ORIGINAL ARTICLE

Variability of the ocean mixed layer depth and the upwelling activity in the Cape Bojador, Morocco

Ismail Bessa[1,2] · Ahmed Makaoui[2] · Aziz Agouzouk[2] · Mohammed Idrissi[2] · Karim Hilmi[2] · Mohamed Afifi[1]

Abstract
This study examines the seasonality of the patterns of the ocean mixed layer depth (MLD) with the coastal upwelling system, using a model data from marine Copernicus with a resolution of $0.083° \times 0.083°$. For that, we examined wind forcing, ocean circulation, sea surface temperature, sea surface salinity, sea surface chlorophyll-a, and mixed layer depth seasonality from 2007 to 2017 in the Cape Bojador south of the Moroccan Atlantic coast. We observed that in the fall season the wind speed was low, and the maximum wind speed is in the summer season. Furthermore, we found that coastal areas are related to a generally shallower MLD all the year in the Cape. We also proved that the source of the upwelling is between 25 and 26°N. However, we observed that the sea surface chlorophyll concentration in the same region is minimum, while in the region between 24.5 and 22°N, the CHL-a is maximum. We suggested that the biological richness in Cape Bojador, due to the activity of upwelling, derives to the south because of the northward ocean filament. Despite the different physical and biological parameters used to detect upwelling activity, we found that upwelling detection based on sea surface temperature is the best method to describe the upwelling activity in this region.

Keywords Ocean mixed layer depth · Costal upwelling · Sea surface chlorophyll-a · Filaments · Sea surface temperature

Introduction

The ocean mixed layer is the ocean region adjacent to the air–sea interface, this layer controls all exchanges between the ocean and the atmosphere, which gives importance to study its variability and due to the fact that it is well mixed, the temperature, salinity, and the density are clearly uniform (Boyer Montégut et al. 2004; Holte and Talley 2009).

The depth of the ocean mixed layer varies highly around the world's oceans in time–space and represents an important factor in the environmental driving phytoplankton blooms (Behrenfeld and Boss 2014). wherefore, the mixed layer depth (MLD) is the main factor for understanding phytoplankton dynamics (Sverdrup 1953).

The MLD is heated near the surface by both short-wave (SW) and long-wave (LW) radiative fluxes, and deeper in the water column from solar radiation in the visible part of the spectrum penetrating into the MLD. This solar radiation is valuable to phytoplankton production (Mitchell et al. 1991). Furthermore, the MLD has been linked to the flux of nutrients in the water column (Ducklow et al. 2007).

The mixed layer is a natural bridge between the atmosphere and the deep ocean (Boyer Montégut et al. 2004; Holte and Talley 2009), and controls all exchanges between air and sea. (Violaine Pellichero 2016). The characteristics of the MLD largely determine the distribution and properties of the ocean water-masses and regulate the ocean capacity to store heat and carbon (Whitworth et al. 1998; de Boyer Montégut et al. 2004; Lévy et al. 2015).

In the Moroccan Atlantic coast, a study of the phytoplankton distribution showed that during the winter season, a high algal density is recorded at 30 m in the north of the region and in the south, generally the values is maximum, with a more coastal algal density maximum, while in summer season is characterized by coastal maximum of density, which is recorded at 10 m except in the north of the region where the maximum is at 30 m (Elghrib et al. 2012). Smith

✉ Ismail Bessa
Bessaismail@gmail.com

1 Laboratory of Engineering and Materials, Faculty of Sciences Ben M'Sik, University of Hassan II, Casablanca, Morocco

2 Oceanography Department, National Institute of Fishery Research, Casablanca, Morocco

and Jones (2015) showed that vertical mixing and phytoplankton biomass are consistent with the critical depth of the MLD.

Coastal upwelling is most marked in the Trade Wind zones, but it can occur wherever and whenever winds cause offshore movement of water. However, it is a difficult process to investigate directly, because it occurs episodically, and because the average speeds of upward motion are very low, generally of the order of 1–2 m per day though sometimes approaching 10 m per day (Brown 1989 book circulation).

Indirect methods are used to detect the activity of the coastal upwelling, all these approaches are based on indirect measuring methods, and these may be based on either the causes or the effects of upwelling. However, there are chemical and biological indicators of upwelling. In practice, it is the physical characteristic of temperature that is most often used to identify and investigate regions of upwelling.

Water that upwells to the surface comes from only 100–200 m depth, but it is significantly colder than surface water. The Cape Bojador is known by a permanent upwelling activity as described by Makaoui et al. (2005), Benazzouz et al. (2014) and Bessa et al. 2017), nevertheless, the seasonality of the MLD is unknown in this region.

The mean objective of this paper is to examine the seasonality of the patterns of the MLD with the coastal upwelling system. For that we examine wind forcing, circulation of the seawater, temperature, salinity, chlorophyll-a, and mixed layer depth seasonality from 2007 to 2017. For that, we studied the seasonality of the deferent ocean parameters of the sea surface. This study covers the zonal band of the Atlantic North-East, between the 26 and 22°N. It is a cyclonic region crossed by several seasonally changing zones (Rosell-Fieschi et al. 2015). The sea surface in this region is characterized by high temperature and salinities, high dissolved oxygen and low nutrient concentrations (Pastor et al. 2012).

