ROFI structure in the gulf of Lions and the NW Mediterranean Sea: *Field and remote sensing observations of surface coherent structures*

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Abstract. The advances in radar sensors may be applied to study the flow in the region of fresh water influence (ROFI) region of the ocean. The Synthetic Aperture Radar (SAR) is a useful tool that may be used to study both marine water dynamics and its pollution. Oil spills and natural slicks may be detected and processed with advanced computer techniques to reveal vortex dynamics and turbulence spectral characteristics of the complex eddy and current interaction in the ocean surface. In the framework of the European Union contract Clean Seas, more than 300 SAR images of the North-west Mediterranean Sea area taken between December 1996 and December 1998 were analyzed. 255 eddies can be detected under certain conditions and we analyzed statistically the appearance, size and position of vortices in the test area. It is shown that the maximum size of the eddies detected near the coast is limited by the Rossby deformation radius

To be discussed

and that there is a decrease in size in the coastal waters in the direction of the Liguro-Provenzal current with the largest eddies occurring near the cape of Rosas. The role of submarine canyons in the vortex generation is indicated by the asymmetry of their distribution with respect to the thalwegs. It is demonstrated that useful information of a geometrical nature obtained by SAR satellite images may be used to estimate relevant dynamical parameters of coastal flows

1. Introduction

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This work is motivated by a wish to obtain a better understanding and compare several types of direct and remote sensing observations of the effects of surface wind turbulence on diffusivity and local circulation measured in the ocean-atmosphere interface. Only a few investigators considered the direct comparisons of in situ measurements together with remote sensing satellite measurements. Here we also address the problem of the effects of background turbulence [1-3].

Indeed, a series of laboratory experiments is presented to investigate the influence of background turbulence on the development of a momentum jet. The video-based Digimage processing technique is used to monitor the diffusion of tracers (milk) and buoys in the coastal regions of the Gulf of Lions and near Barcelona [1],

The Synthetic Aperture Radar SAR is an active radar which emits its energy in the centimetre frequencies range during a very short time period and it is able to receive the echoes. Due to the large orbital velocity of the satellite (7,5 km/s) approximately, its SAR antenna itself may be converted as a virtual antenna of a much larger size. The SAR instrument may be installed on a plane, on a helicopter or on board a satellite. The SAR emits short EM waves in the range of centimetres. The radar backscattering depends on the roughness of the small scale surface. When the surface is rougher (mostly due to capillary waves in the ocean surface) the intensity of the receiving signal is stronger due to Bragg resonant dispersion [ ](Gade and Alpers, 1999). In consequence a white zone is observed in the image when the surface is very rough.

The dark areas are visible when there is a concentration of tensioactive products such as oil. Other phenomenon which has a strong significance in the use of the SAR images to monitor the sea surface is the Langmuir circulation. It is related to the surface particle concentration on the convergence zone between two vertical cells at sea. Algae, zoo-plankton, products of the marine life or waste from industries, spillage from tankers, hazardous waters, dregs at suspension, etc. accumulate on the convergence surface strips between two cells as seen in Figures 1 and 2. It is precisely there that they form the high concentration tensioactive wakes or strips which we can observe clearly in the SAR images. Due to this phenomenon, the SAR images may detect many different oceanic dynamic meso-scale processes, such as internal waves, marine surface currents, hydrographic fronts, vortices and bathymetric characteristics of the sea bottom at coastal areas [ ](Gade and Redondo, 1999) etc....

The meteorological phenomena as cyclones, atmospheric fronts, surface wind, atmospheric internal waves and rains are also detected by the SAR images due to their effect on the sea surface roughness, but because the scale of atmospheric processes is quite different to the ocean dynamics, i.e. Rossby deformation radius 10 times larger, different spectral powers, synoptic front behaviour that can be predicted or checked with cloud presence, etc... Then it is possible to single out most of the typical ocean figures.

Wider figure/wider caption

Figure 1. Dynamic features on sea surface near the Rhone delta. ERS-2 SAR 100Km x 100Km image.

Figure 4 shows the position, the shape and the spatial direction of the 255 elliptical vortices clearly detected in the different SAR images during two years of observations. In order to better visualize the bathymetrical structure of the marine bottom, the "thalwegs" of the submarine canyons have been marked with lines.

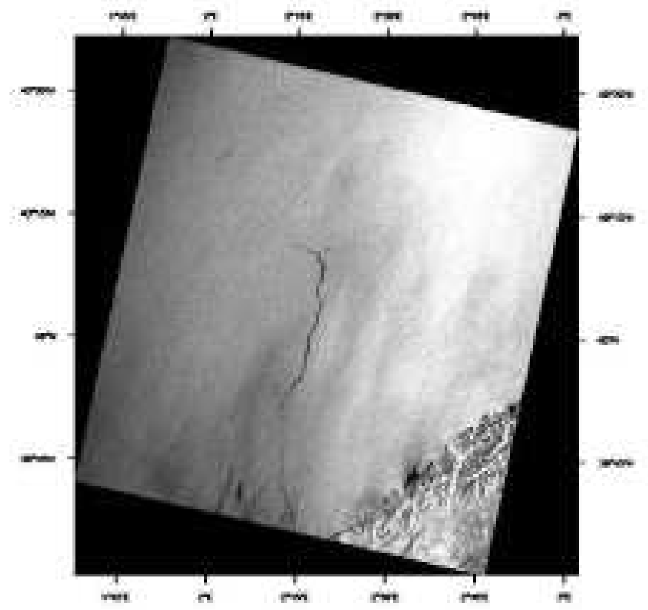

Figure 2. Dynamic features on sea surface near the Balearic Islands. ERS-2 SAR 100Km x 100Km image. An oil spill is clearly seen north of Majorca island.

