Characterization of coastal upwelling events during the generation of the water column stratification in spring (Vilanova i la Geltrú, NW Mediterranean)

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***Abstract*— This article presents some preliminary results on the characterization of inputs of offshore waters (upwelling events) in the coast off Vilanova i la Geltrú (NW Mediterranean) in the spring of the years 2010, 2012 and 2014. The upwelling events are studied in terms of meteorological and oceanographic conditions.**

Keywords—coast; current; upwelling.

I. INTRODUCTION

Regional coastal upwelling is mainly driven by winds blowing parallel to the coast that move surface waters offshore so that deep, cold and usually rich in nutrients waters come to the surface. In addition to along coast winds, cold, dry winds in winter often lead to deep convection of water masses and strong upwelling of nutrients into the euphotic layer that support the development of a strong spring bloom of phytoplankton at the end of winter [1]. Therefore, upwelling of subsurface waters is an important physical process that has a significant impact on primary production. In the Western Mediterranean, the maximum annual productivity in coastal waters is caused by spring upwelling and the influence of upwelling processes over the productivity of some fish species was stated [2, 3]. Our work aims to characterize the inputs of offshore waters (upwelling events) in the coast off Vilanova i la Geltrú (NW Mediterranean) in terms of meteorological and oceanographic conditions from the end of winter (March) to the generation of a well-stablished stratification in the water column in June. The focus is to describe small-scale processes of upwelling in a shallow environment, identifying events and quantifying the volume of offshore waters supplied into the coast. For tackling this subject, time series of winds, currents, and seawater temperature are analyzed in the spring (March to June) of the years 2010, 2012 and 2014.

II. MONITORING SYSTEM

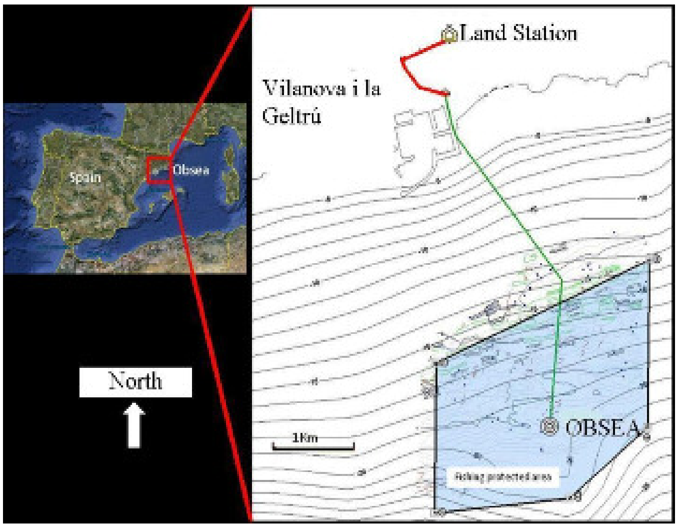

Fig. 1 Map of the western Mediterranean and detailed map of the coastal area in front of Vilanova i la Geltrú showing the location of the OBSEA observatory and the Land Station. Coast is oriented at 75º.

Oceanographic measurements were carried out using some sensors of the expandable Seafloor Observatory (OBSEA) from SARTI (Technological Development Center of Remote Acquisition and Data Processing Systems) operated by the UPC (Universitat Politècnica de Catalunya) [4]. This subsea station was installed at a depth of 20 m and 4 km offshore of Vilanova i la Geltrú (see Fig. 1). Near-bottom seawater temperature is recorded from CTD every 10 seconds. Currents are measured with an ADCP (Nortek ADCP AWAC 1MHz) deployed on a bottom tripod in an upward-looking configuration, collecting information in water cells spaced 1 m, every 10 minutes averaging 1 minute. A total of 7174 velocity profiles (hourly average from ten minutes samples) were considered in the analysis of the springs of three years.

