ORIGINAL ARTICLE

Variability of the mixed layer depth and the ocean surface properties in the Cape Ghir region, Morocco for the period 2002–2014

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Abstract

The mixed layer depth (MLD) is an active part of the marine environment that couples the underlying ocean to the atmosphere. The aim of this original study in Morocco is to investigate for the period 2002–2014 the relationship between the variability of the MLD with the oceanic sea surface properties and the primary productivity in the Cap Ghir region. This area is very productive along the Atlantic coast of Morocco and we examined in this study the monthly variability of the MLD and its relationship with sea surface properties using data from Copernicus—Marine environment monitoring products, coupling between MLD with SST and upwelling activity in the Cape Ghir area. During winter seasons, the MLD is deeper and observed at around 90 m. Compared to others seasons, it is varying between 10 and 25 m. The monthly mean SST show very cold temperature (around 17 °C) during winter season and a warm temperature (around 23 °C), during summer season. In fact, the colder waters in surface coincide with the deepest MLD and the warmer waters coincide with the shallowest MLD. From 2009 to 2011, the MLD was very shallower (40 m) with some observed variability between 30°30N and 31°N, due to the dynamic of Cape Ghir. Regarding to the upwelling activity, the upwelling index shows a clear seasonality (higher activity in summer and weaker in winters) and some relationship between the upwelling index and the MLD were investigated. The characteristic's feature of the variability of the MLD mixed layer in the Cape Ghir area is based on the fast response of the upwelling activity than the other parameters like SST. When the MLD is shallower, the SST is still cooler for two months more. The oceanographic dynamic of the Cape Ghir area is very complex in nature and, following the MLD, this parameter is an adequate parameter for detecting the activity of the upwelling in this area.

Keywords Ocean mixed layer depth · Cape Ghir area · Morocco · Upwelling area · Sea surface temperature

Introduction

The mixing in the upper ocean by heat, energy and freshwater flux results a formation of a homogeneous layer with nearly uniform properties known as the mixed layer. This layer couples the ocean to the atmosphere through the physical and chemical transfers. The ocean surface layer endures a large spatial and temporal variability compared to the rest of the ocean, therefore, it is very important to understanding both short-term and long-term changes of the mixed layer depth (MLD) and its relationship with the upper ocean properties.

Seasonal and internal fluctuations in the upper ocean are also of a great importance especially for the biological production (Polovina et al. 1995). Studying the variability of the MLD and its relationship with the upper ocean properties is for a highly important in the context of understanding the upwelling activity, and the heat release from the Canaries current, which is the most important contribution of oceanic heat transport toward Moroccan Atlantic coast. The time series from Copernicus data provides an excellent monthly means data on the subject of analyses the variations in mixed layer properties for the Cape Ghir region presented in Fig. 1, over different time scales.

The heat stored in the mixed layer regulates the air–sea exchange process including convection and cyclone origins. In addition, the oceanic biological productivity critically depends on the physical and chemical changes taking

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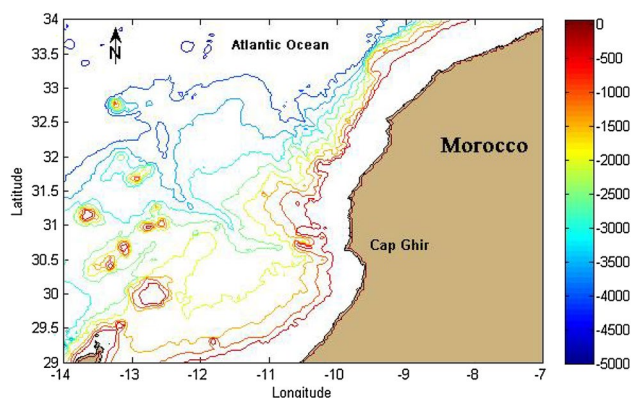
Fig. 1 The bathymetry of the studied area

place within this layer. Spatially, the mixed layer thickness increases from a few tens of meters in the Equator to a few hundreds of meters in the poles (Monterey and Levitus 1997).

Monitoring the monthly cycle of the ocean mixed layer depth in the Cape Ghir region is importance to enhance our knowledge about the Atlantic flow towards the Canaries courant. An understanding of the relationship between the variability of the MLD and the ocean surface properties is essential for quantitative diagnostics for the coupled ocean and atmosphere system and its effect on biogeochemical cycles and ecosystems.

The Cape Ghir situated in the Moroccan Atlantic coast. It is about forty kilometers north-west of Agadir. The strongest winds occur during summer (June–September). In contrast, during winter (November–February), the winds are weak and from northeasterly direction.

Moreover, this region is known by the activity of the coastal upwelling, who is a dynamic factor that brings deep water to the surface, which is cold and nutrient rich favorable for the photosynthesis, encouraging the primary production, and increases the biomass of pelagic resources (Makaoui et al. 2005). The Moroccan coast is among the five known zones influenced by the upwelling phenomenon in the world.

The Cap Ghir region in the Moroccan Atlantic coast is an advantage place to studying the MLD because the region has been unstudied and its features a strong seasonal activity of upwelling phenomena and filaments. The Cape Ghir feature is the large seasonal activity of the coastal upwelling which makes the waters of the upper layers less saline and colder (Makaoui et al. 2005) (Makaoui et al. 2012).

The present paper attempts to understand the monthly mean variability of the mixed layer in relationship with the ocean surface property especially with the sea surface temperature (SST), because it is a key parameter in the ocean atmosphere heat exchange and hence in the climatic regulation. Furthermore, the coupling between mixed layer and

chlorophyll biomass in the Cape Ghir on a seasonal scale is a key area for the recruitment of fishery resources, including the Moroccan sardine. Finally, we compared the variability of the MLD with the upwelling activity in the region.

Data and methods

Model descriptions

The IBI forecast system is based on a NEMO-v3.4 model application driven by high-frequency meteorological, oceanographical, and hydrological forcing data. The NEMO model (Madec 2008), solves the three-dimensional finite difference primitive equations in spherical coordinates discretized on an Arakawa-C grid and, in the present implementation, 50 geopotential vertical levels (z coordinate).