Materiel and methods

Model descriptions

The high-resolution global analysis and forecasting system PSY4V3R1 uses version 3.1 of NEMO ocean model (Madec et al. 2008). The physical configuration is based on the tri-polar ORCA grid type (Madec and Imbard 1996) with a horizontal resolution of 9 km at the equator, 7 km at midlatitudes and 2 km toward the Ross and Weddell seas. The 50-level vertical discretization retained for this system has 1 m resolution at the surface decreasing to 450 m at the bottom, and 22 levels within the upper 100 m. The bathymetry used in the system is a combination of interpolated ETOPO1 (Amante and Eakins 2009) and GEBCO8 (Becker et al. 2009) databases. ETOPO1 datasets are used in regions deeper than 300 m and GEBCO8 is used in regions shallower than 200 m with a linear interpolation in the 200–300 m layer. The atmospheric fields forcing the ocean model are taken from the ECMWF (European Centre for Medium-Range Weather Forecasts) Integrated Forecast System. A 3 h sampling is used to reproduce the diurnal cycle. The system does not include tides. "Partial cells" parameterization (Adcroft et al. 1997) is chosen for a better representation of the topographic floor (Barnier et al. 2006) and the momentum advection term is computed with the energy and entropy conserving scheme proposed by Arakawa and Lamb (1981). The advection of the tracers (temperature and salinity) is computed with a total variance diminishing (TVD) advection scheme (Cravatte et al. 2007). The high frequency gravity waves are filtered out by a free surface (Roullet and Madec 2000). A laplacian lateral isopycnal diffusion on tracers and a horizontal bi-harmonic viscosity for momentum are used. In addition, the vertical mixing is parameterized according to a turbulent closure model (order 1.5). The lateral friction condition is a partial-slip condition with a regionalization of a no-slip condition (over the Mediterranean Sea) and the elastic–viscous–plastic rheology formulation for the
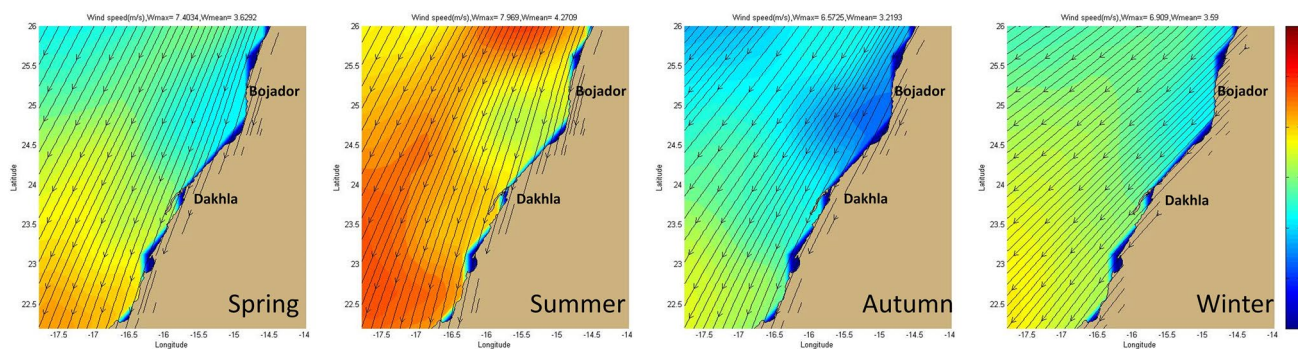

Fig. 1 Average seasonal wind trend (m/s) from 2007 to 2016

LIM2 ice model (hereafter called LIM2_EVP, Fichefet and Maqueda 1997) has been activated (Hunke and Dukowicz 1997). Instead of being constant, the depth of light extinction is separated in red–green–blue bands depending on the chlorophyll data distribution from mean monthly Sea WIFS climatology. Altimeter data, in situ temperature and salinity vertical profiles and satellite sea surface temperature are jointly assimilated to estimate the initial conditions for numerical ocean forecasting. Moreover, satellite sea ice concentration is now assimilated in the PSY4V3R1 system in a mono-variate/mono-data mode.

Data

In this work, we used data from the Mercator Global Operational Ocean Analysis and Forecasting System at a resolution of 1/12°. The system provides global ocean data in 3D updated daily. We used monthly average data from 2007
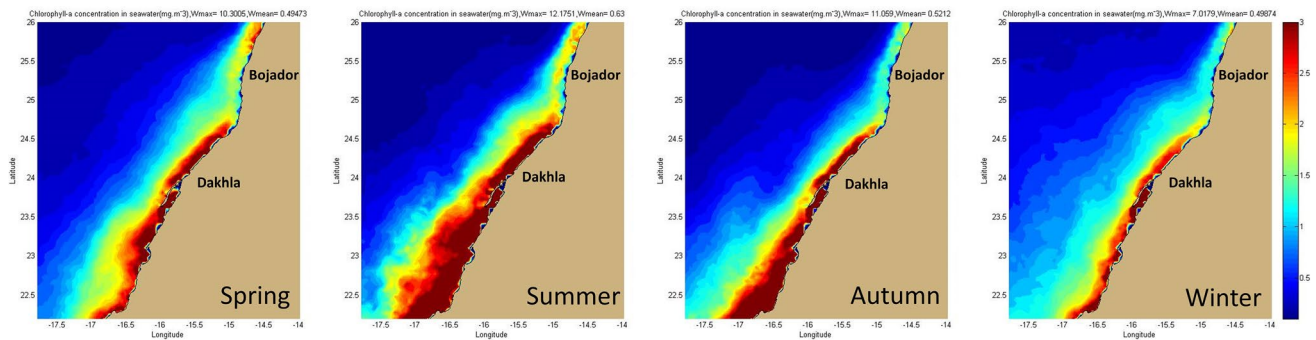

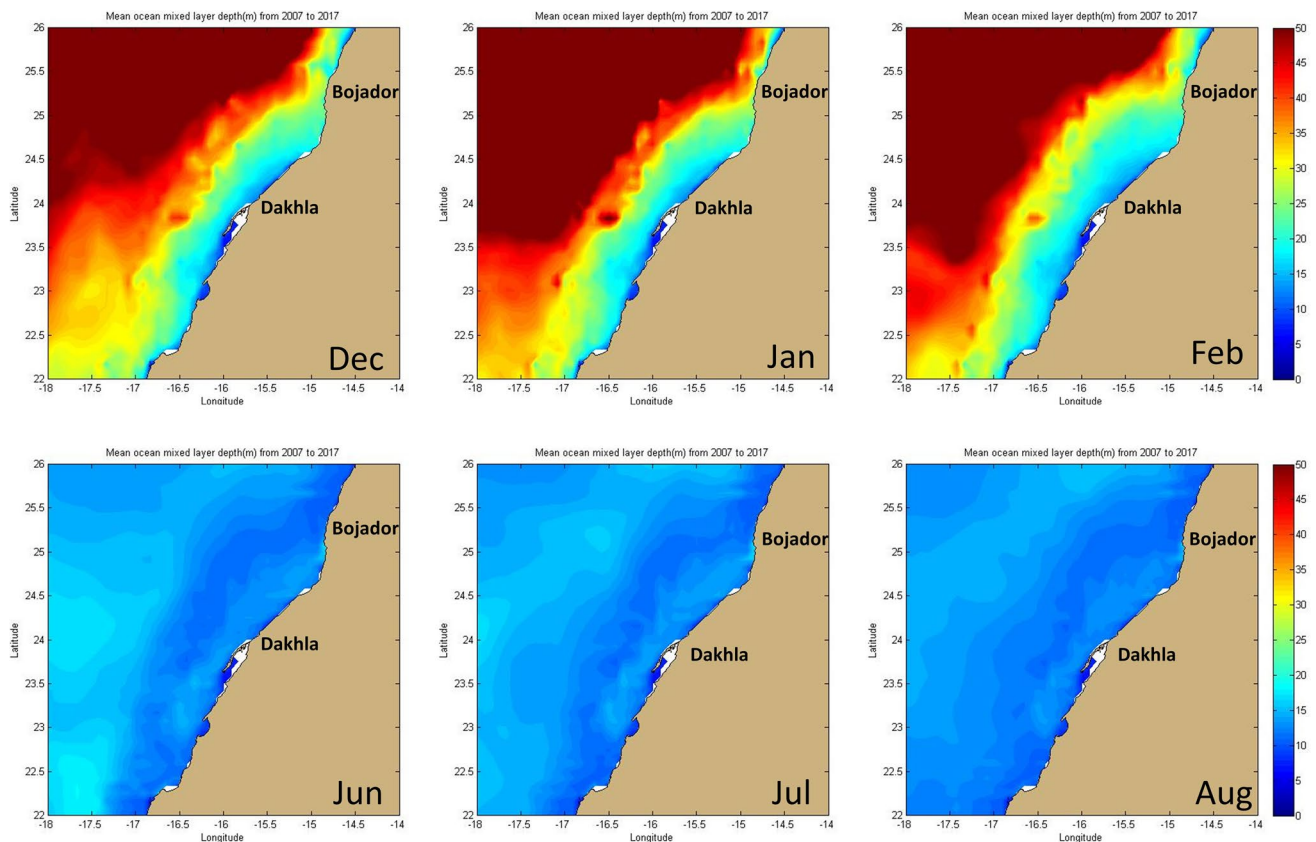**Fig. 2** Average seasonal chlorophyll-a sea surface concentration (mg/m³) from 2007 to 2016

