Multifractal analysis of SAR of the ocean surface, currents, eddy structure, oil slicks and diffusivity analysis

J.M. Redondo(1) J. Grau(2), A. Matulka(1)(3) and A. Platonov(1)

Departament de Fisica Aplicada, B5 Campus Nord
Universitat Politecnica de Catalunya, 08034, Barcelona, Spain.
Tf:34 934016802, Fax:34 934016090, Redondo@fa.upc.edu.

(2) Departament de Mecanica de Fluids, UPC, Barcelona.Spain.
(3) Universite du Sud, Toulon Var. La Garde, France.

1. Introduction

The use of Synthetic Aperture Radar (SAR) to investigate the ocean surface provides a wealth of useful information. Here we will discuss some recent fractal and multi-fractal techniques used to identify oil spills and the dynamic state of the sea regarding turbulent diffusion. The main objectives is to be able to parametrize mixing at the Rossby Deformation Radius and aid in the pollutant dispersion prediction, both in emergency accidental releases and on a day to day operational basis. Results aim to identify different SAR signatures and at the same time provide calibrations for the different local configurations that allow to predict the behaviour of different tracers and tensioactives in the sea surface diffused by means of a Generalized Richardson's Law as well as a geometrical characterization of mixing processes [1-3]. The diffusion of oil spills and slicks in the ocean (Figure 1) have been investigated using several multi-fractal and geometrical techniques developed by the authors [1-5]. Different cases are studied analyzing mixedness, diffusivity and multifractality [2]. It has to be taken into account, nevertheless that the SAR and ASAR sensors have certain limitations depending on the range of local winds over the ocean surface, either with very small winds of less than about (2 m/s) or with very high wind speed (above approx. 12 m/s) oceanic surface films cannot, or may only barely, be identified [6-8], this prevents routine observations in regions of high winds as the north Atlantic, but for the Mediterranean Sea, or other European coastal waters, the conditions are good most of the times [6,7]. On other hand, the sunshine illumination conditions are not a limiting factor for the acquisition of SAR images as the cloud cover is transparent for SAR sensors. The nocturnal conditions are not limiting either because SAR is an active sensor that radiates its own energy. These effects allow us to use remote sensing of the ocean surface even to monitor and police pollution from space. Here we will discuss several techniques that are able to extract geometrical information from the ocean surface (Figures 1 and 2) linked in several ways to the dynamics of a certain area.

2. Topological Fractal measurements

Fractals are geometric entities that present self-similarity and they are often the result of iterative processes such as turbulence. The self-similarity implies that if we have observations from different scales the results are similar, although in natural systems it is enough to have only a certain statistical similarity [3]. These natural entities have usually anisotropic nature and then there may be different scaling laws for the different directions. Examples of these are the surface topography and the clouds, where the vertical coordinate has a smaller magnitude that horizontal coordinates due to stratification [9-13]. Fractal analysis is a very useful tool to characterize these objects in which an additional possibility is the calculation of the corresponding fractal dimension along the different coordinates so it may also reflect the anisotropic scaling. The eddies can also be detected from SAR (Figures 3 and 4) as well as the local self-similarity.

Usually, the detected oil spills by SAR have an elongated structure as these are shed from the ships in motion as they clean their ballast tanks. As turbulent diffusion acts on the plume formed by pollutants, these mix and therefore entrain seawater, so there is a measurable widening of the width of the spill. The natural oil slicks do not have these Euclidean, linear characteristics; the natural organic matter sources are not point sources and they have a diffuse initial character related to both the local currents, turbulence and the zoo and phytoplankton fields, fishery flocks, suspended or floating debry, etc[11,12]. Man-made recent oil spills and other tensioactive products detected in the sea surface by SAR images, 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.

2.1 Ocean surface observations

The analysis made with DigImage and Imacal [11,3]software on the intensity of the grey tones of the selected areas that exhibit the typical spiral features of the natural oil slicks shows the self-similarity character of their mesoscale spatial distribution (Figure 4) and also their fractional dimension character, which may be defined either for each intensity value

