

Lateral Mixing

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LONG-TERM GOALS

I seek to understand the processes controlling lateral mixing in the ocean, particularly at the submesoscale, i.e. 100m-20km.

OBJECTIVES

Existing high resolution regional models typically resolve the mean vertical structure of the upper ocean boundary layer. Physically-based parameterizations of vertical fluxes make it possible to account for subgrid mixing at length scales smaller than the layer depth, but no specialized parameterization is used to represent the dynamics of horizontal mixing below the $O(1)km$ - $O(10)km$ resolution scale. We aim to determine the physical limitations of subgrid parameterization on these scales. These projects address the following questions:

- What physics govern horizontal and vertical mixing in the presence of horizontal variability on the 1-10 km scale?
- What is the relative importance of horizontal and vertical mixing in determining the structure of the boundary layer?
- What physics should be included to improve parameterizations?

APPROACH

During AESOP, Lee and D'Asaro pioneered an innovative approach to measuring submesoscale structure in strong fronts. An adaptive measurement program employed acoustically-tracked, neutrally buoyant Lagrangian floats and a towed, undulating profiler to investigate the relative importance of vertical and horizontal mixing in governing boundary layer structure in the presence of $O(1)$ km scale horizontal variability. Remotely sensed sea surface temperature and ocean color, combined with rapid, high-resolution towed surveys and model results guide float deployments to key locations within fronts. Synoptic, high-resolution surveys followed Lagrangian float drifts to characterize three-dimensional variability within the span of a model grid point. Acoustic tracking allowed towed surveys to follow floats and geolocated all observational assets for later analysis. Measurements characterized boundary layer turbulence and facilitated detailed separation of vertical and horizontal processes.

Report Documentation Page

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These measurements were specifically designed to allow direct comparison with Large Eddy Simulations and thus have direct application to assessing regional model subgrid parameterizations.

This project funds final analysis of 2006 and 2007 AESOP data and D'Asaro's role in the execution and analysis 2011 and 2012 Lateral Mixing experiment.

WORK COMPLETED

In February and March 2012, I participated in the second LATMIX experimental program. This was focused on measuring submesoscale structures in an extremely challenging environment: the North Wall of the Gulf Stream in winter. This combined all of the major elements thought to contribute to strong submesoscale activity. Strong lateral gradients were caused by the convergence of subtropical water carried northward by the Gulf Stream with subpolar water carried southward along the east coast of North America. Strong meteorological forcing occurred in February and March with the climatological winds blowing along the front, a condition that promotes Ekman transport of the cold heavy water over the warm lighter water and thereby causes intense submesoscale activity. Deep mixed layers, occurring at the end of the winter season, increase the potential energy associated with the lateral gradients, thereby increasing the intensity of submesoscale motions.

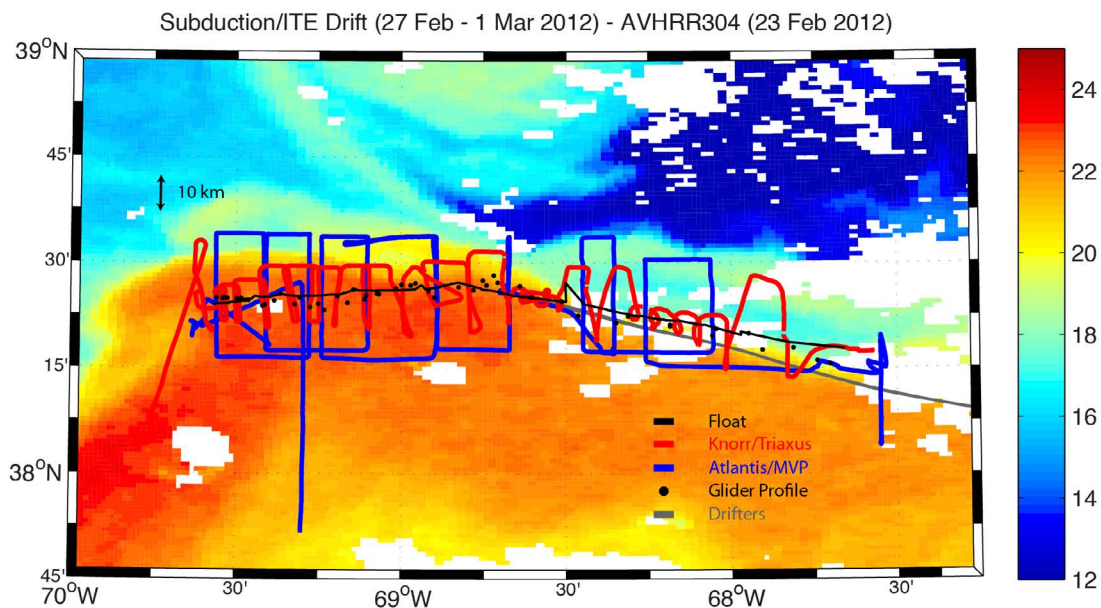


Figure 1. First of 4 intensive 2-ship surveys at the North Wall of the Gulf Stream during the LATMIX 2012 experiment. A Lagrangian float was deployed within the front and drifted downstream at 1-2 m/s while being tracked by the R.V. Knorr. The R.V. Knorr and R.V. Atlantis surveyed around the float on a 1-20 km scale measuring temperature, salinity and velocity down to about 200m. Gliders, surface drifters and in some cases fluorescein dye were also deployed and followed the float.