Most of the vortices are located in a relatively nearby maritime band near to the continental shelf. It is worthwhile to note the correlation between the spatial positions of the vortices and the submarine canyons: most of the vortices are located towards the left side of the submarine canyons.

Not clear?

The spatial direction of the ellipses adjusted to the vortices was determined through the angle between the North direction and the direction of their mayor axis.

Useful?

The other region of concentration of the vortices is situated in the centre of the marine test area. Recent filed campaigns associated to realistic and process oriented modelling [Reffray, Schaeffer, Hu, Flexas, Davies] have pointed out effect of atmospheric forcing and shelf edge current. There seem to be the two main sources of the big eddies in the Gulf of Lion.

A preliminary analysis of the direction of rotation of the vortices shows that 76 have an anticyclonic character and 179 correspond to cyclonic (anticlockwise). Anticycloinc eddies are generally associated to inertial motion induced by wind impulses and turns.

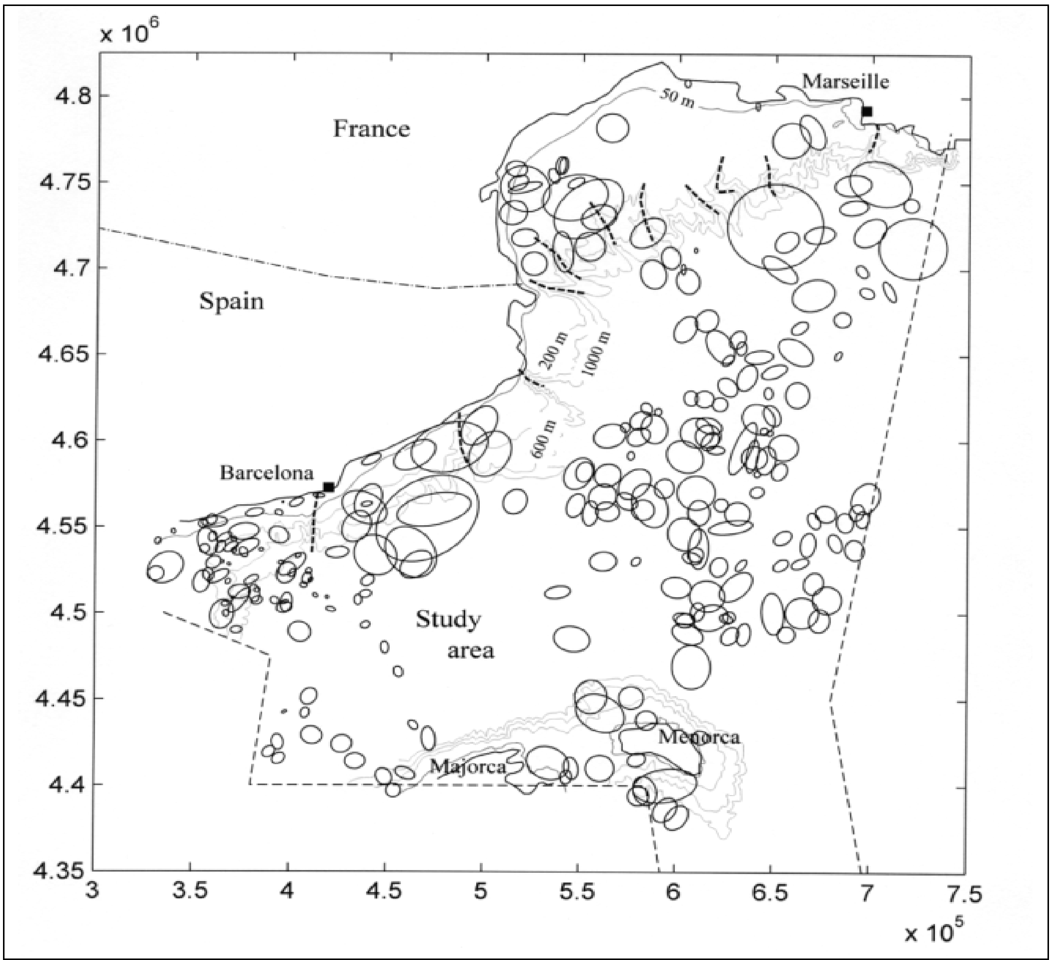

Figure 3. Submarine canyons and the detected vortices in the period between 1996 and 1998 in the NW Mediterranean

2. Feature detection by SAR

3. Statistical analysis of the vortices

The extension of most of the SAR detected vortices (63 %) is less than 100 Km^2. 33% of vortices occupy an area between 100 to 500 Km^2 and only 4% of the vortices possess a large area between 500 and 1200 Km^2 (Figure 3). About a 93% of vortices have a diameter less than 20 Km.
The greatest part of the vortices (79%) have an ellipticity (relation between big and little diameter) near 1.125 – 1.625 that shows that this form is more stability (Figure 4).
En our last studies of the vortices near the Barcelona marine area (Redondo and Platonov, 2001) we show that due to the bi-normal distribution of the vortices and we consider that there exist two main types of mechanisms related to their orientation:
- Dynamical, due to the influence of the Liguro-Provenzal current (about 50% of the detected vortexes have direction angles between 25^0 and 75^0, figure 2).

