Submesoscale Routes to Lateral Mixing in the Ocean

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LONG-TERM GOALS

We aim to understand the role of submesoscale processes in lateral mixing at scales of order 0.1-10 km and to determine whether it arises as a downscale cascade from balanced mesoscale dynamics or due to localized coherent features associated with a loss of balance, internal waves and surface forcing

OBJECTIVES

Our work is testing hypothesis 3 of the white paper "Scalable Lateral Mixing and Coherent Turbulence": Non-QG, submesoscale instabilities feed a forward cascade of energy, scalar and Ertel PV variance, which enhances both isopycnal and diapycnal mixing. Related hypotheses are that submesoscale variability is associated with coherent structures and anisotropic mixing. Further, submesoscale processes are inherently vertical, as well as horizontal, and that submesoscale processes facilitate cross-front exchange.

Our goals are to (1) determine whether lateral mixing at O(0.1-10 km) scales is due to a balanced downscale cascade from the mesoscale, or due to a local processes that lead to a loss of dynamical balance, e.g. at fronts; (2) identify processes that lead to enhanced lateral (along-isopycnal) dispersion on these scales, and to quantify the associated dispersion; (3) examine the relationship between vertical mixing and lateral dispersion; (4) understand the role of specific features and processes on lateral mixing. These include frontal singularities, eddies, filaments, and internal waves, and the impact of surface forcing on these.

APPROACH

Our approach is to run a number of process studies using a three-dimensional non-hydrostatic model, Process Study Ocean Model (PSOM) written by Amala Mahadevan (e.g. Mahadevan and Tandon 2006). The typical model resolution for resolving submesoscales varies from 100m to 1 km in the horizontal. We examined processes in a domain approximately 100 km x 200 km, but recently, we have improved the model to run on much larger domains (approximately 500 km x 1000 km) at the same horizontal resolution.

In the process, we developed two significant tools to explore the sensitivity of the resolved-scale features in meso- and submeso-resolving simulations to the level of sub-grid scale (SGS) dissipation. Firstly, we developed an anisotropic Smagorinsky model (ASM), and used the eddy kinetic energy budgets to estimate physically meaningful levels for the SGS dissipation under quasi-equilibrium conditions where the restratification by submesoscale eddies and destratification tendencies of wind forcing approximately balance.

Secondly, we developed coupling of the Generalized Ocean Turbulence Model (GOTM) to PSOM. This allows us to quantify both Turbulent Kinetic Energy and Dissipation for submesoscale resolving simulations.

Our model experiments are initialized with a stratified ocean on which we impose a lateral density gradient in the from of an idealized front. The ensuing instability of the front, the eddying flow field, and its effect on horizontal and vertical density gradients and buoyancy fluxes, as well as tracer dispersion, are then analyzed. We conduct three kinds of numerical experiments. (1) We study mixed layer restratification in the presence of surface wind and buoyancy forcing. Several parameters are varied to study eddy driven restratification resulting from varying frontal strengths as a function of the along-front wind stress and buoyancy forcing. (2) In another set of experiments, we introduce dye streaks in the pycnocline in the along-front direction and examine the effect of mixed layer eddies on the cross-front dispersion of the dye along isopycnal surfaces. The eddy diffusivity is calculated as the rate of change of the tracer variance with respect to the center of mass of the tracer field. (3) We generate near-inertial internal waves by varying the wind stress in the presence of a front. We examine the near-inertial wave energy, its generation, and propagation beneath the mixed layer as a function of the density structure at the front.

RESULTS

When a surface wind stress acts in the direction of the geostrophic flow (down-front) along a density front, it generates cross-front surface Ekman transport from the dense to buoyant side, convective mixing and an intensification of the front. This can counter the effect of restratification by eddies if the wind-driven overturning is greater in magnitude and opposed to the mean eddy driven overturning, which is restratifying. Similarly, negative buoyancy forcing (e.g. cooling) generates convective mixing that opposes the eddy-driven restratification. We derive a scaling estimate for the strength of wind and cooling that prevent restratification by eddies, and test this through numerical experiments in which we vary the cross-front density gradient, mixed layer depth and wind/buoyancy forcing (Mahadevan et al., 2010). We apply this to observations of the North Atlantic, where we estimate and model the onset of restratification by mixed layer eddies, and find this to be coincident with the onset of the spring phytoplankton bloom (Mahadevan et al., 2012).

Surface mixed layer eddies are found to be effective in dispersing tracers even in the pycnocline, at a depth of a few hundred meters. Streaks of tracer initially aligned with the front along an isopycnal in the the pycnocline are found to evolve in three phases: (i) Diffusively, at first, during the early onset of submesoscale instabilities, (ii) then very rapidly in a super- diffusive regime exhibiting exponential increase in tracer variance, and (iii) finally, entering a Richardson regime, in which spreading rates are more than diffusive, but not exponential.