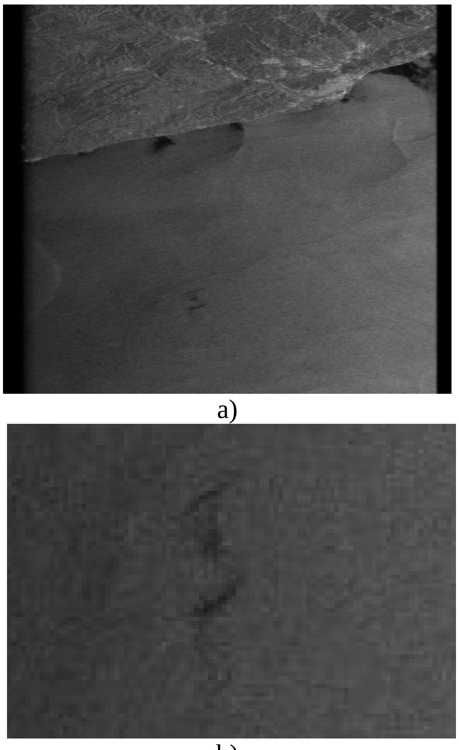
or for the contours separating two neighbour intensity values. This constitutes an array of superposed set of fractal objects which we may analyze in a variety of ways. It has to be noted, though, that it is not possible in all cases to deduce the dynamics that lead to the observations. Nevertheless we may assert certain predictive conclusions comparing different surface features with multi-fractal analysis and here we will just comment a few examples, The basis theoretical justification [3-7] consists in relating the scalar equivalent to the turbulence energy spectrum as a Fourier transform of the correlation, also directly related to the second order structure function. We suppose that the surface flow will advect the regions of different surface roughness, or the Langmuir cells with the same spectra than that of the Turbulent Energy as demonstrated by Batchelor.

The fractal dimension $D(\rho)$ is a function of SAR Intensity r and may be calculated using:

$$D(r) = -\frac{\log N(r)}{\log e}$$

where $N(\rho)$ is the number of boxes of size e needed to cover the SAR contour of intensity ρ or a group of values of intensity close to r.

The box-counting algorithm divides the embedding Euclidean plane in smaller and smaller boxes (e.g., by dividing the initial length λ_0 by n, which is the recurrence level of the iteration). For each box of size λ_0/n it is then decided if the convoluted line, which is analyzed, is intersecting that box. Finally, is plotted N versus λ_0/n (i.e., the size of the box e) in a log-log plot, and the slope of that curve, within reasonable experimental limits, gives the fractal dimension for a single intensity or for a group of similar SAR backscatter intensities. This method of box-counting is used in ImaCalc software [3,11] that we applied to detect the self-similar characteristics for different SAR image grey intensity levels and to identify different sea surface dynamic processes. Each of the intensity values may reflect different physical processes and lead to a different value of its fractal dimension. This entity can be either fractal or not but exhibits a range of values of $D(r)$ 0-2 for each SAR intensity.



a)

b)

Figure 1. *Example of an oil spill affected by a local vortex south of Barcelona*
a) SAR ENVISAT frame.
b) Detail at higher resolution.

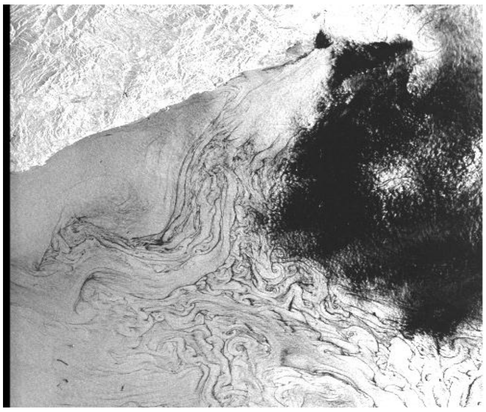


Figure 2. *Complex eddy patterns detected by SAR in the NW Mediterranean sea.*

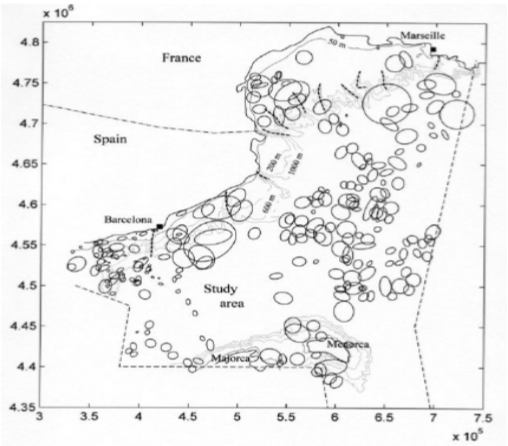


Figure 3. *Identification of vortices and eddy patterns detected by SAR in the NW Mediterranean sea during 2 years.*

2.2. Experimental and Numerical observations

The structure of non-homogeneous turbulence affected by stratification and rotation is investigated both by means of laboratory and numerical experiments. The experiments are used to quantify the different types of dominant instability and the topological aspects of the turbulent cascades detected both horizontally and vertically. Grid turbulence in a rotating stratified two layer system is measured with PIV and sonic anemometry. Observations of the horizontal velocity energy spectra as well as structure functions are used to estimate local intermittency and tracer dispersion. Numerical experiments using both Direct Numerical Simulations (DNS) and Kinematic Simulations (KS) are used to interpret some results in the context of a generalised Richardson's Law affected both by intermittency and by coherent structures, which in the experiments scale with the Rossby deformation Radius.