The model grid is a subset of the Global 1/12° ORCA tripolar grid used by the parent system (MyOcean Global) that provides initial and lateral boundary conditions but refined at 1/36° horizontal resolution (~ 2 km). Vertical mixing is parameterized according to a k–ε model implemented in the generic form proposed by Umlauf and Burchard (2003), including surface wave breaking induced mixing, while tracers and momentum subgrid lateral mixing is parameterized according to bilaplacian operators.

The IBI run is forced with 3-hourly atmospheric fields (10-m wind, surface pressure, 2-m air temperature, relative humidity, precipitations, shortwave and longwave radiative fluxes) provided by ECMWF. CORE empirical bulk formulae (Large and Yeager 2004) are used to compute latent sensible heat fluxes, evaporation, and surface stress.

Lateral open boundary data (temperature, salinity, velocities, and sea level) are interpolated from the daily outputs from the MyOcean Global eddy resolving system. These are complemented by 11 tidal harmonics built from FES2004 (Lyard et al. 2006), and TPXO7.1 (Egbert and Erofeeva 2002) tidal model solutions. Flow-rate data are based on a combination of daily observations, simulated data from SMHI EHYPE hydrological model (http://e-hypeweb.smhi.se) and climatology [monthly climatological data from GRDC (http://www.bafg.de/GRDC)] and French 'Banque Hydro' dataset (http://www.hydro.eaufrance.fr/).

The biogeochemical state of the ocean was simulated through a PISCES model hind-cast run online coupled with the IBI physical ocean reanalysis previously described. This PISCES Biogeochemistry model (Aumont at al. 2008) is a model of intermediate complexity and is part of NEMO modelling platform (Aumont and Bopp 2006). The IBI PISCES model application (Levier et al. 2014) integrates 24 prognostic variables, and simulating ocean biogeochemical cycles.

Regarding initial and boundary conditions, the IBI biogeochemical PISCES model application is initialized with data from the World Ocean Atlas 2001 with GLODAP climatology including anthropogenic CO_2, and alkalinity (Key et al. 2004) and, with model fields from three different sources: atmospheric deposition (Aumont et al. 2008), rivers for nutrients (Ludwig et al. 1996) and inputs from marine sediments. For more information about the scientific validation of the IBI systems refer to (Sotillo et al. 2015).

The MyOcean IBI-FOR system became fully operational in April 2011. From this time, IBI Ocean forecast products are daily updated and made available to any user through the MyOcean web portal. Both visualization and downloading capabilities of IBI datasets are provided. Any user can have access to variables such as temperature, salinity, sea level, and currents on daily averages for the whole water column.

Data

In order to study the monthly variability of the MLD and the physical ocean surface parameters we used the monthly mean data for both physical and biological models, with a high-resolution of 1/12°. The CMEMS IBI-MF provides the reanalysis and comprising physical variables covering the altimetry decade (2002–2014). The Physical IBI reanalysis product is generated through the IBIRYS ocean reanalysis system and is based on a NEMO model. We used the monthly mean data of the mixed layer depth defined by sigma theta, sea surface Temperature, Salinity and Velocity. The 1/12° IBIRYS regional reanalysis system developed and run by Mercator Ocean (Levier et al. 2014) over the European North East Atlantic. Furthermore, we used data from the biogeochemical model PISCES. The Biogeochemistry model provides with 24 prognostic variables, simulating biogeochemical cycles of oxygen, carbon and the main nutrients and phytoplankton. The dataset provides with monthly data into a regular lat/lon grid with 1/12° horizontal resolution. The biogeochemical model used is PISCES (Bopp et al. 2005) in its version NEMO3.2. It is a model of intermediate complexity designed for global ocean applications (Bopp et al. 2005). A detailed description of the numerical application used to generate the IBI MFC biogeochemical multy-year product is provided in (Sotillo et al. 2015).

Upwelling index

To calculate the costal upwelling index we used the SST index of upwelling at each latitudinal point. The upwelling index is defined as the difference in the SST between the coast and the ocean (Rayner et al. 2003) (Reynolds et al. 2007)

$$UI\Delta SST = SSTocean - SSTcoast$$

where SSTcoast is the SST of the grid closest to the coast and SSTocean is the SST of the grid box along the same latitude that is 5° to the west. Therefore, an increase (decrease) in the UIΔSST is equivalent to a decrease (increase) in the intensity of the upwelling.

Results

The monthly mean data of the surface parameters were taken from Copernicus marine environment monitoring service in the study domain (29–34°N and 7–14°W) for the period from 2002 to 2014 with a regular lat/lon grid with 1/12° horizontal resolution. These data assimilations provide valuable information for the sea surface parameters. In this way, it is possible to obtain a complete view of the different-scale hydrographic processes by analyzing ocean patterns.

In this section, we compared the winter-summer seasons climatology of all the upper ocean parameters. We first examined the spatial and temporal variability of MLD by analyzing the monthly mean climatology. To understand the processes affecting the mixed layer variability, we examined the monthly mean climatology of SST, sea surface salinity (SSS), sea surface velocity, sea surface chlorophyll, and sea surface oxygen. Finally, we examine the seasonal variability of the SST, the Chl-*a*, and the upwelling activity to understand the possible link between them and the variability of the mixed layer depth.

