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Spatio-temporal patterns in the north-western Mediterranean from MERIS derived chlorophyll *a* concentration

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SUMMARY: We address the major surface signatures of chlorophyll *a* in the Catalan Sea within the context of the dynamics of the north-western Mediterranean basin. Monthly composites from MERIS measurements and CHL products for Case 1 waters were analysed from June 2002 to June 2005. Composite images of variability were used to identify surface dynamics. The results showed that coastal and open sea waters were separated by a belt of low variability, a permanent oligotrophic belt that is noticeable with respect to the bloom conditions of the surrounding areas. The width of this Catalan Oligotrophic Belt (COB) located along the continental slope, varied between 17 and 30 km and became blurred in the southernmost area. The chlorophyll *a* temporal pattern over the shelf showed an almost steady increase from September to March. A similar behaviour but with lower concentrations was observed in oceanic waters. Both temporal patterns showed a disruption during January and/or February that coincided with the well known deep water formation event in the Gulf of Lions. In 2004, the convection was weaker and the offshore temporal trend was not disrupted; however, the opposite was observed in 2005. The spatial chlorophyll *a* distribution of oceanic waters presented a clear north-south decreasing trend, while the coastal distribution did not show any latitudinal patterns but rather peaks in the areas enriched by river runoff. The observed seasonality was similar to the one published from SeaWiFS data and slightly different from the seasonality shown by CZCS data. Nevertheless, we did not discard the possibility that some of the observed seasonal differences could be a true temporal shift in chlorophyll *a* production.

Keywords: north-western Mediterranean, chlorophyll *a*, remote sensing, MERIS.

RESUMEN: PATRONES ESPACIO-TEMPORALES DE CLOROFILA EN EL MEDITERRÁNEO NOROCCIDENTAL DERIVADOS DEL SENSOR MERIS. – En este estudio se examinan los principales patrones en la distribución superficial de la clorofila *a* en el marco explicativo de la dinámica del Mediterráneo Noroccidental. Para identificar la dinámica en superficie se compusieron imágenes de variabilidad. Los resultados mostraron que entre las aguas costeras y oceánicas se diferenciaba un cinturón de baja variabilidad, permanentemente oligotrófico y visible cuando en las aguas circundantes se producía proliferación algal. La amplitud del Cinturón Oligotrófico del mar Catalán (COB), localizado a lo largo del talud continental, oscilaba entre 17 y 30 km, disipándose en la mitad sur. El patrón temporal de clorofila en la zona de plataforma mostró un claro aumento de septiembre a marzo. Un patrón similar se observó en la concentración superficial en aguas oceánicas. En ambas regiones se observó una interrupción del patrón temporal en enero y/o febrero, coincidiendo con el momento de formación de agua profunda del Golfo de León. En el 2004 el fenómeno de formación de agua profunda fue más débil y el patrón mensual en la región oceánica no sufrió ninguna interrupción, al contrario que en el 2005 donde se observaron máximos. La distribución latitudinal de la clorofila *a* en la región oceánica mostró un claro patrón de disminución norte-sur mientras que en la región de plataforma no se observó ningún patrón pero sí picos de concentración en las áreas enriquecidas por la descarga fluvial. La estacionalidad observada en este estudio es similar a la descrita con datos del sensor SeaWiFS y ligeramente diferente a la publicada con datos de CZCS. No obstante, no se descarta la posibilidad de que parte de las diferencias observadas se deban a un desplazamiento temporal en la producción de clorofila *a*.

Palabras clave: Mediterráneo Noroccidental, clorofila *a*, teledetección, MERIS.

INTRODUCTION

The north-western Mediterranean basin (Fig. 1) is formed by the northern part of the Algero-Provençal basin, and includes the Gulf of Lions, the Ligurian Sea and the Catalan Sea. It is characterised by a relatively stable coastal circulation, the existence of two large rivers that discharge freshwater and nutrients into coastal waters (the Rhone, in the north, and the Ebro, in the south) and the occurrence of deep water formation (Millot, 1991) offshore in the Gulf of Lions. It is one of the most productive regions in the Mediterranean Sea (Cruzado and Velásquez, 1990; Bosc *et al*., 2004).

One of the most noticeable oceanographic features of the basin is the Northern or Liguro-Provençal Current (NC), which flows at the shelf break from the Ligurian Sea, along the coast of Provence, through the Gulf of Lions and continues southwards along the Catalan coast, where it is called the Catalan Current (Salat, 1995), then through the Ibiza Channel (Millot, 1987). Different studies (Masó and Duarte, 1989; Cruzado and Velásquez, 1990; Masó and Tintoré, 1991 Cruzado *et al*., 2002; Salat *et al*., 2002) have shown that this current is in equilibrium with a density front along its entire path (Font *et al*., 1988), where the salinity gradient is the main marker over the Catalan shelf and is reinforced by river runoff (Estrada, 1996). The NC also exhibits a clear seasonality in the mesoscale variability linked with the shelf/slope front (Font *et al*., 1995). The effect of the front has been studied in the last decades, and its role in the distribution of planktonic populations has been shown (Margalef, 1985; Estrada and Margalef, 1988; Sáiz *et al*., 1992; Arin *et al*., 2005). The Catalan front also bounds the spatial dispersion of fish larvae, and is essential in the offshore and inshore limits of coastal and oceanic species respectively (Sabatés *et al*., 2004). Moreover, the location of the frontal system shifts from near to far from the shelf. Consequently, the corresponding accumulation of fish larvae occurs on the coastal side or is dispersed oceanwards (Sabatés, *et al*., 2004).

Estrada (1996) added a diverse range of means of fertilisation to the specific sources of enrichment in this region, such as land runoff in the littoral areas (Cruzado *et al*., 2002) and vertical convection in the central part of the Catalan Sea (Madec *et al*., 1996). Among others it is worth noting the contribution of sporadic fertilisation at frontal zones which also helps to explain the "Mediterranean paradox" (Sournia, 1973), that is, low nutrient reserve vs. moderate level of primary production.

Historical *in situ* observations of chlorophyll *a* in the NW Mediterranean Sea show large variability in time and space (Velásquez, 1997). In the Catalan region inshore-offshore chlorophyll distribution varied greatly among and within studies (Masó and Duarte, 1989; Estrada, 1996). Mesoscale changes in physical and biological coupling showed high chlorophyll *a* values over the shelf in association with continental waters. These were limited by the salinity front, which exhibited high variability in offshore locations in a short period of time, even reversing the inshore-offshore salinity and chlorophyll gradients (Masó *et al*., 1998).