Turbulence decaying and stationary non-homogeneous experiments may be compared to coastal flows. Experiments without rotation (Non-Rotating Stratified Decaying 2D Turbulence), and (Rotating Stratified 2D Turbulence). And these results were compared with Numerical Simulations [4] On the one hand, the non-rotating experiments were a compilation of five sets of mixing experiments traversing a grid parallel to a salt density interface. The initial Richardson number varied several decades. The boundary conditions from all the rotating experiment conditions related to Reynolds Re, Rossby Ro, Ekman Ek and Richardson gradient Rig numbers are used in parametric spaces of Rig, Re and Ro to guide the dominant instability patterns that lead to anomalous diffusion, different than *D2 = c t3* that corresponds to Richardson's Law [4,9] for a turbulent K41 type of cascade .

The large scale physical laboratory experiences were performed on 1m x1m and 2m x 4 m in a five-meter diameter turntable,(Coriolis at Trondheim SINTEF) using the Froude-Rossby similarity. The experimental results under rotating conditions show coherent vortex dynamics and a complex taxonomy of the large-meso scale structures [19-21]. Figures 5 and 6 show the type of measurements that allow to compare the local topology of the flows with Direct Numerical similations such as that shown in figure 7. The laboratory experiments and field simulations may be used to estimate the evolution of the fractal dimension of a spill model in non-dimensional time discussed in next section.

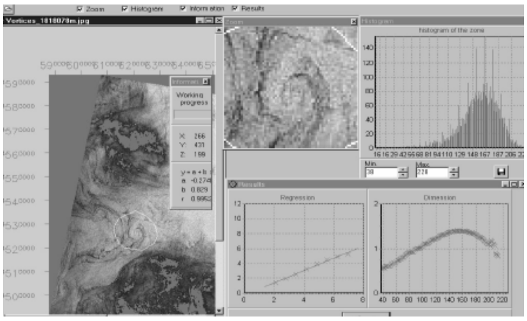


Figure 4. Fractal analysis of eddy patterns detected by SAR using ImaCalc.

3. Eddy Diffusivity measurements

The method of estimation of the average eddy diffusivity from SAR images may also take anisotropy into account, but on the long run, horizontal directions will average out so using a single integral length scale defined in [8] will be enough together with the inertial frequency. The method involving the multi-fractal dimension measurements is much more elaborated and seems to have a better theoretical justification, in the sense that it is possible that different concentrations showing different fractal dimensions may be due to different levels of intermittency and thus different spectra, which are not necessarily inertial nor in equilibrium. The different types of oil as well as the different weather conditions may be parametrized with two basic non-dimensional times, the Damköhler number related to oil diffusion and decay, T_{DK}, and a type of eddy turnover time relevant to the turbulent cascade, which would give us the relative importance of the characteristic time of the oil dispersion, measured as a half time or the time in which a spill of oil reduces its maximum value exponentially to half its original concentration. This time $\tau_{1/2}$, when compared with the characteristic time of turbulence τ_t is:

$$T_{DK} = \tau_{1/2} / \tau_t$$

These effects may be parametrized in several ways as discussed by [11-14] either as an average time scale at the integral scale or as a restoring time for each length scale that would scale as :

$$T(l) = \varepsilon^{-1/3} l^{2/3}$$

using the turbulent integral length scale l and the turbulent energy dissipation ε. We should be also able to relate spatial topological features detected by SAR and their temporal evolution using a non dimensional scale such as:

$$T_{oil} = \frac{\tau_{1/2}}{K^{1/2}} \varepsilon^{1/2}$$

with K the oil turbulent diffusivity. Then reference plots of features such as the maximum fractal dimension or as studied by [11,13] 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.

Such curves <D>(T_{oil}) would grow monotonically in time as seen in figure 8 and may give us information, taking account on the sea surface local weather, on how long ago was a particular oil spill released onto the sea..