The mean results show that, the mixed layer depth during winter (December–January–February) was deeper in the cape Ghir region (Fig. 2), compared to the rest of the months, where it varied between 10 and 25 m. The monthly mean SST shows very cold temperature during winter and a warm temperature during summer. The colder water near the coast indicated the upwelling activity during the summer season (Fig. 3). Figure 4 shows the monthly mean sea surface salinity. In winter, even if it is a wet season, the salinity was higher compared to the summer season. As in summer, the upwelling activity in this region produce a less salinity along the coast. The monthly mean sea surface velocity shows a low velocity in winter in addition of surface eddies (Fig. 5). During summer, we remarked a high speed of sea surface to the south west direction especially near to the coast witch make the filaments moving to the southwest towards the offshore without an appearance of eddies in surface. The monthly mean surface concentration of chlorophyll showed less Chl-*a* in winter season compared to the summer season where we observed higher concentration near the coast (Fig. 6). The monthly mean sea surface oxygen shows a seasonal variability, in winter we noticed that we had homogenize concentration of oxygen in surface however in summer we had the maximum concentration near
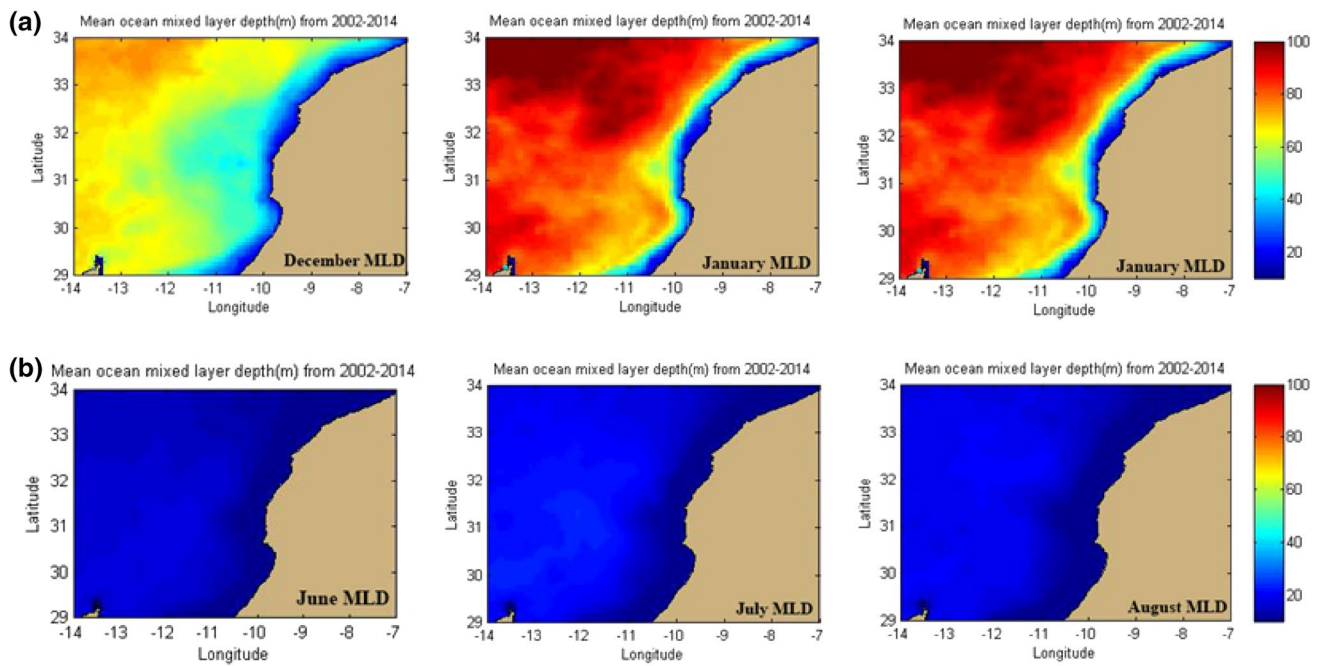
(a)

(b)

Fig. 2 **a** The winter and, **b** the summer monthly mean MLD (m)
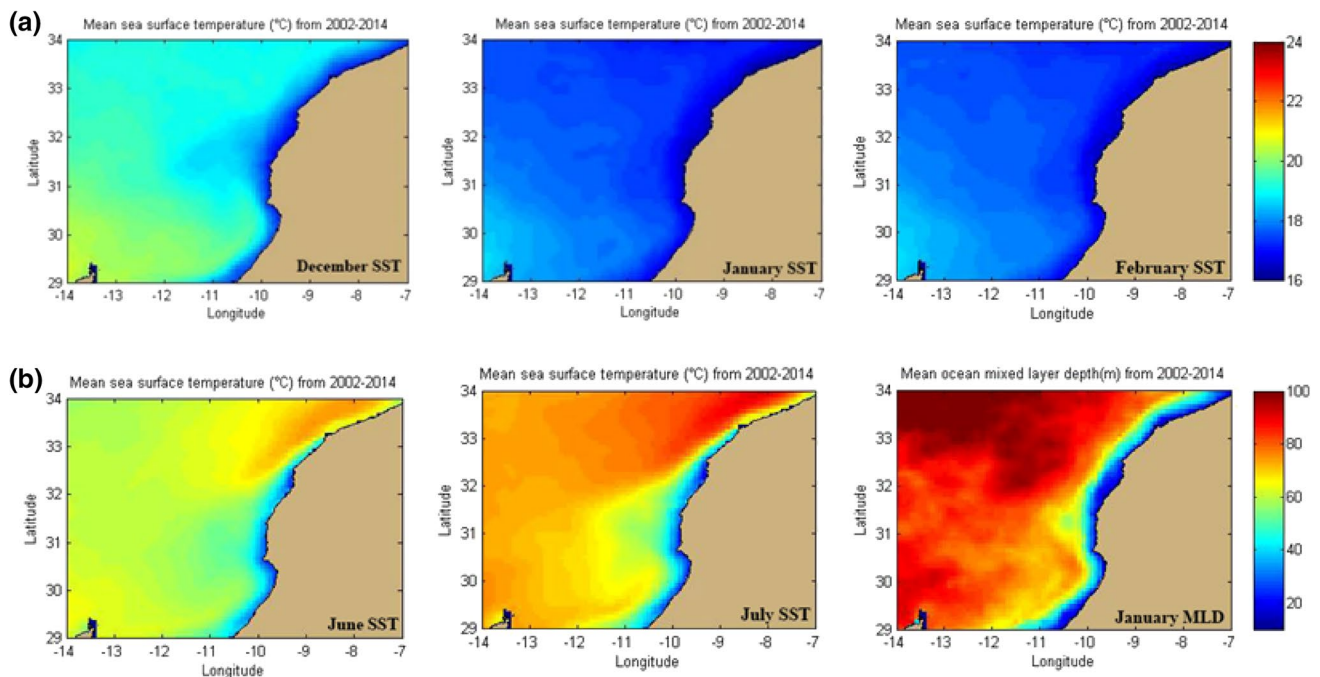
(a)

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Fig. 3 **a** The winter and, **b** the summer monthly mean sea surface temperature (°C)

the coast and we had less concentration of oxygen offshore following the ocean primary production (Fig. 7).