The spatial and temporal coverage of these studies based on *in situ* measurements, provided a limited spatial and temporal picture of the dynamics of the shelf-slope region. However, the spatial and temporal variability of the major hydrographical features within the region, the shelf–slope frontal system, the NC flow (Castellón *et al*., 1990; Conan and Millot, 1995), the intrusion of the River Rhone (Castellón *et al*., 1985; Masó and Tintoré, 1991) and the vertical convection in the central zone, may provide a wide range of potential hydrographical scenarios with different biogeochemical responses.

Over the last years the use of ocean colour data has greatly progressed, and has become an essential tool for describing the biological response of ocean hydrodynamics. There are several studies on ocean colour in the Mediterranean at different spatial scales, from the entire basin (Morel and André, 1991; Barale, 2003; Bosc *et al*., 2004), to some specific regions (Lohrenz *et al*., 1988, Arnone *et al*., 1990, Gitelson *et al*., 1996, Van Dijken and Arrigo, 1996), and also focused on local sites (Gade *et al*., 2003). A recent study of colour imagery of the Gulf of Lions concluded that the NC channels the Rhone river plume south to the Catalan coast (André *et al*., 2005); however, it was also found that in bloom conditions the position of the NC corresponds to an oligotrophic vein. Although this last study did not cover the Catalan coast, Barale *et al*. (2005) composite images showed that the oligotrophic vein intrudes south of this region. Even though the oligotrophic area was visible in both studies in certain months and was located at the NC position, it was only visible in the extreme northern part of the Catalan coast and not in the southward route of this current. Despite the substantial amount of work published on the Cat-

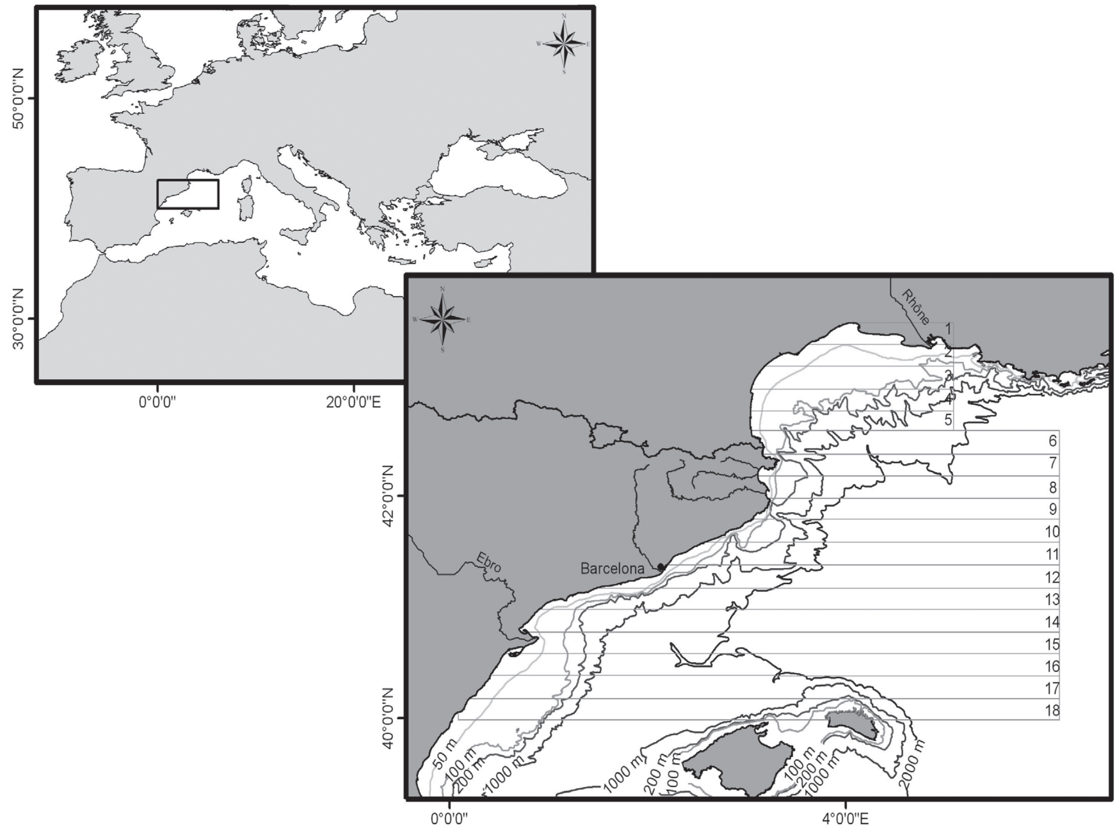

FIG. 1. – Study area showing the divisions considered in the study.

alan Sea, the major surface chlorophyll *a* spatial and temporal signatures are not clearly identified. This is probably due to differences between timing, scales, areas and the objectives of the various studies.

The scope of the present study is to provide a basis for understanding the biological response to the complex hydrography of the north-western Mediterranean Sea. The specific objective is to identify and describe the major spatial and temporal patterns of sea surface chlorophyll *a* derived from the Medium Resolution Imaging Spectrometer (MERIS) in the region, and pay particular attention to the frontal system between shelf and open sea waters in the Catalan Sea (Fig. 1).

DATA AND METHODS

MERIS, an ocean colour sensor developed by the European Space Agency (ESA), is part of the ENVISAT platform launched in March 2002 (Rast *et al*., 1999). A comprehensive summary of the capabilities of MERIS and other ocean colour sensors was given by Bricaud *et al*., (1999). Since the launch of ENVISAT, a study of the ground truth was carried out at the "Centro de Estudios Avanzados de Blanes" (CEAB) for nearly a year as part of ESA's MERIS Calibration/Validation Project. Chlorophyll *a, b, c* measurements and phytoplankton counts were carried out together with hydro observations (Weeks *et al*., 2003). As a result, access to the MERIS ocean colour observations was granted by ESA through Brockmann Consult Ltd.. Weeks *et al*., (2003) showed that the chlorophyll estimates derived from a previous processing version of MERIS did not characterise Mediterranean waters well, as it overestimated *in situ* data below 0.25 Chl *a* mg m^{-3} by a factor of 1.8. This bias is comparable to the bias of SeaWiFS standard products for the Mediterranean basin (Bosc *et al*., 2004) but is smaller in magnitude according to a previous intercomparison (Fournier-Sicre and Belanger, 2002).

The products used for the present study were MER_RR_2P (Level 2), the reduced resolution geophysical product for ocean, land and atmosphere, downloaded from the MERIS website (http://merci-srv.eo.esa.int/merci/queryProducts.do) and processed by Basic ENVISAT (A) ATSR and MERIS toolbox (BEAM MEGS-PC/7.4) software. The dataset was made up of daily chlorophyll *a* concentrations (measured as mg m^{-3}) from the standard MERIS CHL products for Case 1 waters (algal_1). The procedure is based on a band ratio algorithm, which is fully described in the MERIS Algorithm Theoretical Baseline Document (ATBD).

