SAR ANALYSIS OF THE OCEAN SURFACE: APLICATION TO THE NW MEDITERRANEAN MARINE POLLUTION AND DYNAMIC FEATURES.

José Manuel Redondo(1), Alexei Platonov (1), Joan Grau Barceló (1,2)

(1) UPC, Departament de Física Aplicada, Campus Nord, B-5, 08034-Barcelona, Spain,
(2) DDUP, UPC, Barcelona, Spain.

Abstract

The interaction between multiple scales in nature and mainly in turbulent flows produces fractals or multifractal structures. We use multi-fractal analysis to investigate the scales and influence of stratification in different types of surface eddies in the ocean, and specially, near the coastline. We will also show and discuss the structure and residence time in oil spills and slicks in the ocean surface. This method, of multifractal analysis on the intensity SAR signals, as an example will also be applied to experiments of unstable mixing fronts driven by Rayleigh-Taylor Instabilities. These hydrodynamic instabilities are a fundamental buoyancy or acceleration driven mixing process since they are the main causes of mixing and regulate for example the overturning process. A turbulent model is used in order to study the self-similar mixing process. The results are parameterized in terms of the Atwood number, which in terms of initial condition evaluation seems more convenient than using reduced gravity or buoyancy flux. The advance of the mixing front can be compared to several laboratory and field measurements, showing the effects of the initial perturbations and the two-dimensionality and boundary conditions of a model that combines 3 and 2 dimensional effects. The multi-fractal analysis reflects the flow conditions and allows us to understand further the mixing processes.

1.INTRODUCTION

The region of the Gulf of Lions at the northwestern Mediterranean Sea has been studied within a two-year period from December 1996 until November 1998. More than 250 synthetic aperture radar (SAR) images, which have been acquired by the Second European Remote Sensing Satellite (ERS 1/2). In this paper, we present some results of the statistical analyses of several features revealed by SAR such as eddies and oil slicks dynamic features.

Within the project "Clean Seas", which is funded by the European Commission, three test areas in European marginal waters, the southern Baltic Sea and North Sea and the northwestern Mediterranean were chosen for a comparative investigation of the remote sensing of marine pollution and other types of marine and atmospheric phenomena.

Since natural (caused by plankton, fish, etc.) and man-made oil slicks dampen the small-scale surface waves, which are responsible for the radar backscattering from the water surface, they are visible as dark patches or lines in SAR imagery.

Other types of oceanic and atmospheric phenomena also cause signatures due to changes in the surface capillary waves similar to those within oil slicks, these features are advected by the local currents so they are able to reveal the structure of the ocean surface flow.

The SAR images were processed at a resolution of 1 pixel=200m and were provided by the Rapid Information Dissemination System (RAIDS) SAR processing facility in West Freugh, UK.

During the years of our studies 282 SAR images over the test area in the northwestern Mediterranean Sea. We have analyzed one part of SAR image collection with aspect to the occurrence of marine oil pollution as well as several dynamic features near Barcelona (frames 8-10, 19, 20; 81 SAR images).