Furthermore, we examined the relationship between the mixed layer depth and the SST, Upwelling Activity and Chl-*a* concentration. For that, we used the mean data from the coast to − 11°W for the SST and the MLD. Figure 8 shows the Hovmöller Diagrams of MLD and SST from 2002 to 2014. The concordance of the results is clear, when the depth of the MLD is maximum in winter, the sea surface temperature is coolest and when the MLD is low in summer the
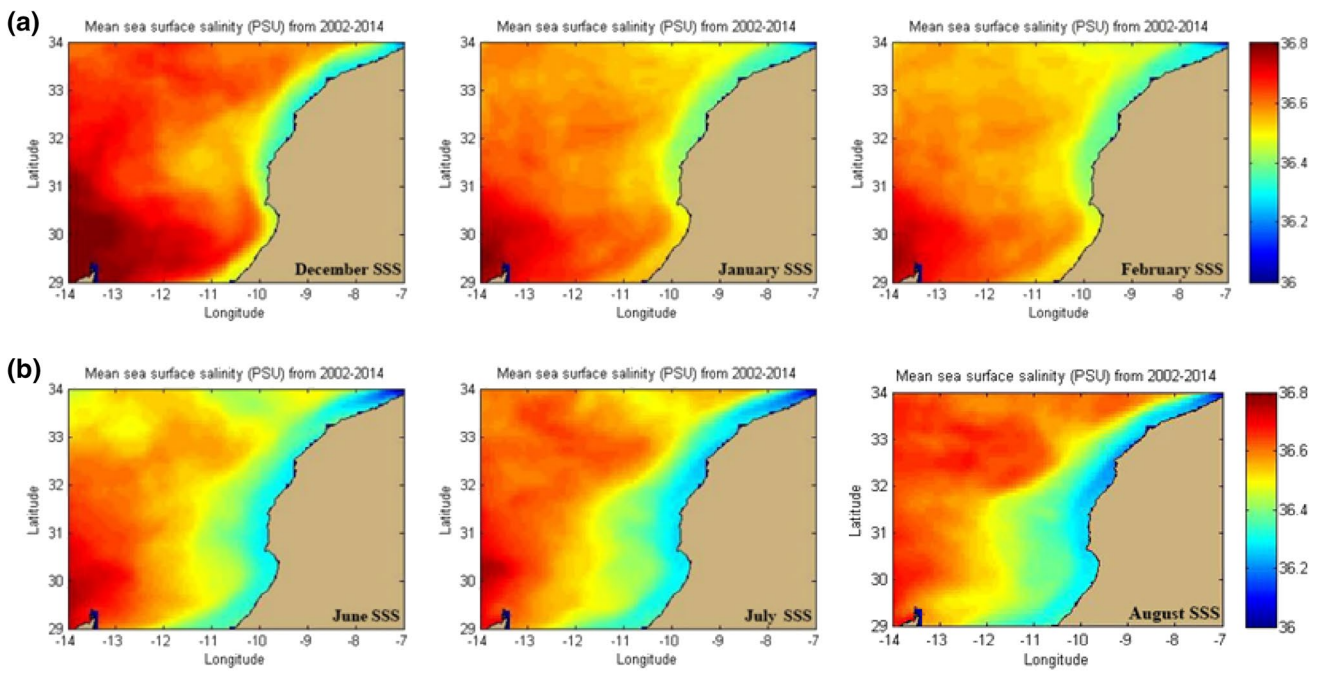
(a)

(b)

Fig. 4 The winter (**a**) and summer (**b**) monthly mean sea surface salinity (PSU)
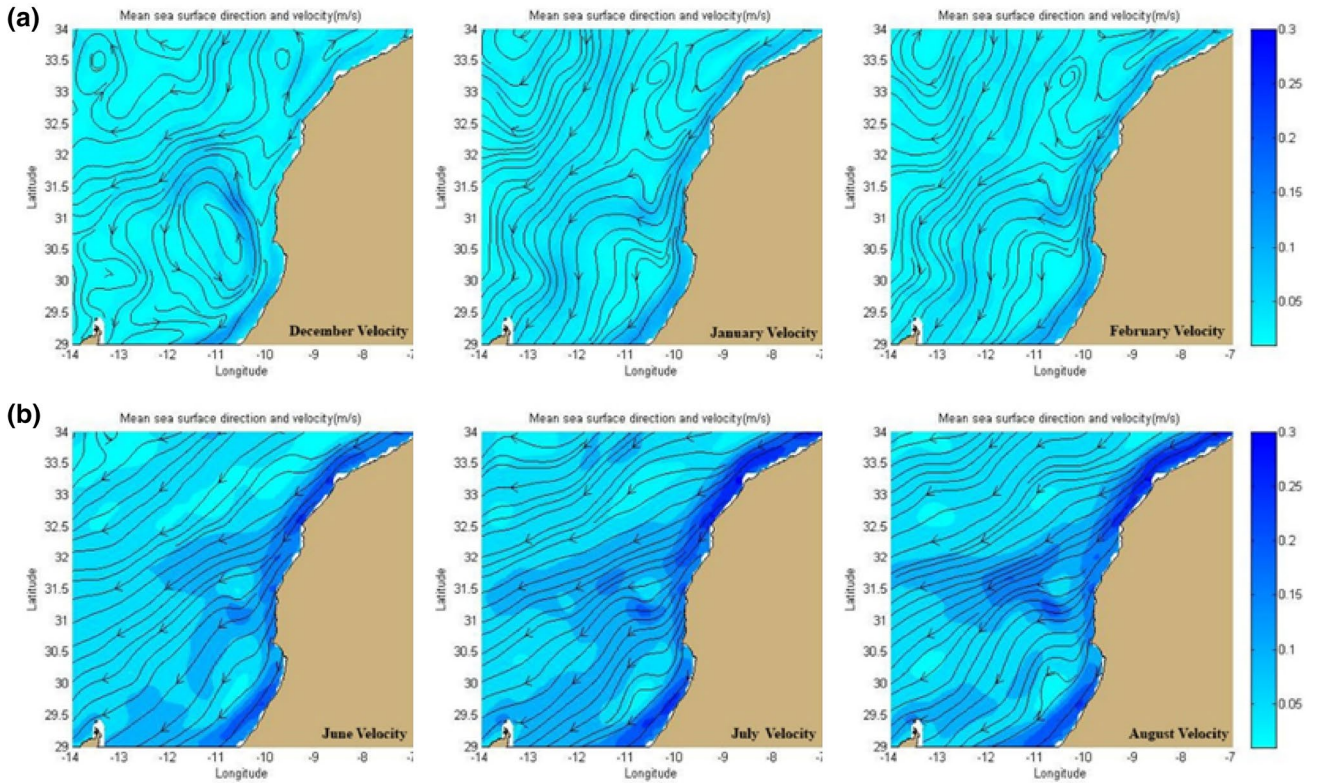
(a)