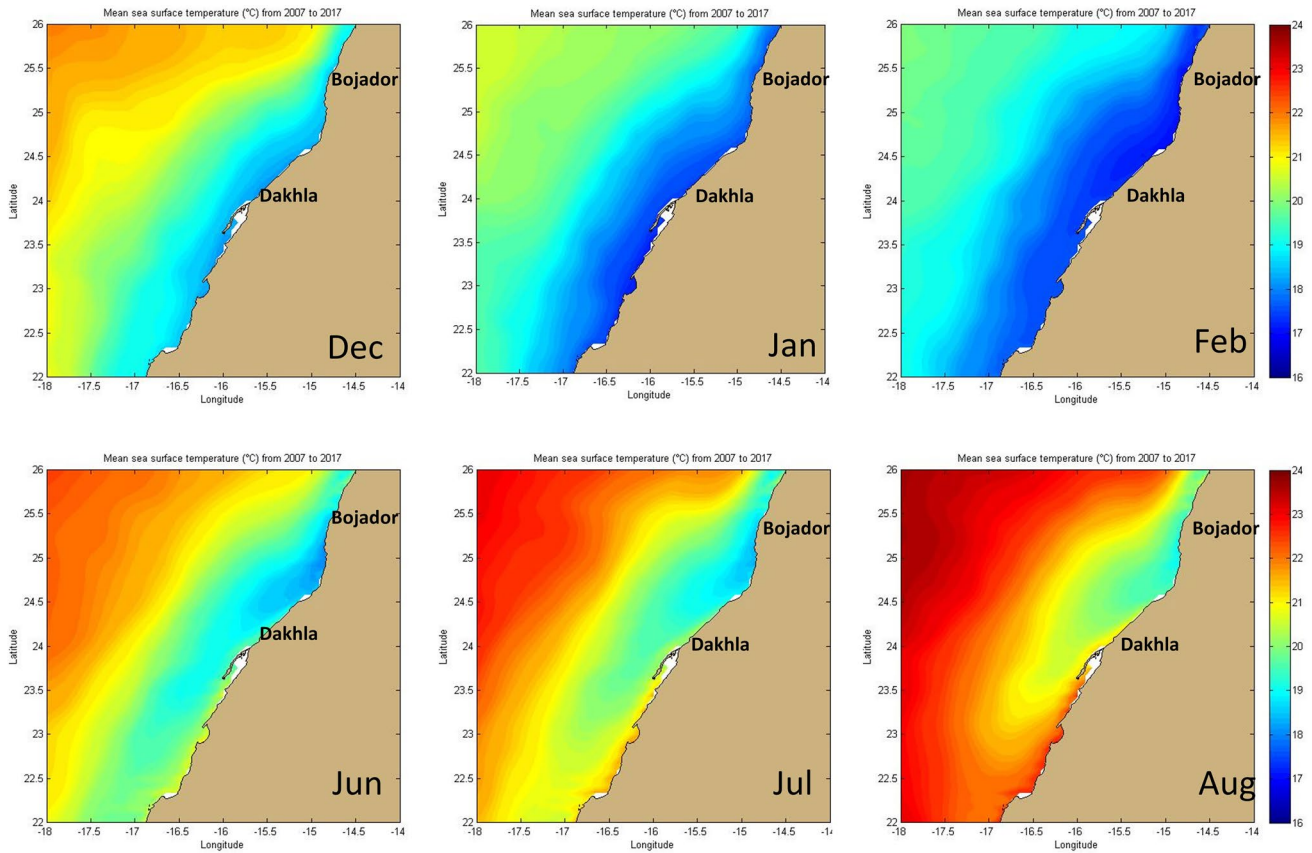**Fig. 3** Average monthly ocean mixed layer depth (m) from 2007 to 2017

Fig. 4 Average monthly sea surface temperature (°C) from 2007 to 2017

to 2017 of temperature, salinity, currents, and depth of the mixed layer covering the Cape Bojador region. The model is corrected with the assimilation of the data with the satellite data and the in situ profile as previously described. We used the SST index to detect the upwelling activity in the region (Reynolds et al. 2007).

The wind data from 2007 to 2016 come from the global ocean surface IFREMER CERSAT surface wind climatology includes wind components (southern and zonal). Wind stress is estimated from ASCAT data. The analyzes are estimated as seasonal data averaged over the global ocean with a spatial resolution of $0.25° \times 0.25°$ in latitude and longitude.

For chlorophyll data from 2007 to 2016, we used the seasonal mean of the global ocean, the surface chlorophyll of the ESA Ocean Color CCI (mg m^{-3}, with a resolution of 4×4 km) using the recommended chlorophyll algorithm OC-CCI available in CMEMS format, with L4 season composites. The Ocean Color technique exploits the electromagnetic radiation emerging from the sea surface in different wavelengths. The spectral variability of this signal defines the color of the ocean, which is affected by the presence of phytoplankton. By comparing reflectance at different wavelengths and calibrating the result against in situ measurements, an estimate of the chlorophyll content can be derived.

A detailed description of the quality, accuracy, and calibration information is available on the official CMEMS website, along with validation reports and quality documentation. (www.marine.copernicus.eu).

Results

In this section, we examined wind forcing, ocean circulation, sea surface temperature, sea surface salinity, sea surface chlorophyll-a, upwelling activity and mixed layer depth seasonality from 2007 to 2017 in the Cape Bojador south of the Moroccan Atlantic coast.

