. Minas *et al.*, 1987; Packard *et al.*, 1988; Rubín *et al.*, 1992). It has been also stated that in the region occupied by the R2 a number of special processes occur as local upwellings due to southward drifting of the Atlantic jet (Sarhan *et al.,* 2000) or enhanced cyclonic circulation (e.g. Rodríguez *et al*., 1998; Beranger *et al*., 2005).

It is known that the wind has a role in the modulation of oceanographic processes in this area as previously proposed in different works (e.g. Crepón, 1965; Cheney and Doblar, 1982; Sarhan *et al.*, 2000; Vargas-Yáñez *et al.*, 2002). The results in the present work confirm that the surface chlorophyll concentration in the ROI and in each one of the regions defined by the EOF analysis is, to some extent, related with the zonal component of the wind field (either westerlies or easterlies) (Fig. 8). Obviously, there could be other sources of variance with a shorter time scale range of action (like those due to tidal forcing) that should not be neglected, as tidal related phenomena are presumed to be of central importance especially in the western side of the area (Macías *et al*., 2006). Nonetheless, the action of wind is undoubtedly a major agent at the spatial and temporal scales which are well analyzed by this regionalization method, accounting for 40% of the total variability of the surface chlorophyll distribution.

The proposed regions R1 and R3 show a positive and significant correlation between the mean chlorophyll concentration and positives values of the zonal wind, but no significant relationship was found for R2 (Fig. 8c). However, in the three regions a positive and significant correlation is found between the chlorophyll anomalies and the mean zonal winds (Figs. 8b, d and f).

The observed differences between the mean chlorophyll concentration and the anomalies of the chlorophyll in R2 with respect to the zonal wind field could be explained by the spatial extension of the upwelling events in R1. As it is shown in Figure 6b, R2 is situated offshore but adjacent to R1. When the coastal upwelling is enhanced (in absence of easterly winds, Table 1), the patches with higher chlorophyll concentration could occupy the area R2 as a result of advection processes from the coastal area. These processes favor the increase in chlorophyll concentration at R2, which can explain the positive correlation between the anomalies of the chlorophyll and the zonal wind field (Fig. 8d). At the same time, when easterlies are blowing, a relatively high chlorophyll concentration can be found in R2 (see Fig. 4b and 9). These two different mechanisms could explain the lack of correlation between the mean chlorophyll in R2 and the mean zonal wind (Fig. 8c).

The climatologic behavior of the chlorophyll concentration in each region also shows important differences between them (Fig. 9). In R1 and R3 the highest levels are found during the winter (when the easterlies are less frequent) and the minimum in summer (when easterlies are common). The similarity in the behavior of the chlorophyll concentration in these two regions and the fact that the values in R1 are, on average, twice those in R3, indicate that the chlorophyll found in the oligotrophic gyre would come from R1 by advection processes, as was proposed by Baldacci *et al.* (2001).

Surprisingly, contrary to previous hypothesis, surface chlorophyll concentration in R1 has a good correlation with the absence of easterlies rather than with the presence of westerlies (see Table 1).This seems to indicate that the coastal upwelling is not being forced by Ekman pumping fed by the presence of westerlies but by different process. Previous works had postulated that an important process for the maintaining of the coastal upwelling should be the presence of the Atlantic jet in the nearby area, because of the north-south oscillation of the frontal zone (Sarhan *et al.,* 2000) or because of vertical motion induced by interfacial friction (Garret and Loder, 1981; Tintoré *et al.*, 1991).

The results obtained here are the first to confirm this last hypothesis. Without wind, the jet tends to be situated closer to the Spanish coast (García-Lafuente *et al.*, 1994) due to the geometry of the basin. In this situation the coastal upwelling is geostrophically enhanced due to the friction of the flowing Atlantic waters and the motionless Mediterranean waters. Under the action of westerly winds the jet varies its position slightly (Sarhan *et al.*, 2000) making the situation similar to that present in the absence of winds, with the coastal upwelling working. This could be the reason of the lack of correlation found between westerlies and surface chlorophyll in the coastal area.

However, when easterlies blow, the speed of the Atlantic jet drops (García-Lafuente *et al.*, 2002; Béranger *et al.*, 2005) and a southward drifting of the jet happens (Sarhan *et al.*, 2000). As the jet separates from the coast, the coastal upwelling weakens and could even disappear as is shown in Figure 4b. Consequently, surface chlorophyll concentration in R1 is only negatively correlated with the presence of easterly winds as shown by the analysis presented here.