(b)

Fig. 5 The winter (**a**) and summer (**b**) monthly mean sea surface velocity (m/s)
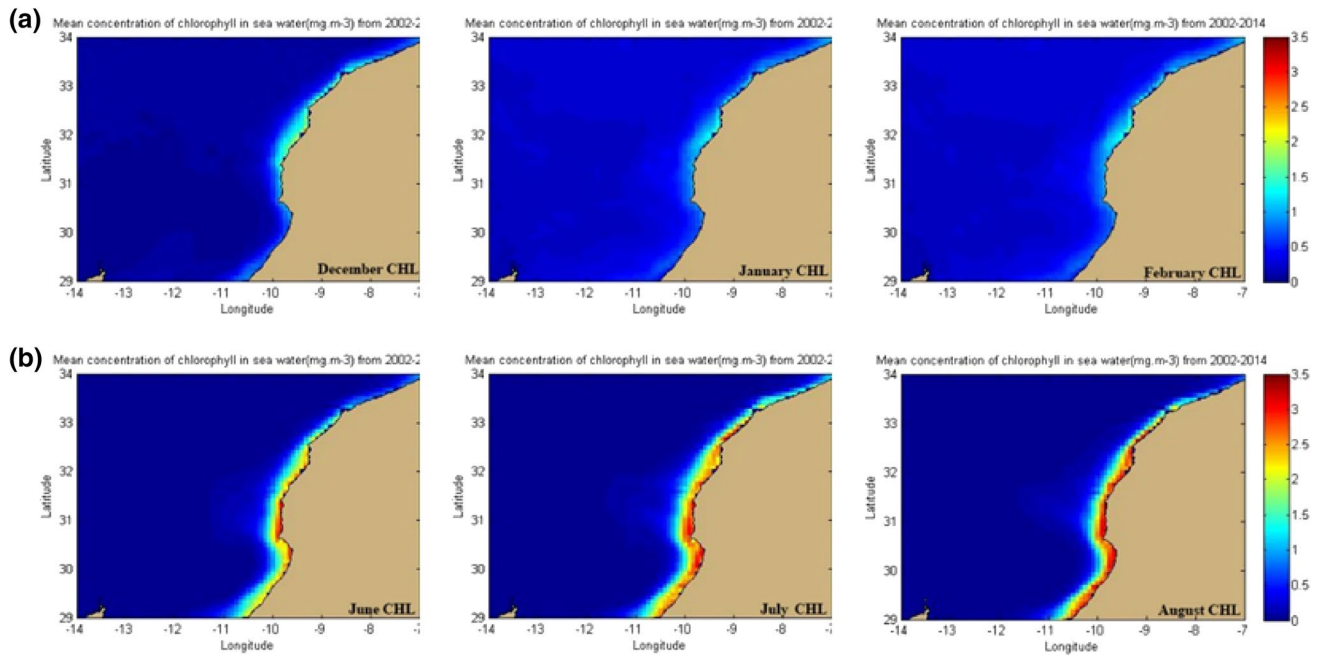
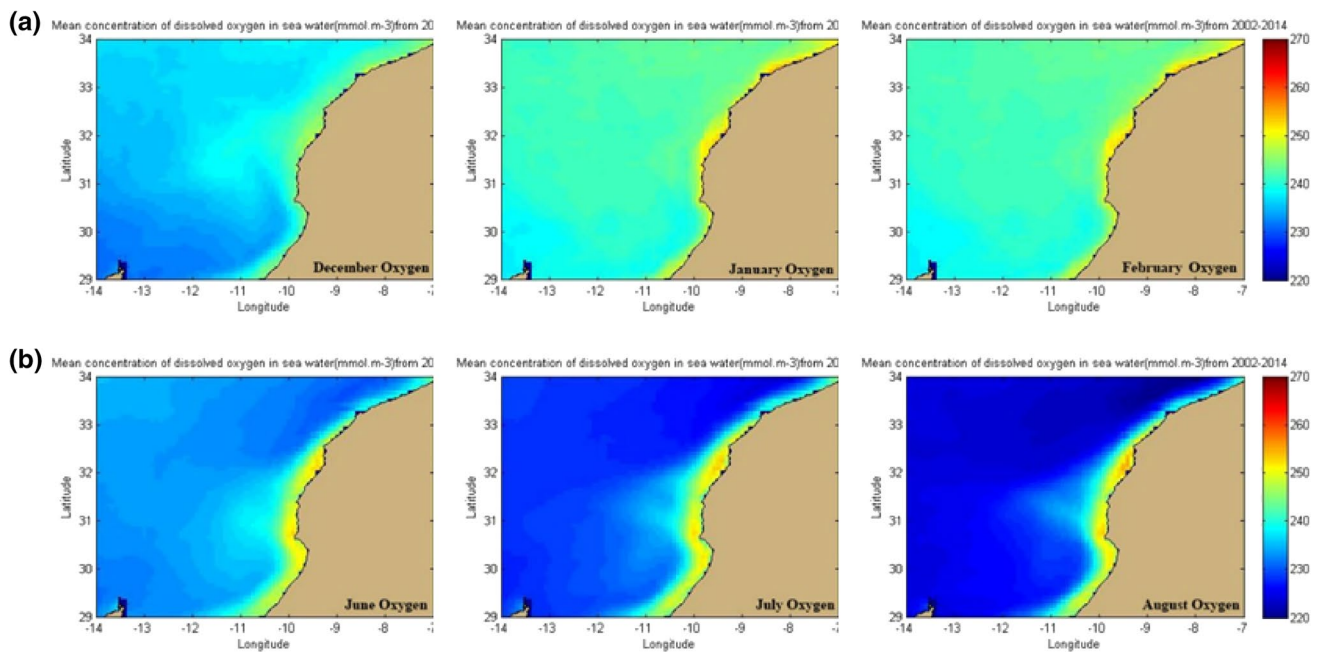Fig. 6 The winter–summer monthly mean sea surface Chlorophyll (mg/m^3)