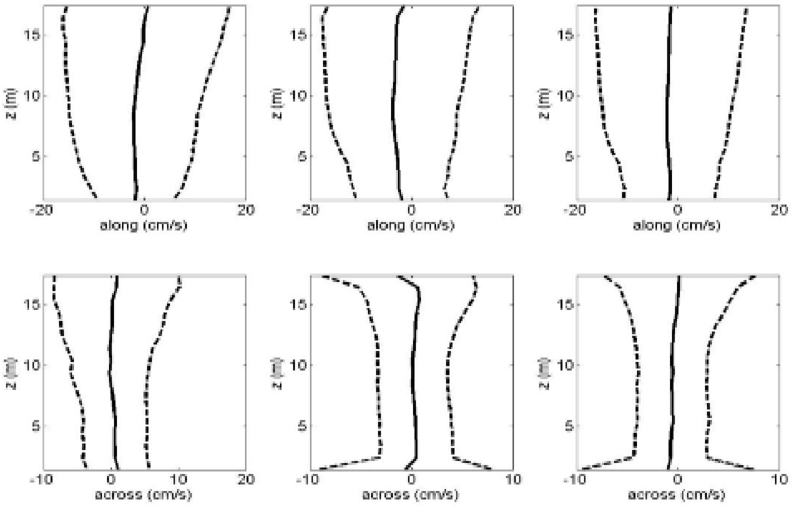

Fig 2. Profiles of velocity (positive values are towards NE and offshore). In bold line mean flow, in dash line mean flow ± deviation. Along velocity on the first row and across velocity on the second row; in columns from left to right the springs of 2010, 2012 and 2014.

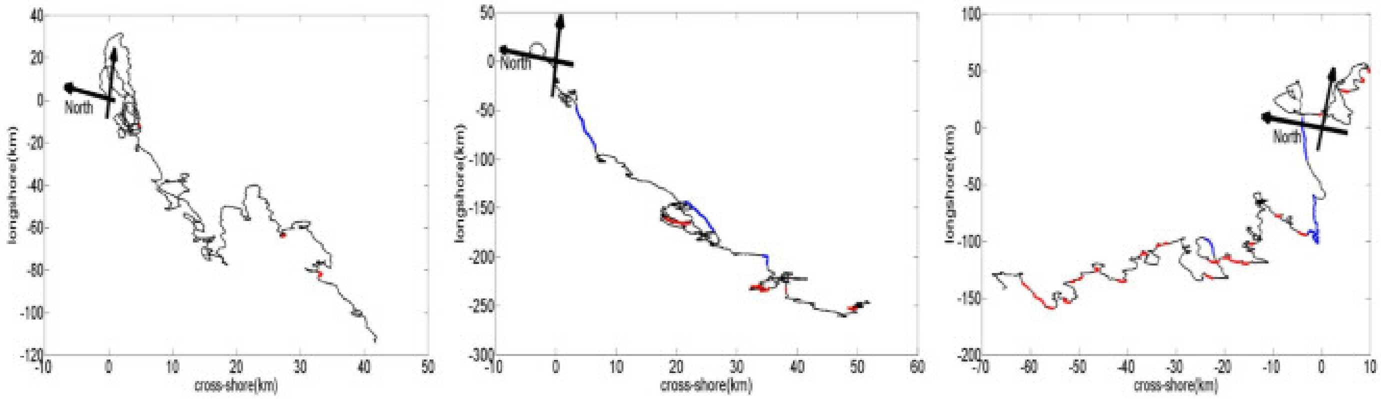

Fig 3. Progressive vector diagram obtained at 3.4 m above bottom in spring of 2010, 2012 and 2014 from left to right. Starting points are (0, 0) corresponding to their real relative locations. Highlighted in red, events of upwelling and, in blue events of high wind speed.

Wind intensity and direction are acquired with a meteorological station on the OBSEA observatory at one minute sample since 2012 and at 2010 wind measurements are obtained from a meteorological land station.

III. CURRENTS

From ADCP measurements two variables are derived: an across and along current, i.e., ocean currents perpendicular and parallel to the coast. Time averaged profiles of across and along velocity in the water column are showed in Fig. 2. Along mean flow is slightly to the southwest in the whole water column during the three springs. Regarding the across velocity, the mean flow is offshore in Spring 2010 meanwhile Spring 2012 has the same behavior except on the top and bottom where it goes slightly onshore. A different pattern can be seen in Spring 2014 where across mean flow goes onshore except on the top of the water column. The progressive vectors illustrate the flow conditions patterns at 3.4 m above bottom (Fig. 3). In the springs of 2010 and 2012, a southwest circulation was noticeable with the across component offshore with a virtual displacement about 40-50 km. In Spring 2014, the alongshore component was similar to previous years, but the across component was onshore with a virtual displacement near of 70 km. Across and along current were subjected to spectral analysis. A pronounced peak at the diurnal frequency was found in the across velocity in all the periods while the along velocity does not show significant peaks. This diurnal frequency is interpreted as related with breezes activity, which preferentially affects the surficial water layer [5].