(http://envisat.esa.int/instruments/meris/pdf/atbd_2_09.pdf). Case 1 waters are defined as waters for which phytoplankton and their associated materials control the optical properties (Morel and Prieur, 1977). Although most of the studied region corresponds to Case 1 waters the optical properties of certain coastal areas, which are influenced by land drainage or sediment resuspension, may be different from those in Case 1.

The time period analysed in this study was from June 2002 to June 2005. The area is within the latitudes 40-42.55ºN and longitudes 0.1-6.15ºE, located in the north-western Mediterranean Sea.

Since this study searched for mesoscale or low resolution features, the spatial and temporal resolution was reduced when monthly composites were constructed. The initial spatial resolution, 1040 m x 1060 m, was reduced to 4269 m x 5551 m (0.05º x 0.05º) and every available image was used for each month. A total of 37 monthly composites was estimated and later examined with the Spatial Analyst extension from ArcGIS 9.1 (1999-2004, ESRI). Overall images were derived by: (1) averaging the monthly images and (2) estimating their statistics of variability (standard deviation (sd) and the coefficient of variation (CV). The summer months (June to August) were excluded in these estimations as it is well known that the pigment contents at the surface are constantly very low at this time, e.g. Estrada (1985), Morel and André, (1991). The inclusion of summer composites would have shifted the overall mean images and reduced the mean value of each grid point but would have had no effect on the overall spatial variability. We used the variability at each location as a statistical tool to identify significant differences in the spatial dynamics in chlorophyll *a* with the aim of identifying distinct regions and boundaries. The coefficient of variation (CV) image was calculated by dividing the standard deviation *(*sd) of each pixel by its mean. This statistic (CV) is dimensionless and independent of the mean and provides information about the relative variability of each pixel or location, while the sd provides information about the absolute variability.

Monthly variability of sea surface chlorophyll *a* concentration was estimated separately for the shelf and open sea regions once the boundaries of these regions had been identified with variability maps. Therefore, in order to examine chlorophyll *a* at different latitudes and also to examine the temporal pattern at each latitude, both regions (shelf and ocean) were divided into 18 latitudinal sectors (0.2º length) (Fig. 1).

RESULTS AND DISCUSSION

The composite chlorophyll *a* images of the mean, standard deviation, and coefficient of variation, from June 2002 to June 2005, are illustrated in Figure 2. Each of these images contains different information that shows different features of the spatial dynamic of chlorophyll *a* in the region. The mean image (Fig. 2) provides limited information and even shows offshore dynamics in a distorted manner. The mean image shows a decreasing offshore gradient in chlorophyll *a* concentration but, as we show later, this pattern may differ greatly from what is observed. It shows the mean values along the shelf and identifies the regions influenced by river discharges. Nevertheless, these areas are very likely influenced by Case 2 waters, so chlorophyll *a* estimations could be distorted and should be considered with caution.

The standard deviation (Fig. 2) gives the absolute values of temporal variability per pixel. This statistic is to some extent dependent on the absolute mean value; areas with high mean values are expected to have higher standard deviations. The image of sd of the coastal waters shows the main features identified in the mean image, with high standard deviation at the Rhone, Llobregat and Ebro river mouths; however, sd images of the open sea areas show a very different picture from the mean image. The open sea area exhibits a high sd variable in spite of the relatively low average chlorophyll *a* (Fig. 2).

The sd separated coastal and oceanic regions by an intermediate zone with very low standard deviation. This zone delineates a belt along the coast of Provence that follows the continental slope in the Gulf of Lions where the shelf widens, and from there flows along the coast of Catalonia, clearly separating open sea and shelf waters at least as south as latitude 41ºN. In short, coastal and oceanic regions are separated by a distinctive region of low variability where the low Chl *a* mean values illustrated in Figure 2

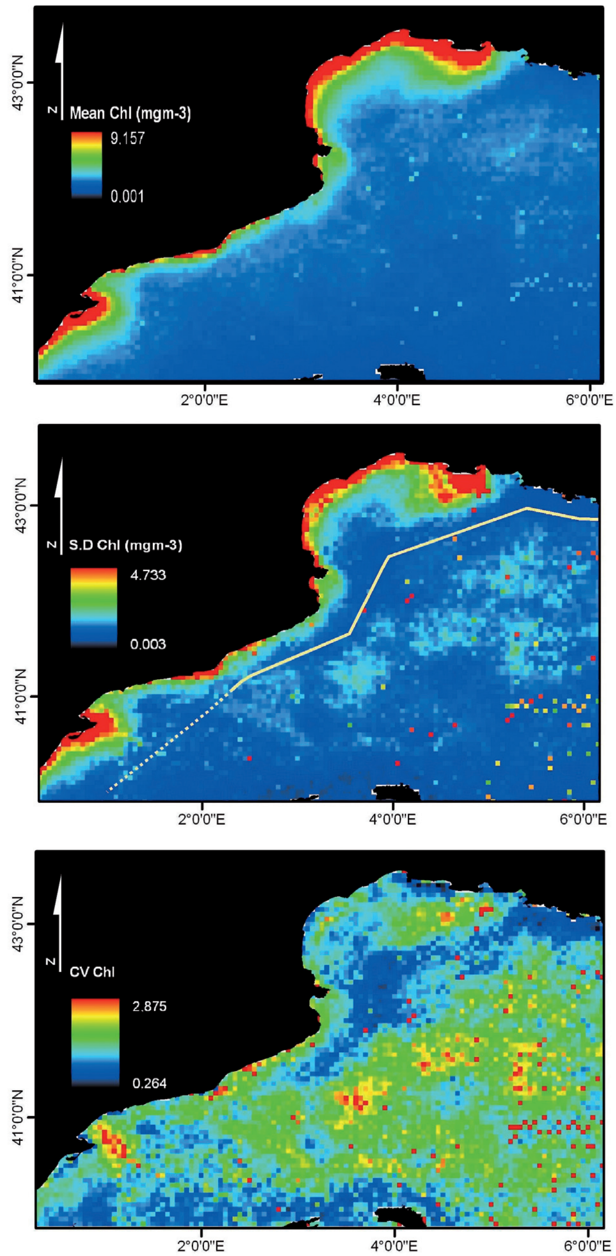

Fig. 2. – Map of mean Chlorophyll from June 2002 to June 2005 and its corresponding standard deviation and coefficient of variation composites (The white line represents the imaginary border between shelf and ocean waters).