- Bathymetrical, due to the influence of the submarine canyons situated mostly perpendicularly to the coast line (25% of the cases the detected vortices have azimuth angles between 125^0 and 145^0).
In the present analysis of the 255 detected vortices, the figure 5 shows that the general orientation of the vortices is direction between NW and NE.

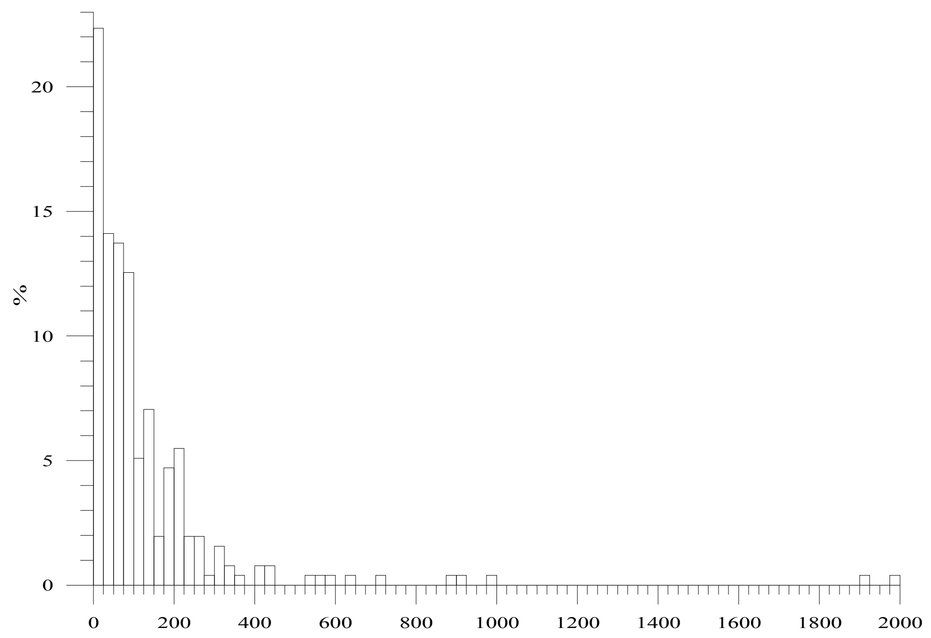

Figure 4. Histogram of the detected vortices in function of their areas

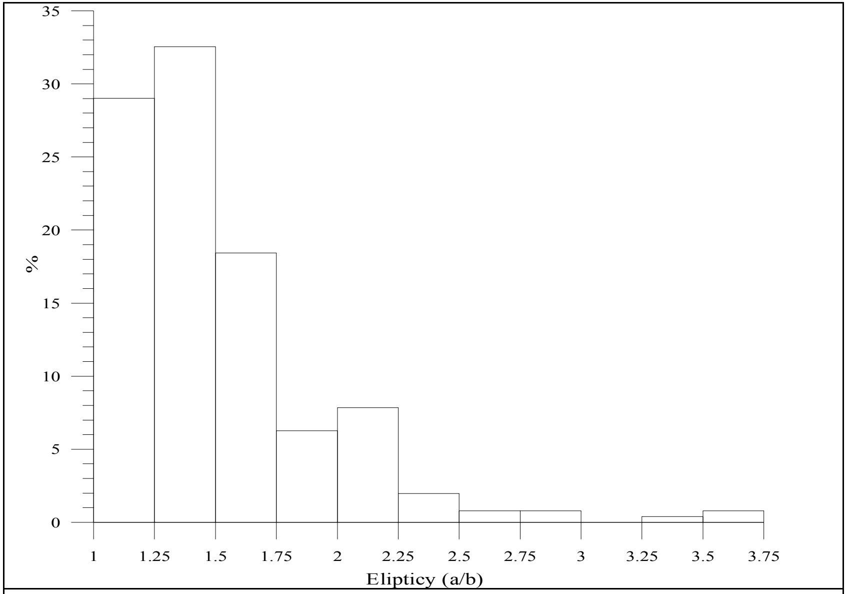

Figure 5. Histogram of the elipcity of the detected vortices (a/b).

