Dynamic effect of quasi-geostrophic turbulence on ocean surface as derived from satellite imagery

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Abstract: In recent years, the application of new methodologies issued from the study of turbulent flows to the study of oceans has led to the design of novel tools for the description of the dynamics on ocean surface layer from satellite data. The use of these techniques, included in the framework of the Microcanonical Multfractal Forrmalism (MMF), allows to extract new dynamic information from the existing products and to design techniques for data recovery, data enhancement and data fusion. In this paper, we will briefly review the applications of MMF to advanced image processing of ocean images, and discuss on future applications.

Keywords: Satellite imagery, signal processing, pattern recognition, ocean surface velocity, Microcanonical Multifractal Formalism

INTRODUCTION:

The study of oceans by means of Earth Observation platforms has a relatively short history, dating from about 30 years ago now. The most widely used remote sensing platforms are dedicated satellite facilities, which have provided us with a plentiful of products, the most important of them being Sea Surface Temperature (SST), Chlorophyll Concentration (CC), and Sea Surface Height (SSH). All this products are nowadays served in web databases with different levels of processing, from raw data to synoptic maps of different spatial and temporal resolution.

At the early states of satellite era, information conveyed by these satellite products was primarily used in a completely straightforward way; oceanographers studied synoptic charts of data and from this analysis they concluded on the presence of oceanographic mesoscale features (like fronts, jets or eddies). An expert assessment of the data allowed deducing the presence of oceanographic processes taking place on the observed locations.

It was early recognized, however, that satellite images could be further exploited in order to obtain more information than the obvious one, mainly of dynamic character. The first successful technique to be applied to that goal was Maximum Cross Correlation (MCC), developed by W. Emery and co-workers [1]. This method was based on the tracking of detectable structures, following them across a sequence of images. The main drawbacks of this method lie in its necessity of having steady, uninterrupted sequences of images and on the difficulties of finding a stable structure to be tracked down, what limits both the spatial and the temporal resolution of the derived velocity fields. However, this technique opened the way to exploit satellite products in a way different to their first intended use.

Modern techniques for the extraction of dynamic information from SST and similar maps of ocean surface include Surface Quasi Geostrophy [2] and Microcanonical Multifractal Formalism (MMF) [3,4,5,6]. This article will be centered on the potential of MMF for satellite image processing.

OVERVIEW OF MMF:

MMF [5] is a theoretical framework which groups together diverse experimental facts (scale-invariance, intermittency) associated to the generation of chaotic, turbulent structures and allows obtaining a geometrical characterization of them. When MMF is exported to the context of satellite imagery of the ocean surface, we gain access to new dynamic information such as instantaneous streamlines [6], horizontal diffusivity and efficient flow characterization in terms of vortices [7]. Additionally, MMF can be applied to specific processing tasks such as pattern recognition, data compression, data fusion and data interpolation, with very good performance.

The essential concept in MMF is the onset of a turbulent cascade in the flow. The presence of such a cascade has been reported since long ago, and has to do with the loss of definite characteristic scales in Navier-Stokes equation when viscosity can be neglected [8]. A direct consequence of this scale-invariance phenomenon is that resolution-dependent variables depend on the resolution scale (also called *scale parameter*) like a power-law; this in turn means that different scales can be related by a multiplicative random process, following the so-called *multiplicative cascade* [9,10]. Scale-invariance and multiplicative cascades are hence the two sides of the same coin. From the point of view of applications to remote-sensing of the sea, and always assuming a microcanonical framework, scale-invariance has been mainly exploited to gain access to new dynamic information [3,4,6], while multiplicative cascades have been used for data reconstruction and inference [11].

The word “microcanonical” in MMF means that scale-invariant entities have a geometrical, precise meaning in each realization of the system under study, in opposition to the “canonical” or classical approach, in which these entities are always regarded as statistical and, depending on the author, merely probabilistic, without real counterpart. The big step forward of MMF is to provide a consistent framework to obtain in a precise manner the geometry of the flow which makes sense as a multifractal system and is compatible with previous findings of the canonical approach. To discuss in detail MMF is out of the scope of the present paper; the interested reader is referred to [5] for an in-depth presentation of the subject. We will just sketch here the main facts concerning scale-invariance; the analysis of microcanonical cascades requires a too long explanation and will thus deferred to later works; you can also consult [11].

