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Potential Roles Of Eddy Kenetic Energy And Turbulence In Controlling The Bio-optical Ocean Proprieties

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Abstract. In the Canary Current System (CCS), coherent structures and concurrent movements of surface waters such as meanders, filaments and eddies strongly control the ocean bio-optical proprieties response to the coastal upwelling process. One of the outstanding problems is to understand the mechanisms of the bio-optical proprieties transfer and the connection mechanism between the coastal band and the ocean interior. We use a combination of satellite data and derived mesoscale indicators to provide a comprehensive view of the relationship between the physical and bio-optical proprieties off Moroccan upwelling region (part of the CCS) in terms of wind impulse responsible of sea turbulence, sea surface temperature (SST) response of the wind stress and ocean color proprieties considered as bio-optical ocean proxy response. To optimize the predicted ranges of these parameters, Generalized Additive Model (GAM) was applied. We conclude that the energetic mesoscales structures as seen from the satellite climatology observations can provide insight into dominant transport pathways controlling the bio-optical exchange from the coastal area to the ocean interior structured as an oceanic corridor connecting the Moroccan area to the Canary archipelagos.

1 Introduction

Transport in the Canary Current System (CCS) is inherently chaotic [1]. Instabilities generated in the upwelling jet [2] is spatially structured into filaments and eddies that remain coherent (Figures 1 a, 1b), relatively persistent and recurrent for several weeks, penetrating up 300's of kilometers offshore and transporting bio-opticcally important materials far into the ocean interior in terms of chlorophyll_a. The alongshore advection of alongshore momentum compensates for interfacing friction, allowing the upwelling jet and associated frontal system to remain active. Developing instabilities in the flow produce oscillations in vertical velocity that result in upwelling and downwelling along

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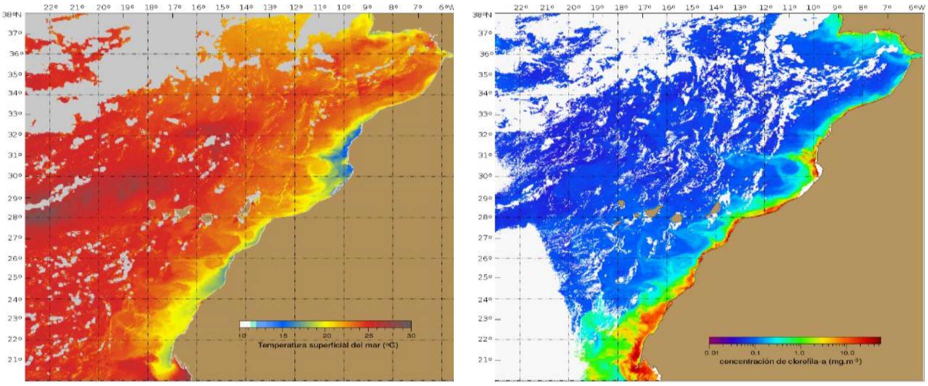
the jet [3]. As pointed out by [2] the coastal jet plays a key role in maintaining the structure of coastal upwelling, even at times of relaxed winds. The horizontal exchange of organic material and nutrients between filaments and surrounding offshore water could sustain high production rates outside the upwelling zone, or, alternatively, nutrient upwelling generated by the filaments dynamics could significantly contribute to the offshore productivity [4]. The objective of the present paper is to derive the meso-scale features dynamics of the Moroccan Atlantic coast populated by cyclonic or anti-cyclonic eddies based on satellite observations and to determine the influence of ocean circulation on bio-optical process.

An issue from our work is the importance of connections between adjacent coastal regions and between the coastal and offshore oceans.



(a) (b)

Fig.1. (a) Sea surface temperature highlighting a strong mesoscale activity; (b) Ocean color highlighting a strong mesoscale activity and offshore extension of the coastal bio-optical proprieties

2 Materials and Methods

2.1 Remote Sensing Data

The signatures of upwelling through remote sensing are cooler sea surface temperature, high chlorophyll_*a* concentration, lower sea level and intense along shore wind stress (Pelegri et al. 2005).

