Obtaining and monitoring of global oceanic circulation patterns by multifractal analysis of MicroWave Sea Surface Temperature images

Antonio Turiel, Jordi Sole, Veronica Nieves and Emilio Garcia-Ladona
Institut de Ciencies del Mar - CMIMA (CSIC)
Passeig Maritim de la Barceloneta, 37-49. 08003 Barcelona. Spain
Emails: {turiel,jsole,vnieves,emilio}@icm.csic.es

***Abstract*—Recent advances in the theory of turbulence, with the introduction of the Microcanonical Multifractal Formalism has favored the development of new techniques for the analysis of remotely sensed data, particularly of scalars as SST. In this work we show that these techniques allow to uncover a fascinating picture in which many features of global ocean circulation patterns emerge in a distinct way. Applications include the characterization of transport, estimation of eddy-mediated mixing, the characterization of the coupling of ENSO perturbation with the equatorial instabilities and a long etc.**

I. Introduction

The advances in the acquisition of Sea Surface Temperature (SST) images, with the introduction of new sensors and merged/interpolated products is giving rise to an unprecedented capability for the constant monitoring of oceans at very different ranges of dynamic scales, synoptically and with very good sampling rate [1]. Data from passive MicroWave (MW) sensors are particularly useful, as nowadays Level 2 MW SST images are produced under almost any weather condition, with global coverage and daily; their main drawback lies on their relatively limited resolution.

It is well-known that SST images are composed by coherent features, which are the result of coherent circulation patterns [2]. For that reason, since long ago SST images have been used in order to derive the surface velocity field from them. However, solving the inverse problem (*i.e.*, determining which velocity field has lead to the observed temperature patterns) is extremely complex due to the non-linear interactions in the flow evolution and also because the temperature distribution is the result of an accumulated (integrated) time evolution. Nevertheless, some techniques based on tracking of SST patterns on sequences of images (the most important one being Maximum Cross Correlation, MCC) have been applied to derive sea surface velocity fields, with remarkable results [3], [4], [5]. The main drawbacks of this methodology lie on its limited resolution, in the problems caused by data gaps and in the necessity of properly identifying and tracking patterns in chaotic and complex signals such as SST. In fact, the pervading character of oceanic turbulence leads to a very complex structure in the fluctuation part (*i.e.*, after subtracting long-rage correlations) of SST field [6], which rends pattern recognition and tracking very difficult.

The Microcanonical Multifractal Formalism (MMF) [7] is a new formalism to deal with data obtained under conditions of turbulence with high Reynolds number. MMF represents the step from the more classical statistical characterization of the turbulence (by means of energy spectra, order-two correlations, etc [8]) to a new geometrical approach, in which the signal is decomposed in a hierarchy of fractal sets characterizing the different rates of turbulent dissipation - this is the reason for the name “multifractal”. This decomposition is performed in a scale-invariant fashion which imitates the physical process of turbulent cascading (in turbulence, energy is injected from the largest to the smallest scales as a cascade, [9], [10], [11]) and so a good spatial resolution of oceanic structures can be attained [12], [7]. Not only that: it has been argued [13] that the multifractal structure of a scalar is preserved by flow advection, what would imply that each fractal component is at each time instant composed by streamlines. This has been checked in [12] by comparing fractal components and altimetry-derived velocity fields, finding a good correspondence. Hence, it seems that the multifractal decomposition allows recognizing the streamlines with the use of a single SST image.

The presence of data gaps is still a problem in MMF, although less critical than in pattern-tracking methodologies as MCC. The effect of gaps is local and so the perturbation does not extend far ago their locations, although they lead to artificial boundary currents which circulate around the area affected by missing data. It is hence convenient to work with different data types in order to infer the correct streamlines by comparison, or even trying to obtain signals with few missing data. This is precisely the case of MW SST, and so we have performed an study on the capabilities of MMF applied to MW SST data in order to produce steady tracking of the oceanic current lines.

II. Singularity analysis

Let us first start by a small introduction to the MMF techniques, and more particularly to singularity analysis, which is the fundamental ingredient to perform the multifractal decomposition. The interested reader can find more details in [14], [12], [15], [7].

The applicability of MMF relies on the existence of local scaling exponents (known as singularity exponents). The singularity exponent of a point is a scale-invariant, dimensionless measure of the degree of regularity or irregularity of the image at that location. The obtaining of singularity exponents allows to detect relevant structures in the flow organization, even subtle structures with very small amplitude [16]. To obtain the singularity exponent of a point, the image must be filtered by means of wavelet projections, in order to reduce the influence of noise and to provide a controlled continuous interpolation over some range of scales. A procedure to assign a singularity exponent to each point in the image is known as a singularity analysis, and is one of the basic ingredients in MMF.