SCALE-INVARIANCE IN THE CONTEXT OF MMF

In the framework of MMF, scale-invariance shows up as the existence of local power laws, evidenced by means of appropriate wavelet projections of the signal under analysis. Let $s(\vec{x})$ be the signal (typically, a satellite-derived 2D map of a oceanographic variable such as SST, SSH or CC), the wavelet projection on a wavelet Ψ [12] of the signal at the point $\vec{x}$ and scale r, denoted by $T_{\Psi}s(\vec{x},r)$, is given by:

$$T_{\Psi}s(\vec{x},r)=\int d\vec{y}\cdot s(\vec{y})\frac{1}{r^{d}}\Psi\left(\frac{\vec{x}-\vec{y}}{r}\right) \qquad (1)$$

where d is the dimension of the embedding system (d=2 for images, d=1 for time series or for transects). We say that the signal is multifractal in the microcanonical sense if for any point $\vec{x}$ we have a local power-law mediated by the associated singularity exponent, $h(\vec{x})$, as follows:

$$T_{\Psi}s(\vec{x},r)=\alpha(\vec{x})r^{h(\vec{x})}+o(r^{h(\vec{x})}) \qquad (2)$$

where the symbol $o(r^{h(\vec{x})})$ means a term which is negligible compared to $r^{h(\vec{x})}$ when r is small enough. The singularity exponent is a dimensionless measure of the local regularity or irregularity of the function around the basis point. An important fact is that the amplitude of any transition is disregarded (this is accounted by the accompanying factor $\alpha(\vec{x})$), so the lines delineated by the level-sets of singularity exponents (singularity fronts) exhibit a great deal of spatial coherency (as shown Fig. 1, top right).

APPLICATIONS ON REMOTE SENSING DATA

The main type of data analyzed in the framework of MMF has been SST images of diverse sources and acquisition facilities [3,4,5,6]. We present an example in Fig. 1, in which a microwave SST image has been processed (top row). As can be observed in the top right panel, singularity lines delineate oceanic structures with great stability. It seems that in fact the extracted structures are current lines. This hypothesis was first formulated in [4], and then more straightly validated with independent data in [6]. In the present example, we have compared singularity lines with new brand of altimetric products derived in the context of MERSEA project, namely SURCOUF altimetry maps of geostrophic currents. As shown in Fig. 1, the mutual comparison is almost perfect. This implies that we can retrieve streamlines with singularity analysis of SST maps, which are more easy to obtain and process than altimetry data, and have better spatial and temporal resolution in general.

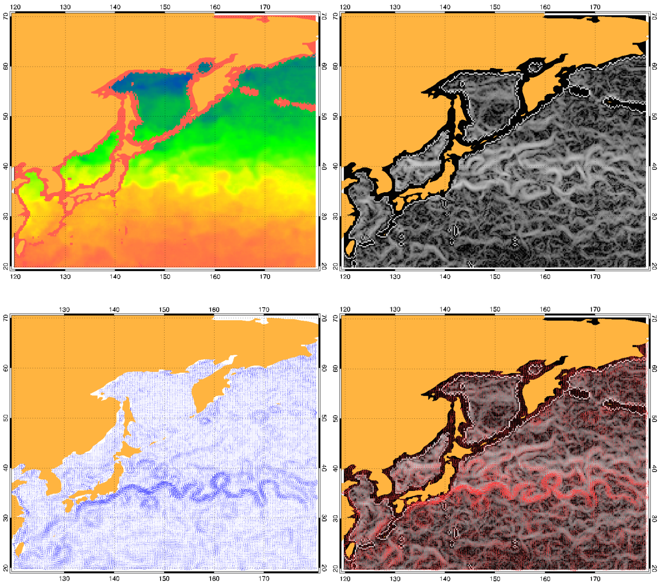

Fig. 1: *(from left to right and from top to bottom):* i) Microwave SST map over the Kuroshio area in February 1st, 2003; ii) associated singularity map; iii) geostrophic velocities derived from the interpolation of four satellite altimeter traces; iv) overimposition of the geostrophic velocities on the singularity maps. As it can be observed, singularities closely resemble the geostrophic streamlines; however, SST images are much less expensive to obtain and more synoptic.

CONCLUSIONS

In this paper we have reviewed the main hot topic of MMF analysis of remote-sensing maps of oceanographic data, most importantly SST. We have shown how singularity analysis, in the context of MMF, can be applied to retrieve information about the streamlines of the flow with a great deal of accuracy. We have pointed out that other approaches, based in the use of microcanonical cascades, can be used to interpolate data gaps and infer missing information.

As future work, we intend to extract more dynamic information from satellite-based maps of 2D oceanic variables. The first, main goal is to derive the full velocity vector from SST and related maps; so far, the streamline derived by singularity analysis just gives information about direction, not modulus or sense, of the velocity vector. Experiments with numerical data suggests that there is a close correspondence between active tracers like potential vorticity and singularity exponents; further research on this line needs to be developed. As a different branch, sequences of singularity exponents have been argued to serve to estimate lateral diffusivities, what can be used to derive properties of oceanic horizontal mixing. Concerning the potential uses of microcanonical cascades, they have an important potential for data fusion, especially on those variables which reflect the same multifractal structure. In summary, the use of MMF can provide further added-value to the existing satellite data.

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