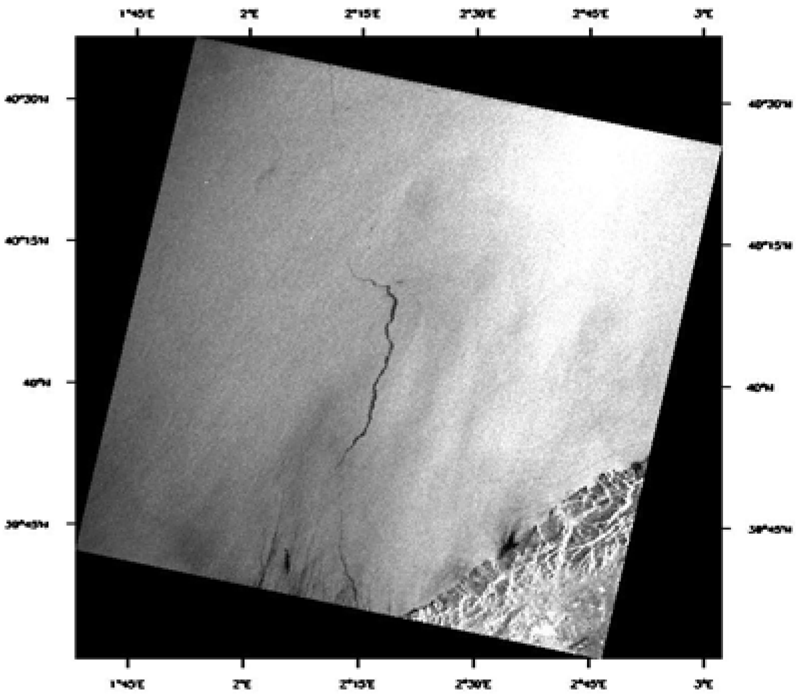


Figure 1: An example of one oil spill deformed by local currents SAR image of ERS-2 on 05.07.98 of area to NE of Mallorca.

As an additional result we also present, together with the bathymetry of the area, the detected eddies and normalized number of the natural oil slick dynamic intensity. The sizes of the circles are proportional to the probability of detecting natural oil slicks in a certain area. The geometry of grey scale ranges was used with multi-fractal analysis techniques to investigate man-made oil spills, Redondo and Platonov (2009), Platonov et al (2008). Both near Barcelona and in a wider section of the gulf of Lyons (Figure 4).

And now we may apply these fully turbulent laboratory flow techniques to the analysis of ocean surface multi-fractal features (eddies, mushroom-like currents, river plumes, oil slicks, etc.) to understand the scale to scale transport. (Benjamin et al 1998, Redondo et al. 2008, Diez et al. 2008). Next we discuss the effects of buoyancy and the characteristics of the turbulent fronts, in section 3, 4 and the Apendix, we show the results and in 5 the link between fractality, intermittency and eddy structure. Finally the conclusions are presented.

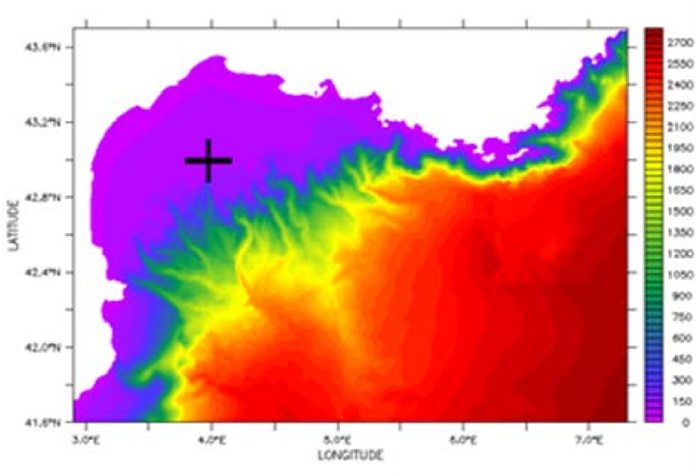
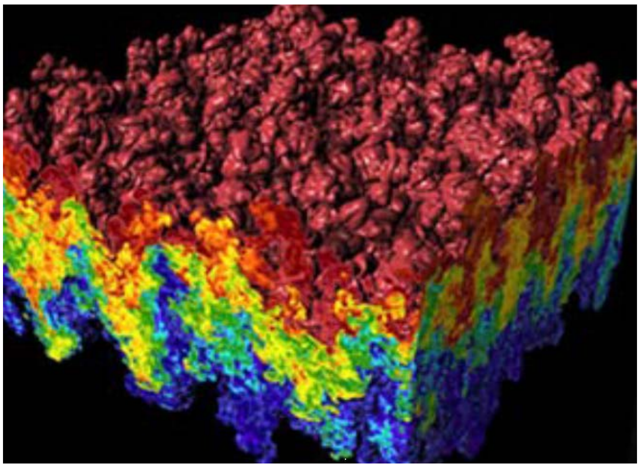
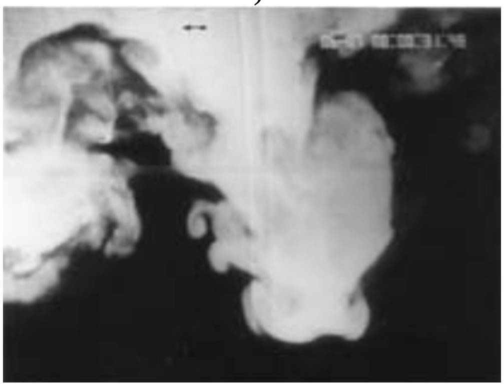


