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Submesoscale Routes to Lateral Mixing in the Ocean

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LONG-TERM GOALS

To determine whether lateral mixing at O(1-10 km) scales is due to a balanced or unbalanced downscale cascade from the mesoscale, or due to local vertical mixing by internal waves and surface forcing.

OBJECTIVES

Our work will test 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.

APPROACH

Our approach is to run a number of process studies using a three-dimensional non-hydrostatic model written by Amala Mahadevan (PI from Boston University *e.g.* Mahadevan and Tandon 2006). The typical model resolution for resolving submesoscales is about 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.

WORK COMPLETED

Masters student, Eric Holmes (UMass Dartmouth) and postdoctoral research associate, Gulatiero Badin (Boston University) have also contributed to this work.

The optimization and scaling done in Year 1 for use on modern multi-core computer architecture, allowed us to model larger domains with meso- and submeso-scale interaction at high resolution. In Year 2 this allowed a series of frontal simulations in a domain 432 km by 768 km, almost 4 times the previous size of 100km by 200km, with a 1km horizontal resolution, and 32 non-uniform levels in the vertical as before, while retaining the free-surface and non-hydrostatic capabilities. Our initial simulations are of a baroclinically unstable front in a periodic channel, in the presence and absence of intial meanders (to trigger mesoscale instability and associated frontogenesis), for both forced and unforced fronts.

We analyzed the spreading of tracer on isopycnal surfaces beneath a mixed layer front. Model simulations of a baroclinically unstable mixed layer front (Mahadevan et al., 2010) were performed in a zonal channel with a north-south density gradient confined only to the mixed layer. Tracer streaks were laid out on isopycnal surfaces (initially flat) beneath the mixed layer. Along-isopycnal mixing of the tracer was analyzed using different measures – variance in the cross-frontal direction, and an effective eddy diffusivity (Nakamura, 1996).

We examined the cross-frontal flux of tracers by means of surface density filaments. The formation of filaments as a function of various parameters is studied with our numerical ocean model.

RESULTS

Coupling to Density Gradients Beneath the Surface Mixed Layer

In simulations without wind stress, the vertical fluxes follow the scaling, as expected from previous work (Fox-Kemper *et al.* 2008). However, the scaling is sensitive to the coupling to the dynamics below the mixed layer, as shown in Fig. 1.

When the density structure below the mixed layer has significant horizontal gradients, the vertical fluxes are larger as can be seen by comparing the left and right panels in Fig. 1. The top left panel in Fig. 1 follows the Fox-Kemper et al. (2009) scaling. In presence of an initial meander which provides a trigger for baroclinic eddies to develop, the fluxes are higher. In addition, the competition between wind stress trying to destratify and mixed layer trying to stratify (Mahadevan *et al.* 2010) leads to higher vertical buoyancy fluxes in presence of wind.

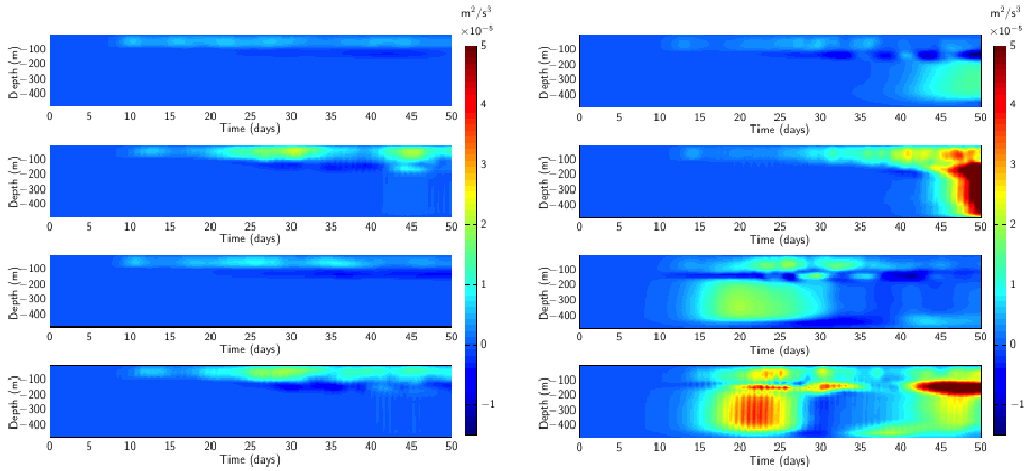
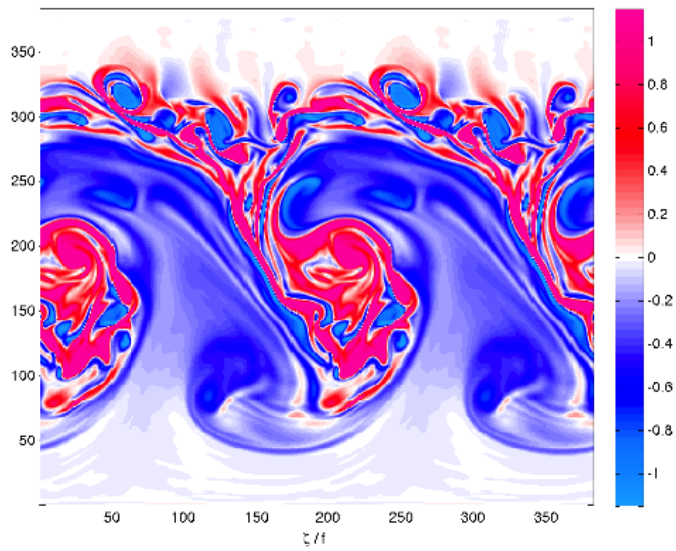