This role of wind forcing in the modulation of the coastal upwelling was previously unknown and has been only detectable by analyzing a long time series of data. Such analysis should be suitable to study many other upwelling areas throughout the world's oceans attempting to elucidate whether wind forcing activate or simply modulate these processes. Also, the understanding of the actual behavior of this particular oceanographic area is of central importance to interpret spatio-temporal patterns of chlorophyll in the western Mediterranean as the Alboran Sea is one of the most productive regions of this basin.

The climatologic pattern in R2, as commented above, shows the opposite tendency, with maximum chlorophyll levels during the summer (coinciding with more frequent episodes of easterlies) and lower values in winter (Fig. 9), in spite of small discrepancies at the beginning of the spring (March). This behavior could be related with the previously mentioned southward drifting of the Atlantic jet in easterly wind conditions. Sarhan *et al.* (2000) showed that when the jet moves southward, an ascent of Mediterranean waters occurs in the area which was previously occupied by the Atlantic jet. These waters come from an intermediate layer characterized by a relatively high nutrient concentration, which are then injected into the surface layer. Also, when the jet separates from the coast, a strong cyclonic circulation cell is created in the vicinity of R2 (e.g. Rodriguez *et al.*, 1994 and 1998; Macías, 2006), which could enhance the upwelling of nutrient in this area far apart from the coast. These combined upwelling processes will be responsible of the generation and maintenance of a moderate phytoplankton bloom in R2 under easterlies conditions.

Another *a priori* key factor that can control the temporal evolution of the chlorophyll concentration is the annual cycle of PAR. However, our results and those reported by García-Gorriz and Carr (1999) indicate that the maximum chlorophyll levels in the ROI usually match with the minimum PAR levels (which happens in the winter months), so, the surface chlorophyll patterns in this area do not seem to be controlled by light availability. Though photoadaptation could be responsible for high levels of chlorophyll with low PAR, some field data taken in the ROI during different periods of the annual cycle have shown that increases in chlorophyll concentration in westerly episodes correspond to increases in phytoplankton biomass, independent of the date of the year (Macias, 2006). So photoadaptation is not controlling surface chlorophyll distribution in the area. Also, nutrient dynamic of the mixed layer could be influencing the chlorophyll patterns. This is a point which needs a more detailed analysis.

Thus, meteorological forcing appears to be one of the main factors controlling the quantity and distribution of surface phytoplanktonic biomass in the NW region of the Alboran Sea. The importance of this forcing has been suggested previously by different authors (Dorman *et al.*, 1995; García-Lafuente *et al.*, 1998; Béranger *et al.*, 2005) but the present study reveals the possibility of defining regions with a homogeneous behavioral response to this forcing, thus potentially elucidating the underlying mechanisms.

Another important result is that the Atlantic jet arises as the main driving factor for the upwelling and bloom processes in the ROI while meteorological variables (wind forcing) only tune these processes in an indirect way, affecting the velocity and position of the jet.

This work has proposed the wind as a very important factor in explaining the variability of the surface chlorophyll in the western Alboran Sea, being only statistically relevant to the zonal component of the wind field, as no correlation was found between meridional constituent and surface chlorophyll. However, the three modes of the EOF used to define the homogeneous regions only explain some 40% of the total variability of the imagery time series. That means that more of the 60% of the variance of surface chlorophyll in the area cannot be associated to the three main regions defined, nor be explained by the wind-controlled mechanisms proposed in the work. As mentioned above, the tidal forcing should be of great importance in the area and some processes, such as the coastal breaking of internal waves in the shelf, could have a great influence in the upwelling processes. In fact, important coastal vertical motion has been measured in this area with presumable influence on biological processes (Rodríguez *et al.*, 2001). Nevertheless, the use of weekly or monthly integrated images (because of the cloudiness of the area) prevents the study of short-scale processes as those related with the tidal cycle. In the future, to perform analyses of the variability of such processes, the use of airborne sensors on board airplanes could be more suitable as it would give the necessary temporal and spatial resolution along with a reasonable spatial coverage.

b. *Interannual variations*

The temporal extension of the satellite imagery series used (1998 to 2004) allows to infer some results about the interannual variability of the chlorophyll values in the ROI. From 1998 to 2001 the mean concentration of chlorophyll in the whole ROI showed a progressive increase (though with a slightly decrease in 2000) while from 2001 to the end of the period there is a general decreasing trend (Fig. 10a). Although a quite high correlation coefficient ($r^2 = 0.45$) is found between chlorophyll and wind at annual scale, this relation is not statistically significant ($p > 0.01$) possibly due to the small number of points (years) used in this analysis ($n = 7$). Figure 10b also illustrates that a number of years (2001, 2003 and 2004) present strong deviations from the linear relationship showing that, at this temporal scale, some extra factors apart from wind-forcing are introducing additional variability.