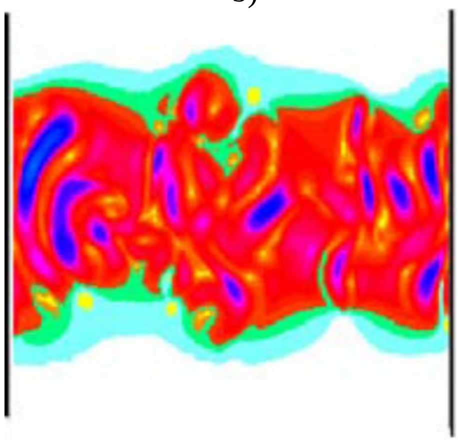
Figure 2: Detection of bathymetric canyons which also affect, Eddies and SAR. dynamic features on sea surface north of Barcelona and the NW Mediterranean.



a)



b)



c)

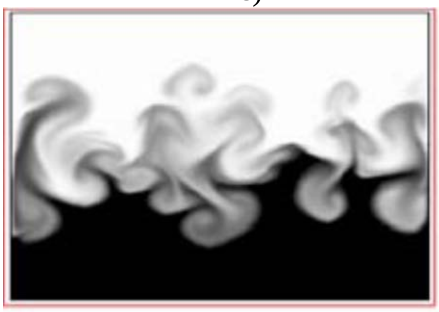


Figure 3: Different visualizations of the Rayleigh Taylor instability (Linden et al 1991,1995).
Comparison of Experimental front (a) RT blob detail b) and LES Energy (c),volume fraction (d)

2. RAYLEIGH-TAYLOR INSTABILITY AND MIXING

A Numerical and Experimental study of the local self-similar mixing structure in the evolution of turbulent fronts driven by both Rayleigh-Taylor and Richtmyer-Meshkov instabilities has shown that active mixing regions that show a local cascade process can be detected using Fractal analysis. Some of the ideas derived from these and other similar experiments have been carried to and used in other observational context, because of the relative independence of the flow process (If sufficiently large Reynolds number, i.e. fully non-linear and turbulent) and the geometric and topological features of the interaction between the Large and small features and instabilities. We just refer here to the spectral and multifractal structure of the fronts driven by the acceleration induced instabilities RT and RM which have been investigated following the Fractal box-counting algorithm for the different sets of marked value ranges, Grau(2005). Linden and Redondo(1991) and Linden et al.(1994) relating the multifractal and spectral measurements of the density field, the volume fraction and the mixing products.