The studied region is known by a northerly wind all the year from 2007 to 2016. We observed that the most significant calm period is the Autumn season when wind speed was low about 5 m/s, and the maximum wind speed between 7 and 8 m/s is remarked in summer season. While in winter and spring seasons, the wind has the same regime, as shown in Fig. 1.
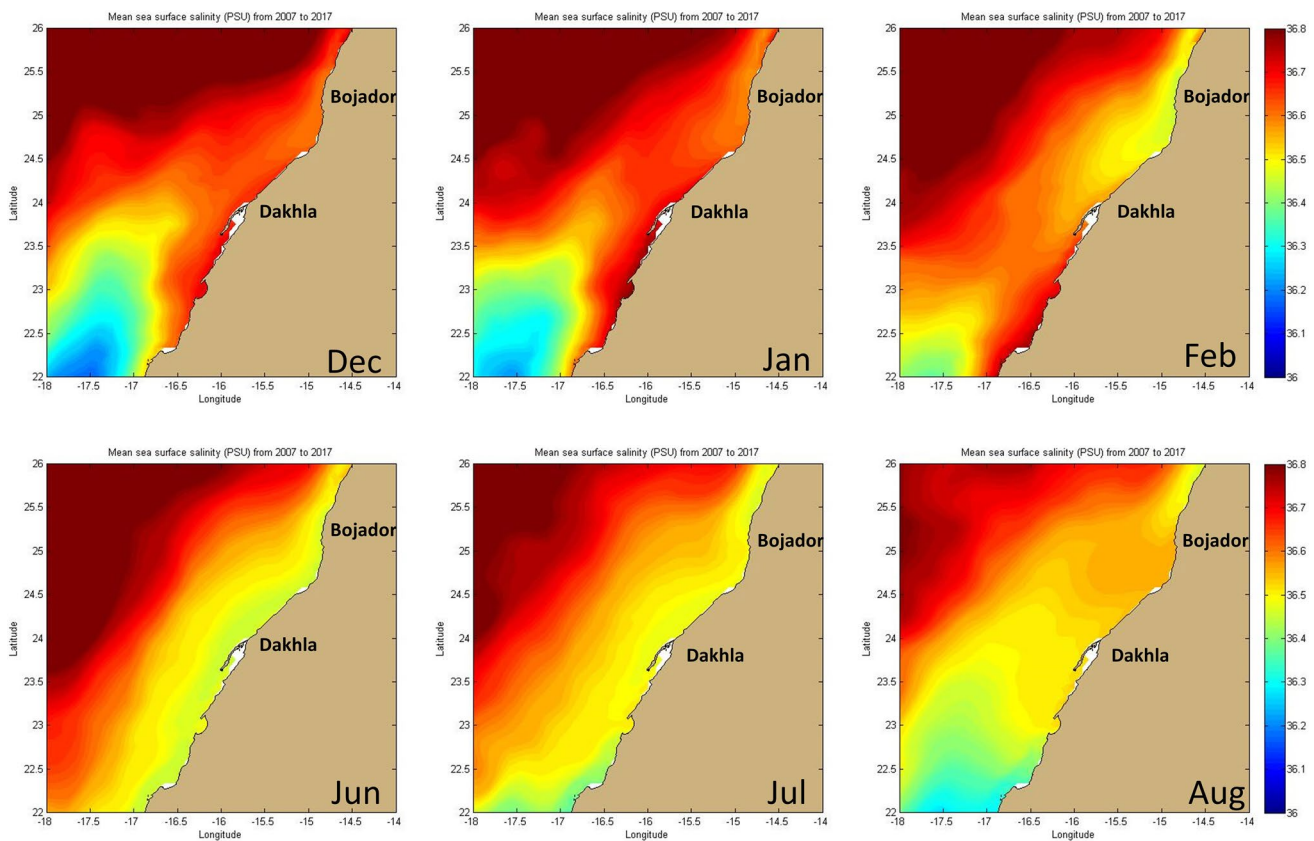
Fig. 5 Average monthly sea surface salinity (PSU) from 2007 to 2017

The average chlorophyll-a concentration in sea surface shows a seasonal variability. The maximum of the CHL-a is observed in summer about 3 mg/m^3, however, the minimum corresponds to winter season between 1 and 2 mg/m^3 moreover, there is less concentration offshore, however spring and autumn act like a transition seasons, as shown in Fig. 2.

The monthly variability of the ocean mixed layer depth from 2007 to 2017 shows a large difference between the coast and offshore. In offshore, the seasonality is clear, the MLD is maximum more than 60 m in the winter season, and it is shallow in the summer season about 10 m. At the coast, the MLD is shallowing in the surface all the year (Fig. 3).

The monthly sea surface temperature (SST) from 2007 to 2017 varies between 16 °C in the winter and 24 °C in the summer season. The SST variability is linked directly to the upwelling activity, we observed a blue spot that illustrate the activity of the upwelling in the Cape Bojador especially in August, and these blue spot resemble to a cold tongue going from Bojador to the south of Dakhla (Fig. 4).

The monthly variability of the sea surface salinity from 2007 to 2017 shows a strong variability from the north to the south of the studied region, and it is varying between 37PSU and 36PSU. The minimum of salinity is remarked especially in December and January in the south of Dakhla between (22°N and 23.7°N) as shown in Fig. 5.

Figure 6 presents the monthly mean variability of the sea surface velocity, and we observed that the maximum of seawater velocity is observed in the summer season, near the coast especially in the Cape Bojador more than 0.5 m/s. In Dec–Jan, we notice less velocity in the region around 0.1–0.25 m/s, and in February the velocity starts raising. Finally, the structure of the filament is very different from the filament in the Cape Ghir region, where the filaments drift from the coast to the offshore (Bessa et al. 2018), the filaments in the Cape Bojador, flow from the Cape to the south and they stick to the coast as shown in Fig. 6. Furthermore, we notice that in all the region where the filaments are present the MLD is shallow.

The upwelling index shows a clear activity of the upwelling between 25 and 26°N. The results show that the upwelling in the Cape Bojador is active almost all year round, and weaker in the winter. In the south of the Cape, the upwelling is less presented as shown in Fig. 7a.