Fig. 7 The winter (**a**) and summer (**b**) monthly mean sea surface oxygen (mmol/m^3)

temperature of sea surface water is higher but between the 32 and 30.5 °N, the cool water temperature persists, that is why we plotted the depth of the mixed layer with the sea surface temperature for three latitudes (30.5°N, 31°N and 31.5°N). Then, the results show that the maximum depth of the ML was observed at about ~ 90 m in winter of 2006, 2009 and

2012 years, at the same period the minimum sea surface temperature was detected at about ~ 16.5 °C (Figs. 8, 9). However, after the summer of 2009 to winter 2011 including all the year of 2010, the MLD was shallow (40 m) without going deeper in winter of 2010 as the others years. In addition, we remarked that in 31.5°N the variation of the MLD

Fig. 8 Hovmöller Diagrams of **a** MLD (m), **b** SST (°C), **c** Upwelling activity, and **d** chlorophyll concentration (mg/m^{-3}) from 2002 to 2014
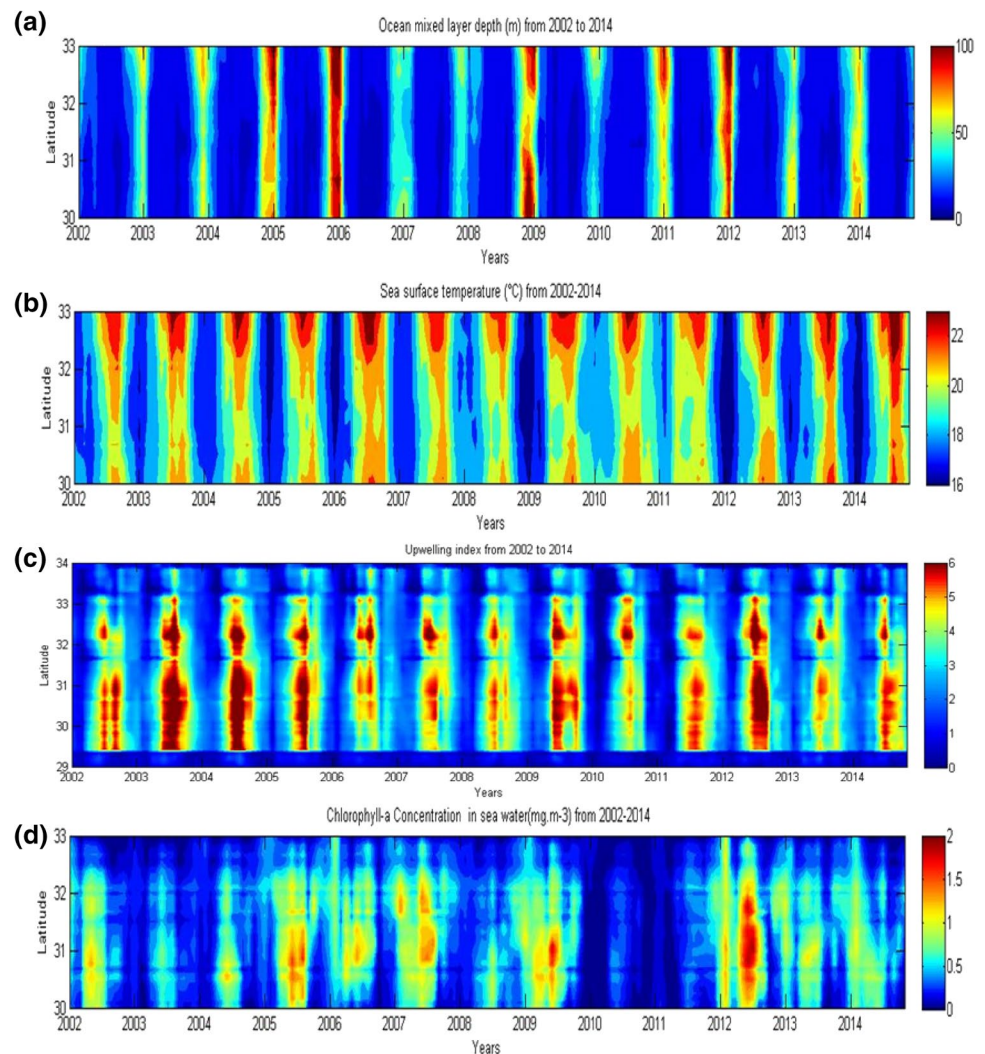
and the SST are in concordance, but in 30.5 and 31°N, this variation had a temporal lag about 2 months (January and February). When the MLD is shallow, the SST is still cooler for 2 more months.