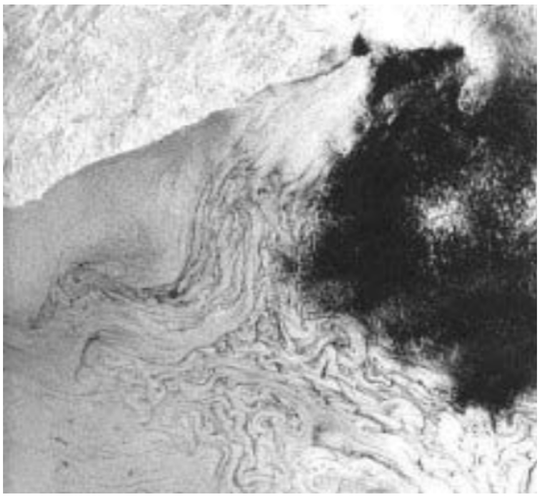
The regions of localized mixing, have a higher range of multifractal dimension values, and using box-counting and wavelet analysis, where the turbulent cascade reaches the Batchelor scales indicates the statistical structure of the instability driven mixing process. Digitalizations of the RT and RM experiments analysed with LIF, Shadowgraph, Reactive colour change and with other diagnostic techniques is seen have a very hetereogeneous mixing structure, with most mixing taking place in the sides of the of the blobs and spikes. The use of LES simulations of RT and RM fronts, as reported by Redondo and Garzon (2004), Redondo et al.(2006) agrees with the experiments and gives further insight on the different cascading processes that take place in the flow, mainly the tracer density spectra, the velocity, the vorticity and the helicity spectra. Mixing efficiency is estimated locally, both in time and space relating the maximum fractal dimension of the velocity and volume fraction sets and comparing the experiments. Both overall mixing efficiency and the evolution of local mixing efficiency are compared for a set of low Atwood number experiments of Rayleigh-Taylor instability. The differences between the continuous acceleration of the RT fronts and the shock induced RM fronts are also discussed. The advance of the turbulent front due to buoyancy is well modelled by equation:

$$h = 2c(A)gA\, t^2.$$

The value of the normally accepted constant but is often also dependent on the Atwood number A is for intermediate Reynolds numbers between 0.030 y 0.035. The experiments have also shown the strong influence of the initial and boundary conditions, both in the amplitude and velocity of the perturbations. After some time the front instabilities show a high degree of self-similarity. The strong dependence observed in the experiments between the maximum fractal dimension and the shape of the multifractal spectra, or relationship between the local fractal dimension for a small range of intensity values and the dominant energy containing scales (usually the larger and instability prone scales).

3. GENERAL EFFECTS IN OCEAN SURFACE INSTABILITIES

The dynamical processes associated with a stably stratified flow such as what occurs in the ocean thermocline are less well understood than those of a turbulent flow generated by convection. This is due to its complexity, and the fact that buoyancy reduces entrainment across density interfaces, in the same way as different local angular momentum (or enstrophy) reduce horizontal mixing, in a very non linear fashion such as in the experiments (Linden 1980, Redondo 1987, 1990, 1996). We present results on numerical simulation of non-homogeneous and density stratified and rotating fluids which has been validated with comparable laboratory experiments where a sharp density interface, such as haloclines or thermoclines, are generated by either salt concentration or heat, and entrains due to local mixing



a)

b)

Figure 3: Near Barcelona. RADARSAT SAR images (fragment) on 21.01.98
River Plume. A recent oil spill from a tanker in motion (brilliant point).

4. RESULTS

A geometry of gray scale ranges and boundaries of spatial dynamic surface features may contain new helpful information. Already we used multifractal analysis techniques to investigate of man-made oil spills, we now work in the application of these techniques to the analysis of ocean surface fractal features (eddies, mushroom-like currents, etc.).

During the duration of the Clean Seas EU project, all SAR images of the NW Mediterranean Sea, as well as other sites in the Baltic and the North Sea were analyzed and the number and sizes of vortices detected at the surface, as well as the traces of tensioactives (Oil Spills and Slicks) were statistically recorded and analysed. (Redondo et al, 2001,2009,2008). Multifractal analysis was also performed, showing that the highest maximum Fractal dimension (of about 2.4) was well correlated with regions of higher local diffusivity (also associated with higher wind and waves)