The climatological sea surface temperature (SST) data have been gathered by the Advanced Very High Resolution Radiometer (AVHRR) sensors of the National Oceanic and Atmospheric Administration (NOAA) satellite series. The ocean color data is provided by MODIS (or Moderate Resolution Imaging Spectroradiometer)

Satellite altimetry is taken from the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO)

The ocean surface winds at 10 meters of sea surface are provided by NOAA/NESDIS utilizing measurements from ASCAT aboard the EUMETSAT METOP satellite.

2.2 Mesoscale hydrodynamic indicators

Several mesoscales indicators have been derived from satellite products:

- Turbulence indice (m/s)$^{-3}$

The energy transferred through the water column by the wind creates turbulence in the surface layers. A wind-mixing index in the upper layer is therefore usually calculated as the cube of wind speed noted here after Turb. We used this index as an indicator of turbulence and mixing in the surface layers (Patti et al. 2007).

$$\text{Turb} = S^3 \tag{1}$$

where S is the wind speed at the sea surface

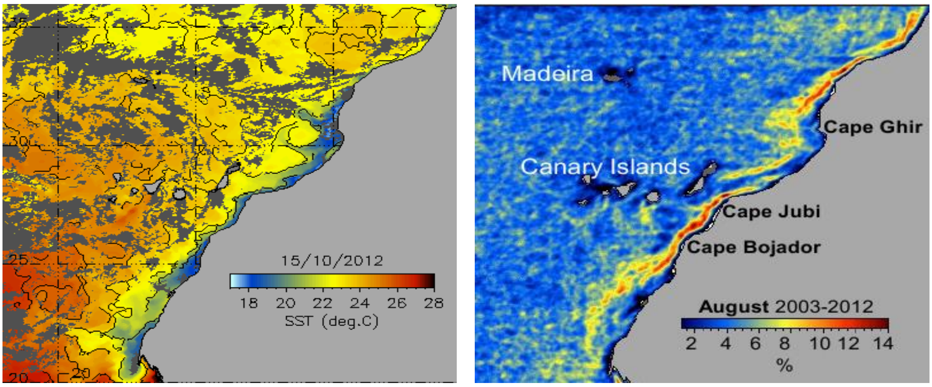
- Thermal Coastal Upwelling index (CUI$_{SST}$(°C))

The ocean response to the wind stress has been classically expressed in terms of SST difference index, calculated as the difference in temperature between upwelled water over the shelf (SST_{min}) and water further offshore(SST_{max}) (Nykjaer and VanCamp, 1994; Benazzouz et al. 2014a):

$$\text{CUI}_{\text{SST}}=\text{SST}_{\text{max\_offshore}} - \text{SST}_{\text{min\_coast}} \tag{2}$$

- Gradient Index (°C km^{-1})

The products related to the gradient index are derived according to the Neito et al. 2102 approach which state on an improved automatic detection of mesoscale frontal activity based on the edge detection algorithm initially developed by Cayula and Cornillon (1995) and used the Sobel edge enhancement kernel to calculate the gradient images (Figure 2).



(a) (b)

Fig.2. (a) Thermal fronts detection; (b) SST image highlighting the climatological frontal structure and the corridor connecting the coastal area to the ocean interior

The gradient value was extracted and assigned to the front edge, on a pixel by pixel basis, in order to compose a frontal gradient, that best quantifies the front.

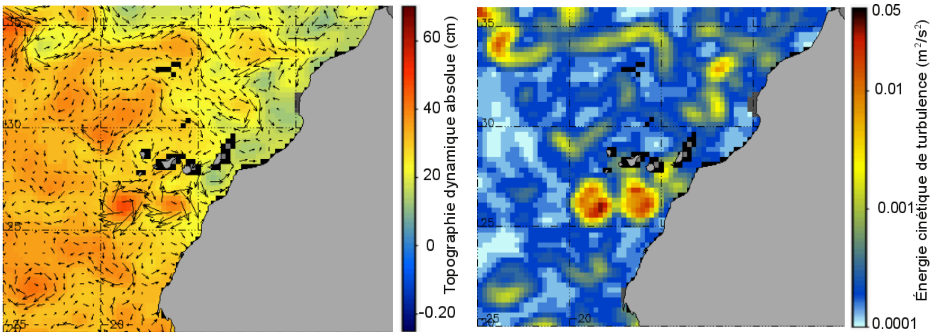
As discussed by Bakun (2006), the importance of fronts to ecosystem processes lies in the fact that any distinct front that persists are associated with a convergence zone and therefore to the formation of slightly sinking intermediate density water that concentrates particles and forms privileged areas of high biological activity. Consequently, the construction of mesoscale frontal activity indices in the ocean is a way of quantifying an important effect of mesoscale features on the transfer far offshore of the bio-opticals proprieties and the production.