IV. UPWELLING EVENTS CHARACTERIZATION

We defined an upwelling event when the across velocity is onshore, higher than 5 cm/s in a water layer ≥ 3 m thick and during a period ≥ 6 hours. Consecutive events with a difference of three hours were merged into a single one. Based on this criteria, there were detected 3, 6 and 25 upwelling events in the springs of 2010, 2012 and 2014 respectively. Expressed in terms of total hours of upwelling, the events summed up 22, 70 and 235 hours for the studied periods of years 2010, 2012 and 2014.

Besides the above definition, a cluster analysis was performed to classify the 7174 velocity profiles for the across component we were interested for. We use the average linkage for the clustering, while the distance

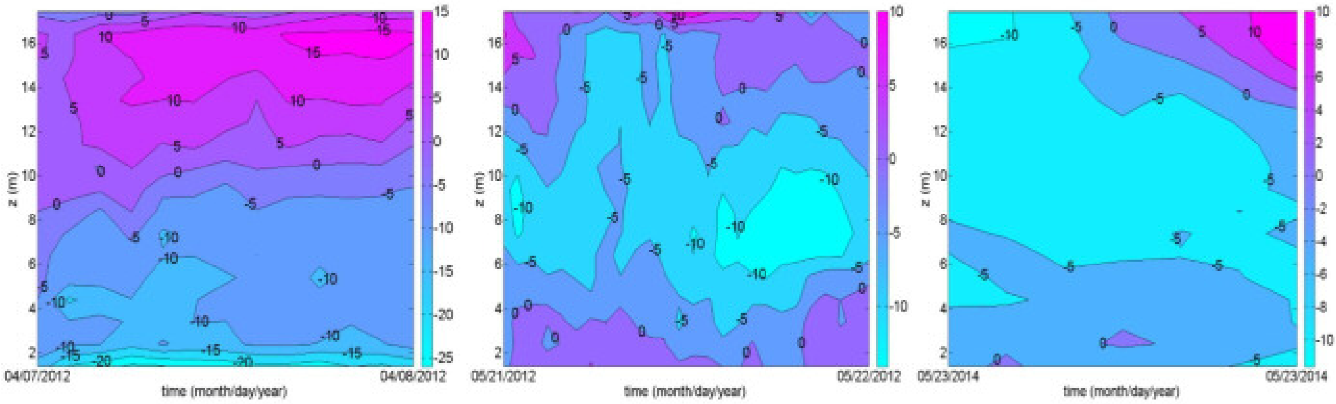

Fig 4. Contour of the across velocity (cm s^{-1}) on an upwelling events. First figure from the left belonging to S-profile class and the second and third figures belonging to C-profiles class.