Following the upwelling index, we note that the upwelling activity shows a clear seasonality, we had a higher activity of upwelling in summer and a weaker activity in winter season. Furthermore, when the upwelling was active the thickness of the MLD is thin which make its temperature increase by the atmosphere in surface and when the activity of the upwelling was weak in winter season the MLD is large the effect of the atmosphere is lower and the water column of the MLD is not heated (Fig. 8). That's make difficult the detection of upwelling phenomenon by the temperature. However, we note a quick response of the MLD to the upwelling activity.

The Hovmöller Diagrams of the MLD and the Chl-*a* show a good concordance, the shallow ML corresponds to the maximum of the chlorophyll concentration and the deepest MLD corresponds to the minimum chlorophyll concentration (Fig. 8). We observed that the maximum of chlorophyll concentration was noticed in summer ~ 1.5 mg/m^{-3}, with a higher concentration localized in latitude 31°N. However, in 2010 when the upwelling was characterized by shallower MLD all the year, the pattern of Chlorophyll shows less phytoplankton richness. Moreover, the correlation is clear in plots of the MLD with the chlorophyll concentration for different latitudes (Fig. 10).

Discussion

To investigate the variability of the MLD and its relationships with the sea surface properties, we made continuous observations of sea surface temperature, sea surface salinity, sea surface velocity, sea surface chlorophyll, and sea surface oxygen. The mean results shows that the water propriety in the Cape Ghir region is characterize by a seasonal variability.

The MLD is defined as a surface layer where there is nearly no variation in density with depth (Clayson et al.
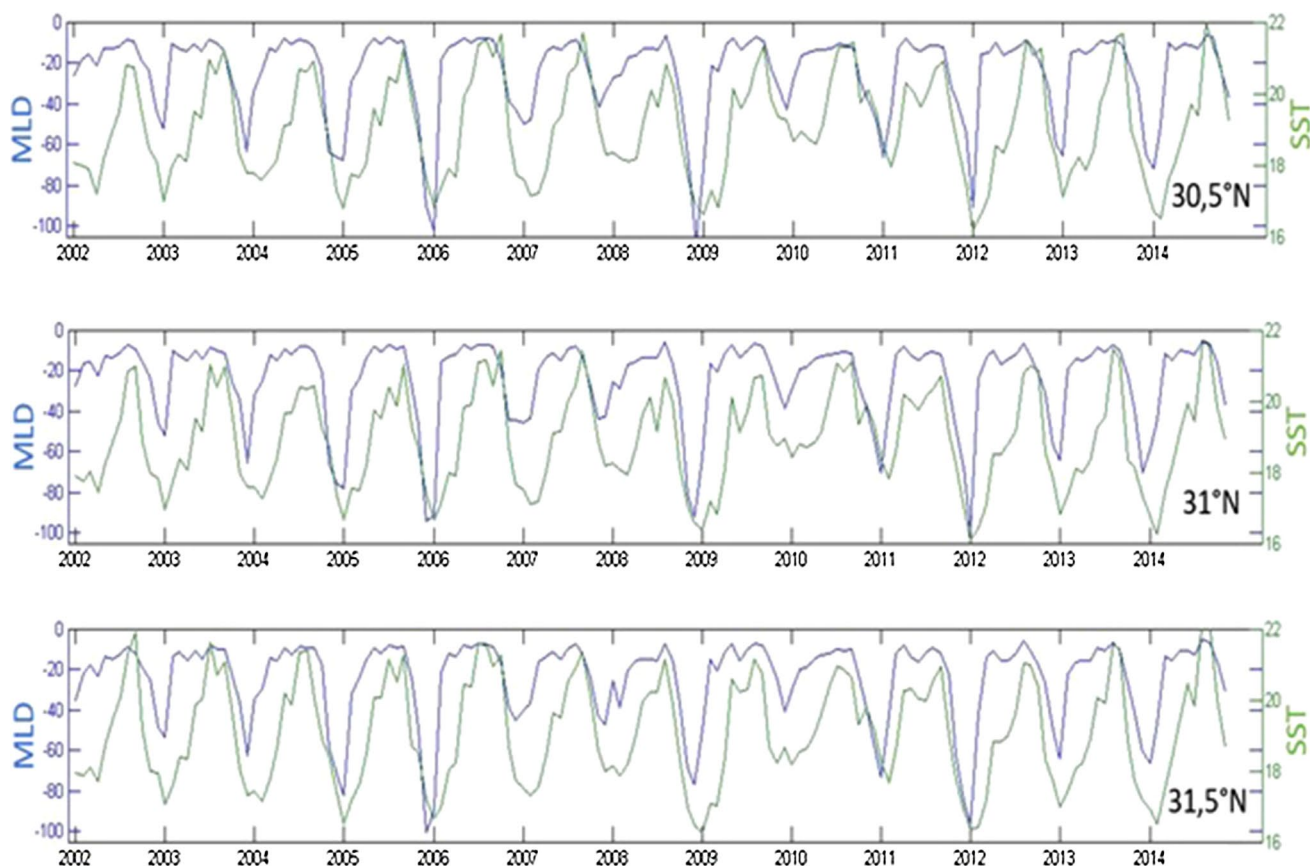
Fig. 9 Plots of the MLD (m) with the SST (°C) for three different latitudes (30.5°N, 31°N and 31.5°N)

2000). Kara et al. (2003), had provided and examined the spatial and temporal variability of the MLD for the global ocean. However, their paper does not cover the cape Ghir region. Little has been done in the context of studying the evolution and variability of the mixed layer in the Moroccan Atlantic coast.

Evenly, the distribution of phytoplankton from winter to spring are strongly linked to the variability of the surface mixed layer (Itoh et al. 2015). The phytoplankton bloom occurs when the ML becomes shallower to a critical depth (Sverdrup 1953). Obata et al. (1996), found that the features of the spring bloom in the North Atlantic and western North Pacific, where the chlorophyll a concentration at the surface typically doubles, when the mixed layer depth becomes shallower.

Whereas, the light availability for phytoplankton cells should be related more to the intensity of turbulence than to the MLD, which it practically defined by a density profile (Taylor and Ferrari 2011). A comprehensive definition of the MLD should include the turbulent surface layer in the real ocean, where surface stirring by the wind usually contributes to mixing (Itoh et al. 2015).

