# OCEAN CLASSIFICATION OF DYNAMICAL STRUCTURES DETECTED BY SAR AND SPECTRAL METHODS

**J.M. Redondo**[1], **J.J. Martinez-Benjamin**[1], **J.D. Tellez**[1], **J.Jorge**[1], **M. Diez**[2], **and E. Sekula**[2]

[1]*UPC Barcelona Tech. B5 Campus Nord, 09034 Barcelona, Spain*
[2]*Ports de la Generalitat, 08800 Vilanova i la Geltru, Spain*

## ABSTRACT

We discuss a taxonomy of different dynamical features in the ocean surface and provide some eddy and front statistics, as well as describing some events detected by several satellites and even with additional cruise observations and measurements, in the North-west Mediterranean Sea area between 1996 and 2012. The structure of the flows are presented using self-similar traces that may be used to parametrize mixing at both limits of the Rossby Deformation Radius scale, $RL$. Results show the ability to identify different SAR signatures and at the same time provide calibrations for the different local configurations of vortices, spirals, Langmuir cells, oil spills and tensioactive slicks that eventually allow the study of the self-similar structure of the turbulence. Depending on the surface wind and wave level, and also on the fetch. the bathimetry, the spiral parameters and the resolution of vortical features change. Previous descriptions did not include the new wind and buoyancy features. SAR images also show the turbulence structure of the coastal area and the Regions of Fresh Water Influence (ROFI). It is noteworthy tt such complex coastal field-dependent behavior is strongly influenced by stratification and rotation of the turbulence spectrum is observed only in the range smaller than the local Rossby deformation radius, RL. The measures of diffusivity from buoy or tracer experiments are used to calibrate the behavior of different tracers and pollutants, both natural and man-made in the NW Mediterranean Sea. Thanks to different polarization and intensity levels in ASAR satellite imagery, these can be used to distinguish between natural and man-made sea surface features due to their distinct self-similar and fractal as a function of spill and slick parameters, environmental conditions and history of both oil releases and weather conditions. Eddy diffusivity map derived from SAR measurements of the ocean surface, performing a feature spatial correlation of the available images of the region are presented. Both the multi fractal discrimination of the local features and the diffusivity measurements are important to evaluate the state of the environment. The distribution of meso-scale vortices of size, the Rossby deformation scale and other dominant features can be used to distinguish features in the ocean surface. Multi-fractal analysis is then very usefull. The SAR images exhibited a large variation of natural features produced by winds, internal waves, the bathymetric distribution, by convection, rain, etc as all of these produce variations in the sea surface roughness so that the topological changes may be studied and classified. In a similar way bathimetry may be studied with the methodology described here using the coastline and the thalwegs as generators of local vertical vorticity.

Key words: SAR analysis; Vortex Statistics; Oil slicks; Ocean Turbulence; Fractal Spectra; Diffusion.

## 1. INTRODUCTION

Digital analysis of video images recorded after the release of dye patches in the ocean surface (Bezerra et al. 1998) has been used to investigate the structure of the surf-zone and its turbulent mixing. This technique of directly measuring the area spread of a marker allows to study both, the internal structure of the dye blobs and to quantify the 2D dispersion coefficients. Experimental results on temporal and spatial evolution of these coefficients in the nearshore zone, and also on board several cruises (Martinez-Benjamin et al. 1998), (Redondo and Platonov 2009) under different low energy conditions are presented as a possible interactive calibration of satellite images (Redondo et al. 2008a,b). We used a novel techniques to study turbulent diffusion by means of digital processing of images taken from remote sensing and also of video recordings of the sea surface. The use of image analysis allows to measure variations of several decades in horizontal local diffusivity values using directly Einstein's equation. (Bezerra et al 1998) found that near the coast there is a power law increase of diffusivity with wave height but only for large wave Wave Reynolds numbers. Other important factors are wind speed and tidal currents.