Filaments emanate from fronts, through the nonlinear growth of baroclinic frontal instability. They are regions of strong vorticity and strain. Density filaments are associated with strong downwelling if they are denser than their surroundings. Water from the surface is subducted along the flanks of the filaments. The filaments drive a strong cross-front eddy flux that is proportional to the cross-front density gradient and mixed layer depth. The Nakamura diffusivity is large at the flanks of the filament, but not in the center of the filament which experiences strong horizontal shear and is itself a barrier to diapycnal exchange.

From our study of internal waves at fronts, we find that the near-inertial waves (NIW) generated in the surface ocean by variations in wind stress are much stronger in the presence of fronts. The NIW propagate downward from the surface in the presence of fronts, and the sloping isopycnals facilitate energy transfer to depth. The wavenumber is sensitive to the strength of the front, because the effective frequency of the waves is modified by the vorticity of the frontal jet.

Our studies of submesoscale dynamics via fronts, mixed layer eddies, and filaments reveal that these features are energetic and efficient at dispersing tracers cross front, through adiabatic advective processes. The associated eddy fluxes are dependent on the available potential energy (lateral buoyancy gradient and depth). Mixed layer eddies tend to stratify, converting horizontal density gradients to vertical gradients, but restratification can be countered by vertical mixing induced by surface wind and buoyancy fluxes. The competing effects of eddies and surface forcing are played out in the upper ocean.

Our most recent contributions in this DRI are threefold: in improving sub-grid parameterizations for process models investigating submesoscale turbulence, in investigating near-inertial waves near strong fronts and contributing via ongoing process studies related to LATMIX 2011 experiment.

The resolved eddy kinetic energy balance is sensitive to the SGS dissipation; this points to importance of the sub-grid parameterization in submesoscale resolving models. The ASM scheme shows excellent agreement with theoretically expected extraction of available potential energy. We also discovered that while the ASM showed high sensitivity to lateral SGS coefficients, this sensitivity decreased substantially when a two-equation parameterization of turbulent mixing via GOTM coupling was included. Our submesoscale simulations (Fig. 1) also show the forward kinetic energy cascade seen first by the UCLA group for the ROMS submesoscale simulations off California coast. This shows that forward kinetic energy cascade (with a -2 slope) appears to be a common signature of submesoscale flows. Another significant characteristic is that both ASM and GOTM closures show enhanced dissipation at submesoscale fronts as seen in observations.

We also conducted process studies with strong deep fronts, such as the Kuroshio. Observations near Kuroshio have shown banded structures in ageostrophic shear, perhaps a signature of loss of balance and near-inertial waves radiating away from this front. We explore this hypothesis using PSOM. The model is initialized by an observed hydrographic section, assumed to be in thermal wind balance. The unforced front goes baroclinically unstable to both mesoscale meanders and sub-mesoscale eddies and filaments. In addition, there is spontaneous generation of near inertial waves from the unstable front in bursts and at specific locations of the mesoscale meander, particularly east of the meander trough. Banded structures in horizontal divergence (Fig. 2) also signify near inertial wave generation. The associated wave energy fluxes show clockwise turning in the anticyclonic trapping regions as expected from interaction of near inertial waves with a baroclinic jet. The average internal wave flux magnitudes are higher during frontogenetic events. The radiated energy flux in our unforced simulations is comparable to the canonical wind generated near inertial wave fluxes. This indicates that frontogenesis along strong fronts can lead to a loss of cyclostrophic balance and radiation of near inertial internal waves that provide a route for energy transfer to the ocean interior, an important hypothesis to be explored in future.

During the current analysis phase, we have conducted submeoscale process simulations initialized with LATMIX1 Triaxus section, on June 12th 2011. This shows a density front extending to about 100m, with a shallow mixed layer (ML) of 20m. Temperature dominates the density, although the salinity front acts to partly compensate. These unforced simulations evolve into frontal instabilities characterized by O(5km) eddies, that stir salinity along isopycnal surfaces, resulting in intrusions (Fig. 3). Since the aspect ratios and scales of these intrusions are similar to those observed in the MVP and Triaxus sections, it is possible that the submesoscale frontal instabilities play a role in creating these intrusions.

Observations (LATMIX2 and Argo profiles) show the persistence of frontal gradients deeper than the mixed layer. This motivated several simulations to explore the consequences of deep baroclinicity for the buoyancy and tracer fluxes. We find deep baroclinicity, through quasi-geostrophic baroclinic instability, gives rise to enhanced isopycnal fluxes in the interior. Such fluxes promote adiabatic coupling between the mixed layer and the deeper ocean for sufficiently weak pycnocline stratification. Another important finding is that ageostrophic baroclinic instability, without accounting for symmetric instability, can lead to isopycnal subduction of passive tracers from the surface. This has important implications for the interpretation of LATMIX2 observations which show strong isopycnal subduction of dye injected into the mixed layer. In particular, our results emphasize the need for including ageostrophic instability and frontogenesis in the analysis of dye transport.