- Altimetry derived indices

Velocities fileds are obtained from surface geostrophic velocities estimated from sea level anomalies from the merged mapped product AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) using measures of Topex Poseidon and ERS (European Remote Sensing).

We potentially derived the SSH (SeaSurface Height), the geostrophic flow (Fig.3a) and the Eddy Kenetic Energy (Figure 3b) considered as the balance between Coriolis force and pressure gradient force.

$$\bar{u} = -\frac{g}{f}\frac{\partial(\text{ADT})}{\partial y} \quad \bar{v} = \frac{g}{f}\frac{\partial(\text{ADT})}{\partial x} \tag{3}$$



(a) (b)

Fig.3. (a) Overlapping of sea surface height and derived geostrophic velocity fileld; (b) Eddy Kinetic Energy derived from AVISO data

-Eddy Kinetic Energy: EKE (m/s)^2

In order to understand the mesoscale activity, we have determined the Kinetic Energy distribution and the eddy flows has been analyzed.

$$\text{EKE}=\frac{1}{2}(\bar{u}^2 + \bar{v}^2) \tag{4}$$

where $\bar{u}^2$ and $\bar{v}^2$ are the zonal and the meridional geostrophic flow components derived from altimetry data.

The surface-intensified equatorward jet develops next to the coast in response to strong upwelling favorable wind (Benazzouz et al. 2014b). This jet, and a developing eddy field move offshore during strongest wind period mostly during summer and fall (Figure 4).

The climatological velocities field from surface geostrophic flow (Figure 3a) revealed a clear and highly energetically dynamic on the surface eddy kinetic energy (EKE) (Figure 3b) in the Moroccan coastal area.

In the mean velocity field, along the studied area the current appears to be significantly intensified, flowing close to the coast southward and offshore. This agrees with the distributions of the energy associated with the mean flow where, a significant increase in the EKE occurs simultaneously with an intensification of the current, attesting the transfer of energy from eddy field to mean current.

- Ocean color integrated chlorophyll extension: Chl$_{ext}$ (mg/m^3 km)

According to Demarcq (2009), the Chl$_{\text{ext}}$ was estimated as the spatial integration of the chlorophyll_a concentration from the coast to an offshore isoline of 1mg/m^3 .

$$\mathrm{Chl_{ext}} = \int_0^{1\mathrm{mg/m3}} (\mathrm{chl}_a)\,\mathrm{ds} \qquad (5)$$

The index captured both the cross-shelf structure and the major part of the chlorophyll-rich areas. This index was used to examine the average seasonality variability in phytoplankton biomass and to set the offshore trace of the exported richness from the coast.

3 Results

3.1 Seasonal variability

The hydrodynamical processes in this region are extremely complicated as a consequence of topography and changing meteorological conditions.

The inter-relationship between the forcing factors and $\mathrm{Chl_{ext}}$ responses shows that wind forcing (Turb), EKE, SSH and SST (Figure 4) do exhibit a similar pattern particularly further south. Bio-optical proprieties on the inner shelf of the Morccan Atlantic coast to a large degree mirrors the pattern of wind stress variability (Figure 4).

The Figure 4 shows that the location of the chlorophyll extention was always farther offshore in the southern part of the system when the wind impulse is strong and permanent, also when the EKE is remrakably strong, suggesting that the response of the phytoplonkton to the to upwelling processes extended beyond the main physical frontal zone associated to the continental shelf.