A method for evaluating mesoscale eddy diffusivities in the ocean from the measured distribution of integral length scales and the eddy turnover times associated to inertial oscillations associated to the local Coriolis parameter $f(y)$ are also discussed here, because of the importance of vertical vorticity i the ocean surface. Using the integral lenthscale distribution $l(x, y)$ as function of longitude $x$ and latitude $x$, estimated through a variety of Eulerian or Lagrangian ways, we may calculate, using dimensional analysis, the eddy diffusivity as $K(x, y) = l(x, y)^2 f(y)$ where $K(x, y)$ is the horizontal diffusivity at latitude $y$ and longitude $x$. A further refinement, that takes into account the multifractality of the images and the relation between fractal dimensions and velocity spectra relevant in the spectra, inertial,l range between the integral length scale $l(x, y)$ and the Kolmogorov lengthscale or the pixel resolution of the images is discussed in section 2 for SAR images, In section 3 we discuss further the relation between vorticity, fractal spectra and structure functions. Presenting some statistical classification of dynamical features detected in the ocean surface and discussing the results.

## 2. SAR IMAGES OF THE OCEAN

The satellite-borne SAR and ASAR is an excellent system not only to detect manmade oil spills and slicks ( Redondo and Platonov 2001, 2009), but it also detects dynamic features and the ocean eddies of different sizes. The study of the topology of the regions of different rugosity of the ocean surface can map the eddy shaped elliptic regions as well as the hyperbolic or shear dominated areas, it is also a convenient tool to investigate the eddy structures, the scale to scale energy and enstrophy transfer of a certain area, and to calculate the eddy diffusivity values. The effect of bathymetry and local currents are important in describing the ocean surface behavior, and specially the non-homogeneous transition between the coastline and open sea ( ROFI). In the NW Mediterranean the maximum eddy size agrees statisticallt with the limit imposed by the local Rossby deformation radius, Redondo and Platonov (2001, 2009). This is attained when local buoyancy and Coriolis forces are in equilibrium. In the region $RL$ depends on the season and stratification, but lies between 15-40 Km.

Quantifying coastal diffusion in presence of waves and (wind and/or wave driven) currents is a very difficult and complex task because most of the times their temporal and spatial hydrodynamic scales are overlapped, so there is a combination of these effects. To quantitatively estimate the dispersion of a pollutant substance in coastal waters, previous experiments were carried out in order to establish some empirical relationships with the dimensionless numbers associated to the different dominant effects such as wave activity, wind and currents. It is important to relate the length scale of the turbulent processes and the velocity field in the mass of water to effective eddy diffusivities. Similarly to the molecular diffusion process, it is hypotetized that the density or concentration flux along a specific direction is proportional to the concentration gradient in such direction, the turbulent diffusion coefficient ($K$) and the density ($\rho$), .$K$ evolves in time ( and space) following initially a ballistic fase following $t^2$, when it is of the size of the scale $l(x, y)$ it follows Richardson's law i.e. $t^3$, also depending on intermittency, but finally at sufficiently large scales it follows a Brownian law, proportional to $t$.

Video analysis of the dispersion of dye streaks or blobs in the ocean as well as Satellite SAR measurements allow to estimate eddy difusivities assuming a dependance on the integral lengthscale of the relevant sea surface features and we may also estimate the energy ( or tracer scalar ) spectra from theoretical grounds. The method discussed above using dimensional analysis to estimate the "dominant" mesoscale eddy difusivity (as a velocity times a length scale) from the integral measured length scales and the eddy turnover times associated to inertial ( or internal, or tidal, etc...) oscillations. $K(x, y) = l(x, y)^2 f(y)$ where K is the horizontal diffusivity,$l$, now from SAR images, the integral lengthscale of reflectivities and $f$ the Coriolis parameter defined as: $f = 2\Omega sen\phi$. ( $\Omega$ is the rotation of the Earth and $\phi$. the latitude), the integral scales, either for velocity or SAR intensity $i$, may be calculated over distance $r$ as:

$$l(r) = \int_0^{Lmax} R(r)dr \tag{1}$$

with $R(r)$ as the velocity or scalar spatial cross correlation.