In winter, we remarked the deepest MLD in the Cape. In the same season, we had the coolest SST, the higher sea surface salinity, a weaker current velocity and a low chlorophyll concentration. During summer the MLD reach its shallower depth, when the SST is maximum, SSS minimum with a higher sea surface velocity and a maximum of the chlorophyll concentration. We noticed that there is a high correlation between the different parameters as the MLD, SST and the Chl-*a*. We suggest that the variability of the MLD play a primordial role in the physical and biological ocean aspects in the cape Ghir region.

The slow response of the sea surface temperature to the upwelling phenomena make difficult to detect the upwelling activity immediately by the temperature. However, we note a quick reaction of the MLD to the upwelling activity. We suggest that the depth of the mixed layer can be a better index for the upwelling activity.
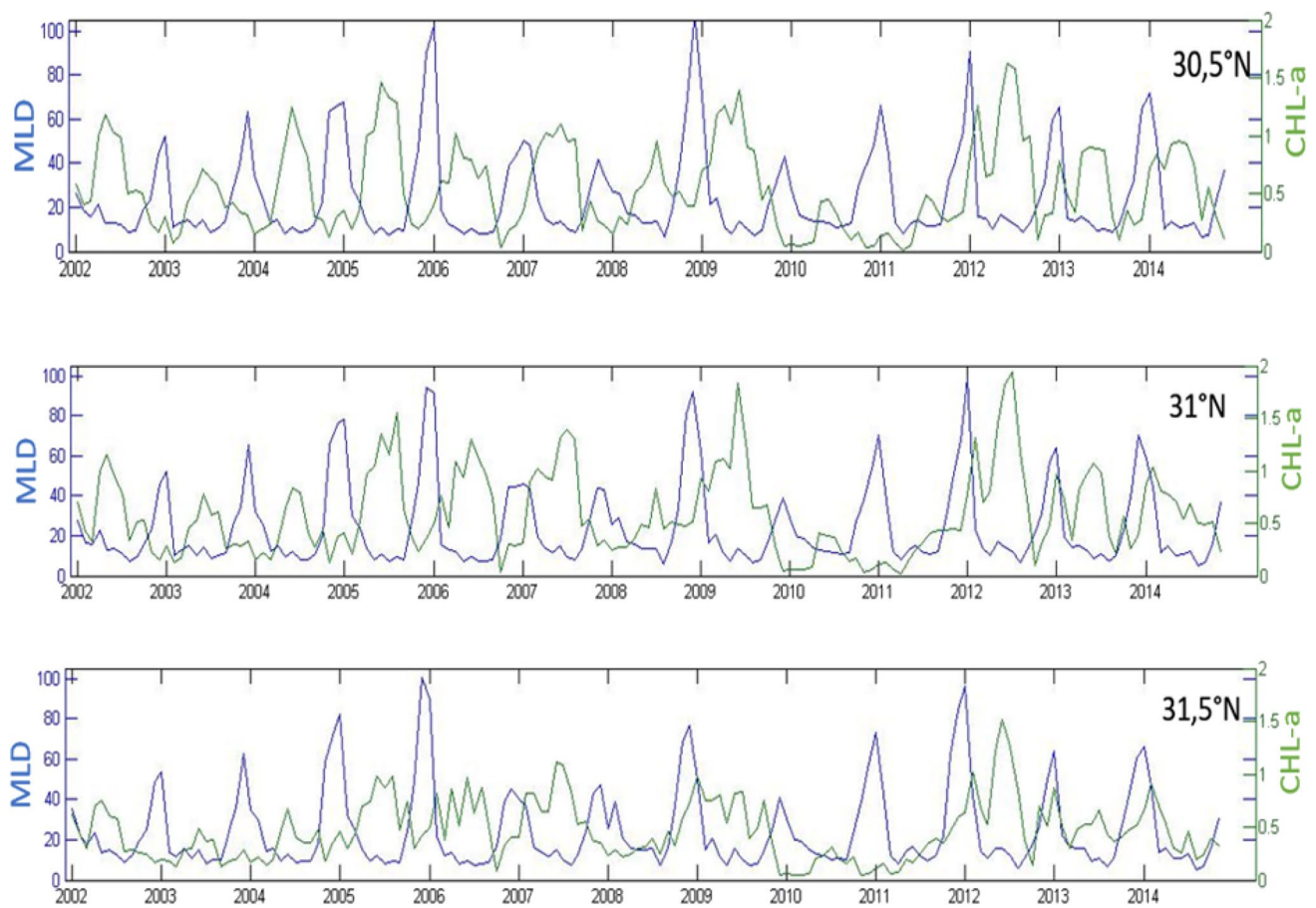
Fig. 10 Plots of the MLD (m) with the chlorophyll concentration (mg/m^{-3}) for three latitudes (30.5°N, 31°N and 31.5°N)

Conclusion

In this work, we examined the less explored coupling between mixed layer variability and sea surface properties by assembling all the available data from marine Copernicus data model. In winter, we had the deepest ML, however in the other months the MLD was shallow. Moreover, in winter, we remarked, the coolest SST, the higher sea surface salinity, a weak velocity and a low chlorophyll concentration. During summer the MLD shallow in surface, correspond with the maximum of the SST, less SSS, higher sea surface velocity and a maximum of the chlorophyll concentration. We noticed that the correlation between the MLD and the SST it is evident and the picks of the Chl-*a* match with the shallow MLD and the lowest Chl-*a* concentration link with the deepest ML. During the interannual variability of the MLD, the year of 2010 was characterized by a shallow depth all the year witch had an impact on the weak concentration of the chl and the high temperature.

The main results we meet in this work show that the characteristic feature of the variability of mixed layer depth in the Cap Ghir was based on the quick response of the upwelling then the other parameters as the temperature. When the ML is shallow, the SST is still cooler for 2 months more. Then, the MLD is an adequate parameter for detecting the activity of the upwelling activity immediately.

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