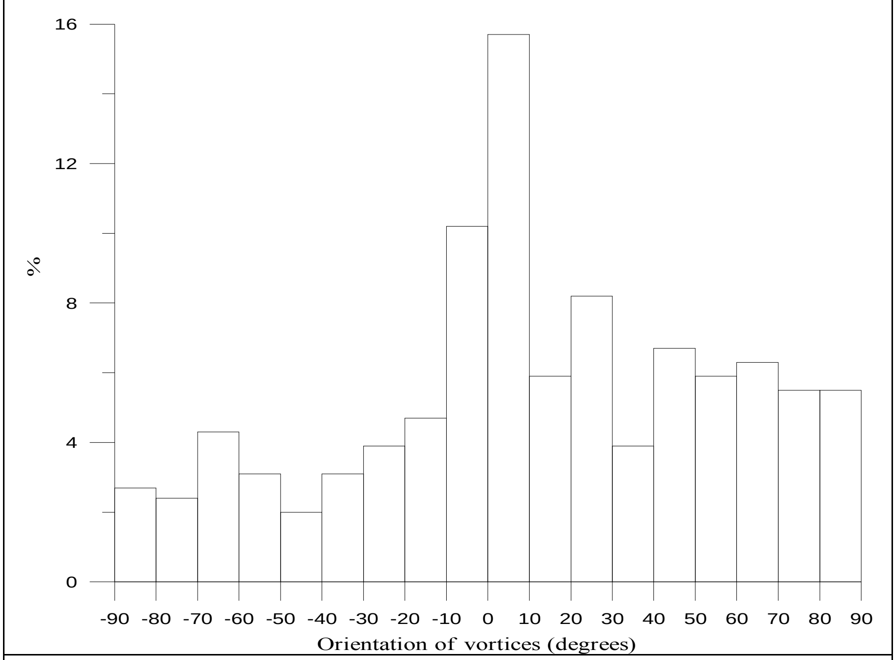

Figure 6. Histogram of the vortices function of the angles (between the North and the direction of their greater axis; clockwise direction is positive). with short caption (caption centred).

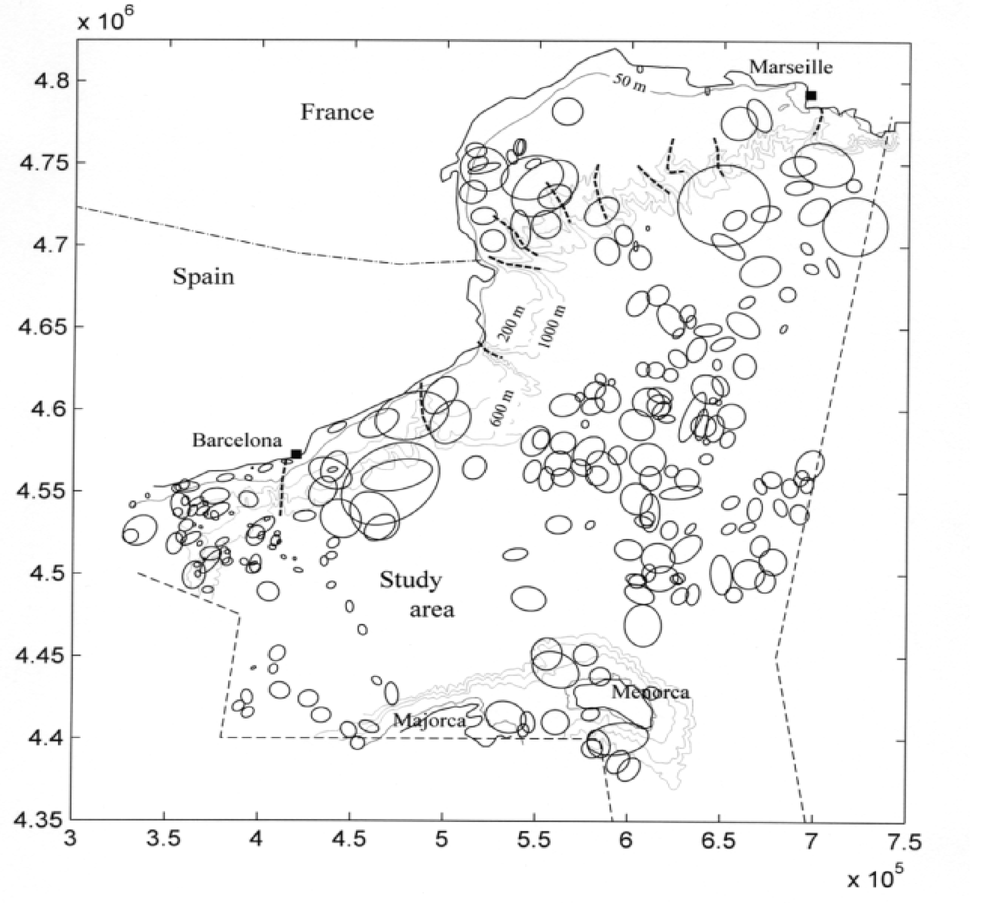

Figure 7. Submarine canyons and the detected vortices in the period between 1996 and 1998 in the NW Mediterranean

Figure 7 is same as figure 3 ?

4. Velocity measurements from coastal Radar

HF radar technology was recently used in the eastern part of the Gulf of Lions (Schaeffer) that allowed pointing out the occurrence of an anticyclonic eddy confined on the narrow shelf. Such a vortex was observed several times during winter 2005 with a duration of several days. Process oriented modelling exercises allowed to relate the eddy formation to the wind dynamical forcing and local complex bathymetry.