Another method that also takes into account the fractal dimension of the SAR images and the relation between fractal dimensions and velocity spectra Gade and Redondo(1999) is used to provide more detailled estimates of the seasonal variations of eddy diffusivities. Here an integration of the obtained local fractal spectra is used to estimate the relevant velocity $v(x, y)$, and then:

$$v(x, y) = (E(x, y)l(x, y))^{1/2} \tag{2}$$

and then an alternative way to estimate the spatial distribution of horizontal eddy diffusivity taking into account the flow structure is:

$$K(x, y) = l(x, y)v(x, y) = l(x, y)^{3/2} E(x, y)^{1/2}. \tag{3}$$

This provides a simple relationship between the geometrical selfsimilarity of the area detected by the fractal dimension of the dye streaks or of the SAR image intensity which is detected by both the fractal dimension $D$ and the integral length scale $l(x, y)$. Redondo(1996), Castilla et al.(2007) found that on a 2D surface, using the wavenumber $k$, a traditional (K41) relationship between the power spectrum of velocity $E(k) = k^{-\beta}$ and the fractal dimension may be found as $\beta = 5-2D$, and that, then, both the spectra and the fractal dimension measurements may be also influenced by the intermittency within the turbulence cascade.

It is of fundamental importance to investigate the different influence of these topological diverse regions on the eddy diffusivity, and to calibrate numerical models with higher order descriptors. A Smagorinski formulation may be used to investigate both local and non-local dynamics. The role of self similarity in non-homogeneous systems forces a carefull definition of the resulting eddy diffusivity which plays an important role in the prediction of environmental turbulence. Ways in which turbulence parametrizations may be used in environmental flows have to include the complexity of the Eulerian and Lagrangian topology defined as the non-homogeneous distribution in the physical space of vorticity gradients and strain. These play an important role in the understanding and prediction of dispersion in the environment.

The fractal dimension is calculated as the maximum fractal dimension of all possible intensity contours of the SAR reflected intensity which exhibit a complex geometry.( Redondo(1995), Nicoleau et al. 2011) One additional important hypothesis is that the topological complexity of dye and tracer dispersion in the images is supposed induced by the dynamics of the velocity field at the sea surface. It is not thought that a precise distinction of the features produced by the wind and those produced by the wave field or local currents is needed, because as shown by Bezerra et al(1998), Rodriguez et al.(1997, 1999) all effects produce a combined turbulent diffusion at the sea surface.

Other features in the gulf of Lions, and specially near Barcelona and the Rhone and Ebro Deltas are used in the periods where several instruments are available, being able to compare coastal radar based in situ measurements with remote sensing satellite measurements. The meteorological phenomena such as cyclones, atmospheric fronts, surface wind, atmospheric internal waves and rains, all at larger scales, are also detected by the SAR The coupling between wind and ocean rugossity is best studied using a friction velocity $u^*$, as friction at a horizontal (or wavy) surface produces vertical shear $\frac{\partial u}{\partial z}$ and if friction velocity is due to the turbulent stresses $\tau = \rho\overline{u'w'}$ then $u_* = \sqrt{\frac{\tau}{\rho}}$ and we have, assuming on dimensional grounds that eddies scale from the distance to the ocean surface ( or coastline), that

$$\frac{du}{dz} = \frac{u*}{kz} = \frac{1}{kz}\left(\frac{\tau}{\rho}\right)^{1/2} \tag{4}$$

where $k$ is here Von Karman's constant $k = 0.42$, producing the usual turbulent logaritmic profile

$$u = \frac{u^*}{k} ln(\frac{z}{z_0}) \tag{5}$$

This is a well known result for the wind in the atmospheric boundary, also used for the bottom stress in ocean currents and tidal stirring, here we may also use it for lateral shear, with $z_0$ a modified roughness parameter.