are quite constant throughout the year. However, the low Chl *a* values of the oceanic region varies in a wider range. The observed belt of low standard deviation in chlorophyll *a* shows almost the same course (imaginary line plotted in Figure 2) described for the Northern Current (Millot, 1991). The criterion chosen to establish the limits of the belt was the isolines corresponding to 50% variability (CV = 0.5). The width of this belt varies between 37 km and 17 km, and becomes blurred in the southernmost area. The latter result could be explained by the general circulation observed in the area where the Catalan current is dominated by successive fragmentations associated with changes in the orientation of the continental slope (Salat, 1995). The estimated width of the blue belt also lies within the range given for the width of the Northern Current (Castellón *et al*., 1990). The results show that the northern current supports low Chl *a* at least at the sea surface where the hydrodynamics of the current may restrain the proliferation of algae. From the different *in situ* studies in this area, only those by Masó *et al*., (1998) are in agreement with our findings. These authors found the frontal zone to be characterised by low chlorophyll *a* compared with inshore and open sea waters. The reason why other studies (i.e. Estrada and Salat, 1989; Estrada 1991; Sabatés *et al*., 2001) did not find the low productive belt could be due to study areas which were further south (around 41ºN) where this belt is indiscernible or inexistent. Nevertheless, the oligotrophic influence of the north Mediterranean current was already observed in the Gulf of Lions (Gaudy *et al*., 2003).

The coefficient of variation showed the North Current (NC) as a belt of permanently low production of chlorophyll *a* and clearly showed the high variability of open sea waters, which was buffered by the sd due to its dependence on mean values. It is illustrative to compare the information provided by CV images with that given by the mean or standard deviation images in order to understand the effect of the two main rivers on their respective adjacent areas. The CV values are not extremely high at the river mouths as the influence of the river here is permanently high; therefore, pigments are permanently high and consequently CV is low. However, those areas that are episodically affected by river runoff show high CV, north of the Ebro and south of the Rhone. In summary, low CV identifies regions with low variability, either with permanent, high Chl *a* (where sd is high) or with permanent, low Chl *a* values (where sd is low).

The monthly mean images showed that, in the open sea, the maximum variability in chlorophyll *a* concentration takes place from February to April (Fig. 3). In this period, a “blue hole” is clearly visible every year. The term “blue hole” was given by Barale (2003) and describes the lack of chlorophyll in the deep water formation area during the vertical convection events because until the surface layer becomes stable, algae development is inefficient (Morel and André, 1991). The blue hole begins in January every year but its maximum manifestation, at least in our data series,

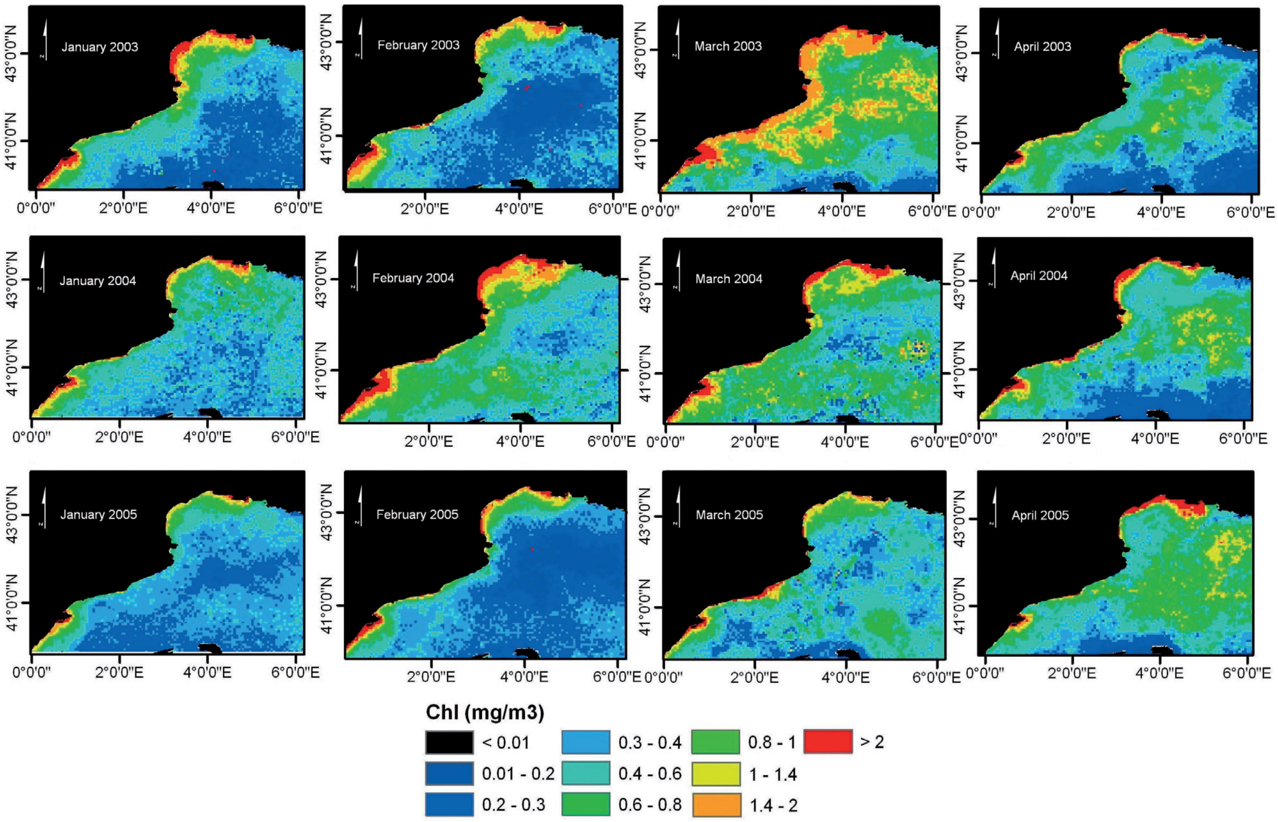

FIG. 3. - Maps of mean monthly Chlorophyll derived from MERIS data for the years 2003, 2004 and 2005.

takes place in February (Fig. 3). The blue hole varies between years in magnitude, shape, duration and location. In February 2005 the convection event seemed to intrude on the shelf, reaching the littoral at Zone 9. Assuming that its extension and duration are indicative of the strength of the convection phenomenon, the strongest event took place in 2005, when the hole reached the northern part of the Gulf of Lions. In contrast, 2004 showed very weak convection while 2003 exhibited an intermediate case. The exceptional episode of deep water formation in 2005 has already been observed (Canals *et al.*, 2006; Font e*t al*., 2007) and explained by the strong and persistent northerly winds during that winter. Our data show that the bigger the hole, the higher the subsequent chlorophyll *a* concentration (Fig. 3). The Chl *a* concentration in the blue hole was estimated between 0.06 and 0.1 mg m^{-3} from the standard SeaWiFS products in February 1999 (Bosc *et al*., 2004). In the present study, MERIS estimations for the same month comprised a wider range of values from 0.01 to 0.2 mg m^{-3} but they did not show any positive or negative bias with respect to SeaWiFS data. Different SeaWiFS data provided by different reprocessing (3 and 4), systematically overestimated Chl *a* in oligotrophic areas of the basin (Bosc *et al*., 2004). As the data shown here does not show any bias compared to the data of Bosc *et al*., (2004) they also probably overestimate oligotrophic conditions.