5. Integrated ROFI measurements and observations

Moreover, previous investigation (Reffray) using a factor analysis related eddy formation in the neighbouring of the Rhône river plume. Wind forcing, Liguro Provenzal shelf current and river plume fronts influences were investigated separately and non linear effects were found to be the same order of magnitude in the location of eddy formation.

6. Discussion

The satellite-borne SAR seems to be a good system to detect man-made oil spills and oil slicks, the dynamic feature detection gives information over the surface motions at different scales. It is also a convenient tool to investigate the eddy structures of a certain area, such as the cases where the effect of bathymetry and local currents are important in describing the ocean surface behaviour.
In the example presented near Barcelona, the maximum eddy size agrees remarkably well with the limit imposed by the local Rossby deformation radius using the usual thermocline induced stratification, Redondo and Platonov (2001). The Rossby deformation radius, defined as *Rd = (N/f)h,* where ***N*** is the Brunt-Vaisalla frequency

$$N^2 = \frac{g}{\rho}\frac{\partial \rho}{\partial Z}$$

f is the local Coriolis parameter (*f=2□sin□*, where □ is the rotation of the earth and □ is the latitude) and *h* is the thermocline depth, with the measured data, the average Rossby deformation radius of the area, *Rd* is about 20 Km.

The strong vertical stratification of the surface water aids the development of the largest vortices. As the frequency *N* strongly depends on the seasonal thermal balance, the wave mixing activity and other local bathymetry induced processes that affect the water column, the range and spatial distribution of detected vortices is very useful in the predictive behaviour of a marine zone.
Seasonal data such as the difference between the surface and maximum density in picnocline, and also its thickness (or depth) are the general factors that determine the kinetic energy of the vortices, as well as their size.
The use of thematic maps that may be updated from combined satellite sensors and images and validated with space in situ observations may be even used to predict local diffusion as in [Kolmogorov, 1941].

In such a manner, more sophisticated data analysis such as the evaluation of integral length scales or local fractal dimensions of the sea surface appearance, together with the detailed information of the position and sizes of the mesoscale dominant eddies of size about R_D provides useful information on the mesoscale ocean turbulence.
A large collection of more than 900 SAR images obtained from three European coastal areas (Baltic Sea, North Sea and NW Mediterranean) by the ERS-1 and ERS-2 were analyzed and compared with other Satellite images. The research was done in the framework of the CLEAN SEAS European Union project and more information is available at [Platonov, 2002] and [Jolly et al., 2000].
The use of routine satellite information by SAR or other sensor types may be of great interest to build a seasonal database of the dynamic conditions of the mesoscale turbulence in the ocean, after several

years of observations the dominant patterns and the causes for different topological characterisations (Mandelbrot, 1985) might be understood. It is important to characterize the types and structure of the main vortices detected as well as the spectral cascade processes that take place, these may be investigated by using fractal methods on images of the area.

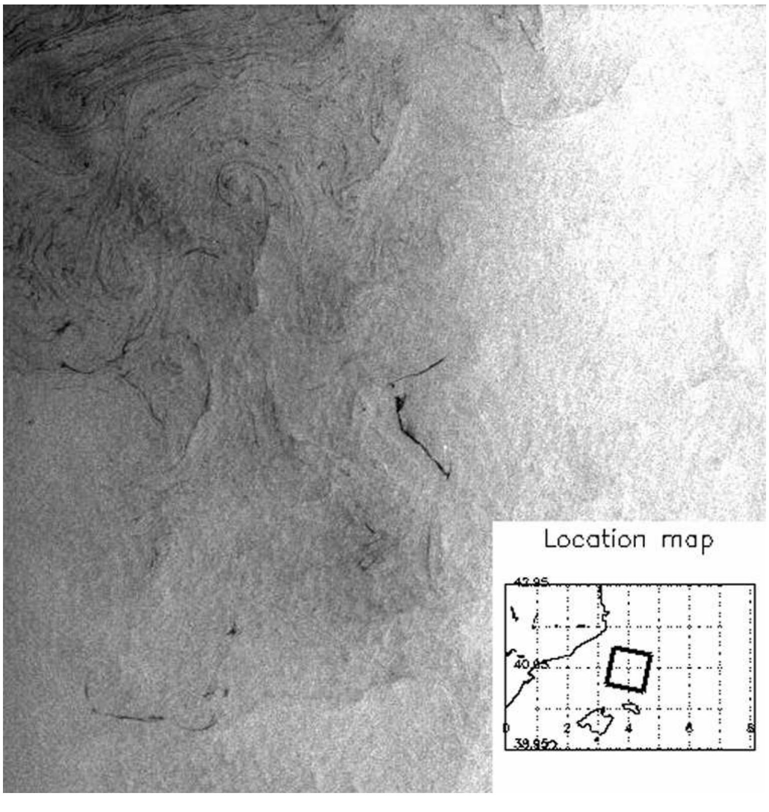

Figure 8. Figure with short caption (caption centred).

7. Discussion

Turbulent diffusion in the Ocean

As mentioned above the evaluation of a certain turbulence time scale will give information on the persistence of a SAR detected feature in the ocean surface, which is also very important.
It is also possible to analyse in a statistical integrated way all available frames in a region to characterize its mesoscale turbulence, for the NW Mediterranean with SAR images from frames 8, 9, 10, 19 and 20 (see [24]).