In the complex and varying distribution vortices in the ocean, local shear will transform slicks in the surface to align and follow the local flow so the resulting pattern tends to be spiral. The mixing processes at large scale produce stirring, which maintains large gradients of the tracers. But in order to mix at molecular level in an irreversible fashion, the energy has to cascade to the smallest internal scales (Kolmogorov or Batchelor scales). In time the area where diffusion takes place increases and the variation of area in time may be used as a measure of the overall diffusion coefficient, what is often noticed in time sequences of the eddy distribution is the occasional energetic burst that in a couple of days destroys the existing eddy distribution, after these sudden meteorological or hydraulic driven intermittent forcing, the eddies tend to grow and decay. Thermal images of the ocean, coupled with clorophyl-colour ones are suited to describe the different forcing and time evolution, but the effect of the cloud cover precisely hampers the study of the most active forcing periods. SAR images on the other hand are not affected by clouds or bad weather and the obtained eddy statistics have no weather related bias. In figure 1 a SAR image near Barcelona shows the complex structure of the dominant eddies, Their distribution is apparent when they are classified, grouping them in a time period ( one year, 1997) as shown in figure 2. The distribution of oil spills was performed by (Gade and Redondo 1999) and Redondo and Platonov(2001,2009).

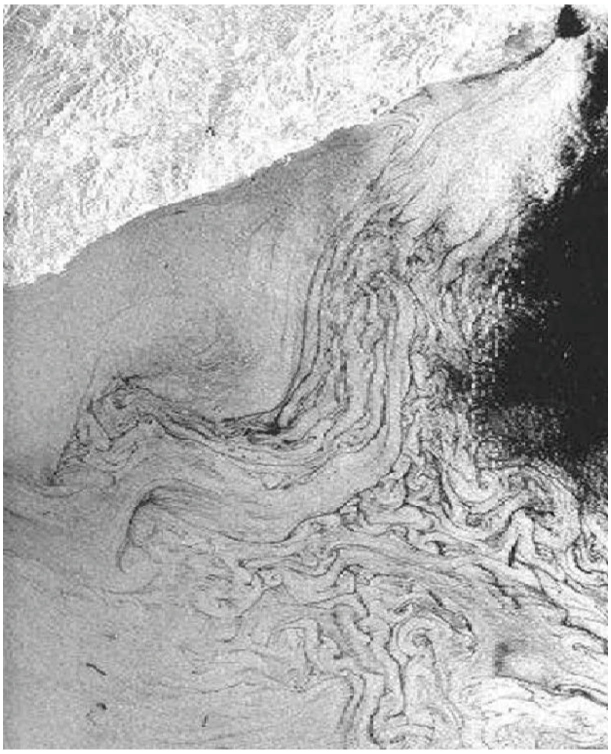


*Figure 1. Example of SAR image from the study area showing the structure of the ocean surface flow*

Besides ERS-1/2, RADARSAT and ENVISAT, eddies were also observed on TSM SPOT images in northerly land out-shore wind condition able to reconnect the re suspended coastal waters to the river plume, enabling offshore transport of sediment and ROFI tracers. In this case, secondary counter rotating vortices play also a very important role in local mixing and transport. Numer-