The sea surface chlorophyll *a* images outline, only by contrast, the oligotrophic belt when the surrounding waters are productive. Thus, it is only manifest in spring images, when blooming is generalised, in coastal and open sea waters (Fig. 3). The oligotrophic influence of the NC has already been observed in the Gulf of Lions (Gaudy *et al*., 2003) where it corresponds to offshore regions. The NC current also represents the Catalan oligotrophic belt (COB). At the peak of production (April), the COB is clearly visible though it loses strength offshore the city of Barcelona, at least at the surface, the absence or weakening of this frontal structure may facilitate shelf-slope exchanges at this latitude. In the same latitude, Sabatés *et al*., (2001) found a strip of low salinity water over the shelf-slope identified as continental influence water (CIW) which is enhanced by low wind speed and increasing thermal stratification (Sabatés *et al*., 2001). Results given for the CIW show that, firstly, this strip had the same speed of 25 km day^{-1} that has already been estimated for the NC

(Castellón *et al*., 1990), and secondly its width offshore from Barcelona was about 15 km. Our estimations give a width for the COB of about 17 km at that same latitude. The major difference between their CIW strip and our COB belt is that they found these waters to be highly productive while, in this study, the COB is characterised by the opposite condition. However, at certain months and off Barcelona, the COB is not so clear and may only partially support the findings of Sabatés *et al*., (2001) (e.g. March 2003 Fig. 3). Nevertheless, we cannot reject that particular scenarios with high Chl *a* concentrations at the COB could be due to the influence of continental enrichment. This hypothesis is supported by previous studies that show that the River Llobregat (south of Barcelona) exhibits a relevant plume offshore and southwards (Gade *et al*., 2003). In short, we suggest that the COB is a visualisation, from ocean colour imagery, of the upper layer of the NC by the distinction of its low Chl *a* concentrations with respect to the higher values of the surrounding waters. The 3 composites shown in Figure 2 permit us to infer that there is a region of permanent, low Chl *a* that clearly differs from the temporal dynamic of the surrounding waters. The limitation of ocean colour imagery is that when the surrounding waters with strong seasonal variability reach low values that are very similar to those in the COB region, it is very difficult to determine whether the COB is invisible or inexistent. Consequently, its temporal extension cannot be determined from sea surface Chl *a*. However, the spatial location can be estimated from the extension of the highly stable water masses (Fig. 2).

Chlorophyll *a* dynamics were also analysed with statistics estimated separately for open sea and coastal regions. The boundary between coastal and oceanic waters in the Catalan Sea, from Zone 6 to 18 (Fig. 1), was defined by the imaginary middle line along the oligotrophic belt (Fig. 2). Mean temporal patterns of the Chl *a* of coastal and open sea and their differences are illustrated in Figure 4. It stands out that concentration peaks over the shelf always took place in March, while they vary around March or April in the oceanic region depending on the year. The chlorophyll *a* temporal patterns both over the shelf and in oceanic waters are very similar and show a steady increase from September to March but are disrupted between January and February when convection takes place. These results did not differ significantly from Morel and André (1991) in 1981, although at that time convection extended to

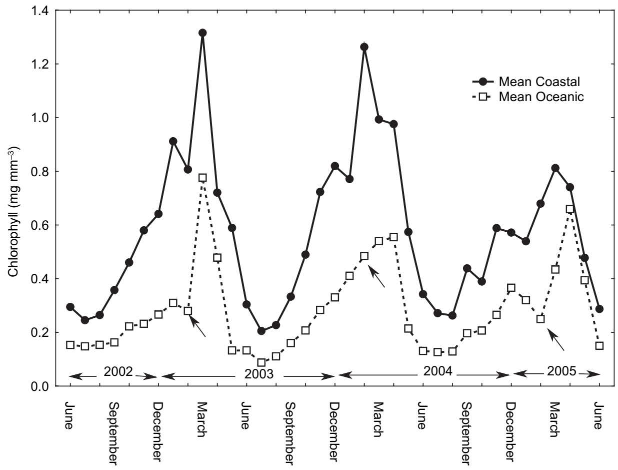

FIG. 4. – Mean monthly Chlorophyll from June 2002 to June 2005 for the coastal and oceanic regions separately (arrows indicate the month of maximum deep water formation in the Gulf of Lions).

March. After the convection event, the chlorophyll *a* production increased, reaching higher peaks than in years with weak vertical convection. The convection event was almost absent in 2004, when we observed that the oceanic production also presented a steady increase from summer to the following spring that was similar to the one observed on the shelf but with a lower magnitude. In 2004, the chlorophyll peak in the oceanic region was lower than in other years, but since the increasing trend was not disrupted in January or February, the cumulative chlorophyll was higher than in the years with strong vertical convection events.

The scenario seen in 2004, when Chl *a* concentrations in January and February did not drop, could favour the survival of larvae of oceanic fish species that spawn in winter (Sabatés *et al*., 2007). Moreover, secondary production could also be favoured by a steady increase in Chl *a* during winter, as zooplankton consume more particles that contain Chl *a* in winter than in spring (Gaudy *et al*., 2003) when there is more abundant Chl *a*. The shelf regions also show a notably low concentration during winter and early spring in 2005, when the reduction in food supply could have had a negative impact on some coastal species. Our results in the area are influenced by the vertical convection and differ from those of Morel and André (1991) in the duration of convection and in the time of blooming. These authors studied images from 1981 and from CZCS, and found that convection lasted almost one month more, extending up to March, and that blooming was in April.