Furthermore, we observed that the upwelling activity effect directly the sea surface temperature. Figure 7b shows
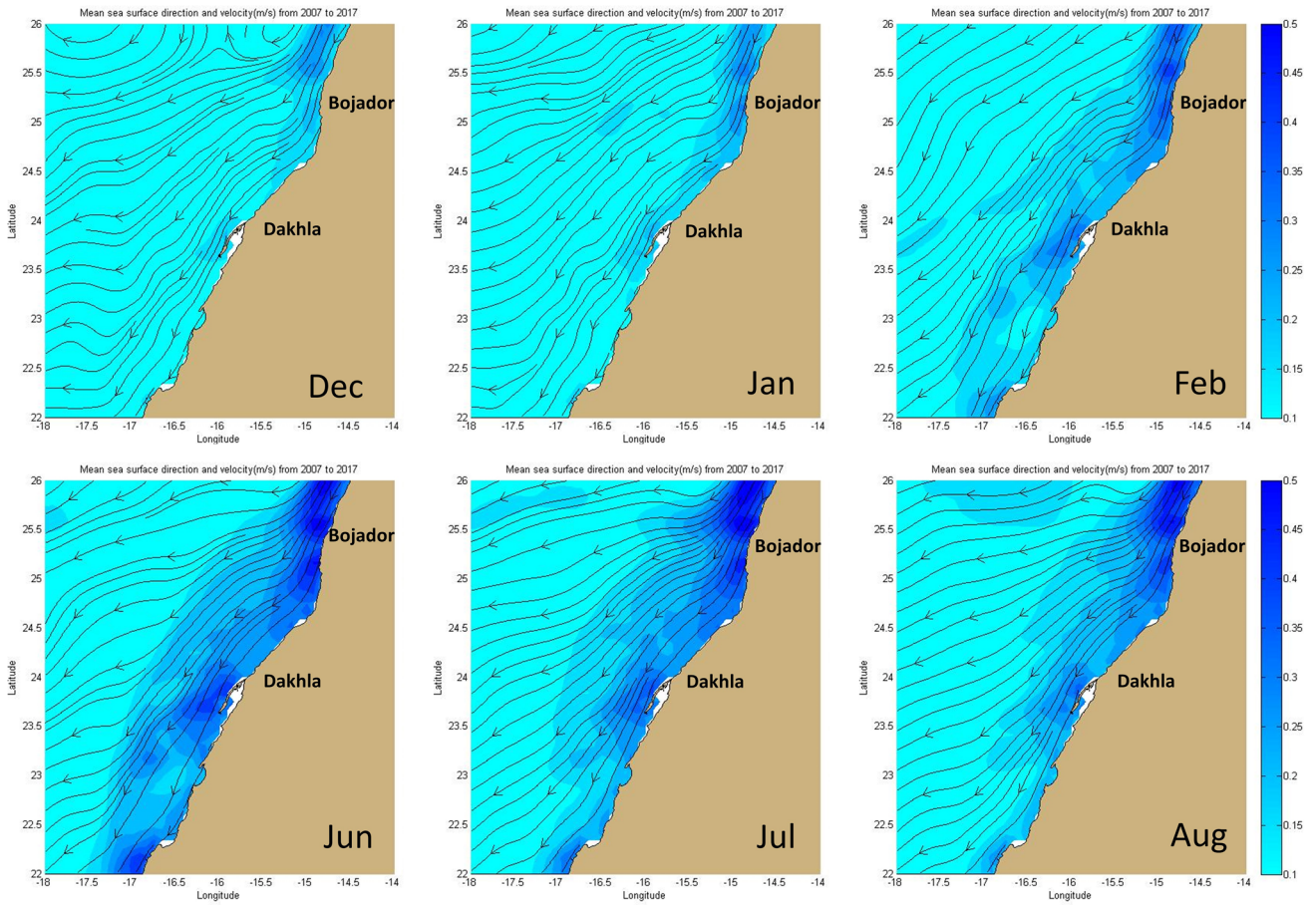
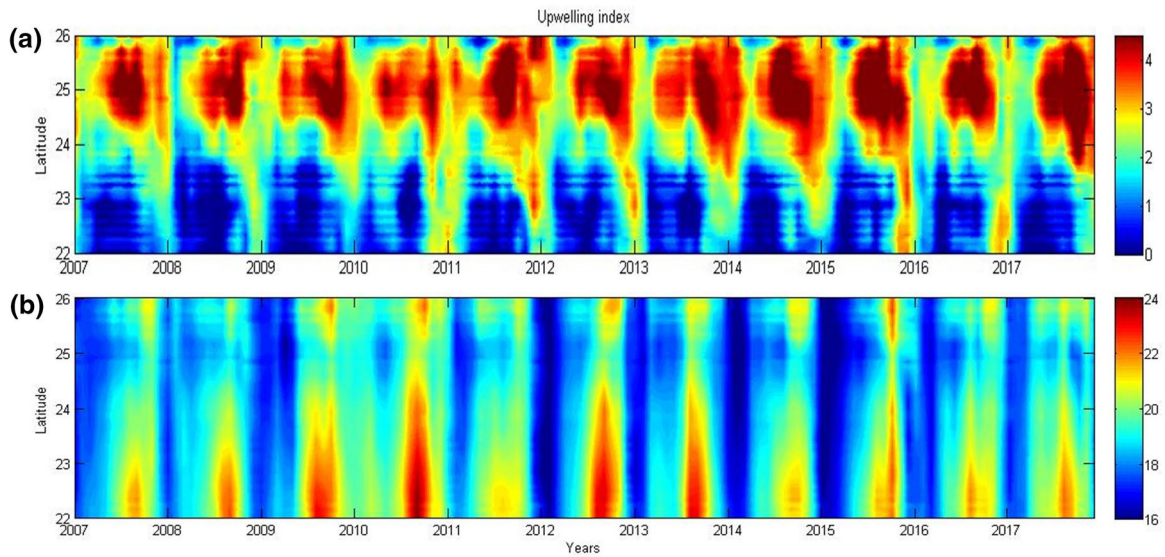**Fig. 6** Average monthly sea surface velocity (m/s) from 2007 to 2017