In our case, singularity analysis is performed by a wavelet analysis of numerical estimates of the modulus of the gradient. Let $\theta(\vec{x})$ the value of SST at a point $\vec{x}$ of the image; its gradient will be denoted by $\nabla\theta(\vec{x})$. Given a wavelet Ψ, we define the wavelet projection $T_\Psi|\nabla\theta|(\vec{x},r)$ of its gradient modulus of θ at the point $\vec{x}$ and with scale r as:

$$T_\Psi|\nabla\theta|(\vec{x},r) \;=\; \int d\vec{y}\,|\nabla\theta(\vec{y})|\,\frac{1}{r^2}\Psi\left(\frac{\vec{x}-\vec{y}}{r}\right) \qquad (1)$$

The signal θ will have a singularity exponent $h(\vec{x})$ at the point $\vec{x}$ is the following equality holds:

$$T_\Psi|\nabla\theta|(\vec{x},r) \;=\; \alpha_\Psi(\vec{x})\, r^{h(\vec{x})} \;+\; o\left(r^{h(\vec{x})}\right) \qquad (2)$$

where the symbol "$o\left(r^{h(\vec{x})}\right)$" means a quantity which decays to zero if divided by $r^{h(\vec{x})}$ when $r \to 0$. If a signal θ admits singularity exponents at all its points we will say that this signal is multifractal [14]. The conditions which allow applying the MMF are a bit more restrictive although rather technical and not essential for the course of this paper; the interested reader can find the precise framework in [17], and the verification of its validity on SST images in [7].

The accuracy and resolution capability in the determination of the singularity exponents depends on the wavelet used. As discussed in [18], the wavelets leading to the best results are positive functions with adjusted tail decay. Notice that although properly speaking a positive function cannot be a wavelet (they do not verify the admissibility condition, [19], [20]), this fact does not prevent their use for singularity analysis (admissibility is required to represent signals, not to analyze signals).

The other ingredient in MMF is the presence of a particular arrangement of singularities in variables dominated by turbulence. When turbulence is well developed, all the variables for which the stirring by the flow is important enough develop a multifractal arrangement of singularity exponents [21], [8]. In those cases, singularity exponents are arranged in accordance with the multiplicative cascade predicted by the theory [9], [22], [10]. Besides, for those scalars for which advection is dominant enough, the singularity exponents are plainly advected by the flow, at least in a first-order approximation. For that reason, the singularity exponents on SST images allow to delineate the instantaneous streamlines of the motion.

For the experiences shown in this paper, we have used a numerical implementation of the order-1 Lorentzian wavelet (see [14], [18]). This wavelet is defined by its numerical weights and has been designed to optimize reconstruction from the most singular values [23]. The exponents are obtained by a linear regression of $\log T_\Psi|\nabla\theta|(\vec{x},r)$ vs $\log r$ for $r = 1$ to $r = 8$ pixels sampled uniformly in the logarithmic domain.

As discussed in [14], [12], [7], the values that the experimental singularity exponents can take is contained in the interval $(-1, 2)$, although a narrower range, as $(-0.5, 0.5)$ usually contains around 99% of the total values. For that reason, we are more interested in taken this range as the dynamic range for the variable $h(\vec{x})$, in order to enhance details. Besides, the smallest values (*i.e.*, those closest to -0.5) delineate sharp structures, while the greatest values (closest to 0.5) represent smooth behaviors and are associated to areas without any distinguishable structure. Something which is a bit surprising when singularity analysis is applied is the large amount of emerging singular structures (see figures in the following). In fact, this should be expected as the exponent $h(\vec{x})$ obtained from equation (2) is a measure of the sharpness or smoothness of the transition (that is, the *speed* of the change) but it is independent of its absolute amplitude (which is contained in the factor $\alpha_\Psi(\vec{x})$). So, singularity analysis always gives access to all transitions in the data, even the subtlest ones, and in the case of scalars submitted to turbulence these transitions must be the response of the scalar to the action of the flow shear, so they follow the streamlines.