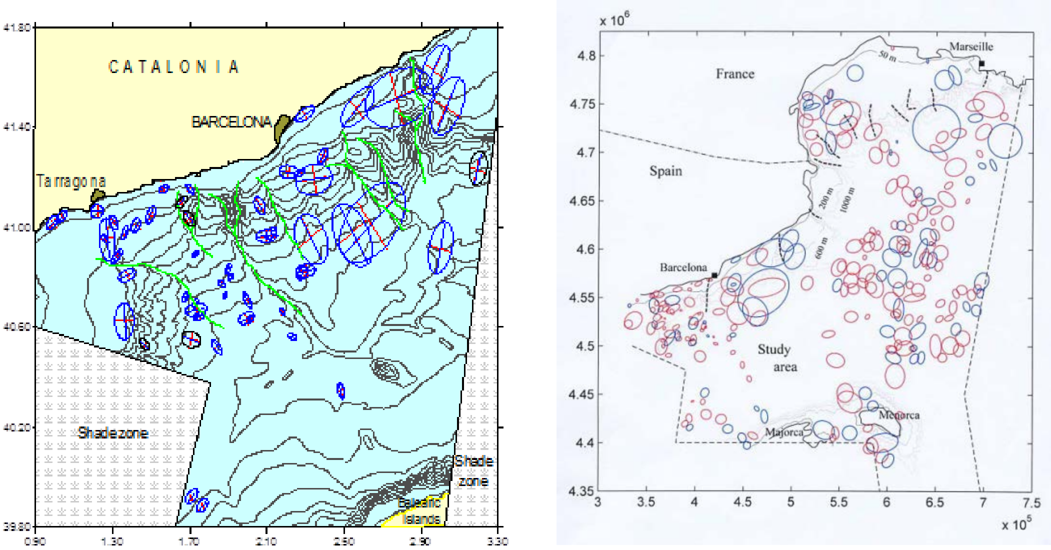


Figure 4:Detected eddies during the period 1996-1998, (left) Near Barcelona.

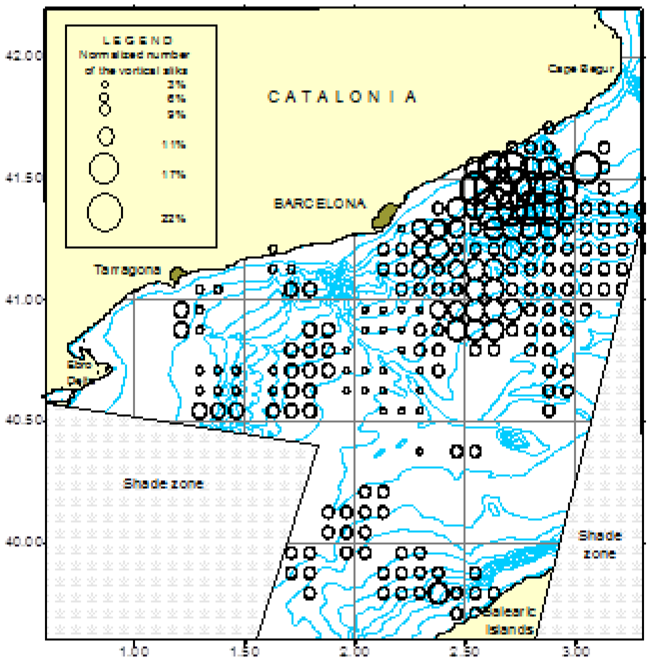


Figure 5 :Normalized number of the vertical shaped oil slicks measured in a 5'x5' grid during the period 19961998.

5. SUMMARY AND CONCLUSIONS

The satellite-borne SAR seems to be a good system for man-made oil spills and oil sliks' dynamic features detection. lt is also a convenient tool to investigate the eddy structures of a certain area where the effect of bathymetry and local currents are important in describing the ocean surface behavior.

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 (2000). The Rossby deformation radius, defined as $\boldsymbol{Rd = (N/f)h}$, where $\boldsymbol{N}$ is the Brunt-Vaisalla frequency ($N^2 = \frac{g}{\rho}\frac{\partial \rho}{\partial Z}$), $\boldsymbol{f}$ is the local Coriolis parameter ($\boldsymbol{f=2\Omega \sin\Theta}$, where $\boldsymbol{\Omega}$ is the rotation of the earth and $\boldsymbol{\Theta}$ is the latitude) and $\boldsymbol{h}$ is the thermocline depth, $\boldsymbol{Rd}$ is about 20 Km.