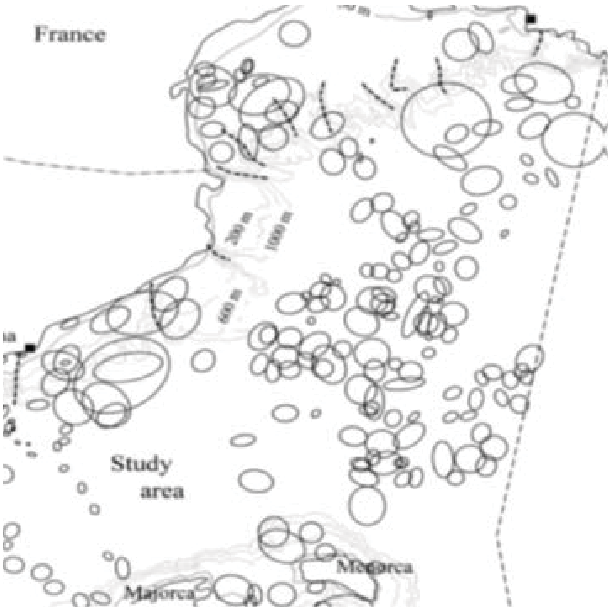


*Figure 2. Statistical description of eddies for the study area of the gulf of Lions in Clean Seas project (Redondo and Platonov 2001)*

ical coastal model forced by wind are in good agreement with observations.Many resulting patterns tends to be spiral. Many features have been identified with structures and phenomena observed in several experiments, and understanding of atmospheric and ocean dynamics has been significantly advanced being able to compare different features marking the ocean surface to its velocity dynamics (Figure 3). The experiments and observations have provided new insights about the dynamics and have revealed a wide range of nonlinear behaviour. When the instability is caused by differential heating or by buoyancy there seems to be a range of very different dynamic regimes detected in laboratory experiments, but not identified in the ocean. Work by (Carrillo et al., 2001, 2008) has revealed the complex interactions possible between lateral (or coastal) stirring and the rotating-stratified flow dynamics. The investigation of such strongly non-homogeneous flow that leads to intermittent two dimensional turbulence is believed very important if correct parametrizations of pollutant dispersion (such as Oil spills) in coastal areas are to be improved. We present in Table 1, the probability of ocurrence of different types of features in the region shown in figure 2. The classification “ eliptic eddies” also includes longitudinal fronts, as for the larger sizes, the distinction was unclear. The multi-fractal classification (Gade and Redondo 1999) is expected to help.

## 3. THEORETICAL BACKGROUND

Kolmogorov’s K41 prediction that for the $p$ th-order longitudinal velocity structure function $\delta u_l$ at scale $l$ in the inertial range of three-dimensional fully developed turbulence is related by

*Table 1. Average Percentage of eddies, spirals and fronts in the Western Mediterranean.*

| Sizes | round eddies | eliptic eddies | spirals |
|---|---|---|---|
| 1-2 Km | 0.27 | 0.07 | 0.14 |
| 2-5 Km | 0.20 | 0.14 | 0.15 |
| 5-10 Km | 0.12 | 0.16 | 0.18 |
| 10-20 Km | 0.19 | 0.19 | 0.23 |
| 20-50 Km | 0.13 | 0.16 | 0.12 |
| 50-100 Km | 0.06 | 0.12 | 0.08 |
| 100-200 Km | 0.02 | 0.09 | 0.04 |
| 200-500 Km | 0.01 | 0.03 | 0.06 |

$$\langle \delta u_l^p \rangle = \langle (u(x+l) - u(x))^p \rangle \sim \epsilon_0^{p/3} l^{p/3} \qquad (6)$$

where $\langle ... \rangle$ represents the spatial average over flow domain, $\epsilon_0$ is the mean energy dissipation per unit mass and $l$ is now the separation distance, but could reach the integral length-scale. The initial theory did not take into account intermittency, meaning that turbulence is not uniformly distributed in space. The refined Kolmogorov similarity hypothesis K62 allows for a fractal distribution of dissipation, and transforms equation (6) into

$$\langle \delta u_l^p \rangle \sim \langle \epsilon_l^{p/3} \rangle l^{p/3} \sim l^{\xi_p} \qquad (7)$$

