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Lagrangian reconstructions of temperature and velocity in a model of surface ocean turbulence

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ABSTRACT

The characterization of submesoscale dynamics is crucial to apprehend their impact on the global ocean properties. Direct measurements of fine structures over the world oceans, nevertheless, are at present severely limited by the spatial resolution of available satellite products. In this work we numerically investigate the possibility to reconstruct tracer fields, like surface temperature, at small scales, from low-resolution data using a Lagrangian technique based on the properties of chaotic advection. The capabilities of the method are explored in the context of a forced Surface Quasi Geostrophic (SQG) turbulent flow representing a large-scale meandering jet and smaller-scale eddies. Both qualitative and quantitative comparisons are performed between the original (high-resolution) fields and their reconstructions that use only low-resolution data. Good agreement is found for filamentary structures, even in the presence of a large-scale forcing on the tracer dynamics. The statistics of tracer gradients, which are relevant for assessing the possibility to detect fronts, are found to be accurately reproduced. Exploiting SQG theory, the reconstruction technique is also extended to obtain the velocity field in three dimensions when temperature is the tracer. The results indicate that relevant features of dynamical quantities at small scales may be adequately deduced from only low-resolution temperature data. However, the ability to reconstruct the flow is critically limited by the energetic level of submesoscales. Indeed, only structures generated by non-local mesoscale features can be well retrieved, while those associated to the local dynamics of submesoscale eddies cannot be recovered.

1. Introduction

In recent years our picture of ocean dynamics has considerably evolved towards that of a highly complex system characterized by strong nonlinear interactions, whose spatiotemporal variability extends over a wide range of scales. In particular, the role played by relatively small scales is being viewed as more and more important. These scales, termed submesoscales, are characterized by thin ($\sim$10 km) filamentary and frontal structures elongated over several hundreds of kilometers (Ledwell et al., 1993), which are created by the stirring of mesoscale ($\sim$100 km) eddies. Here we define submesoscales in a broad sense, as scales below the deformation radius, with relative vorticities of the order of the Coriolis frequency. This generally implies order one Rossby number and ageostrophic velocities comparable in magnitude to the geostrophic ones (but note, too, that QG theory has been shown to still apply at these scales, see e.g., Klein et al., 2008). Signatures of such features have been detected in high-resolution observations of sea surface temperature (SST) and ocean color. Recent theoretical work suggests that submesoscale fronts play a leading role in the vertical transport of biochemical tracers and heat exchanges (Lévy, 2008; Klein and Lapeyre, 2009; Ferrari, 2011). Indeed, high-resolution three-dimensional (3D) numerical simulations showed that the energetic content of submesoscales is much higher than previously hypothesized (Capet et al., 2008; Klein et al., 2008).

A major problem in studying submesoscale dynamics, however, is that we still practically have no experimental access to these scales, except for in situ observations (Thomas et al., 2010; Shcherbina et al., 2010; Cole and Rudnick, 2012) or for data from surface drifters (see, e.g., LaCasce and Ohlmann, 2003; Koszalka et al., 2009; Lumpkin and Elipot, 2010; Berti et al., 2011). On a global scale, direct measurement of submesoscale features is limited by the spatial resolution of available satellite products. For instance, altimetry now routinely provides measurements over the world oceans of surface currents, geostrophically derived from sea surface height (SSH), but it only allows to resolve structures of size

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~100 km (Le Traon et al., 1998). The resolution of the velocity fields can be enhanced through the use of combined altimeters (see, e.g., Pascual et al., 2006), but the requirements needed for resolving submesoscale motions are still not met. Similarly, estimates of SST from microwave radiometers, such as AMSR-E, have a resolution of order 50 km, also not suited for the direct detection of submesoscale structures. High-resolution products are also available, such as those obtained from instruments like AVHRR which provide SST data at a resolution of about 1 km. Nevertheless, even in this case it is rare to have good quality images over large regions, due to cloud coverage.

Together with the efforts dedicated to improving the knowledge of horizontal surface flows, a further great challenge for the oceanographic community is currently represented by the determination of the full 3D structure of submesoscale features. While satellites provide information on the ocean surface, subsurface information is considerably more difficult to retrieve.

In order to tackle the above questions an interesting approach is to resort to new techniques, relying on transport processes, that suggest the possibility to infer some characteristics of submesoscale dynamics from low-resolution data (SSH or SST). In this paper we consider a Lagrangian method, based on the properties of chaotic advection (Ottino, 1989) or the tracer cascade to small scales (Batchelor, 1959), for the reconstruction of small scales and fronts of SST. Our main goal here is to test such a method in numerical simulations of upper-ocean turbulence. The dynamical configuration we consider is obtained in the framework of the Surface Quasi Geostrophic (SQG) model (see e.g., Lapeyre and Klein, 2006), which has been shown to resemble surface flows like the Gulf Stream or the Antarctic Circumpolar Current, at mesoscale and submesoscale. In particular we will be concerned with the reconstruction of filamentary and frontal structures. Then, by exploiting the basic relations defining SQG dynamics, in conjunction with the Lagrangian technique, we provide an extension of the reconstruction method to calculate the 3D velocity field.