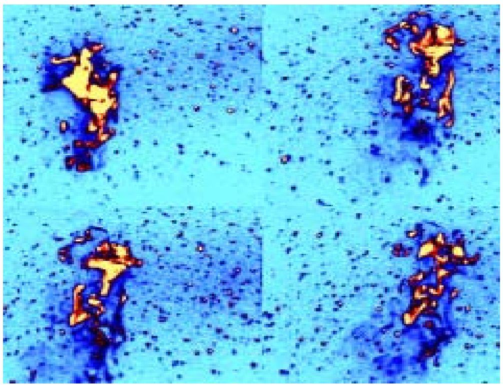


Figure 5. *Complex eddy patterns detected by SAR in the NW Mediterranean sea.*

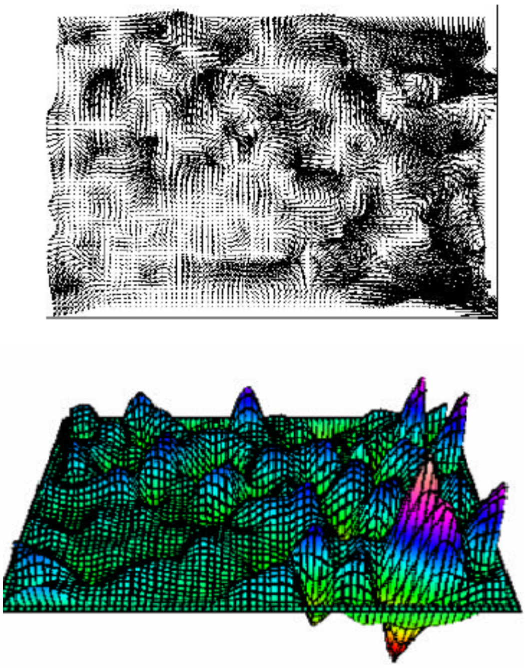


Figure 6. *Complex eddy patterns detected by PIV in a laboratory experiment of a turbulent interface (colour shows local vorticity, below 3D view)*

It is not straightforward to calculate *Toil* in the ocean, because often the type of oil is unknown and there is a large uncertainty about the local weather conditions in the ocean at the time of the SAR observation, nevertheless, better predictions and more frequent observations will reduce the errors.

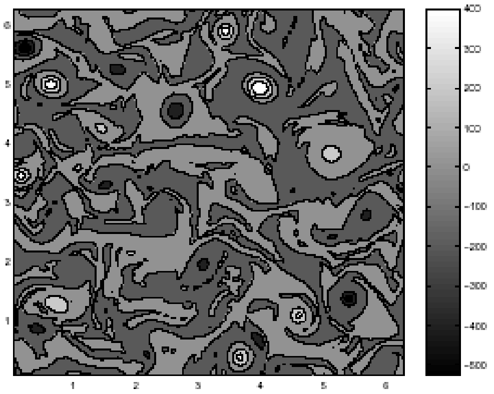


Figure 7. *Normalized multifractal patterns exhibited by natural slicks(above) and oil spils (below).*

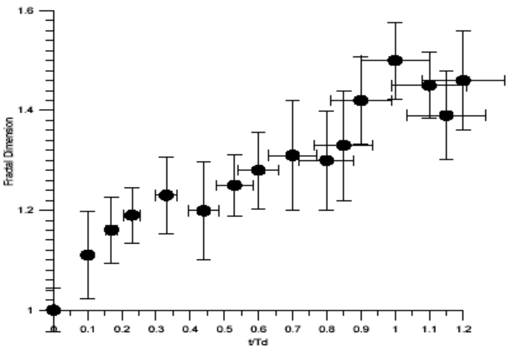


Figure 8. *Normalized multifractal patterns exhibited by natural slicks(above) and oil spils (below).*

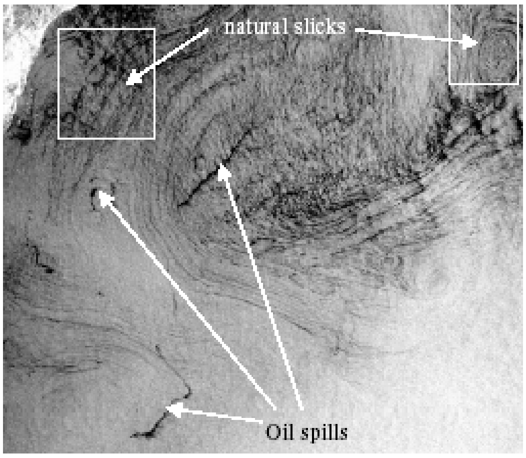


Figure 9. *Comparison of antropogenic oil spills and natural slicks detected by SAR in the NW Mediterranean sea.*