with

$$\xi_p = \frac{p}{3} + \tau_{p/3} \qquad (8)$$

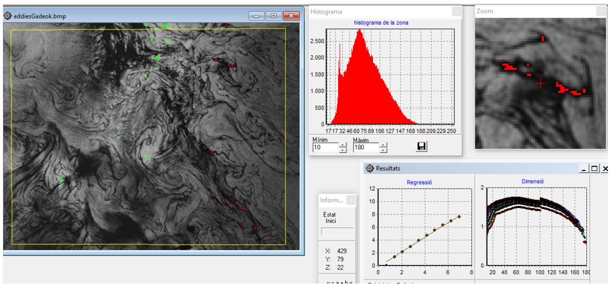
We may also assume that the most appropiate magnitude with which to describe horizontal turbulent exchanges and mixing is related to vorticity, as in the ocean the tidal stirring shows characteristic cicloidal trayectories of tracer buoys almost everywhere. The turbulent vorticity is defined as the curl of the velocity, and may also be descomposed into a mean value and its fluctuation. Hence instead of correlating velocity, we may use vorticity or a scalar indicator. then: $\omega' = \omega - \overline{\omega} = \nabla \times u'$ Thus the expression for the component $\omega_1$ of the vorticity fluctuations is then

$$\omega_1' = \left( \frac{\partial u_3'}{\partial x_2} - \frac{\partial u_2'}{\partial x_3} \right) \; = \; \frac{\partial \ell_\omega}{\partial x_2} . \nabla \overline{u_3} - \frac{\partial \ell}{\partial x_3} . \nabla \overline{u_2} + \ell_\omega . \nabla \overline{\omega_1} \, . \qquad (9)$$

It follows (Matulka et al. 2014) that the vectorial expression for the vorticity fluctuations may be also written in terms of a vorticity transfer lengthscale, $\ell_\omega$, which is very important in entrainment and mixing rocesses as

$$\omega_i' = \ell . \nabla \overline{\omega_i} + \epsilon_{ijk} \frac{\partial \ell}{\partial x_j} . \nabla \overline{u_k} \qquad (10)$$

*Figure 3. SAR image from the study of Gade et al.(2013)*



Mínim 10
Màxim 180

X: 429
Y: 79
Z: 22

*Figure 4. Use of ImaCalc on figure 3 showing the histogram and multifractal spectra of the SAR intensity of the complex surface flow*

Thus, vorticity fluctuations and transport can arise due to several causes, one contribution is given by the distribution of the mean vorticity, and arises when a fluid region moves to a level of different local mean vorticity; there is also a local vorticity transfer due to the variations in shear of the mean velocity felt by the fluid in its displacements, the scaling arguments for velocity and velocity structure functions may also be generalized for vorticity, and the equilibrium between velocity( energy) and vorticity (enstrophy) cascades will help to describe the area.

## 4. DISCUSSION AND CONCLUSIONS

Then reference plots of features such as the maximum fractal dimension with the integral of the fractal dimension over all possible intensity levels of SAR can be used to predict the behaviour of the oil spills. The topological structure may also help us to distinguish between oil seeps from the ocean bottom (more distributed) and oil spills from ships (elongated). (Redondo and Platonov 2009). The distribution of meso-scale vortices of size the Rossby deformation scale and other dominant features, it has been confirmed that for local scales larger than $Rl$. circular vortices are destroyed. Multi-fractal analysis can be used to distinguish different dynamical features in the ocean surface. The SAR images exhibited a large variation of natural features produced by winds, internal waves, the bathymetric distribution, by convection, rain, etc. as all of these produce variations in the sea surface roughness so that the topological changes may be studied and classified. In a similar way topography or altimetry may be studied with the methodology described. An additional parameter is obtained that characterizes the overall spatial fractal dimension of the system integrating the multifractal functions between the spatial limits of interest but here a Stommel diagram is needed. Several polarizations of the SAR exhibit their different structure functions up to 6th order. The flatness or Kurthosis is a statistic parameter which indicates the shape of the pdfs of the SAR intensity, and seems to be a very good indicator of the degree of existing structure; when flatness changes with scale following a potencial law, intermittency is present.