Fig. 7 Hovmöller diagrams of **a** upwelling index from 2007 to 2017, **b** minimum of sea surface temperature in (°C) from 2007 to 2017
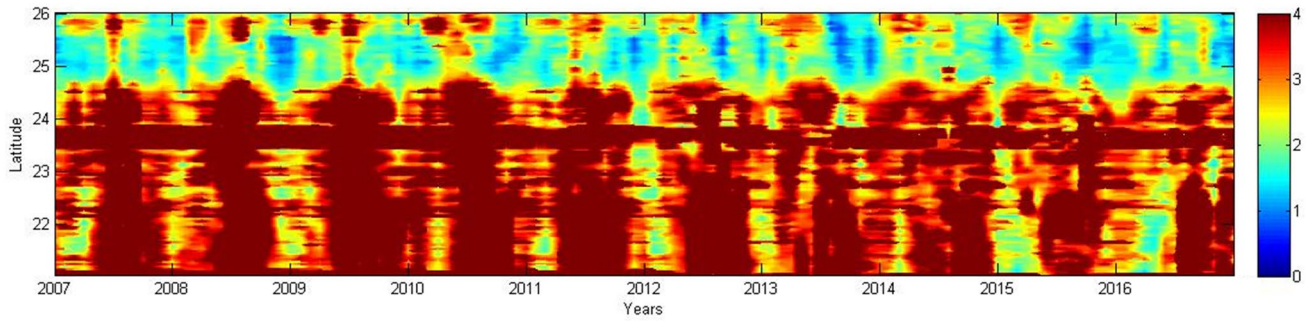
Fig. 8 Hovmöller diagram of the maximum sea surface chlorophyll-a concentration (mg/m³) from 2007 to 2016
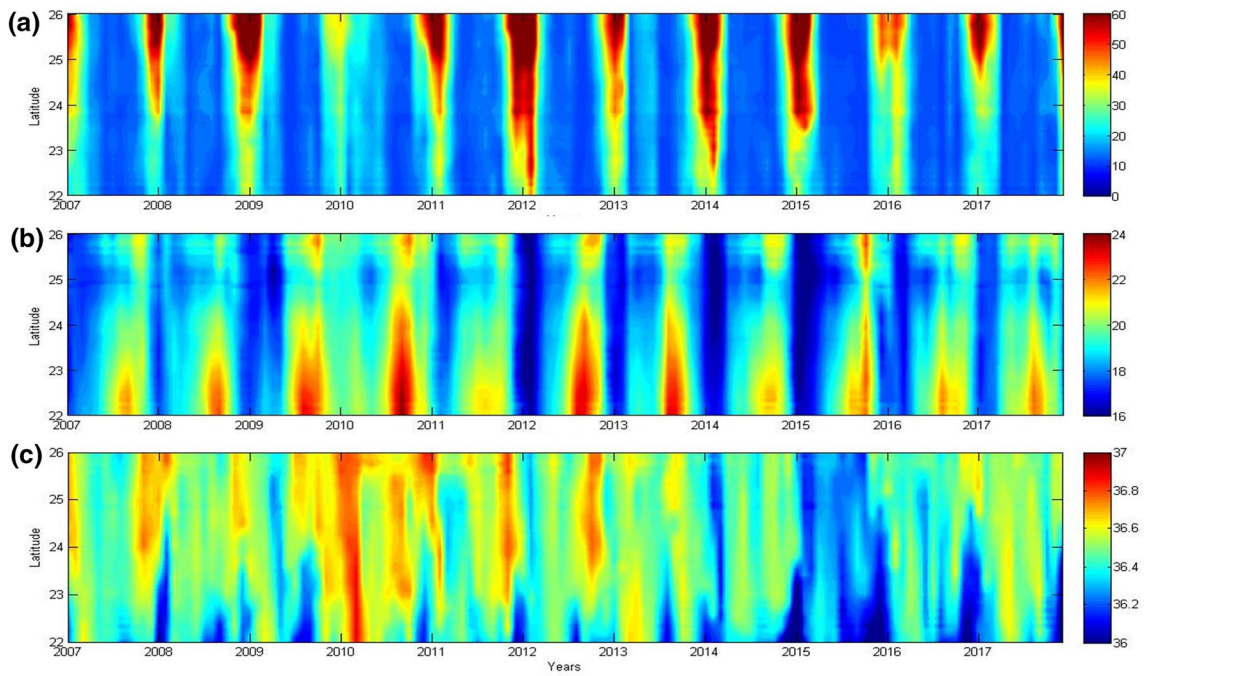

Fig. 9 Hovmöller diagrams of; **a** the average ocean mixed layer (m), **b** the minimum of sea surface temperature (°C), **c** the minimum of the sea surface salinity (PSU), from 2007 to 2017
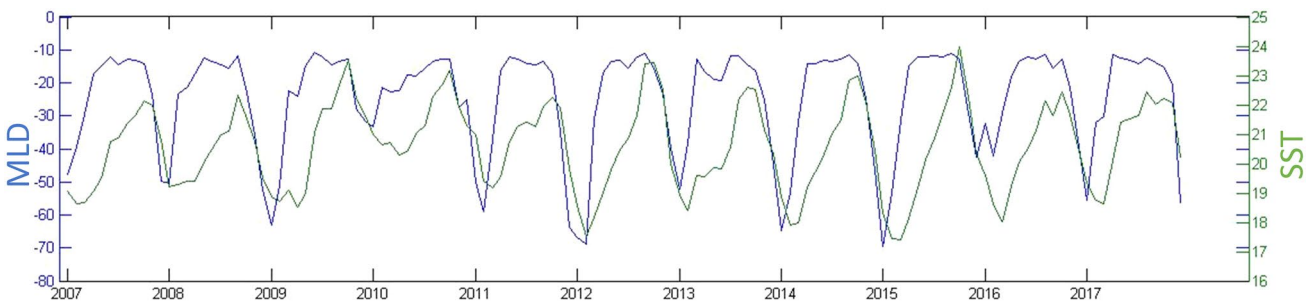

Fig. 10 The average of the ocean mixed layer depth (m) in blue and minimum sea surface temperature in latitude 25°N 2007–2017

the minimum of the SST in the Cape Bojador, with a minimum of temperature about 16 °C all year round. While in the south of the region, we notice a normal seasonality of the SST that varies between 24 °C in the summer and 16 °C in the winter season. From that, we suggest that Cape Bojador is the source of the upwelling in the region.

Discussion

Figure 8 shows the maximum of the sea surface chlorophyll concentration from 2007 to 2017. We remarked that the region between 25 and 26°N shows the minimum of the CHL-a concentration, and the region from 24.5 to 22°N, indicates the maximum of the CHL-a concentration. We suggested that all the biological richness in Cape Bojador due to the activity of upwelling, it derives to the south because of the ocean filaments directions. From that, we propose that the method of the sea surface temperature is most efficient to identify and investigate regions of upwelling, and the biological indicator of upwelling is less accurate to detect the upwelling activity in this area of studies.

The strong upwelling activity is confirmed by vertical variability analysis of the phytoplankton densities in the region, which has no significant difference between levels sampled, with homogeneity in the phytoplankton due to a strong vertical mixture of the mass of water. On the other hand, in winter, the vertical variation of the densities was significantly different, with maxima recorded at 30 m depth in the region (Elghrib et al. 2012). These results can be explained by the variability of the ocean mixed layer depth which influences the phytoplankton densities distribution.

The diagram of the MLD shows a strong seasonality. The MLD is deep in winter and the MLD in the other seasons shallow. In winter 2010, we notice an anomaly represented with a shallow MLD all the year, this anomaly affected directly the sea surface temperature (SST), and sea surface salinity (SSS). We observed that when the MLD shallows all the year, the SST remains high, and that affects the SSS which reaches the maximum about more than 37PSU in 2010 (Fig. 9).