PUBLICATIONS

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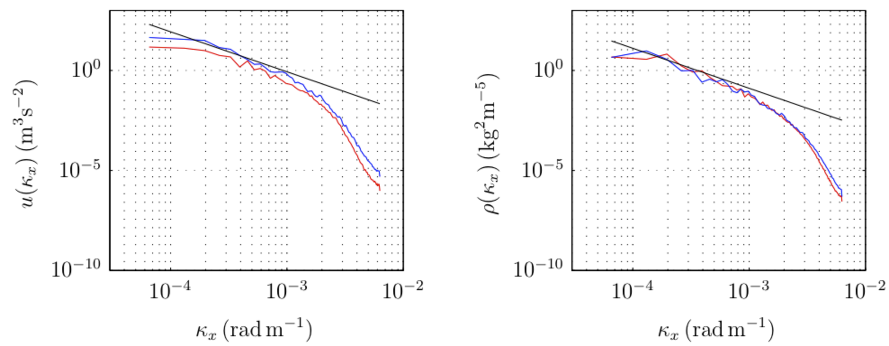

Figure 1 : Zonal velocity and density spectra from our wind driven submesoscale resolving simulations. The red and blue curves denote spectra averaged zonally, meridionally (near the front) and temporally (over one inertial period), after twenty inertial periods. The simulation for the red curve has a frontal gradient that extends below the mixed layer (~100m) to a depth of 450m while the front is confined to the mixed layer (~100m) in the simulation for the blue curve. The black solid line has a slope of -2.

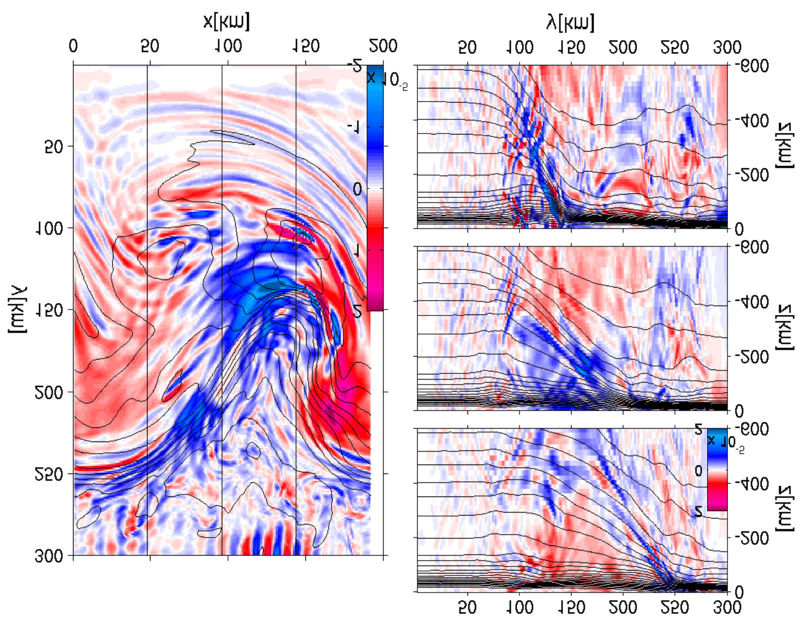

Figure 2: Divergence/convergence values, in plan view (left) and three sections (right) on a mesoscale frontal meander, showing both their sub-mesoscale extent and near-inertial wave signatures near the front.