We show in Figure 5 the probability of detection of the vortical slicks as a feature akin to a vortex. The submarine canyon presence were shown to affect strongly the situation of the detected vortices and their distribution of angles, shapes and size over the whole measurement period. There are several apparent relationships between the number of detected eddies and their size the area of the observed vertical slicks and the distance from Cape Begur as shown by Redondo Platonov [24, 25].

Relevant geometrical information of different areas is also given by the maximum fractal dimension, which is related to the energy spectrum of the flow. Using all the available information it is possible to investigate the spatial variability of the horizontal eddy diffusivity *K(x,y)*. This information would be very important when trying to model numerically the behaviour in time of the oil spills.

A simple method for evaluating the relevant meso-scale eddy diffusivity is straight forward using dimensional analysis (as a velocity times a length scale) from the measured distribution of integral length scales and the eddy turnover times associated to inertial oscillations associated to the local Coriolis parameter $f = 2\Omega \sin\Theta$ where Ω is the rotation of the earth and Θ is the latitude.

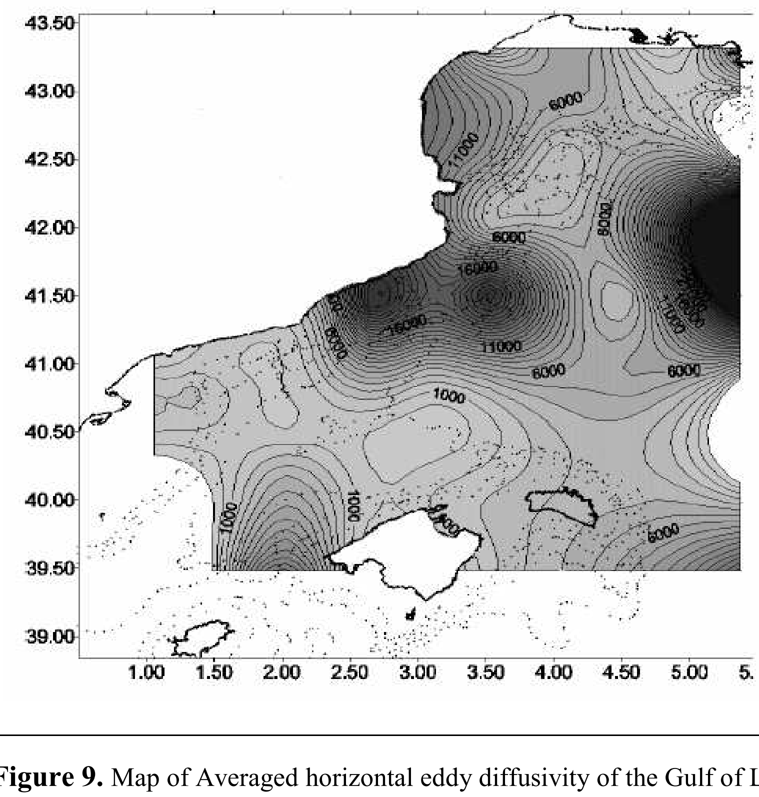

Figure 9. Map of Averaged horizontal eddy diffusivity of the Gulf of Lion area obtained by SAR analysis during 1997 and 1998.X is Longitude and Y Latitude. The Eddy diffusivity average values are in (m2s-1) calculated according to Richardson's 4/3 law for a 10 km spill.

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial s^2}$$

$$F(\ell) = \varepsilon \ell^{4/3}$$

$$K_m = -\ell_m (x, y, z)^2 \left| \frac{d\bar{u}}{dz} \right|$$

$$K_w = \ell_w L * \frac{\partial w}{\partial y}$$

$$\frac{\partial c}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\Pr^2 \frac{\partial c}{\partial r} \right)$$

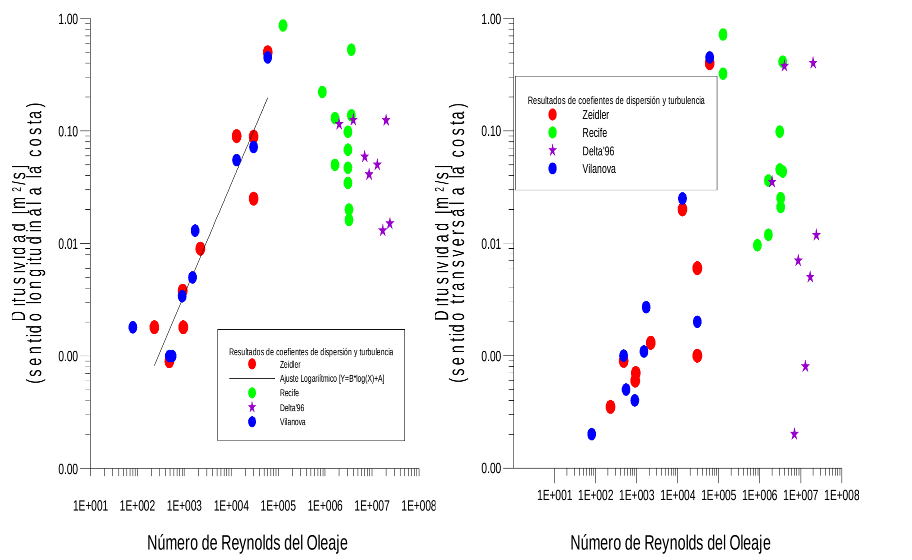

Figure 10. Figure with dye measured croshore and longshore diffusivity measured near Barcelona []Bezerra...