Turbulent mixing diagnostic based on Laboratory methods of visualization calculating difusivity with Einsteins Law. We are interested in the local topology and influence on the conditions for turbulent mixing, the influence of subsequent vortices and waves. Future work will include spectral and fractal descriptors in (Re, Ri, Ro ) parameter space (Redondo et al. 2008)(Tarquis et al. 2014).

The flatness or Kurthosis is a statistic parameter which indicates the shape of the pdfs of the SAR intensity, and seems to be a very good indicator of the degree of existing structure; when flatness changes with scale following a potencial law, intermittency is present. Both the multifractal spectra and the distributions are useful tools to measure intermittency, when it is applied to the correlations between the different SAR polarizations. Comparisons with the standard multi-fractal formalism also may reveal the importance of anisotropy. (Castilla et al. 2007, Nicoleau et al 2011) Environmental factors determine spreading, drift and weathering of oil on the sea surface, but note that coastal turbulence becomes helical l and stratified, and is also modified by the intermittency andreflects changes in the maximum fractal dimension, related to the energy (and also to vorticity and enstrophy) spectra of the flow. Using all the available scaling information, it is possible to investigate the spatial variability of the horizontal eddy diffusivity $K(x, y)$ in different coastal regions and weather conditions.

## ACKNOWLEDGMENTS

The authors thank the ENV4-CT96-0334 European Union Project, INTAS, ISTC1481, and ESA-IP2240 as well as MEC projects SB2000-0076 and ESP2005-07551. We thank Dr. A. Platonov for organizing and expanding the SAR Image Database of Clean Seas Project and Drs. J. Grau and A. Carrillo for implementations of programs ImaCalc, SpilSim and OilKart.

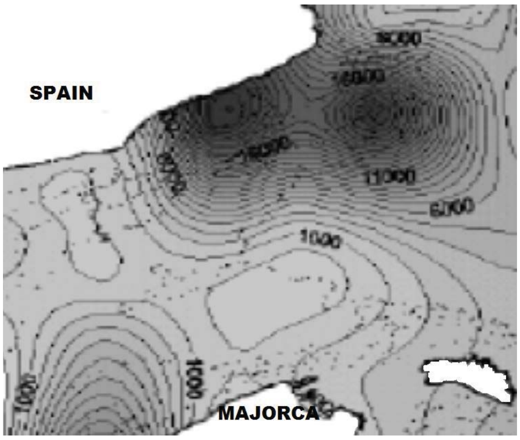


*Figure 5. Diffusivity map of the coastal region near Barcelona obtained using the parametrization of figure (3) and the SAR detected eddy sizes in the study area during 1997.*

## REFERENCES

[1] Bezerra, M.O., M. Diez, C. Medeiros, A. Rodriguez, E. Bahia., A. Sanchez-Arcilla and J.M. Redondo. Study on the influence of waves on coastal diffusion using image analysis. Applied Scientific Research (1998) 59. 191-204.

[2] Martinez-Benjamin J.J., Medeiros C. , Chic O. , Bezerra M.O. and Redondo J.M. (1998) Incidence of SAR images on the study of NE-Brazilian coast and shelf waters", Proc. SPIE 3496, Earth Surface Remote Sensing II, 212; doi:10.1117/12.332726; http://dx.doi.org/10.1117/12.332726

[3] Redondo J.M. and Platonov A. (2009)Self-similar distribution of oil spills in European coastal waters. Environ. Res. Lett. 4, 14008.

[4] Redondo J.M. (1995) Difusion in the atmosphere and ocean, Ed. M. Velarde and C. Christos, 584-597.

[5] Redondo J.M., Grau J., Platonov A and Garzon G.(2008) Analisis multifractal de procesos autosimilares, Imagenes de satelite e inestabilidades baroclinas. Rev. Int. Met. Num. Calc. Dis. Ing. 24, 1, 25-48.