Although coastal estimations of chlorophyll *a* are clearly higher in the areas enriched by river runoff

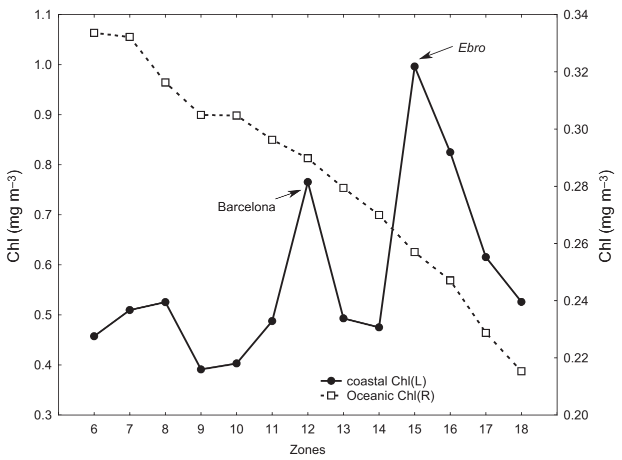

FIG. 5. – Overall mean Chlorophyll for the coastal and oceanic regions for each zone separately (north-south trend).

(Fig. 5) some distortion should be expected in the results. The degree of distortion of each mean will depend on the proportion of grids with Case 2 waters in each zone. Zones 7 and 8 are enriched by three small rivers (Muga, Fluvià and Ter), while two small rivers plus urban and industrial water from Barcelona city discharge at Zone 12. The maximum value corresponds to Zone 15, which is enriched by the Ebro River due to its high release of nutrients (Cruzado *et al*., 2002); however, maximum distortion should also be expected in this estimation. The spatial chlorophyll *a* distribution of oceanic waters presented a clear north-south decreasing pattern.

North-south distributions in both coastal and oceanic areas showed relevant monthly and interannual variability (Fig. 6). In 2004, every month had the standard chlorophyll *a* coastal zonation. In 2005 there was a noticeable drop at Zone 15, which could be due to a decrease in the Ebro river discharge due to the low precipitation observed during that winter (Font *et al,*. 2007). Our results show that Coastal Zones 9 and 10 are characterised by low chlorophyll *a* and we presume this could be due to NC waters intruding in the littoral, as in February and March in 2005 (Fig. 3), favoured by the steep bathymetry of this area (Fig. 1). The latitudinal pattern of chlorophyll *a* in the open sea waters (Fig. 6) presented high monthly variability and a consistent southward decrease is only observed during April. The latitudinal pattern in 2004 reversed twice in three successive months (February-April) but kept high monthly mean values. This supports our previous conjecture that the physical stability of 2004 prevented chlorophyll *a* maxima but permitted a steady increase (Fig. 4), which resulted in a higher total amount of chlorophyll *a*. This result, if corroborated by future studies, would make it possible to predict a relatively high annual standing stock and extension in years in which advection is weak and the blue hole is not very noticeable in remote sensing images.

Finally, we contrasted seasonal patterns, regardless of their values, from the MERIS product with the main divergences between CZCS (Morel and André, 1991) and SeaWiFS products observed by Bosc *et al*., (2004) for this region. The MERIS data agree with SeaWiFS in the following patterns: 1) the seasonal pattern of chlorophyll *a* with minimum values from June to August (CZCS in winter); 2) the progressive increase from September to December (CZCS a distinct autumn bloom); 3) the spring bloom from late February to early May (CZCS from mid-April to early May). However, some of the observed divergences should be attributed only to differences between different products. Patterns 1 and 3 mentioned above do not differ from the most recent CZCS products (Barale *et al*., 1999). Moreover, Volpe *et al*., (2007) have recently developed a new regional algorithm (MedOC4) for the Mediterranean basin which corrects the bias of previous SeaWiFS products. Volpe *et al*. point out that MODIS and MERIS estimations are also likely to be biased and also emphasise the need to develop regional algorithms and re-analyse the SeaWiFS dataset. Consequently, although the sensors cover distinct time periods, CZCS from 1979 to 1983, SeaWiFS from 1997 to 2001, we should not discard or accept too easily that the differences between them are due to the effect of some real climatic temporal shifts.

CONCLUSION

In summary, our results capture several important biological and oceanographic features and their dynamics in the north-western Mediterranean Sea. We warn against the extended use of mean composite images over different time periods to describe the spatial dynamics in chlorophyll *a* because the composite image may hide the real spatial dynamics. The results have shown that chlorophyll *a* distribution does not show the decreasing offshore trend from the coastal to the oceanic domain described in most of the studies carried out in this region and the resulting assertion that the open sea is separated from coastal areas by an intermediate frontal zone (Barale *et al*., 2005). The oligotrophic belt, along the Catalan shelf, shows that the frontal zone in this