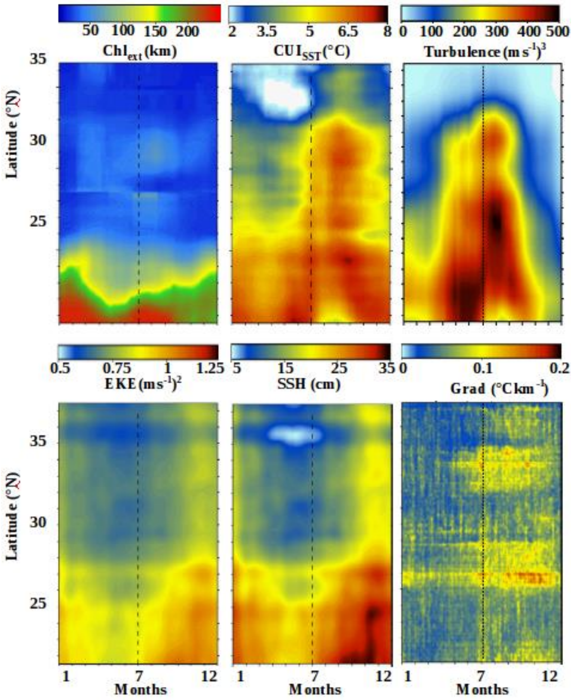


Fig.4. Hovmoller diagrams of the seasonal variability off the mesoscale indices along the Moroccan Atlantic coast

It's can be depicted that the maximum extent of the bio-opticals proprieties in the southern part of the system is approximately up to 300kms from the coast. This offshore extent is likely dominated by the upwelling activity as inferred by the CUI_{SST}, the Edie kenetic Energy and turbulence.

3.2 Modelling approach

Based on R software, a multivariate Generalized Additive Model (GAM) with Gaussian distribution was applied to investigate the potential influence of the hydrodynamical process on Chl_{ext}. GAM is a non-parametric generalization of multiple linear regressions, which is less restrictive in assumptions of the underlying statistical data distribution allowing for complex correlations between explained and explicatives variables (Hastie & Tibshirani, 1986).

The plots of paired variables in a form of matrix of scatter plots where constructed and the collinearity between predictives environnemental variables was constructed and tested (Figure 5). Variables with a high Pearson's correlation coefficient (r) (>0.9) were considered correlated, and one of the pair was removed. A model selection procedure based on analysis of variance was used to identify the greatest explanatory power. The significance of each variable in the model was determined by means of analysis of variance.

-Scatter plots

It may be expected that phytoplankton extension is highly correlated with environmental factors indicating a strong relationship.

The scatterplot (Figure 5) shows that the chlorophyll offshore extension is positively correlated to the Edie Kenetic Energy (EKE) with r^2=0.7, to the SSH with r^2=0.71, to the Turbulence with r^2=0.74 and slightly correlated to the upwelling activity (CUI_{SST}) with r^2=0.30.

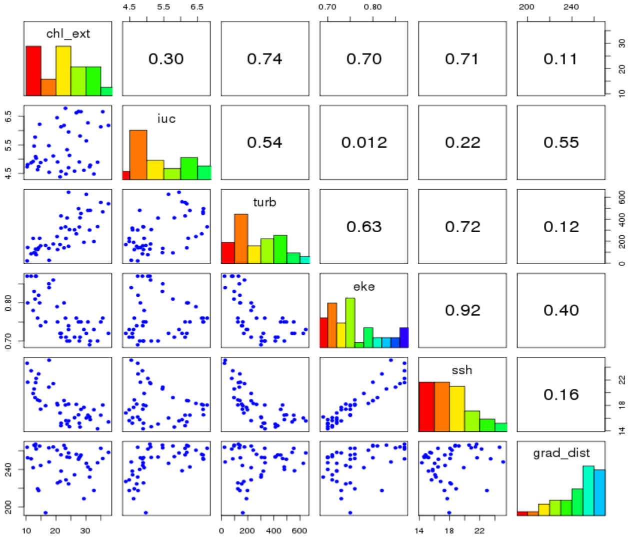


Fig.5. Pairs plot for all the explanatory variables in the data set used for this study of (Chl_{ext}) in Moroccan Atlantic coast. The upper diagonal panel shows the Pearson's correlation coefficient, and the lower diagonal panel shows the scatterplots to visualize the pattern.

This indicates the importance of the mesoscale structures in transporting water masses and their constituent physical and biological contents across the shelf break. Increases in oceanic chlorophyll concentrations through the dissipation of a filament, could represent the most important exchange mechanism between the coast and the deep ocean. The change in off-shelf chlorophyll was mirrored by a change in mean SST and wind stress exserced at the sea surface (Figure 5).

