Studies of stirring and mixing at the submesoscale in the ocean: FY2013 Annual Report

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LONG-TERM GOALS

As part of the theoretical and numerical modeling efforts associated with the ONR "Scalable Lateral Mixing and Coherent Turbulence" DRI, our goal is to understand and quantify the stirring and mixing of submesoscale tracers by turbulent processses at the mesoscale and submesoscale. Our intention is to both delineate the fundamental processes at work, and to guide the interpretation of tracer release, hydrographic, and microstructure observations that constitute the core of the field campaigns. In particular, we intend to (1) determine the degree to which baroclinically unstable flows at the mesoscale generate tracer stirring at the submesoscale via a direct cascade of tracer variance; (2) understand how mixed layer turbulence generated by surface buoyancy loss or down-front winds interacts with a submesoscale lateral density front; and (3) characterize the nature of the balanced mesoscale eddy field in the observational field sites.

OBJECTIVES

Our objectives are to conduct numerical experiments, and analyze data from the two LatMix campaigns, both directed at understanding stirring and mixing on lateral scales of O(10 m)-O(100 km). Our efforts have focused on the hypothesis (internally called H2) that mesoscale stirring, generated by ubiquitous baroclinic instability of the mean flow, generates a forward cascade of potential vorticity and scalar variance sufficient to explain the observed structure of natural and experimental tracers. This perspective is motivated by the results of Smith and Ferrari (2009), who demonstrated that this effect could explain the generation of T-S finestructure and the lateral spreading of an injected tracer in the North Atlantic Tracer Release Experiment (NATRE) described in Ledwell et al. (1998).

While NATRE took place in a relatively low-eddy-energy region, with a dye release at about 300m depth that was observed over a period of many months, the Latmix campaigns were focused on the flanks of the Gulf Stream jet, in the surface ocean, and each lasted for just a few weeks, thereby sampling a more complex array of processes, including mixed-layer instabilities, frontogenesis and near-inertial oscillations. In addition, geostrophic eddy stirring exhibits a very different character near the surface than at depth. Our objective is to ferret out to what degree each of these mechanisms control tracer structure in the Latmix campaigns.

To this end, we have engaged in a number of projects. PI Ferrari and former postdoctoral researcher John Taylor (now at DAMTP in Cambridge) have run primitive equation simulations on subdomains of a few kilometers squared to study the interactions between lateral stirring and turbulent mixing at lateral scales of O(10 m)-O(1 km) in the surface mixed layer. The simulations offer new insight for the interpretations of tracer release, hydrographic, and microstructure observations that constitute the core of the field campaigns focusing on frontal dynamics in the upper ocean. PI Smith and John Taylor have run a series of identically initialized, freely-evolving QG and PE simulations of a baroclinically unstable front. The simulations are performed for a range of domain-scale Rossby numbers and each stirs a tracer driven by a constant mean gradient. The results have shed new light on the balanced and unbalanced components of submesoscale tracer stirring. MIT graduate student Jörn Callies, under Ferrari's supervision, has analyzed in situ observations from the summer and winter LatMix campaigns, computing spectra of kinetic and potential energy and spice variance. His results find energy spectra consistent with geostrophic turbulence theory, but variance spectra that are harder to interpret. In collaboration with Ferrari and Smith, Callies in now in the process of running numerical simulations forced by the observed stratification and shear, with the goal of understanding the mechanisms that produce the observed spectra. Finally, postdoctoral fellow Jeffrey Early and Smith are working with Miles Sundermeyer to analyze GPS drifter data from the summer LatMix campaign. Early has found intriguing discrepancies from tracer-based estimates of turbulent diffusivity, and is currently analyzing kinematic models and numerical experiments to understand the causes.

WORK COMPLETED

1. Diagnosing submesoscale stirring with ocean observations

One of main objectives of this DRI is to use ocean observations to quantify the relative importance of different classes of motions in stirring tracers at the submesoscale. Data have been collected by an outstanding team of PIs in 2011 and 2012. We have now joined forces with the team in analyzing the data and putting the results in the context of previous observations to obtain the first detailed view of dynamics at the submesoscale.