Figure 10 represents the variability of the mean MLD and the mean SST in the latitude 25°N, from the coast to offshore (18°W). We notice that there is a clear correlation between the two parameters when the MLD becomes shallower, the sea surface temperature increases, and when the MLD becomes deeper, the SST decries. In addition, we noticed that in 2010, the maximum depth of ML was 30 m,

and this influenced directly the temperature, because it did not exceed 20 °C this year.

Conclusion

The ocean mixed layer is a practically worldwide feature of the world oceanography. The depth of the mixed layer (MLD) influences the exchange of heat and gases between the atmosphere and the ocean and constitutes one of the major factors controlling ocean primary production as it affects the vertical distribution of biological and chemical components in near-surface waters (Christian Stranne et al. 2018).

In this study, we showed that in coastal areas is related to the generally shallower MLD all the year in the Cape Bojador region, and that can be explained by the almost permanent activity of the upwelling in the Cap. We also, investigated the relationship between the MLD and the SST, and we found that there is a positive correlation between the two parameters, in other words, when the MLD is deeper, the SST is minimum, and when the MLD shallow in the surface, the SST is maximum. However, the bathymetry of the study area must be considered to have a better understanding of the MLD variability.

We investigate the costal upwelling activity, and we suggest that the source of the upwelling is between latitudes 25 and 26°N. However, the sea surface chlorophyll concentration shows different results, we observed that the region between 25 and 26°N, shows the minimum of the CHL-a concentration, and the region from 24.5 to 22°N, indicates the maximum of the CHL-a concentration. We suggest that all the biological richness in Cape Bojador due to the activity of upwelling derives to the south following the filament direction. From that, we propose that the method of the sea surface temperature is the most efficient method to detect the upwelling activity, and the biological indicator of upwelling is less accurate to detect the upwelling in this area of studies.
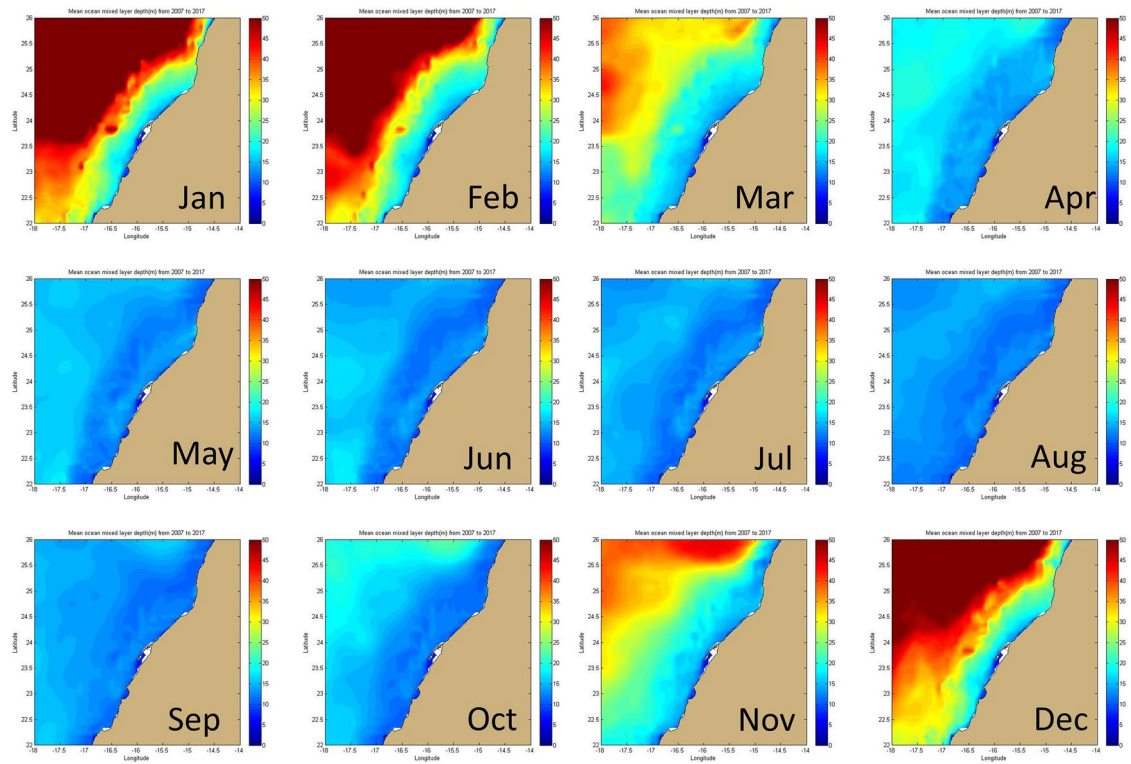
Appendix

See Figs. 11, 12, 13 and 14.

Fig. 11 Average monthly ocean mixed layer depth (m) from 2007 to 2017
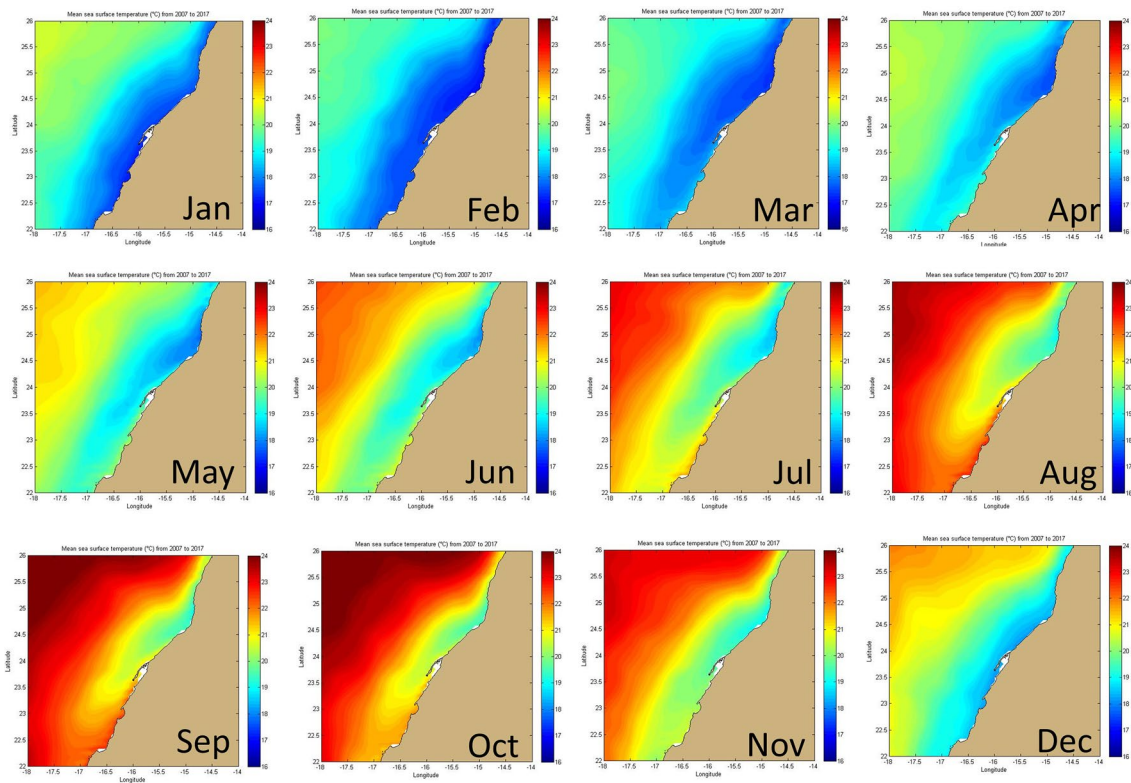