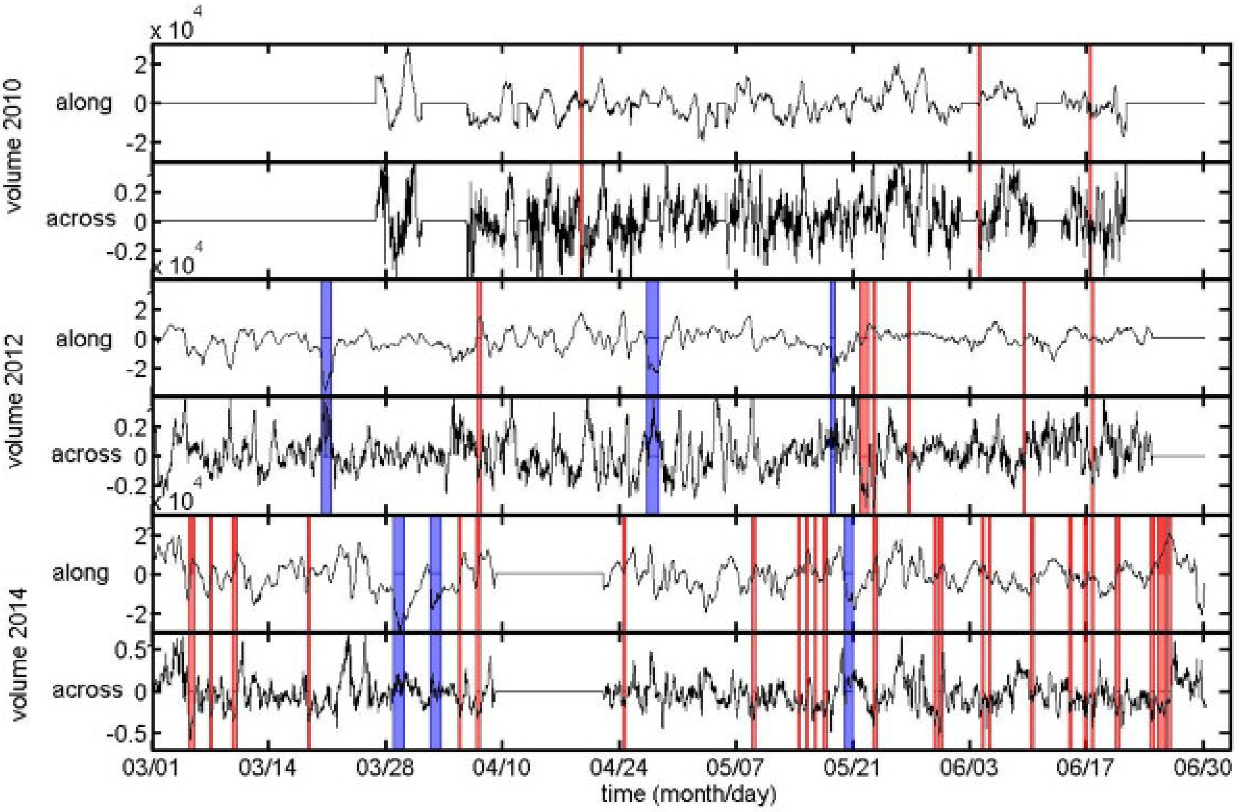

Fig 5. Volume of water (m^3/m) that flows in the along and across direction in spring of 2010, 2012 and 2014 from top to bottom. Highlighted in red, events of upwelling and, in blue events of high wind speed.

between two velocity profiles *i* and *j* (u_{ik} and u_{jk}. where $k = 1,..., K$, runs for all the depths where the velocities are measured), is defined as the distance of the two *K*-dimensional vectors, i.e. $\sqrt{\sum_k (u_{ik} - u_{jk})^2}$. Amongst the resulting clusters, the ones identified as upwelling events detected up to 94% of the aforementioned upwelling events.

The across velocity behavior of upwelling events can be simplified into two classes (see Fig. 4). In the first class (S-profile herein), the across velocity is onshore near the bottom and offshore on the top, matching the classic upwelling process, during which deeper water goes to the coast by means of nearbottom currents. The second upwelling class (C-profile) includes events with across velocity onshore in the middle of the water column and offshore on the top and bottom and those in which the across velocity is onshore in the entire water column. There are 11 events belonging to the class S-profile, with a mean duration of 9 hours, in which the temperature decrease in averaged 0.25ºC and they occur in April (3), May (4) and June (4). In the C-profile class there are more events (23), with a similar mean duration (10 hours) and they occur in March (4), April (3), May (6) and mainly in June (10). The

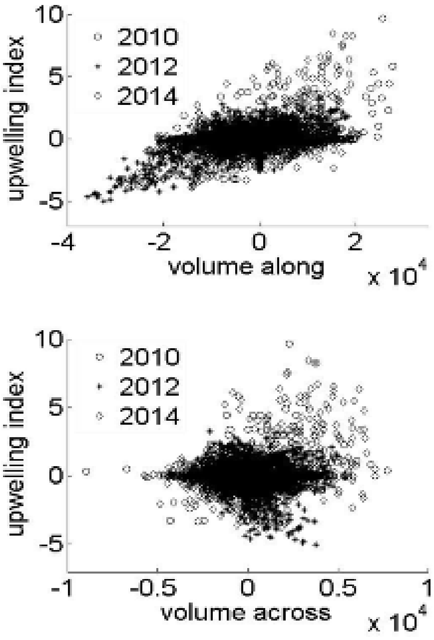

Fig 6. Upwelling index ($m^3 s^{-1} km^{-1}$) versus the volume of water (m^3/m) on the along (top) and across (bottom) direction in the springs of the years 2010, 2012 and 2014.

temperature in the C-profile class decreases, in averaged 0.14ºC, but maximum decrease of 1.2ºC is reached in an upwelling event of this class at June 25, 2014. Therefore, both classes of upwelling events occurred with different hydrographic conditions (well-mixed water column in March or well-developed stratification in June). However, the most frequent upwelling events are of the class C-profile and they preferentially occur in May and June, when the thermocline is well-developed.