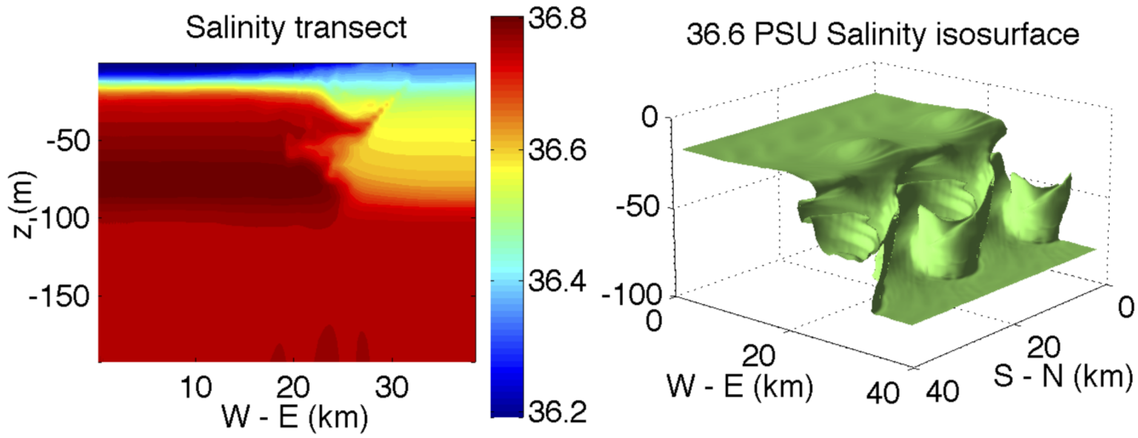

Figure 3: Section (left) and isosurface (right) of salinity from the model initialized by a 2011 LATMIX1 transect. The isosurface convolutions reveal that it is along-isopycnal fluxes by the eddies, rather than cross-isopycnal mixing, that creates the intrusion.

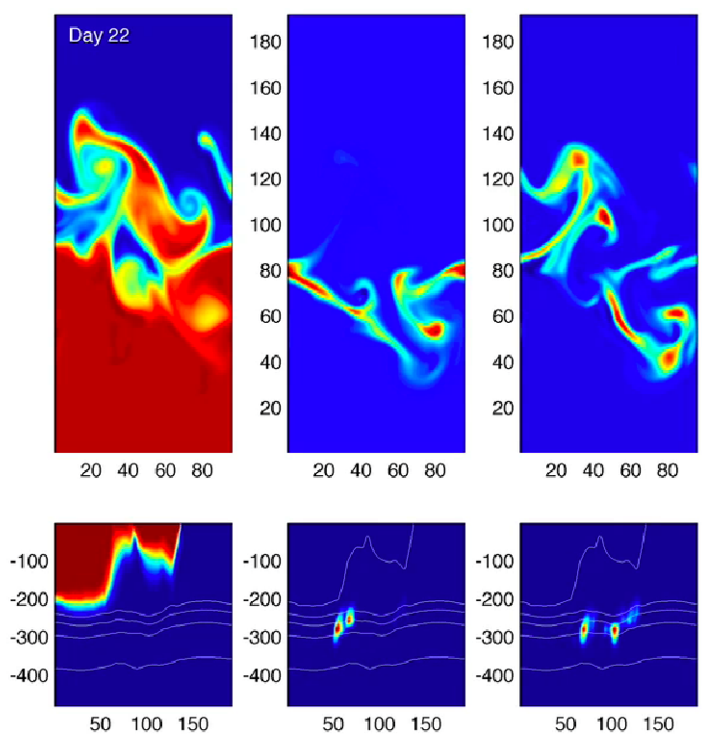

Figure 4: Tracer dispersion by submesoscale frontal and eddy processes as seen in model simulations of an unstable front. Top panels show surface and along-isopycnal surface views; lower panels show vertical sections through the front (contours are isopycnals). The tracer is colored red and spreads cross-front due to eddies and filaments The leftmost panels show tracer (red) initialized on the buoyant side of a mixed layer front. The middle and right panels show the evolution of along-front tracer streak on an isopycnal surface in the pcynocline.

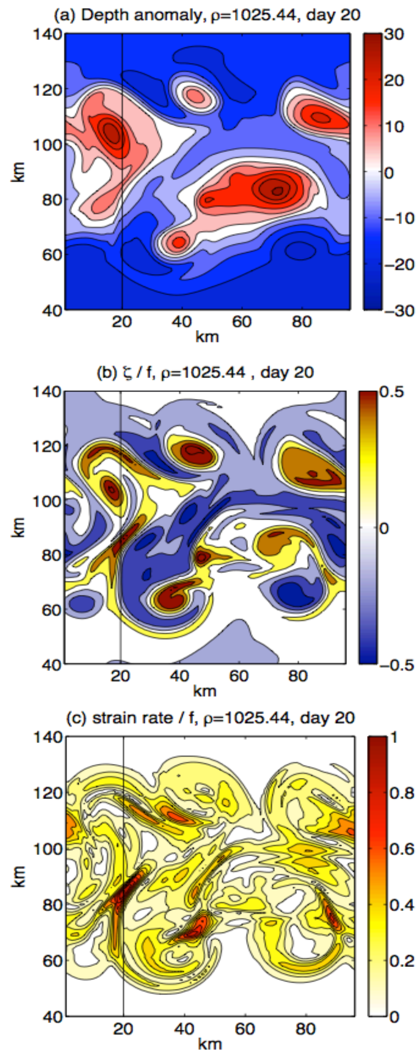

Figure 5: Along isopycnal properties beneath a mixed layer front. (a) Isopycnal height in meters, (b) vorticity normalized by f, and (c) strain rate normalized by f. Regions of strong vorticity and strain are coincident at submesoscales