The most extreme example of this deviation is year 2001, in which the highest mean surface chlorophyll concentration of all the studied period was detected and there were frequent easterly winds. The mean distribution of surface chlorophyll during this year (not shown) indicates a displacement of the maximum concentrations from R1 to R2. This different spatial distribution could be related with a relaxation of the coastal upwelling which could also cause the shift in phytoplankton community composition in R1 detected

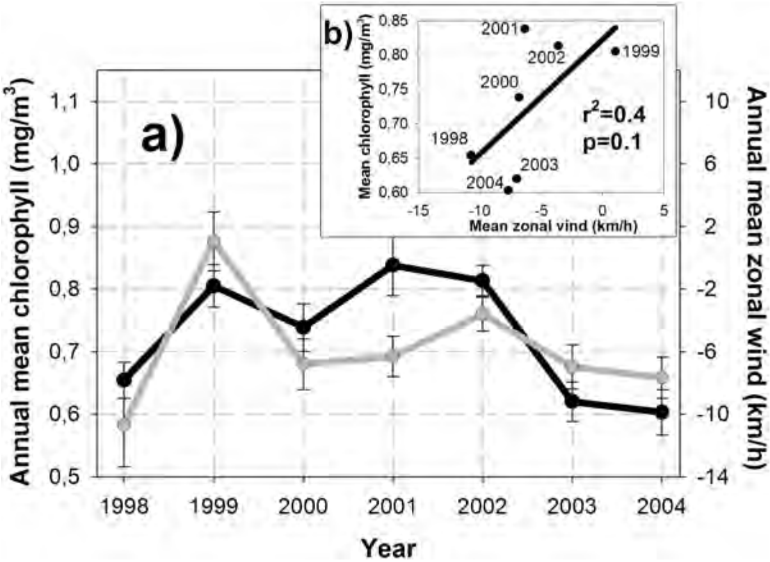

Figure 10. (a) Annual mean chlorophyll concentration in the ROI (black line) and wind component (gray line). (b) Annual mean chlorophyll vs. zonal wind.

by Mercado *et al.* (2005) for 2001. These authors found that, in this period, the main phytoplankton species change from diatoms (typical of upwelling areas) to cocolitophorides.

This weakening of the coastal upwelling could be associated with a change in the circulation patterns in the NW Alboran Sea during this year, as was shown by Beranger *et al.* (2005).Using a hydrodynamic model covering the North Atlantic basin and the Alboran Sea, this study found an enhanced cyclonic circulation in the northern edge of the WAG (where R2 is situated). This circulation pattern would enhance the upwelling of deep waters within the R2 area, fertilizing the upper layers and favoring the subsequently development of phytoplankton blooms.

This high variability of inter-annual surface chlorophyll indicates the presence of many different factors introducing patterns of variability essentially different to that associated with the wind fields. However, to improve understanding of these other factors, a longer time series of observations and/or detailed modeling exercises are required.

5. Conclusions

- There are three regions in the NW Alboran Sea in which the surface chlorophyll shows homogeneous behavior in their temporal variability. The temporal dynamics of surface chlorophyll concentration in each of these areas is quite unique, showing different annual cycles.

- Wind forcing is estimated to be responsible of some 40% of the total variability of the surface chlorophyll distribution in the studied area, with the zonal component of the wind being particularly important.
- The highest concentrations of surface chlorophyll in the area of study are located within the coastal upwelling region in front of Estepona-Marbella and Málaga.
- For coastal upwelling, we find that westerly winds are not required, but that the absence of easterly wind is necessary. This seems to show that these phenomena are regulated by other processes; for instance, the entrance of the Atlantic jet in the Alboran Sea is the most likely.
- A secondary upwelling area is detected offshore in front of Estepona, along the path usually followed by the Atlantic jet when it is situated near the Spanish coast. This upwelling seems to be activated in the presence of easterly winds that usually drift the jet to the south (García-Lafuente, 1998), favoring the ascent of intermediate waters to the upper layer (Sarhan *et al.*, 2000).
- There are strong interannual variations in the mean chlorophyll concentration in the ROI and in its spatial distribution patterns, making it necessary to use the high spatial resolution long-time series to clearly identify spatial and temporal patterns with accuracy.

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