- *General Additive Model*

To identify the functional relationships between the explanatory oceanographic environmental variables and the predicted bio-optical (Chl_{ext}) proprieties, Generalized Additive Model (GAM) was applied (Table 1).

The GAM was used to determine the nature of the relationship between the offshore chlorophyll extension and the environmental variables. Data exploration highlighted collinearity between CUI_{SST}, GRAD, and Turb (Figure 5), supported by $r^2 > 0.5$. Therefore, CUI_{SST} and GRAD were removed from the model. Only two variables (Tur and EKE) were included in the GAM and including an interaction term, showed that the Chl_{ext} is significantly and positively correlated to the turbulence and the EKE in the Moroccan Atlantic coast ($p < 0.001$).

The final GAM construction for Chl_{ext} followed the following equation and explained 71.2% of the total deviance:

$$CHL_{ext} = \beta + s(EKE) + s(Turb) + \epsilon \qquad (6)$$

where β equals the intercept and ϵ the residual error.

Table 1. Results of generalized additive models (GAM) based on Chl_{ext} data on explanatory variables (EKE and Turb), deviance explained (Dev. Expl.=71.2 %), coefficient of determination (r^2=0.661), generalized cross-validation score (GCV) score:23.911 ; The value of the scale estimate (Scale est.)=19.827 ; Significances codes: <000.1 '***' 0.001'**' 0.01 '*' 0.05

Parametric coefficients				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	21.591	0.754	28.63	<2e-16***
Approximate significance of smooth terms				
	Estimate of degrees of freedom (edf)	**Reference degrees of freedom (Ref.df)**	**Chi squared (Chi.sq)**	**p-value**
s(EKE)	1	1	6.757	0.01330*
s(Turb)	5.515	6.631	3.915	0.00306**

The biomass indicator in term of Chl_{ext} seems to be modulated by the physical mesoscale indicators (P-value <0.001) explaining one parte of the observed pattern along the shelf break, where production is enhanced by upwelling and water turbulence, both of which increase the transport and nutrient input of organic matter into the water column (Pinazo et al., 1996).

4 Discussion and Conclusions

We have examined the dynamics of coastal upwelling off Moroccan Atlantic area through the seasonality off potential mesoscale indicators.

A detailed analysis on available remote sensing data basically based on Hovmollers diagrams and statistical modelling approach has paved the way to establish the linkages between predicted bio-optical proprieties (Chl_{ext}) and explanatory mesoscales indicators derived wind stress, SSH and SST.

The distribution of eddies shows positives fluxes concentrated at the inshore side of the strong boundary currents. The outward (coast-ocean interior) gradient in eddy flux indicates that a net transport occurs from the coastal band to the ocean interior. This transport is not orthognal to the coastline but it's oiriented southward. Oceanic fronts work as a physical barrier seperating the coastal cold and rich upwelling band to the oligotrophic offshore warm water. Therefore, we could possibly expect that the connection between the coastal area and the open ocean would closely dominated by the eddies and the frontal structures which are spatially structured into corridor connecting the Moroccan coastal area to the ocean inerior by transfering the bio-optical proprietises throghout a soutward coastal jet as shown in the figure 2b resuming the climatological frontal occurrence percentage.

Mesoscale structures has been shown to be a major process in the cross shelf transport off the Moroccan Atlantic coast patterening the pelagic ecosystem, affecting the organismal abundance, ditribution and productivity. In the southern part of the system (South of 23°N), Kostianoy and Zatsepin (1996) estimated that half of the upwelled waters flow across the upwelling front in filaments. To investigate the possible role of mesoscale dynamics, the alongshore variations of eddy kinetic energy was examinated, assuming that strong mesoscale and submesoscale activity result in a high eddy kinetic energy (EKE) in our region. It is high downwind of the Canary archipelagos. Progressing south associated of the end of the cooridor creating strong turbulence, EKE clearly increases alongshore. The Chl_{ext} width may thus increase southward due to an increase of the horizontal mixing induced by mesoscale processes and to the quasi permanent upwelling process. Note that the nature of the mesoscale processes involved can be various, as for instance mesoscale eddies, baroclinic instabilities of the upwelling jet, coastal and planetary waves and that mesoscale dynamics and wind stress are interlinked and cannot be considered as two separate processes.

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