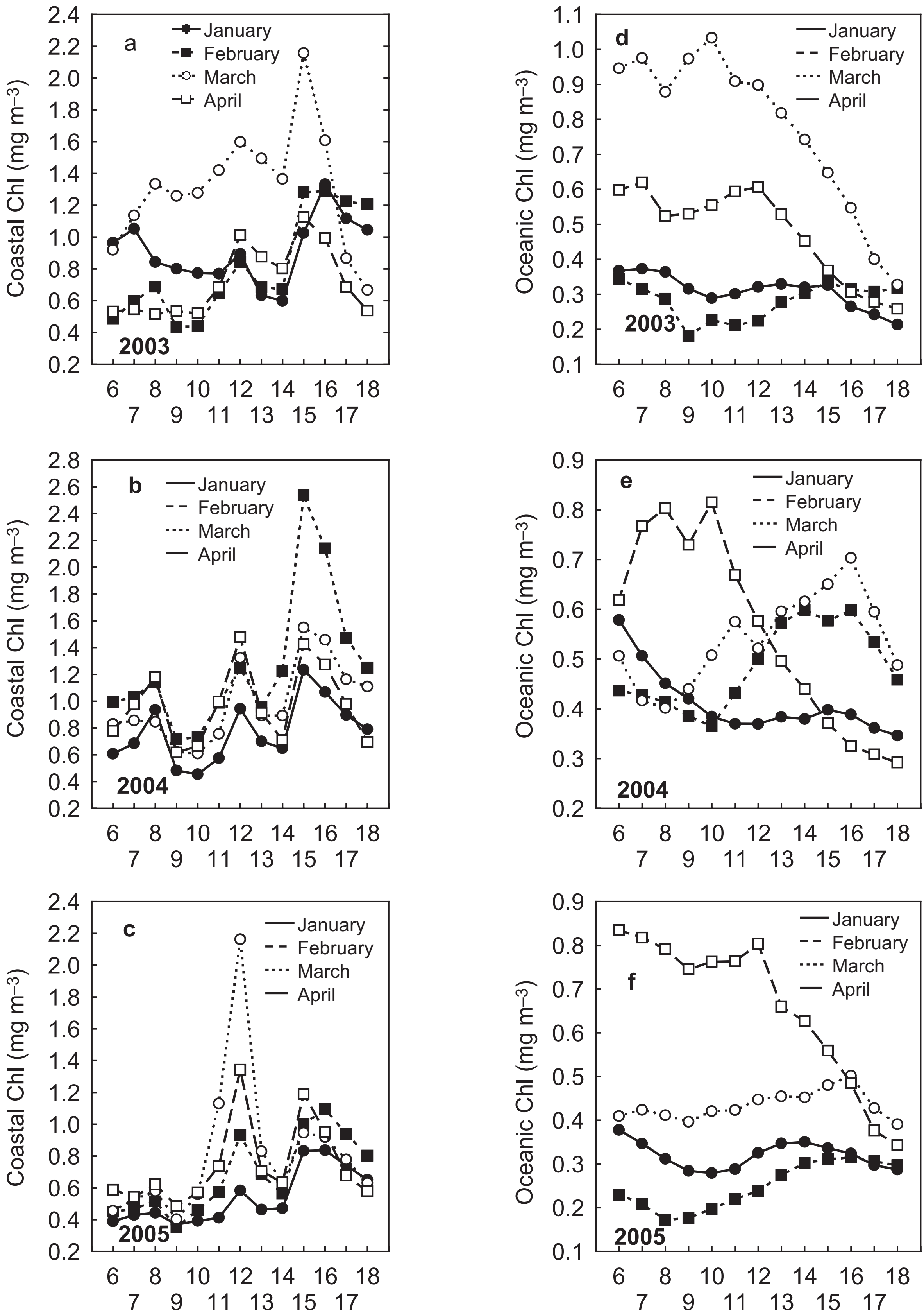

FIG. 6. – Mean monthly chlorophyll per year, zone and region: coastal (a-c) and oceanic (d-f).

area is more a region of disruption than of transition. The dynamics and productivity of the COB are influenced weakly by both the coastal and oceanic domains, at least during the peak of standing stock. This also explains the clear spatial segmentation observed in previous studies between fish larvae of shelf and oceanic origins and the low possibility of overlapping in certain areas. The variability of the COB shows that the disruption between coastal and oceanic waters, at least in the upper layer, is weaker south of Barcelona. Thus, we conclude that offshore–inshore exchange as well as both passive and active transport could be made easier at this latitude. Another relevant result is that oceanic Chl *a* in this region is not insignificant. Although we found that strength of vertical convection enhances the subsequent increase of chlorophyll *a*, we conclude that the overall chlorophyll *a* over the season may not differ greatly between years, whether or not convection in the Gulf of Lions takes place. Finally, we suggest that, as timing and thus biological coupling with marine production are important factors in ecosystems, the observed monthly variability between years may favour some species over others and consequently affect fish resources differently.

REFERENCES

André, G., P. Garreau and P. Fraunié. – 2005. Comparison between sea surface features from ocean color imagery and 3D modeling in the Gulf of Lions (Northern Mediterranean Sea). *Oceans Europe 2005*, 1078-1083. IEEE Brest, France.

Arin, L., M. Estrada, J. Salat and A. Cruzado. – 2005. Spatio-temporal variability of size fractioned phytoplankton on the shelf adjacent to the Ebro river (NW Mediterranean). *Cont. Shelf Res.*, 25(9): 1081-1095.

Arnone, R.A., D.A. Wiesenburg and K.D. Saunders. – 1990. The origin and characteristics of the Algerian Current. *J. Geophys. Res. B*., 95: 1597-1598.

Barale, V., D. Larkin, L. Fusco, J.M. Melinotte and G. Pittella. – 1999. OCEAN Project: the European archive of CZCS historical data. *Int. J. Remote Sens*., 20(7): 1201-1218.

Barale, V. – 2003. Enviromental Remote Sensing of the Mediterranean Sea. *J. Environ. Sci. Health*., A38: 1681-1688.

Barale, V., M. Masó, M. Vila, A. Lugliè, N. Sechi and M.G. Giacobbe. – 2005. Satellite observations of bio-optical indicators related to dinoflagellates blooms in selected Mediterranean coastal regions. In: A. Marçal (eds.), *Global Developments in Environmental Earth Observation from Space, 25th EARSeL* Symposium, Porto, Portugal, pp. 685-696. Millpress, Rotterdam.

Bosc, E., A. Bricaud and D. Antoine. – 2004. Seasonal and interannual variability in algal biomass and primary production in the Mediterranean Sea, as derived from 4 years of SeaWiFS observations. *Global Biogeochem. Cycles*, 18: 1-17.

Bricaud, A., A. Morel and V. Barale. – 1999. MERIS potential for ocean colour studies in the open ocean. *Int. J. Remote Sens*., 20: 1757-1769.

Canals, M., P. Puig, X. Durrieu de Madron, S. Heussner, A. Palanques and J. Fabrés. – 2006. Flushing submarine canyons. *Nature*, 444: 354-357.

Castellón, A., J. Salat and M. Masó. – 1985. Some observations on Rhône fresh water plume in the Catalan Coast. *Rapp. P-V, Commn. Int. Explor. Scient. Mer Méditerr.,* 29: 3.

Castellón, A., J. Font and E. Garcia. – 1990. The Liguro-Provençal-Catalan current (NW Mediterranean) observed by Doppler profiling in the Balearic Sea. *Sci. Mar*., 54: 269-276.

Conan, P. and C. Millot. – 1995. Variability of the Northern Current off Marseilles, western Mediterranean Sea, from February to June 1992. *Oceanol. Acta*, 18: 193-205.

Cruzado, A. and Z. Velásquez. – 1990. Nutrients and phytoplankton in the Gulf of Lions, northwestern Mediterranean. *Cont. Shelf Res.*, 10: 931-942.

Cruzado, A., Z. Velázquez, M.C. Pérez, N. Bahamón, N.S. Grimaldo and F. Ridolfi. – 2002. Nutrient fluxes from the Ebro river and subsequent across-shelf dispersión. *Cont. Shelf Res.*, 22: 349-360.

Estrada, M. – 1985. Deep phytoplankton and chlorophyll maxima in the Western Mediterranean. In: M. Moraitou-Apostolopoulou and V. Kortsis (eds.), *Mediterranean Marine Ecosystems*, pp. 247-277. Plenum Press, New York.

Estrada, M. and R. Margalef. – 1988. Supply of nutrients to the Mediterranean photic zone along a persistent front. *Oceanol. Acta*, 9: 133-142.

Estrada, M. and J. Salat. – 1989. Phytoplankton assemblages of deep and surface water layers in a Mediterranean frontal zone. *Sci. Mar*., 53: 203-214.

Estrada, M. – 1991. Phytoplankton assemblages across a NW Mediterranean front: changes from winter mixing to spring stratification. In: J.D. Ros and N. Prat (eds.) Homage to Ramon Margalef; or, Why there is such a pleasure in studying nature. *Oecol. Aquat*., 10: 157-185.