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. In the NW Mediterranean the maximum eddy size agrees with the limit imposed by the local Rossby deformation radius, Redondo and Platonov (2001, 2009). This is attained when buoyancy and Coriolis forces are in equilibrium, it is defined as $Rd = (N/f)h$, (where N is the Brunt-Vaisalla frequency, f is the local Coriolis (Diez et al, Fraunie et al 2008)

ACKNOWLEDGMENTS

We would like to acknowledge the financial support both from the European Research Community on Flow Turbulence and Combustion (ERCOFTAC) and Ministerio de Educación, Cultura y Deporte (SB2000-0076), we thank also the CLEAN SEAS (ENV4-CT96-0334) European Union Project for the SAR images provided.

APENDIX

We should be able to relate spatial topological features detected by SAR to the local diffusivity K, which depends on Waves, wind and local bathimetry as shown by Bezerra et al.(1998). The relation between the fractal dimension and the diffusivity may is derived from basic spectral and dimensional analysis (Diez et al 2008). 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). We know that if $H(2) = 3$, (Kolmogorov, 3D scaling) and in a similar way for Kraichnan´s 2D enstrophy cascade region where $p = 3$ then. If we use the maximum fractal dimension like Redondo (1990, 1996) then from $_{u\,Eu}p = 2E + 1 - 2D$, so for 3D flows $_3 p = 7 - 2D$ and for 2D flows $p = 5 - 2D$. So in a fully 3D flow $D = 2.66$ and if $p = 3$ then $D = 1$. If a Kolomogorov spectra appears in a 2D flow then $D = 1.66$. Both types of flows can co-exist both in the Atmosphere and the Ocean as indicated by Platonov et al. (2008). The role of intermittency would give other values. 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, $K(x,y)$. Richardson's law has to be applied and different sizes of spills will comply with the 4/3 law. Both numerical simulations Castilla et al.(1993,2003) and laboratory experiments confirm the conditions for hyper-diffusion

$$(D^2 = c\, t^{n(f,N)} \text{ with } n(f,N) > 3)$$

to exist, as well as the trapping associated with coherent structures and vortices. Figure 3a) is an eddy diffusivity map derived from SAR measurements of the ocean surface, using the Rossby deformation radius obtained loccally by performing a feature spatial correlation of the available images of the region. 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 topography may be studied with the methodology described above. An additional unique value that characterizes the overall spatial fractal dimension of the system is to integrate the multifractal functions. 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 potential law, intermittency is present. Both the multifractal spectra and the distribution of the Flatness function F are found to be useful tools to measure intermittency, when it is applied to the correlations between the different SAR polarizations. Comparisons with the standard multifractal algorithms show that the additional control of range of sizes and of intensity values allows a deeper understanding of the mixing and diffusion processes.

REFERENCES

- Bunimovich L.A., Ostrovsky A.G., Umatani S. (1993). Observations of the fractal properties of the Japan Sea surface temperature patterns. Int. J. Remote Sensing, v. 14, No 11, pp. 2185-2201.

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

- Gade, M. and W. Alpers. (1999). Using ERS-2 SAR images for routine observation of marine pollution in European margins. Mediterranean Target Project (MPT)-EUROMARGE-NB Project. Luxemburg, 38, 57.

- Gade, M., and J. M. Redondo (1999) 'Marine pollution in European coastal waters monitored by the ERS-2 SAR: a comprehensive statistical analysis". IGARSS 99. Hamburg. v. III, 1637-1639., pp. 308-312.

- Jolly G. W., A. Mangin, F. Cauneau, M. Calatuyud, V. Barale, H. M. Snaith, O.Rud, M. Ishii, M. Gade, J. M. Redondo, A. Platonov (2000). *The Clean Seas Project Final Report* (ENV4-CT96-0334). Ed. DG XII/D, Brusselas.