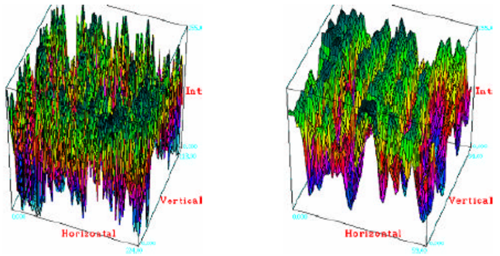


Figure 10. *Analyzed by DigImage the results of 3D structure on false colour derived from intensity of SAR signals that reflects surface roughness:Langmuir cells (right) and self-similar vortical surface feature (left) taken from figure 9.*

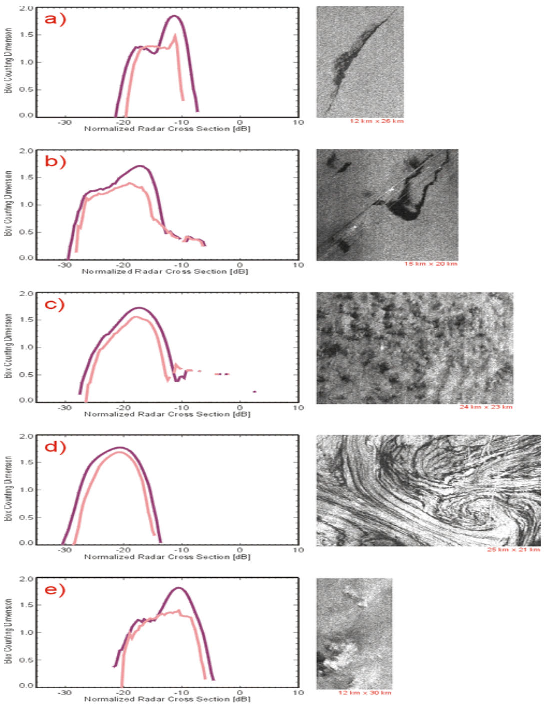


Figure 11. *Multifractal D(r) curves for different features in SAR images [17].a,b) spills,c) convection, d) eddy, e)rain.*

4. Results and Discussion

Experimental observations of SAR features are investigated with multi-scale fractal techniques in order to extract relevant information on the spectral characteristics of mixing and diffusive events. Both density and tracer marked oil spills and slicks are investigated in detail using third order structure function analysis that indicates strong inverse cascades towards the large scales producing spectral variations [4]. The different local mixing processes are compared by mapping their different multifractal scaling.

In figure 9, we may observe the very different topological characteristics of natural sliks and oil spills. In figure 10, advanced flow visualization techniques aid the identification of vortices or of Langmuir cells. The different causes of the slicks as shown in figure 11 are also reflected in the $D(r)$ plots discussed above and used first by Gade and Redondo (1998). Other multifractal measurements can also be related to physical mechanisms that affect in a different fashion the different scalar intensities used to identify the flows, as in [22-24] where stratification is shown to affect clearly the maximum fractal dimension.

The correlations of intensity values and the radial integral of these, indicates the spatial scale l where the SAR intensities are well correlated. If we suppose that the surface currents are responsible (at least partly) for the spatial distribution of the ocean roughness for two main reasons, first the slope at both sides of an eddy is very different at producing radar backscatter from a side (as happens with ERS-1/2 and also ENVISAT and RADARSAT)

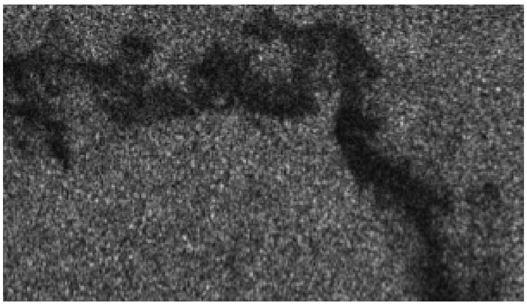


Figure 12. *ASAR higher resolution image of a wethered oil spill..*

For example, the oil spill shown in figure 12, at a higher resolution using ASAR would correspond to a range of non- dimensional times T_{oil} between 0.7 and 0.8 matching the fractal dimension of 1.3-1.4. There are other indications that may be useful from the SAR observations, such as the low local wind at the time the image was taken. There is a consistent pattern that distinguishes the recent oil spills and the natural slicks that have adapted to the multi-scale turbulent flow of the ocean surface. Figures 12 show some of the differences between recent, characterized by the low fractal dimension of low SAR reflectivity values, and weathered oil spills or slicks, which exhibit parabolic behaviour of the curve $D(r)$.