The paper is organized as follows. The first two sections are devoted to general aspects: in Section 2 we introduce the Lagrangian method of reconstruction, and in Section 3 we describe the flow configuration that is used, corresponding to an instance of forced SQG turbulence, that will create our synthetic SST high-resolution field. The analysis of the results obtained from reconstructions is presented in Section 4. There, we discuss the effect of reconstructions on SST fields by means of qualitative comparisons and we focus our attention on the quantification of statistical properties of reconstructed SST fields. In particular, we address the potential of the Lagrangian technique for the detection of fronts. We then consider the possibility to reconstruct the velocity field. In Section 5 we discuss how the dynamical properties of the advecting flow affect the quality of reconstructions. In particular we show that local dynamics of the velocity field represent a major limitation of the present method. Indeed, we find that only structures generated by the stirring of non-local mesoscale features can be well reconstructed, while oceanic submesoscales are often characterized by local dynamics. Finally, we offer a discussion and some conclusions in Section 6.

2. Lagrangian reconstruction method

Let $C(\mathbf{x},t)$ be a tracer field and $\mathbf{u}(\mathbf{x},t)$ the velocity field transporting it. The evolution of C is, then, described by the following equation:

$$\frac{\partial C}{\partial t} + \mathbf{u}\cdot\nabla C = H, \tag{1}$$

where H accounts for source and sink terms. If we assume that, at least in a certain range of scales, the contributions from sources and sinks are negligible, then the tracer is conserved along the Lagrangian flow:

$$\frac{DC}{Dt} = 0, \tag{2}$$

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{u}(\mathbf{x}(t),t). \tag{3}$$

This conservation property is at the base of the reconstruction technique we want to use.

The method of reconstruction of the tracer field consists in advecting a large number N_p of particles (defined by their position $\mathbf{x}_p$ and their tracer value $C(\mathbf{x}_p(t),t)$) with the flow field $\mathbf{u}$, i.e.,

$$\frac{d}{dt}\mathbf{x}_p = \mathbf{u}(\mathbf{x}_p,t), \tag{4}$$

where $p = 1,2,\ldots,N_p$ is an index labeling the trajectory associated with a particle. Under the hypothesis that the tracer is a passive field, by conservation of particle identity (Bennett, 2006), its value at the position (at time t) $\mathbf{x}_p(t)$ of a trajectory will be the same as the one at its Lagrangian origin ($\mathbf{x}_p(t-\tau_a)$ at the previous time $t-\tau_a$), i.e., $C(\mathbf{x}_p(t),t) = C(\mathbf{x}_p(t-\tau_a),t-\tau_a)$, and the latter can be assigned to the new particle position (see Fig. 1).

For low-resolution tracer fields, the property of chaotic advection to generate small-scale structures (Welander, 1955; Batchelor, 1959; Ottino, 1989) implies that the resulting tracer field computed at the new particle positions, i.e., the reconstructed one, will have a higher resolution than the low-resolution tracer field we start with. The method described above does not generally provide a tracer field on a regular grid: particles advected forward in time starting from uniformly spaced positions get concentrated in particular regions of space (e.g., eddies). However, one can easily avoid this inconvenient by advecting particles backward in time. Assume that we have a low-resolution tracer field at time $t-\tau_a$ on a regular grid of spacing Δx. The initial positions of the particles are chosen on the finer grid corresponding to the resolution we want to sample (at time t), with grid spacing $\delta x < \Delta x$. After advecting backward our particles, we assign to each particle the value of C at time $t-\tau_a$ by doing spatial interpolation on the low-resolution grid at time $t-\tau_a$ (see Fig. 1).

This method has been developed and validated for stratospheric flows (Sutton et al., 1994; Mariotti et al., 1997; Orsolini et al., 2001) and tropospheric flows (Legras et al., 2005). Concerning oceanic flows, it was recently used by Desprès et al. (2011a,b) to address the dynamics of frontal structures in the North Atlantic subpolar gyre, by advecting sea surface salinity (SSS) or SST with altimetry derived geostrophic flows. A critical review of Lagrangian methods using virtual tracers for diagnosing lateral mixing in the ocean has been recently carried out by Keating et al. (2011).

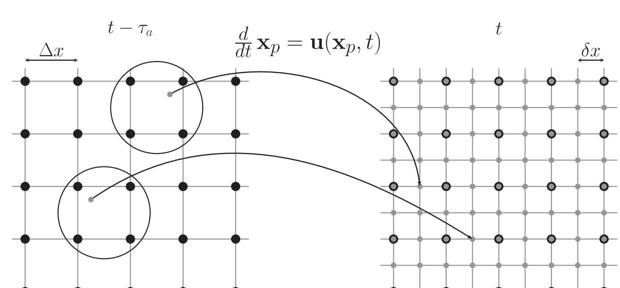

Fig. 1. Schematic view of the Lagrangian method (see text in Section 2) based on backward advection of synthetic particles from time t to time $t-\tau_a$.