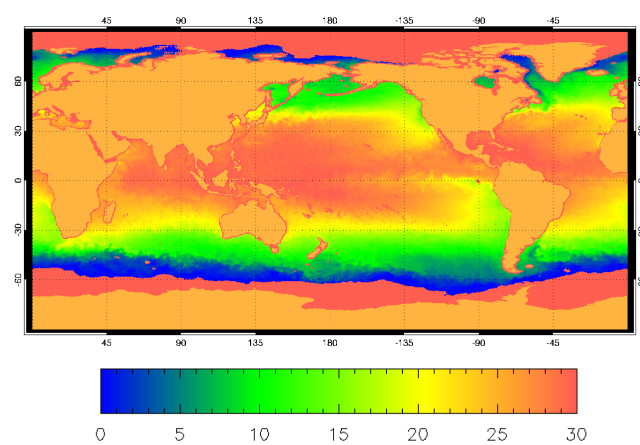

Fig. 1. MW SST image for October 1st, 2005 (cylindric projection). Temperatures in the color bar are expressed in Celsius degrees.

III. Examples of Application

In Figure 1 we present a typical MW SST image for the whole globe. Some circulation patterns are obvious by visual inspection on this image (as the Gulf Stream and Kuroshio sharp thermal signatures), but over the majority of the areas temperature appear to change rather smoothly and no pattern is recognized. On the contrary, singularity analysis of this image, Figure 2, reveals a complex system of currents, with strong filamentation, eddy creation and propagating waves.

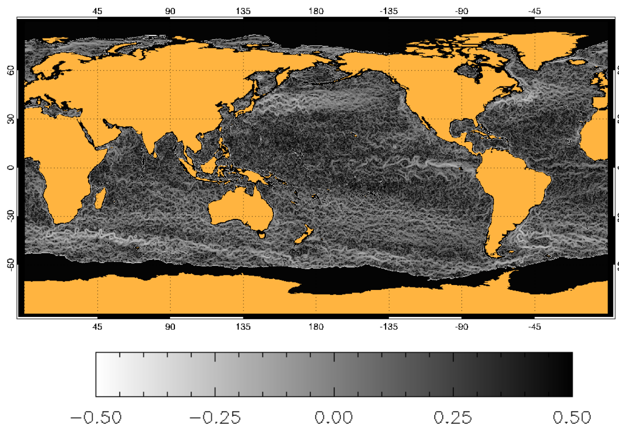

Fig. 2. Singularity exponents obtained from MW SST images for the whole globe. Results for October 1st, 2005.

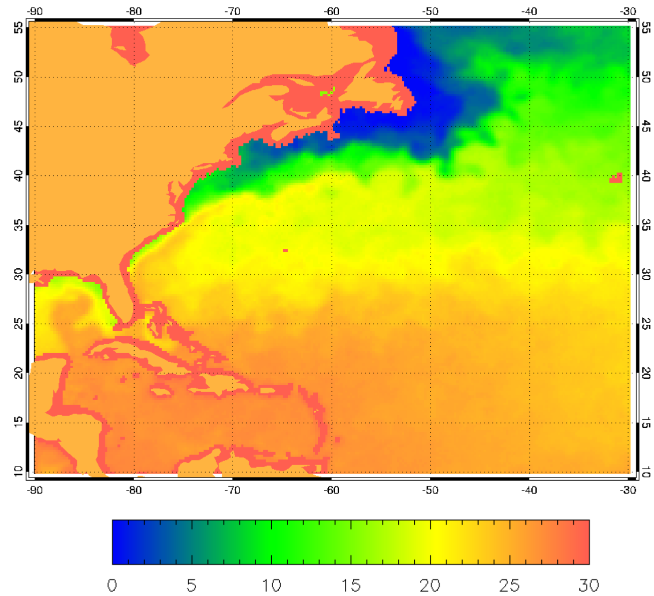

Fig. 3. MW SST image for February 1st, 2003 at the Gulf Stream area (cylindric projection). Temperatures in the color bar are expressed in Celsius degrees.

Let us study in detail some specific geographical areas. In Figure 3 we present a MW SST image for the Gulf Stream area in the North West Atlantic basin. As mentioned above, the thermal signature of this western boundary current is plainly evident in the image, and some close eddies can be guessed. The presence of these eddies is confirmed after the application of singularity analysis, see Figure 4. Not only that, but many filaments spawning from the Gulf Stream and other currents lines now become evident. Such stirring patterns and filaments have great impact in biological aspects as for instance primary production [24].

A different kind of study is posed when analyzing phenomena such as the Tropical Instability Waves (TIW) in the Eastern Equatorial Pacific; see Figure 5.

Here, the propagation speed of TIW and their evolution can be evaluated by comparing the singularity exponents at different days. In addition, several motion modes can be recognized: observe the double wave front at about -135 degrees in Longitude in August 1st, 2005, which finally merges, interfering in a constructive way in August 15th. The resulting patterns are to Kelvin-Helmholtz instabilities, which are produced in the interface between two horizontal parallel streams of different velocities and densities; the improved detection capability furnished by singularity extraction would allow to improve our underdtanding on TIW generation and evolution.