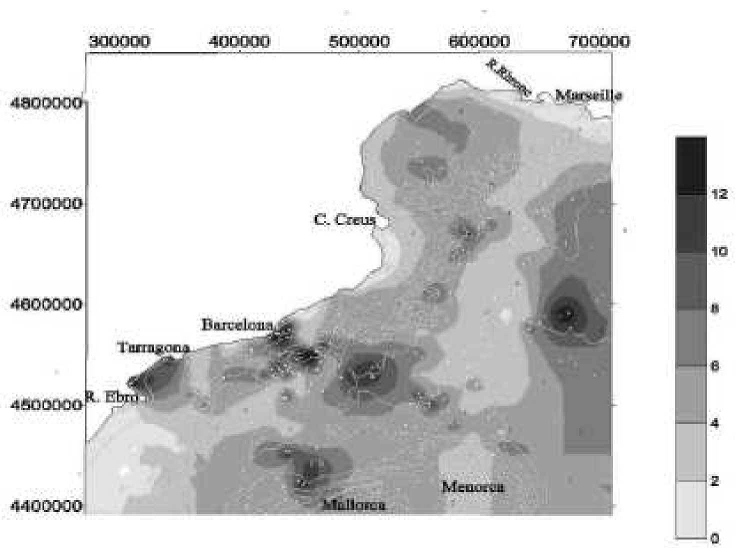

Figure 11. Number of normalized average detection of oil spills over a period of observation of 36 days, calculated with a persistence factor of 3 days for the oil spills[]Redondo and Platonov 2009.

The results indicate that there is a strong dependence of horizontal eddy diffusivities with the Wave Reynolds number as well as with the wind stress measured as the friction velocity from wind profiles measured at the coastline. Part of these results have been published in Bexerra(2000) and Bezerra et al. 1998 , but the present paper integrates also measurements inside harbours or at locations protected by wave-breakers.

Both wind and wave efects are very important and give several decades of variation of eddy diffusivities measured near the coastline (between 0.0001 and 2 m2/s). Longshore currents are also important near the coast and it is interesting to compare two similar sites with and without side harbours that hamper the longshore current formation. Experiments of dye diffusion such as those performed filming and video recording the evolution of sliks allow to characterize the ranges of Kx and Ky using Einstein's equation as a function of the distance to the coast and other environmental factors such as Wave height and frequency, wind stress, tides and mean currents the particle trajectories can be used for the direct investigation of absolute and relative dispersion.

In addition, Lagrangian descriptions of local flows are compared with Eulerian, singel point measurements description, but care is needed when transforming Eulerian into Lagrangian measurements.

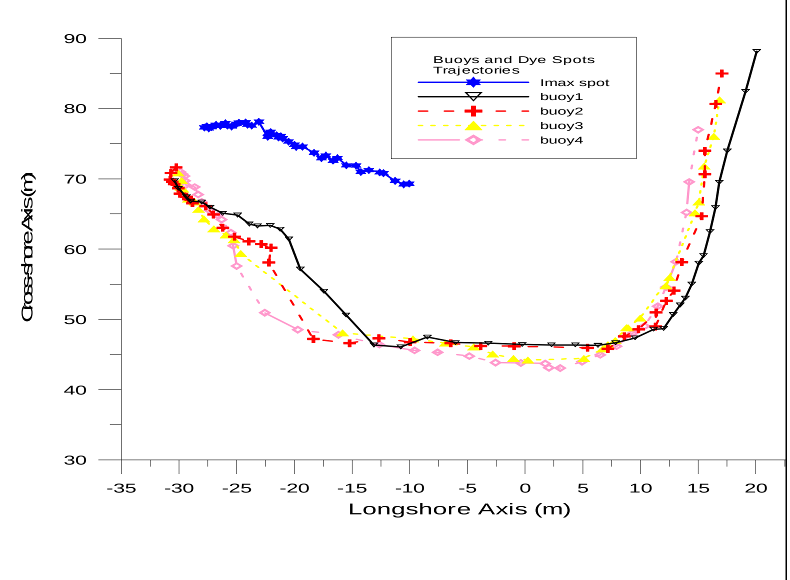

Figure 12. Buoy tracking near the coast [] Diez (caption centred).

Horizontal mixing and momentum transport is indicated by the correlations between velocity and concentration of the dispersed agent (dye, temperature, density differences, or between different components of velocity.