Estrada, M. – 1996. Primary Production in the Northwestern Mediterranean. *Sci. Mar.,* 60: 55-64.

Font, J., J. Salat and J. Tintoré. – 1988. Permanent features of the circulation in the Catalan Sea. *Oceanol. Acta*, 9: 51-57.

Font, J., E. Garcia-Ladona and E.G. Gorriz. – 1995. The seasonality of mesoscale motion in the Northern Current of the western Mediterranean: several years of evidence. *Oceanol. Acta*, 18: 207-219.

Font, J., P. Puig, J. Salat, A. Palanques and M. Emelianov. – 2007. Hydrographic changes in NW Mediterranean deep water due to the exceptional winter of 2005. *Sci. Mar.,* 71: 339-346.

Fournier-Sicre, V. and S. Belanger. – 2002. Intercomparison of SeaWiFS and MERIS marine products on Case 1 waters. *Envisat Validation Workshop*. December 2002 Frascati, Italy.

Gade, M., V. Barale and H.M. Snaith. – 2003. Multisensor monitoring of pluma dynamics in the northwestern Mediterranean Sea. *J. Coast Conserv.,* 9: 91-96.

Gaudy, R., F. Youssara, F. Diaz and P. Raimbault. – 2003. Biomass, metabolism and nutrition of zooplankton in the Gulf of Lions (NW Mediterranean). *Oceanol. Acta,* 26: 357,372.

Gitelson, A., A. Karnieli, N. Goldman, Y.Z. Yacobi and M. Mayo. – 1996. Chlorophyll estimation in the Southeastern Mediterranean using CZCS images: Adaptation of an algorithm and its validtation. *J Mar. Syst.,* 9: 283-290.

Lohrenz, S.E., A. Arnone, D.A. Wiesenburg and I.P. DePalma. – 1988. Satellite detection of transient enhanced primary production in the western Mediterranean Sea. *Nature*, 335: 245-247.

Madec, G., F. Lott, P. Delecluse and M. Crepon. – 1996. Large-scale preconditioning of deep-water formation in the northwestern Mediterranean Sea. *J. Phys. Oceanogr.,* 26: 1393-1408.

Margalef, R. – 1985. Environmental control of the mesoscale distribution of primary producers and its bearing to primary production in the Western Mediterranean. In: M. Moraitou-Apostolopoulou and V. Kortsis (eds.), *Mediterranean Marine Ecosystems*, pp. 213-229. Plenum Press, New York.

Masó, M. and C.M. Duarte. – 1989. The spatial and temporal structure of hydrographic and phytoplankton biomass heterogeneity along the Catalan Coast (NW Mediterranean). *J. Mar. Res.*, 47: 813-827.

Masó, M. and Tintoré, J. – 1991. Variability of the shelf water off the northeast Spanish coast. *J. Mar. Syst*. 1: 441-450.

Masó, M., A. Sabatés and M.P. Olivar. – 1998. Short-term physical and biological variability in the shelf-slope region of the NW Mediterranean during the spring transition period. *Cont. Shelf Res.*, 18: 661-675.

Millot, C. – 1987. Circulation in the western Mediterranean Sea. *Oceanol. Acta,* 10: 143-149.

Millot, C. – 1991. Mesoscale and Seasonal Variabilities of the Circulation in the Western Mediterranean. *Dyn. Atmos. Oceans*, 15: 179-214.
Morel, A. and L. Prieur. – 1977. Analysis of variations in ocean color. *Limnol. Oceanogr.*, 22(4): 709-722.
Morel, A. and J.M. André. – 1991. Pigment distribution and primary production in the western Mediterranean as derived and modeled from coastal zone color scanner observations. *J. Geophys. Res.,* 96: 12685-12698.
Rast, M., J.L. Bezy and S. Bruzzi. – 1999. The ESA Medium Resolution Imaging Spectrometer MERIS - a review of the instrument and its mission. *Int. J.Remote Sens*., 20: 1679-1680.
Sabatés, A., J. Salat and M.P. Olivar. – 2001. dvection of continental water as an export mechanism for anchovy, Engraulis encrasicolus, larvae. *Sci. Mar.,* 65: 77-88.
Sabatés, A., J. Salat and M. Masó. – 2004. Spatial heterogeneity of fish larvae across a meandering current in the northwestern Mediterranean. *Deep-Sea Res.,* 51: 545-557.
Sabatés, A., M.P. Olivar, J. Salat, I. Palomera and F. Alemany. – 2007. Physical and biological processes controlling the distribution of fish larvae in the NW Mediterranean. *Prog. Oceanog*., 74: 355-376.
Sáiz, E., V. Rodríguez and M. Alcaraz. – 1992. Spatial distribution and feeding rates of Centropages typicus in relation to frontal hydrographic structures in the Catalan Sea (Western Mediterranean). *Mar. Biol.,* 112: 49-56.
Salat, J. – 1995. The interaction between the Catalan and Balearic currents in the southern Catalan Sea. *Oceanol. Acta*, 18: 227-234.
Salat, J., M.A. Garcia, A. Cruzado, A. Palanques, L. Arín, D. Gomis, J. Guillén, A. León, J. Puigdefàbregas, J. Sospedra and Z.R. Velázquez. – 2002. Seasonal changes of water mass structure and shelf slope exchanges at the Ebro Shelf (NW Mediterranean). *Cont. Shelf Res.*, 22: 327-348.
Sournia, A. – 1973. La production primaire planctonique en Méditerranée: Essai de mise à jour. *Bull. Etud. Commn. Méditerr.*, 5.
Van Dijken, G.L. and K.R. Arrigo. – 1996. Ocean color remote sensing of the southeastern Mediterranean Sea. *Eos. Trans.,* AGU (Suppl. 167), 76 (3).
Velásquez, Z.R. – 1997. *El fitoplancton en el Mediterráneo Noroccidental*. Ph.D. thesis, Univ. Politècnica de Catalunya, pp 258.
Volpe, G., R. Santoleri, V. Velucci, M. Ribera d'Alcalà, S. Marullo and F. D'Ortenzio. – 2007. The colour of the Mediterranean Sea: Global versus regional bio-optical algorithms evaluation and implication for satellite chlorophyll estimates. *Remote Sens. Environ.*, 107: 625-638.
Weeks, A., I. Robinson, A. Cruzado, Z. Velásquez and N. Bahamon. – 2003. MERIS validation in the North West Mediterranean and the Mascarene Ridge area of the Indian Ocean. *ESA MAVT Symposium*. Frascati. Italy.

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