- Martinez Benjamin J.J., L.M. Redondo, J.Jorge & A.Platonov.(1999). *Aplication of SAR images in the western Mediterranean Sea.* Remote Sensing in 21st Century: Economic and Environmental Applications. Proceedings of the 19th EARSel Symposium on Remote Sensing in the 21st Century. Eds. A.A. Balkema ,Ed. J.L. Casanova. Rotterdam / Brookfiel. pp. 461-465.

- Redondo J.M. (1990) "The structure of density interfaces". PhD Thesis U. Cambridge.

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

- Redondo J.M. and Cantalapiedra I.R. (1993) "Mixing in horizontally heterogeneous flows", Applied Scientific Research, 51, 217-222.

- Redondo J.M., M.A- Sanchez, I.R. Cantalapiedra and R. Castilla (1998) "Vortical structures in stratified turbulent flows". Annales Geophysicae. Abstract (16), 1133.

- Redondo, J.U (1996) Fractal description of density interfaces. Institute of Mathematics and its Applications vol. 56.

- Redondo, José M., Alexei K. Platonov. (2001). Aplicación de las imágenes SAR en el estudio de la dinámica de las aguas y de la polución del mar Mediterráneo cerca de Barcelona. Ingeniería del Agua, v. 8/1. Villareal (Castellón), España. pp. 15-23

- Redondo,J.M. (1995). Diffúsion in the atmosphere and ocean, Eds. M. Velarde and C. Christos, 584-597.

- Sole, J., Cuesta,I., Garcia-Ladona, E., Grau, X. Effect of Langmuir Circulations in particle dispersion.(2000) Turbulent Diffusion in the Environment. J.M. Redondo & A.Babiano (Eds). © XDFTG, UPC, Barcelona

- Bracco, A., J. von Hardenberg, A. Provenzale, J.B.Weiss and J. C. McWilliams(2004) Dispersion and Mixing in Quasigeostrophic Turbulence, *Phys. Rev. Lett.* 2004. **92**, 8-27.

- Carrillo, A.; Sanchez, M.A.; Platonov, A.; Redondo, J.M., (201): Coastal and Interfacial Mixing. Laboratory Experiments and Satellite Observations. *Physics and Chemistry of the Earth*, 2001 B, **26/4**. 305-311.

- 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.

- Castilla R., Sanchez, M.A. and Redondo, J.M. Vortical structures in stratified turbulent flows, in *Turbulent diffusion in the environmen*t (Eds. Redondo J.M. and Babiano A. Ed. FRAGMA. (1993). 113-120.

- Redondo J. M. *The structure of density interfaces*, Ph. D. Thesis, CUP, University of Cambridge. (1990).

- R. Castilla, Redondo, J.M., A. K. Platonov. (2003). SpillSim Manual Version 1.4. DFA/UPC. Barcelona, Spain. pp. 1-33.

- Bezerra, M. O., Castilla, R., Sanchez, M. A., & Redondo, J. M. Turbulent diffusion in close beaches. In *Proceedings of the Second International Conference on the Mediterranean Coastal Environment*, (1995) 1189-1198.

- Redondo J.M.(2001) Mixing efficiencies of different kinds of turbulent processes and instabilities, Applications to the environment" in Turbulent mixing in geophysical flows. Eds. Linden P.F. and Redondo J.M., pp. 131-157.

- 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.

- Fraunie P., Berreba S. Chashechkin Yu.D., Velasco D. and Redondo J.M. (2008). Large eddy simulation and laboratory experiments on the decay of grid wakes in strongly stratified flows. Il Nuovo Cimento C 31, 909-930.

- Matulka, A., López, 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.

- Castilla R., Oñate E. and Redondo J.M. (2007) Models, Experiments and Computations in Turbulence. CIMNE, Barcelona, 255.

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