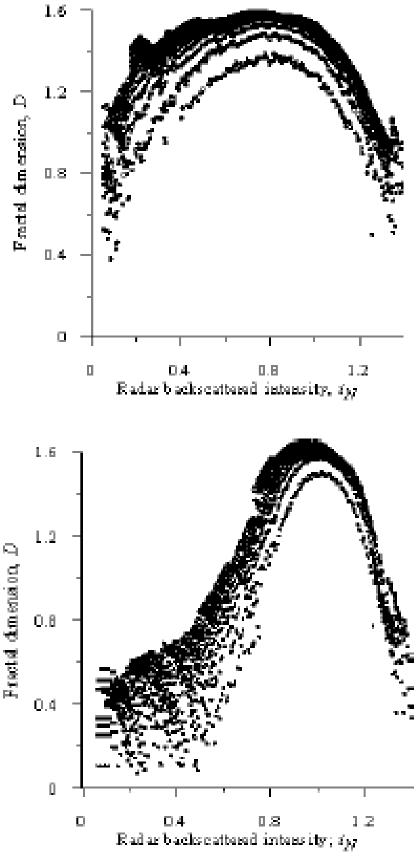


Figure 13. *Normalized multifractal patterns exhibited by natural slicks(above) and oil spils (below).*

Several uses of these new techniques are proposed taking advantage of Zipf's Law, both for anthropogenic oil spills and other features, it is possible to predict the likely probability of oil spill accidents of different sizes, as well as the local eddy characteristics that strongly influence the turbulent horizontal diffusivity, $K(x,y)$. As an example from [6], figure 14 shows a map of local average diffusivities derived from SAR observations near Barcelona, of course Richardson's law has to be applied and different sizes of spills will comply with the 4/3 law. Both numerical simulations [4] and laboratory experiments confirm the conditions for hyperdiffusion ($D^2 = c\, t^{n(f,N)}$ with $n(f,N) > 3$) to exist, as well as the trapping associated with coherent structures and vortices in the ocean, which are well detected under the

Weilburn distribution of prevailing winds in the NW Mediterranean Sea..

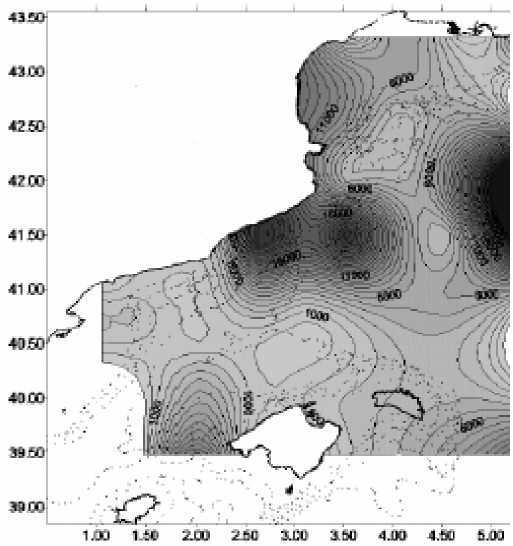


Figure 14. *2D map of Eddy diffusivity values derived from local estimates of the integral scale from SAR images.*

5. Conclusions

By using the multifractal "Box counting Algorithm" as a function of the SAR intensity and a suitable non dimensional Damkholer time, based on the local dissipation in the ocean surface, it is possible to distinguish between recent oil spills and natural slicks and to relate certain patterns to physical processes on the ocean surface. The routine observations also help to identify pollution patterns and to predict possible accidents. It is also ossible to estimate the local values of horizontal eddy diffusivity and to deduce the persistence of oil spills and slicks in the ocean. The eddy structure and local characteristics are invaluable when a prediction of tracer or surfactant path has to be made. In current numerical models that do not account for the strong spectral content at $R= N\,h/f$, with N the Brunt Vaisalla frecuency and f the Coriolis parameter, only Gaussian order predictions are available, on the other hand intermittency and higher order dose and persistency predictions are needed for practical remedial situations.

6. Acknowledgements

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