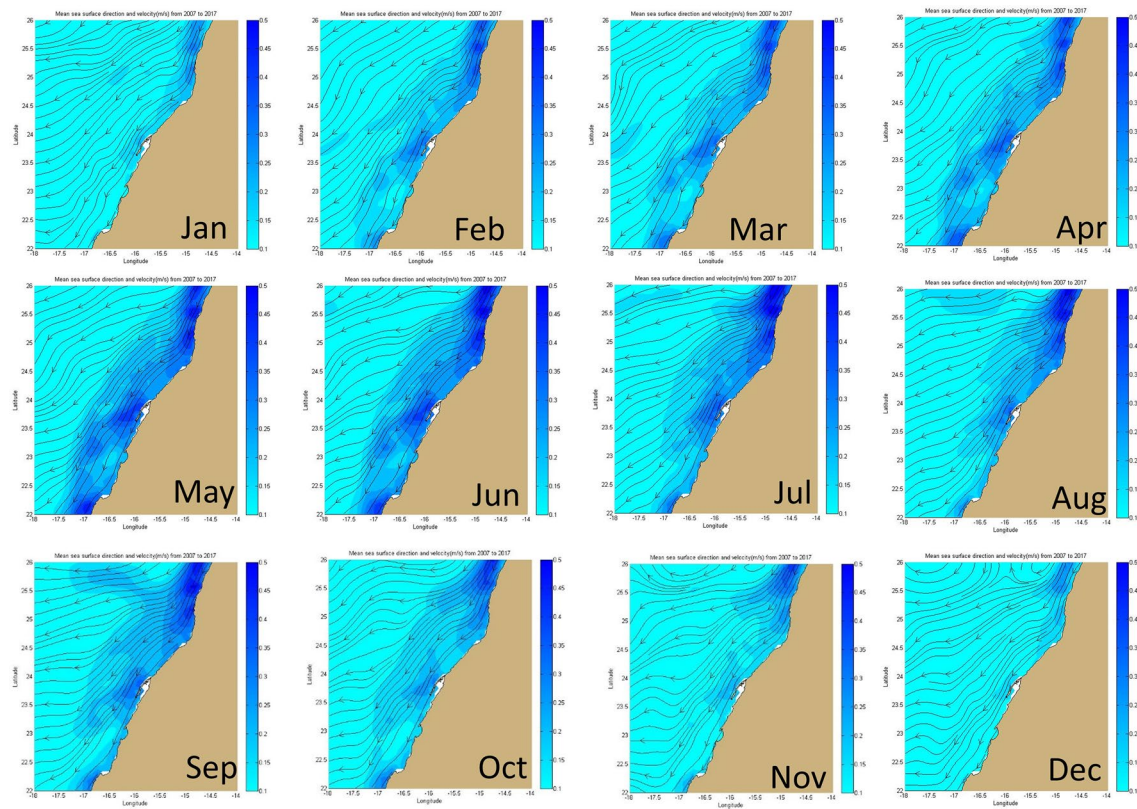**Fig. 12** Average monthly sea surface temperature (°C) from 2007 to 2017

Fig. 13 Average monthly sea surface velocity (m/s) from 2007 to 2017
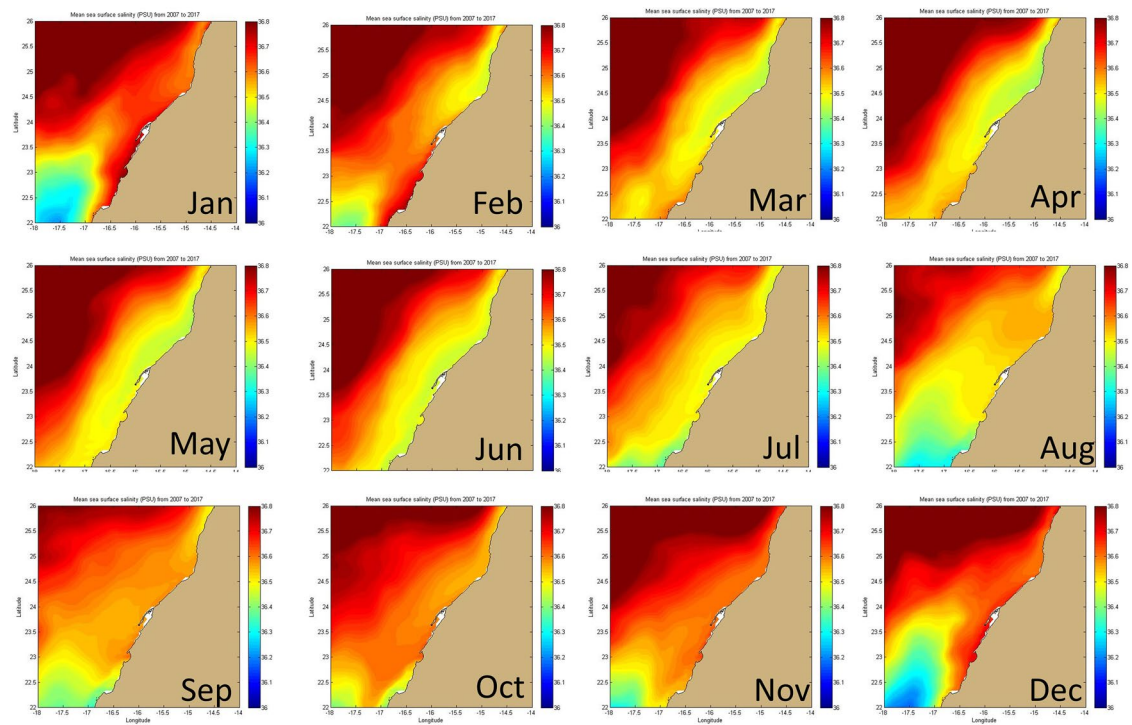

Fig. 14 Average monthly sea surface salinity (PSU) from 2007 to 2017

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