LAGRANGIAN RECONSTRUCTIONS 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 limited by the spatial resolution of satellite products. A method for the reconstruction of the small scales of tracer fields is here numerically studied. Tracers are reconstructed using a Lagrangian technique based on the property of chaotic advection by large (mesoscale) eddies to generate small scales from a low-resolution tracer field. The capabilities of the method are investigated in the context of a forced turbulent flow in the Surface Quasi Geostrophic (SQG) regime. 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, with an optimal reconstruction time of the order of few eddy turnover times. Moreover, the statistics of tracer gradients, which are relevant for assessing the possibility to detect fronts, are found to be accurately reproduced.

RECONSTRUCTION METHOD

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 of relatively small scales is emerging as being 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, which are created by the stirring of mesoscale ($\sim$ 100 km) eddies. 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 [1, 2, 3]. Indeed, high-resolution three-dimensional numerical simulations showed that the energetic content of submesoscales is much higher than previously hypothesized [4, 5]. 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. Direct measurement of submesoscale features on a global scale, is at present severely limited by the spatial resolution of available satellite products, or cloud coverage. As a consequence, the development of techniques for the reconstruction of small scale features from low resolution data is needed.
In this work we consider a Lagrangian method, based on the properties of chaotic advection [6] for the reconstruction of small scales and fronts of SST. We test such a method in a dynamical configuration of upper-ocean turbulence [7] that has been shown to resemble surface flows of the real ocean, like the Gulf Stream, at mesoscale and submesoscale.

The reconstruction method consists in advecting a large number N_p of particles, defined by their position $\mathbf{x}_p$ ($p = 1, ..., N_p$) and their tracer value, e.g. SST, $\Theta(\mathbf{x}_p(t), t)$ with a given flow field $\mathbf{u}(\mathbf{x}, t)$. Under the hypothesis that the tracer is a passive field, its value at the final position of a trajectory will be the same as the one at its Lagrangian origin, i.e. $\Theta(\mathbf{x}_p(t), t) = \Theta(\mathbf{x}_p(t_0), t_0)$, and the latter can be assigned to the new particle position. For low-resolution tracer fields, the property of chaotic advection to generate small scale structures 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 we start with. The method briefly described above does not generally provide a tracer field on a regular grid. 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 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 of them the value of Θ at time $t - \tau_a$ by doing spatial interpolation on the low-resolution grid at time $t - \tau_a$.

RESULTS

For oceanographic purposes, it is interesting to work with a turbulent flow characterized by the simultaneous presence of a jet and vortices, as well as by a mean meridional temperature gradient. In order to obtain such a flow, we considered the dynamics of surface temperature in the SQG approximation [8]. By means of direct numerical simulations of SQG turbulence, we obtained the high-resolution ($\delta x = 2\pi/N_{hr}$ with $N_{hr} = 512$) fields Θ_{hr} and $\mathbf{u}_{hr}$ which constitute the numerical "reality" against which we want to test the reconstructions. These were performed using only low-resolution ($\Delta x \simeq 8\delta x$) data Θ_{lr} and $\mathbf{u}_{lr}$ obtained from Θ_{hr} and $\mathbf{u}_{hr}$ by application of a low-pass filter. Notice that this situation is close to a realistic one, where satellite data are available at a resolution $\Delta x \approx 100$ km and one is interested in submesoscale features of size $\delta x \approx 10$ km. The reconstructed field Θ_{rec} has the same resolution as the original field Θ_{hr}. An important aspect of the present study is that the tracer to reconstruct is not a purely passive field, but, instead, it is forced by a relaxation term to a mean temperature profile. This forcing mechanism is intended to mimick a coupling with the atmosphere.

We present our main findings below. As shown in Fig. 1, the Lagrangian method allows to recover the majority of small scales of the SST field, particularly the filamentary structures produced by the stretching of large scale eddies. We found that in the range $1 < \tau_a < 2$ of advective time intervals, to be compared with the characteristic timescale of large eddies $\tau_E \simeq 0.35$, reconstructions appear to perform optimally. The value of this optimal timescale is confirmed by the analysis of statistical quantities, like power spectra of temperature fluctuations.

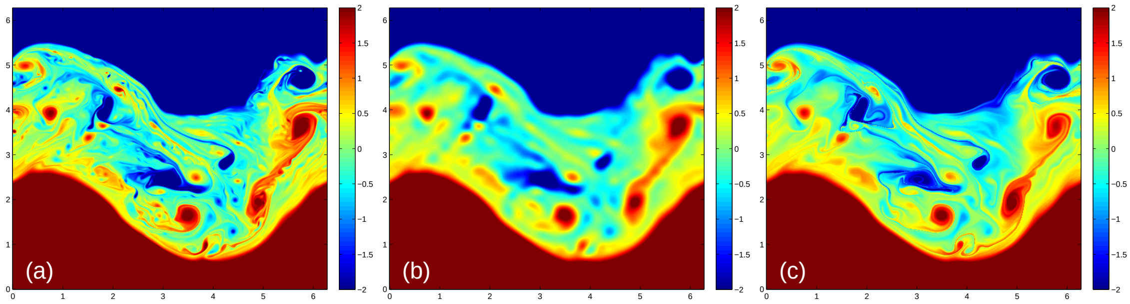

Figure 1. Reconstructions of SST: (a) original field Θ_{hr}, (b) low-resolution field Θ_{lr}, (c) reconstruction Θ_{rec} for $\tau_a = 1.5 \simeq 4\tau_E$.

The possibility to detect thermal fronts (i.e., the gradients of SST) was also analysed. For what concerns the statistical properties, the results are quite striking (see Fig. 2). Indeed, the probability distributions of SST gradients display an excellent agreement between the statistics of thermal fronts in the original and reconstructed fields in a narrow range of reconstruction time intervals centred around the optimal value ($4\tau_E < \tau_a < 5\tau_E$).

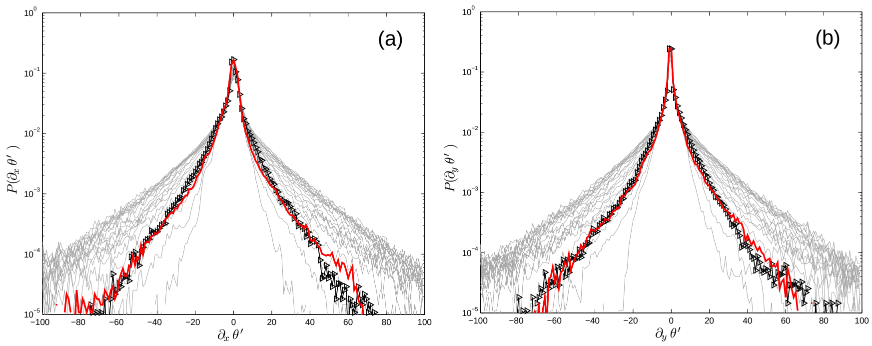

Figure 2. Probability distributions of thermal fronts, in the zonal (a) and meridional (b) direction, at various advection times $\tau_a = 0.5, 1, 1.5, ..., 10$ from inside out (grey curves). Black triangles are for the original field, the red curve is for a reconstruction with $\tau_a = 1.7 \simeq 5\tau_E$.

To conclude, our analysis shows a strong potential of Lagrangian methods for the reconstruction of fine scale features of tracer fields (as, e.g., SST) in oceanic flows, even in the presence of an external forcing. As a consequence, they can provide very useful for detailed investigations of small scale turbulent motions in the ocean.

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