Figure 1 (Left Panel) Hovmuller plot of horizontally averaged vertical buoyancy flux w'b' for four simulations WITHOUT any baroclinicity below the mixed layer. The top panel shows the development due to mixed layer eddies in the top 100m, the second panel shows the influence of wind (no mesoscale meanders), the third shows the effect of an initial mesoscale meander (no wind), and the final panel shows fluxes in presence of both meander and wind. The panel on the right shows the averaged vertically buoyancy flux for simulations WITH the baroclinicity below the mixed layer.

The right panels in Fig.1 show the results in presence of baroclinicity below the mixed layer. In case with meander, in presence of wind and baroclinicity below the mixed layer, the high vertical fluxes are triggered quickly compared to the absence of these influences. These simulations strongly suggest that the sub-mesoscale characteristics in the LATMIX observational program would differ based on the horizontal density structure below the mixed layer (i.e, the mesoscale environment around the observations). In the moderate gradients experimental observations of 2011 with weaker baroclinic gradients underneath, the vertical fluxes will be low and vice-versa.

In preparation for the 2012 fieldwork in areas of more intense density gradients, we are now in the process of initializing the model with a section from the Kuroshio front (Nagai *et al.* 2009). This leads to intense mesoscale and sub-mesoscale structures to co-develop, as shown in a figure from a preliminary run in Figure 2. Early results indicate that the anticyclonic side of the front also begins to radiate near-inertial (and internal) waves, although this needs further analysis.



Mixing on Isopycnal Surface

Figure 2 A snapshot of vertical vorticity from a frontal simulation initiated with a section taken across the Kuroshio from Nagai, et al. (2009). Both mesoscale and sub-mesoscale structures are seen to develop with intense vertical vorticity values. The 200km by 400km solution is repeated zonally to show the mesoscale and sub-mesoscale structure in a square aspect ratio.

In our numerical experiments of mixed layer baroclinic instability, the submesoscale eddies that are formed in the mixed layer begin to penetrate into the pycnocline as is seen in the along-isopycnal vorticity (Fig 3). The eddy kinetic energy decays with depth beneath the base of the mixed layer. Tracer streaks on the isopycnal surface begin to fold and stretch, until they break into blobs that are advecting with the flow (Fig. 3). The spreading of tracers shows three distict phases. The first regime is diffusive; the tracer streak is contiguous, and the variance grows linearly in time. The second regime is highly super-diffusive. In this phase, the tracer gets advected in cross-front filaments of high strain. Cross-frontal spreading occurs at an exponential rate. Finally, a third regime is reached, where the tracer streak is dismembered into distinct blobs that are advected by the flow.