The study of TIWs is also important in order to characterize some of the effects associated to El Niño-Southern Oscillation (ENSO): it is well-known that the presence of ENSO interferes with the generation of TIW, which become of less amplitude and smaller spatial frequency. With this technique, the phenomenon can be studied in greater detail.

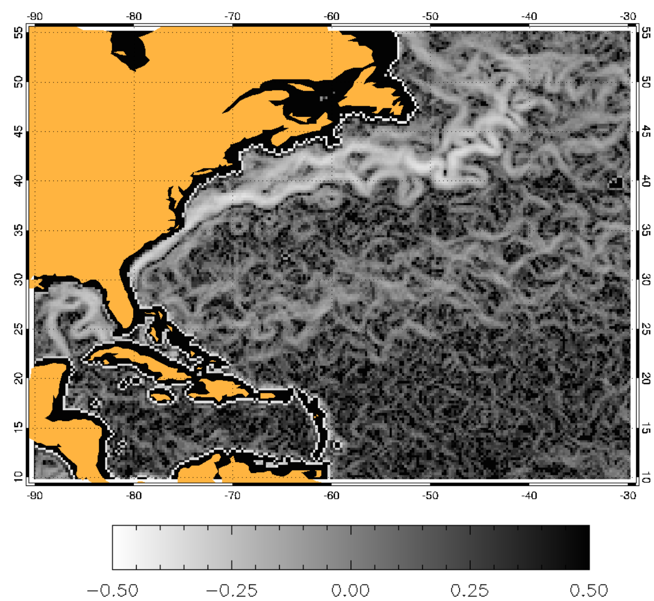

Fig. 4. Singularity exponents obtained from MW SST images at the Gulf Stream area. Results for February 1st, 2003.

IV. Conclusion

In this paper, we have seen the potential of the Microcanonical Multifractal Formalism, and particularly of the so-called singularity analysis, for the study of oceanic processes in a steady-basis. An essential ingredient to assess these process is the use of MicroWave Sea Surface Temperature (MW SST) images as starting data, as this kind of images are less affected by cloud cover and strong weather conditions.

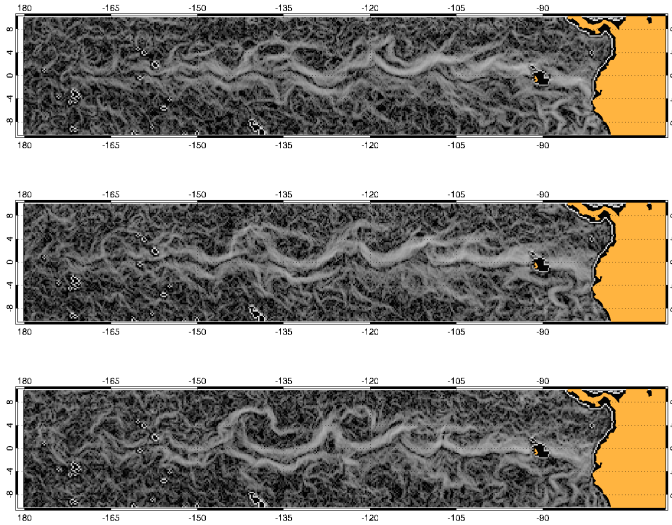

Fig. 5. Singularity exponents obtained from MW SST images at the Eastern Equatorial Pacific. Results for August 1st (top), 8th (middle) and 15th (bottom), 2005.

With this approach we can study the filamentation of the stronger jet currents, as Gulf Stream, the Kuroshio extension, the Agulhas current, the Malvines current, the Antartic Circumpolar current, etc. The analysis of the structure of the main currents has two main implications. First, the geometry of currents gives information about the way in which the energy of such currents is propagated towards small scales (i.e. if the energy is disipated mainly through vortices or waves), and what is the time sequence of such phenomena. On the other hand these currents are active parts of the main oceanic gyres, which in turn are the physical expression of the mechanisms that control, between others, the global heat budget in the Earth or the deep water formation. On the other hand, many mesoscale eddies are revealed, and the path of their evolution can be tracked; the propagation and characteristics of equatorial instabilities are also neatly evidenced. Particularly important is the possibility of precisely determine the position of oceanic fronts due to their impact in the three dimensional structure of the oceanic waters. This later point would be crucial in studying the upwelling zones, which have a great impact, for instance, in the fisheries.

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