In Callies and Ferrari (2013), we report that energy and tracer spectra in the submesoscale range fall off like k^{-2} in the eastern subtropical North Pacific in winter from the 1997 Spice project, partly funded by ONR. The result is consistent with predictions from frontogenetic turbulence at the ocean surface. However, we also find that tracer spectra do not seem to show a transition from surface dynamics to interior dynamics, as expected from theoretical arguments. The 2012 winter Latmix campaign has also revealed a rich submesoscale structure. Evidence for frontal instabilities and the creation of submesoscale filaments was found. Shcherbina et al. (2013) report energy spectra from the winter experiment that closely follow k^{-2} power law in the mixed layer and decay significantly below. This indicates that there is strong submesoscale turbulence in the mixed layer that decays rapidly below, consistent with theoretical arguments and modeling. This is the first reported observation of surface-enhanced submesoscale turbulence. Interestingly the Oleander data set, from the same region, shows that the k^{-2} surface spectra become much steeper in summer implying the submesoscale dynamics dies off when mixed layers are shallow.

In order to better understand the observations of submesoscale turbulence, we run QG simulations of the regions reported on in Callies and Ferrari (2013) and Shcherbina et al. (2013). These simulations are used to study the nature of submesoscale turbulence and the role of the mixed layer. The simulations are doubly periodic with prescribed mean states from the OCCA climatology; they are equilibrated by quadratic bottom drag. The simulations are not computationally expensive and can be run with high horizontal and vertical resolution.

If run for winter conditions, with a deep mixed layer, the simulations produce flat energy spectra in the mixed layer. The spectra decay and steepen below. The energy levels match the observations quite well in the mixed layer. Below, the observations appear to be dominated by internal waves not present in the QG simulations, but adding the Garrett and Munk model spectrum to the simulated spectra brings model and data into agreement. If run for summer conditions, with much shallower mixed layers, the simulations are much less energetic in the submesoscale range: the near-surface energy spectra are now steep. This demonstrates the crucial role of the mixed layer for submesoscale turbulence. The sharp change in stratification at the base of the mixed layer is associated with a strong PV gradient, similar to the tropopause in the atmosphere. For winter conditions, linear stability analysis shows rapidly growing modes at the deformation scale of the mixed layer (about 10 km). These PV gradients and mixed layer instabilities appear to be responsible for the flat energy spectra in the mixed layer.

2. Lagrangian estimates of submesoscale eddy diffusivity

In order to improve our understanding of the eddy diffusivities inferred from the spreading of the dye, we have investigated how a similar inference model could be applied to Lagrangian particles, and applied the results to the GPS drifters deployed with the Rhodamine dye release in the summer 2011 campaign. As a first step, we construct a stochastic model of Lagrangian trajectories that assumes a two-dimensional velocity field characterized by a spatially-homogeneous, time-dependent background flow added to a time-independent field with constant strain and vorticity, perturbed by a discrete Wiener process with variance σ^2. A model for a dye stirred by the same field, but diffused isotropically with diffusivity κ, can be made equivalent to the Lagrangian model by setting $\kappa = \sigma^2/t$. Given observed particle trajectories, the first moments (centers of mass) can be used to determine the homogeneous background flow, and the second moments to determine the strain and vorticity. Finally, the diffusivity can be estimated by inverting the equations for the second moments.

Figure 1 shows the six-day GPS tracks of the nine drifters released with the Rhodamine patch in the summer 2011 campaign (see caption for details). Applying the model described above to the data, we find that (1) the assumption of a time-independent strain and small vorticity is reasonable; (2) simulated trajectories using the inferred mean flow parameters and stochastic noise with the inferred variance are qualitatively similar to the observed tracks; and (3) the lateral diffusivity inferred from the drifters is somewhat smaller than that found by analysis of the dye patch spreading (see Miles Sundermeyers abstract). The next step is to use this method in the above-mentioned simulations to ensure an equivalent method of determining diffusivities in models and observations.

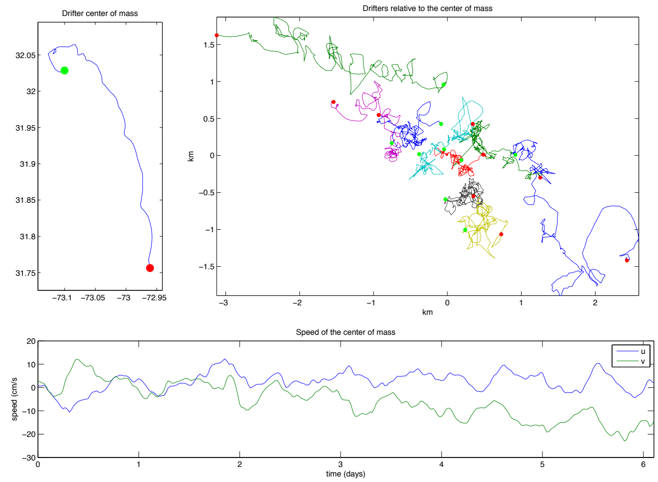

Figure 1: Upper left: path of the center of mass (green dots indicate start of track). Upper right: drifters' positions relative to the center of mass. Bottom: center-of-mass velocity.