8. Conclusions

When comparing different topological characteristics of the spatial features of a SAR image, we have to note that the information we have is the result of a dynamical complex process that involves many hydrometeorological and sea surface processes such as tensioactivity, buoyancy, Langmuir cells, etc… From just the geometrical information it is not possible in all cases to deduce the dynamics that lead to the observations. Nevertheless we can make certain predictive conclusions comparing different surface features with multi-fractal analysis and here we will just comment a few examples: Man-made recent oil spills and other tensioactive products detected in the sea surface by SAR images, normally have two general peculiarities that seem universal. A well defined axis indicating the advected continuous spill, with a tendency along the spill to increase its thickness. Due to mass conservation and the application of the diffusion process (Fick's Law). At the same time, there is a significant decrease of the concentration (intensity of the grey tones) along its length due to the turbulent diffusion and other non-lineal processes.

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[1] Milson R, Coley A, Pravda V and Pravdova A 2004 Alignment and algebraically special tensors *Preprint* gr-qc/0401010

8.1.1. References to books, conference proceedings and reports. References to books, proceedings and reports are similar to journal references, but have only two changes of font (see table 7).

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Element	**Style**
Authors	Roman type
Date	Roman type
Book title	Italic type
Editors	Roman type
Place (city, town etc) of publication	Roman type
Publisher	Roman type
Volume	Roman type
Page number(s)	Roman type

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- Book titles are in italic and should be spelt out in full with initial capital letters for all except minor words. Words such as Proceedings, Symposium, International, Conference, Second, etc should be abbreviated to *Proc.*, *Symp.*, *Int.*, *Conf.*, *2nd*, respectively, but the rest of the title should be given in full, followed by the date of the conference and the town or city where the conference was held. For Laboratory Reports the Laboratory should be spelt out wherever possible, e.g. *Argonne National Laboratory Report*.

- The volume number, for example vol 2, should be followed by the editors, if any, in a form such as 'ed A J Smith and P R Jones'. Use *et al* if there are more than two editors. Next comes the town of publication and publisher, within brackets and separated by a colon, and finally the page numbers preceded by p if only one number is given or pp if both the initial and final numbers are given.

Examples taken from published papers:

[1] Kurata M 1982 *Numerical Analysis for Semiconductor Devices* (Lexington, MA: Heath)
[2] Selberherr S 1984 *Analysis and Simulation of Semiconductor Devices* (Berlin: Springer)
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8.1.2. References to IOP Conference Series: Earth and Environmental Science (EES) articles Each conference proceeding published in EES will be a separate volume and papers are published using an article numbering system; consequently, references to papers published in EES should use the following style:

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Unpublished conferences and reports should generally not be included in the reference list and articles in the course of publication should be entered only if the journal of publication is known. A thesis submitted for a higher degree may be included in the reference list if it has not been superseded by a published paper and is available through a library; sufficient information should be given for it to be traced readily.

9. Cross referencing

- *References.* References should be cited in the text using square brackets; for example, '[3]'.
- *Figures.* Figures should be referenced in the text as 'figure 1', 'figure 2' etc.
- *Tables.* Tables should be referenced as 'table 1', 'table 2' etc.
- *Sections, subsections and subsubsections.* For example 'section 3.1' *not* 'sec. 3.1'.
- *Equations.* Equations references should contain the equation number in parentheses, such as (3.1). Note that it is not normally necessary to include the word 'equation' before an equation number except where the number starts a sentence. The word 'equation' should not be abbreviated.

Acknowledgments

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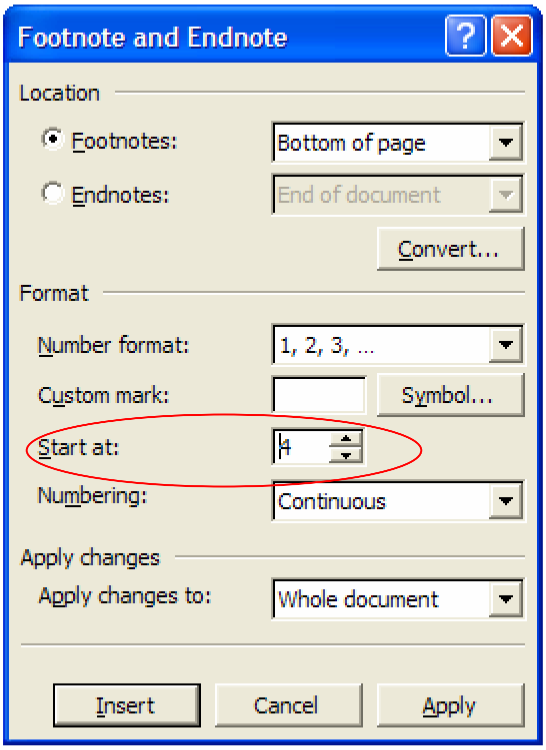
Appendix A. Inserting footnotes with Microsoft Word

Suppose you need to format an author list as follows:

J Mucklow[1,4], J E Thomas[2,5] and A J Cox[3,6]

where superscripts 1, 2 and 3 refer to addresses and superscripts 4 and 5 are to provide further information, via footnotes, such as to indicate the corresponding author (4) and details of research funding (5). So, we need to have the first footnote as number 4. Fortunately, Word allows you to set the number at which footnotes start.

From the **Insert** menu option, select **Reference** (or the equivalent option if you are not using Word XP) to display a dialog box that controls the insertion of footnotes and endnotes:



Because we need the first footnote to start at 4, type '4' in the '**Start at:**' text box as shown above. Click **Apply** to restart the numbering.