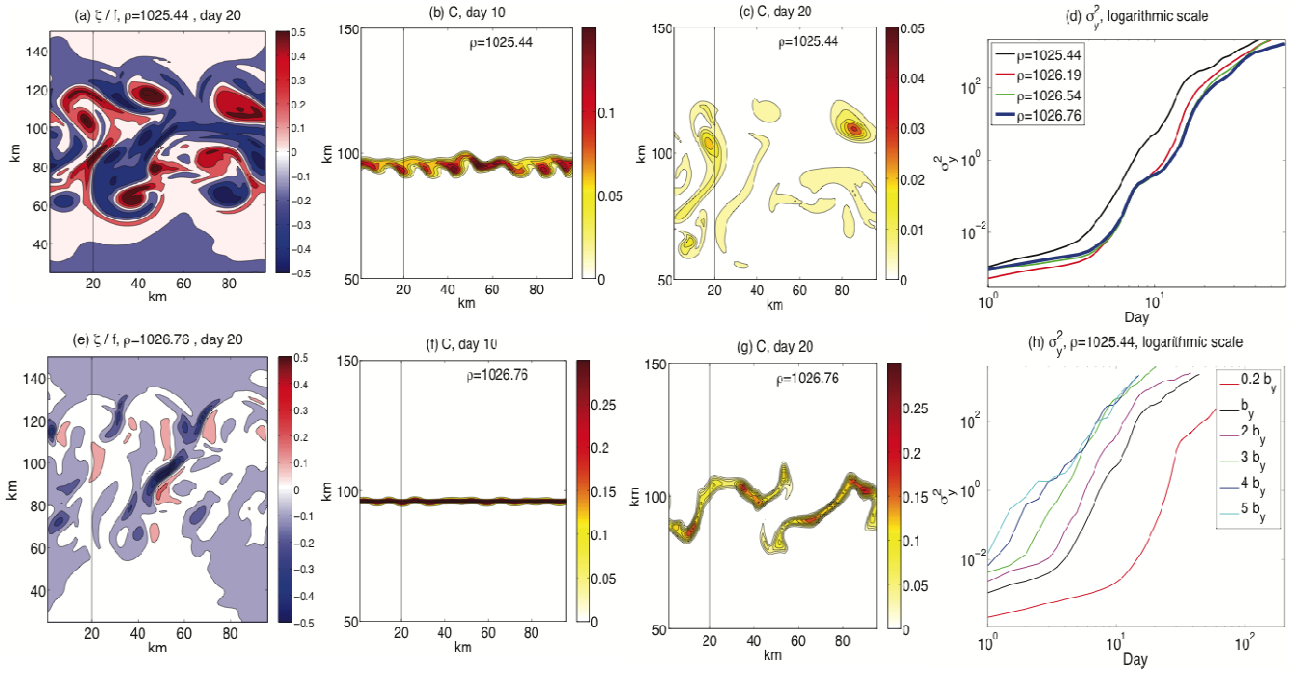


Fig. 3. Mixing by submesoscale mixed layer eddies is examined on isopycnal surfaces beneath the mixed layer. (a)-(c) show the isopycnal sigma=25.44, and (e)-(g) sigma=26.76. Panels (a) and (e) show the vertical component of vorticity (normalized by f) on the isopycnal.. A streak of tracer, 1 grid cell wide is laid down across the entire east-west extent of the domain at the time of initialization on each of the isopycnal surfaces. (b),(c) and (f),(g) show the tracer concentration on the isopycnals 10 days and 20 days after initialization, respectively. (d),(h) Cross-front variance of the tracer concentration on the isopycnal surfaces is plotted as a function of time in log-log space to determine the power law relationship. (d) 3 regimes are seen on different isopycnal surfaces (h) Curves represent varying strengths of the cross-frontal buoyancy gradient.

OTHER ACTIVITIES

Holmes, Tandon and Mahadevan gave presentations at the AGU Ocean Sciences meeting 2010 in Portland.

Mahadevan, Tandon and Badin participated in the Eur-Oceans and Europole Mer 2010 workshop on the Influence of meso- and submesoscale ocean dynamics on the global carbon cycle and marine ecosystems.

Mahadevan, Tandon and Badin individually made presentations at the GFD summer school at Woods Hole in summer 2010.

A modeling workshop on Lateral Mixing was organized for the DRI in Boston in July 2010 with Mahadevan and Badin as local hosts.

Other seminars and presentations include Stanford, URI, UCAR, U.Waterloo, MIT.

Tandon conducted an ocean circulation workshop for high school teachers in summer 2010, and also presented ocean circulation related experiments at the Working Waterfront Festival in New Bedford Harbor in September 2009 and September 2010.

REFERENCES

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PUBLICATIONS

Mahadevan, A., A. Tandon and R. Ferrari, 2010, Rapid changes in mixed layer stratification driven by submesoscale instabilities and winds, *J. Geophys. Res.,* 115, C03017, doi:10.1029/2008JC005203.

Manuscripts in Preparation

Badin, G., A. Tandon and A. Mahadevan, Submesoscale lateral mixing in the pycnocline.
Mahadevan, A., J-L.Thiffeault and A. Tandon, Effects of strain and shear on mixing in the ocean.
Holmes, E., M.S. Thesis, Effect of mesoscale-submesoscale interaction on tracer fluxes.
Badin, G., A. Tandon and A. Mahadevan, Cross-frontal mixing via filaments.