3. Stirring by mesoscale straining and unbalanced submesoscale processes

Stirring by a geostrophic eddy field drives a cascade of PV to the submesoscale, the so-called enstrophy cascade. However as the cascade proceeds, PV filaments can reach finite Rossby numbers and small Richardson numbers and violate QG scaling. This typically happens at scales of less than 10 km. Surprisingly little work has been done to compare QG and primitive equation simulations at high resolution to determine whether departures from QG have important measurable effects on tracer and PV distributions.

We have now run a suite of QG simulations in parallel with Boussinesq Primitive Equation (PE) simulations (using the Diablo code), systematicaly varying the domain-scale Rossby number. The simulations start from a geostrophically balanced density front which goes baroclinically unstable. A tracer with a fixed constant lateral mean gradient is stirred by the flow, and we study how its structure evolves during the spindown of the front. At low Rossby numbers the frontal spindown in the QG and PE simulations is dominated by a vigorous inverse energy cascade resulting in eddies progressively growing in size. The QG and PE simulations at low Rossby number exhibit very similar behaviors, while at higher Rossby numbers, the PE simulations additionally yield a forward energy cascade, resulting in more small scale turbulence and a flatter energy spectrum (Fig. 2, first two panels).

A key question of relevance to this DRI concerns the part of the flow that generates the variance of tracers in the submesoscales: does the enhanced turbulence at the smaller scales of the PE simulation significantly enhance stirring over that generated by the mesoscale? In the present case, in spite of the shallow $k^{-5/3}$ energy spectrum that evolves at small scales in the PE simulation, we nevertheless find a k^{-1} variance slope for the tracer in both the PE and QG simulations (right panel of Fig. 2). By analyzing the spectral variance flux decomposed into parts generated by the high-pass and low-pass velocity fields, we find that the flux due to the large-scale flow is a few orders of magnitude larger than that generated by the small-scale flow, indicating that the unbalanced, non-QG flow that arises in the PE simulation at higher Rossby number has very little effect on the stirring of the tracer, which remains controlled by the large-scale flow (equivalent to the mesoscales in an oceanic context).

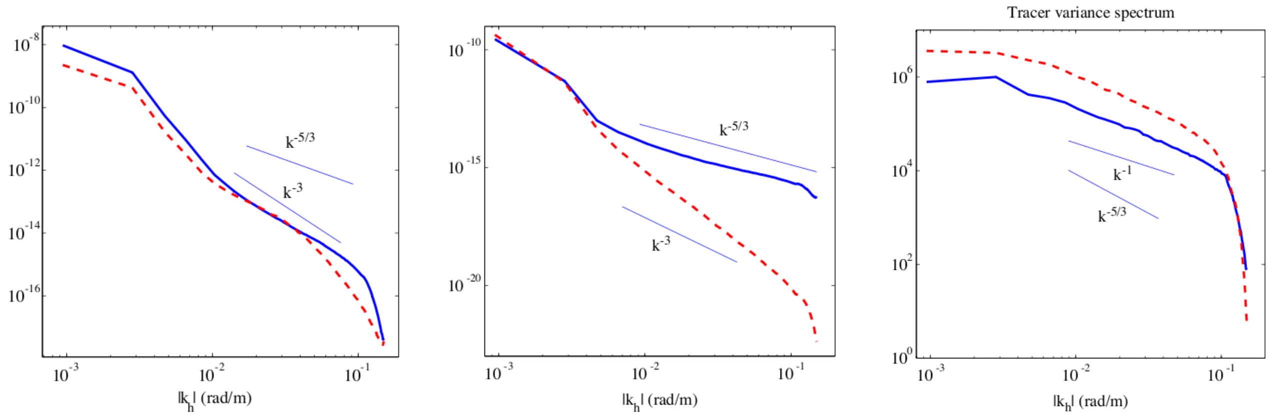

Figure 2: Energy spectra for QG (red dashed) and PE (blue solid) simulations with Ro = .125 (left) and Ro = .418 (right). The spectra of variance fluxes for the PE simulation with Ro=.418.

PUBLICATIONS

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