[6] Redondo J.M., Grau J., Platonov A. and Matulka A. (2008) Multifractal analysis of SAR of the ocean surface currents, eddy structure, oil sliks and diffusivity analysis. Instrumentation viewpoint, 13, 107-108.

[7] Rodriguez A., Sanchez-Arcilla A., E. Bahia Redondo J.M. and M. Diez (1997) Study of Surf-zone Mixing Using Video Images. Coastal Research Through Large Scale Experiments, Ed. D. Huntley (ISBN 0-905227-86-7) 182-183.

[8] Redondo J.M. and Platonov A. (2001) Aplicaciones de las imagenes SAR en el estudio de la dinamica de las aguas y de la polucion en el mar Mediterraneo cerca de Barcelona. Ingenieria del Agua 8, 1, 15-23.

[9] Rodriguez A.,C. Mosso, Sanchez-Arcilla A., Redondo J.M and E. Bahia (1999) Macroturbulence in the Surf Zone: Field and Laboratory Measurements. Experiments in Fluids,

[10] Redondo, J. M. and Platonov, A. Self-similar distribution of oil spills in European coastal waters, Environ. Res. Lett.,(2009) 4, 14008.

[11] Redondo J.M. (1996) Vertical microstructure and mixing in stratified flows. Advances in Turbulence VI. Eds. S. Gavrilakis et al. 605-608.

[12] Bezerra M.O., Diez M., Medeiros C. Rodriguez A., Bahia E., Sanchez Arcilla A. and Redondo J.M. (1998) " Study on the influence of waves on coastal diffusion using image analysis Applied Scientific Research, 59, 127-142.

[13] Rodriguez A., Bahia E., Diez M.,Sanchez-Arcilla A., J.M. Redondo and M. Mestres (1997), IV Jornadas Espanolas de ingenieria de costas y puertos. Ed. J.C. Serra, Cadiz. (ISBN 84-7721-573-1). 643-656.

[14] Gade, M., V. Byfield, S. Ermakov, O. Lavrova, and L. Mitnik. 2013. Slicks as indicators for marine processes. Oceanography 26(2):138149, http://dx.doi.org/10.5670/oceanog.2013.39.

[15] Carrillo, A.; Sanchez, M.A.; Platonov, A.; Redondo, J.M., : Coastal and Interfacial Mixing. Laboratory Experiments and Satellite Observations. Physics and Chemistry of the Earth, (2001) B, 26/4. 305-311.

[16] Carrillo A., Redondo J.M., Fraunie P. and Durand N. Induced structures under seasonal flow conditions in the Ebro delta shelf. Laboratory and numerical models, Il Nuovo Cimento C (2008) 31, 5-6, 771-790.

[17] Gade M. and Redondo J.M. (1999) Marine pollution in European coastal waters monitored by the ERS-2 SAR: a comprehensive statistical analysis. OCEANS'99 MTS/IEEE. Riding the Crest into the 21st Century, IEEE. 3, 1239-1243.

[18] Nicolleau, F.C.G.A.; Cambon, C.; Redondo, J.M.; Vassilicos, J.C.; Reeks, M.; Nowakowski, A.F. (Eds.)(2011) New Approaches in Modeling Multiphase Flows and Dispersion in Turbulence, Fractal Methods and Synthetic Turbulence. ERCOFTAC Series.

[19] Matulka, A., Lpez, P., Redondo, J. M., and Tarquis, A.(2014) On the entrainment coefficient in a forced plume: quantitative effects of source parameters, Nonlin. Processes Geophys., 21, 269-278.

[20] Castilla R., Onate E. and Redondo J.M. (2007) Models, Experiments and Computations in Turbulence. CIMNE, Barcelona, 255.

[21] Tarquis, A. M., Platonov, A., Matulka, A., Grau, J., Sekula, E., Diez, M. and Redondo, J. M. (2014). Application of multifractal analysis to the study of SAR features and oil spills on the ocean surface. Nonlinear Processes in Geophysics, 21(2), 439-450.