It was calculated the total volume of water (m^3/m) that flows in the across and along direction each hour (see Fig. 5). The range of volume is ten times higher in the along direction than in the across. During the upwelling events (highlighted in red in Fig. 5), the dominant flux in the across direction is always onshore while in the along direction there is no dominant direction. The onshore water fluxes during upwelling events represent approximately $81 \cdot 10^3$, $176 \cdot 10^3$ and $624 \cdot 10^3$ m^3/m in the springs of 2010, 2012 and 2014 respectively. As expected, the largest number of upwelling events and the greatest volume of water onshore occurred in Spring 2014. Water inputs related with the near-bottom upwelling process represent 0.11%, 0.62% and 1% from the total in 2010, 2012 and 2014 respectively. In all the years, the upwelling events with the C-profile class provide more water inputs than those with S-profile.

Intriguingly, periods with high wind speed (highlighted in red in Fig. 5), correspond with strong along currents towards the south (in 2012) and to the southwest (in 2014), but they seem to be unrelated with upwelling events. In order to evaluate the potential relation between observed upwelling events and wind conditions the Upwelling Index (UI, $m^3 s^{-1} km^{-1}$) was calculated following [6]:

$$UI = - \frac{\rho_{air} C_D \ |V| \ V_{along}}{\rho_{sw} f} \qquad (1)$$

where ρ_{air} is the density of the air, 1.22 kg m^{-3} at 15ºC, C_D is an empirical drag coefficient ($1.3 \cdot 10^{-3}$ dimensionless) ; f is the Coriolis parameter at 41º latitude; ρ_{sw} is the density of sea water, 1025 kg m^{-3}; and $|V|$ and V_{along} are the wind speed and the component of the wind parallel to the coast. No relationship has been found between Upwelling Index and upwelling events (Fig. 6). For high negative/positive UI a net volume flux of water parallel to the coast in the southwest/northeast direction is observed. However, the net volume flux perpendicular to the coast doesn't show a relationship with the UI (Fig. 6). The lack of relations is probably due to the fact that wind-related upwelling index were developed for large temporal and spatial scales, whereas observations in very shallow areas show that small-scale circulation patterns are complex, with presence of gyres, intrusions of filaments from offshore and, in general, a 3D circulation pattern which is not fully captured by punctual observations or a general index.

V. CONCLUDING REMARKS

Inputs of offshore waters to the coast of Vilanova during upwelling events occur as near-bottom onshore currents below a surface layer flowing offshore (S-profile) or as an onshore flow in the middle or the entire water column (C-profile), probably related with a more complex 3D coastal circulation pattern. In terms of the intensity of upwelling events, it is demonstrated a strong interannual variability, probably related to general oceanographic and meteorological conditions. The volume of water supplied to the coastal zone during upwelling events for each season varies between $80 \cdot 10^3$ m^3/m to $600 \cdot 10^3$ m^3/m of which only about 1.4% of the total water is supplied as near-bottom onshore currents. These large amounts of colder waters supplied to the coastal zone should play a relevant role in the coastal ecosystem.

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REFERENCES

[1] P. Auger, C. Ulses, C. Estournel, L. Stemmann, S. Somot, and F. Diaz, "Interannual control of plankton communities by deep winter mixing and prey/predator interactions in the NW Mediterranean: Results from a 30-year 3D modeling study". Prog.Oceanogr., 124, 12–27. 2014.

[2] M. Coll, L. Shannon, C. Moloney, I. Palomera, S. Tudela, "Comparing trophic flows and fishing impacts of a NW Mediterranean ecosystem with coastal upwelling systems by means of standardized models and indicators". Ecological modelling, 198, 53–70. 2006.

[3] J. Lloret, I. Palomera, J. Salat, I. Sole, "Impact of freshwater input and wind on landings of anchovy (Engraulis encrasicolus) and sardine (Sardina pilchardus) in shelf waters surrounding the Ebre (Ebro) River delta (north-western Mediterranean)". Fish. Oceanogr. 13:2, 102–110. 2004.

[4] A. Mànuel, M. Nogueras, J. Del Rio, "OBSEA an Expandable Seafloor Observatory". Sea Technology, 51 (7). 37-39. 2010.

[5] J. Antonijuan, G. Simarro, J. Guillén, M. Nogueras, A. Mànuel, A. Palanques, P. Puig, "Breeze influence on waves and vertical current profile in the coastal area based on EOF analysis (Vilanova i la Geltrú, Barcelona)", 5th MARTECH International Workshop On Marine Technology. 140-143. 2013.

[6] F.B. Schwing, M. O'Farrell, J.M. Steger, K. Baltz, "Coastal upwelling indices, West Coast of North America, 1946–1995". NOAA Tech. Memo. NOAA-TM- NMFS-SWFSC-231, 144. 1996.