The experiment work involved two global class vessels, the *R.V. Knorr* and *R.V. Atlantis*, each carrying a towed/profiling CTD package for making km-scale temperature, salinity, density and velocity surveys. This project paid for the preparation of two Lagrangian floats, designed to accurately track the three-dimensional motion of water parcels. A Trackpoint-II system was installed on the *R.V. Knorr* and used to acoustically track the float; the deep mixed layers and high quality of the WHOI mounting system allowed unusually good tracking, often exceeding ranges of 5 km. Each float measured temperature and salinity at its top and bottom (1.4 m separation) and high frequency velocity relative to the float. The float provided a central point for each of 4 intensive surveys at the North Wall as shown in Figure 1. In each, the float was deployed close to the front, the *R.V. Knorr* surveyed on a 5-km-scale around the float, while the *R.V. Atlantis* surveyed on a 10-20-km-scale. Up to 4 gliders were deployed nearby and also navigated to stay near the float. On some surveys, multiple surface drifters were deployed. On three of the four surveys, dye was injected near the float and its evolution mapped by the two-ship surveys.

An additional experimental effort surveyed the more homogeneous region south of the Gulf Stream. Here, deep mixed layers and the continual lateral injection of potential vorticity and scalars is predicted to create an intense ‘submesoscale soup’ of high small-scale variance shown in the left-hand panel of Figure 2. The combination of small scales and the expected high-frequency near-inertial oscillations presents a particularly challenging sampling problem. We overcame this by driving the two ships 1-km apart along a set of lines through the region, thereby getting km-scale simultaneous spatial differences in the cross-track direction and nearly simultaneous spatial differences on km-scale in the long-track direction.

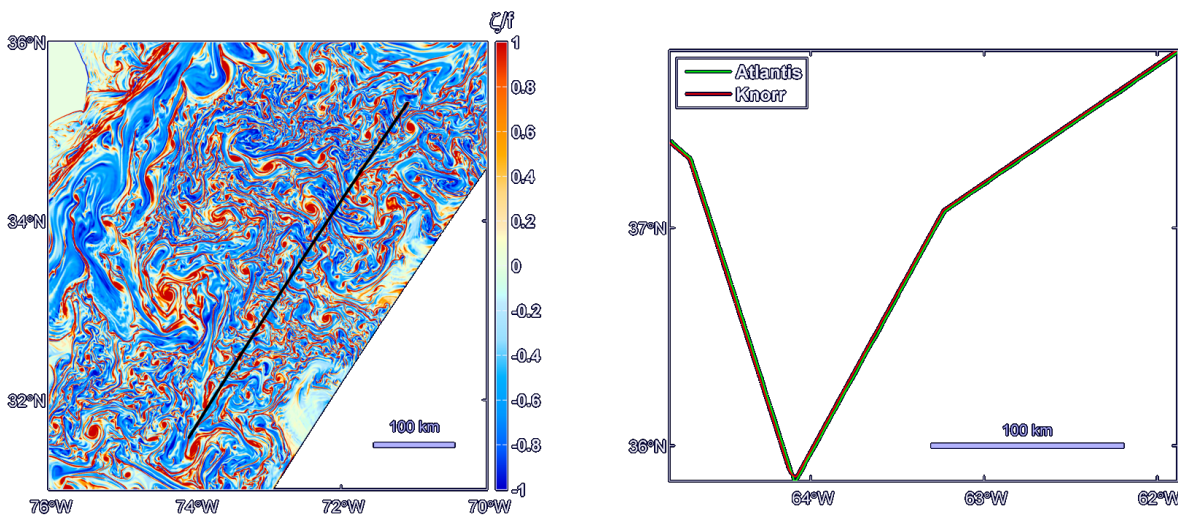


Figure 2. ‘Submesoscale Soup’ survey during the 2012 LATMIX experiment. Left: Numerical models (this figure courtesy of J. Molemaker) predict intense vorticity fluctuations on km-scale southeast of the Gulf Stream. Right: This region was sampled by driving both ships in parallel tracks 1 km apart along an approximately 500 km long pattern.

RESULTS

The four Gulf-Stream surveys yielded detailed surveys of the evolution of the front. Some specific results include:

- A thin ribbon of negative potential vorticity (PV) was commonly found at the front, as would be expected theoretically given the prevailing strong downfront winds and a strong front. This 20-100m thick layer was typified by stable stratification, driving PV positive, and a strong lateral density gradient and vertical shear, driving PV negative. The second term dominated over the first at the front, resulting in negative PV.
- Float trajectories and dye injections within this negative PV layer show rapid mixing across isopycnals in the upper part of the boundary layer, and along isopycnals in its lower parts. An example is shown in Figure 3. This is consistent with mixing by symmetric instability, similar but deeper and more energetic than seen by D'Asaro et. al (2011).
- The symmetric instability is modulated by energetic near-inertial oscillations, as would be expected given the stormy wind forcing. However, these are strongly modified by the frontal structure and, in turn, modulate the symmetric instability.
- The structure and statistics of the 'submesoscale soup' is remarkably similar to that predicted by the submesoscale-resolving model in Figure 2.

IMPACT/APPLICATIONS

We were surprised that our array of a float, gliders and dye could remain coherent for several days in a region of such large velocities and high strain. This suggests that autonomous sampling systems, with proper control, can coherently sample even in the most energetic oceanic conditions.

The combined AESOP/LATMIX studies show the complexity of submesoscale phenomena at fronts, but also show strong agreement with models and theory, suggesting that rapid progress is likely.

PUBLICATIONS

HONORS/AWARDS/PRIZES

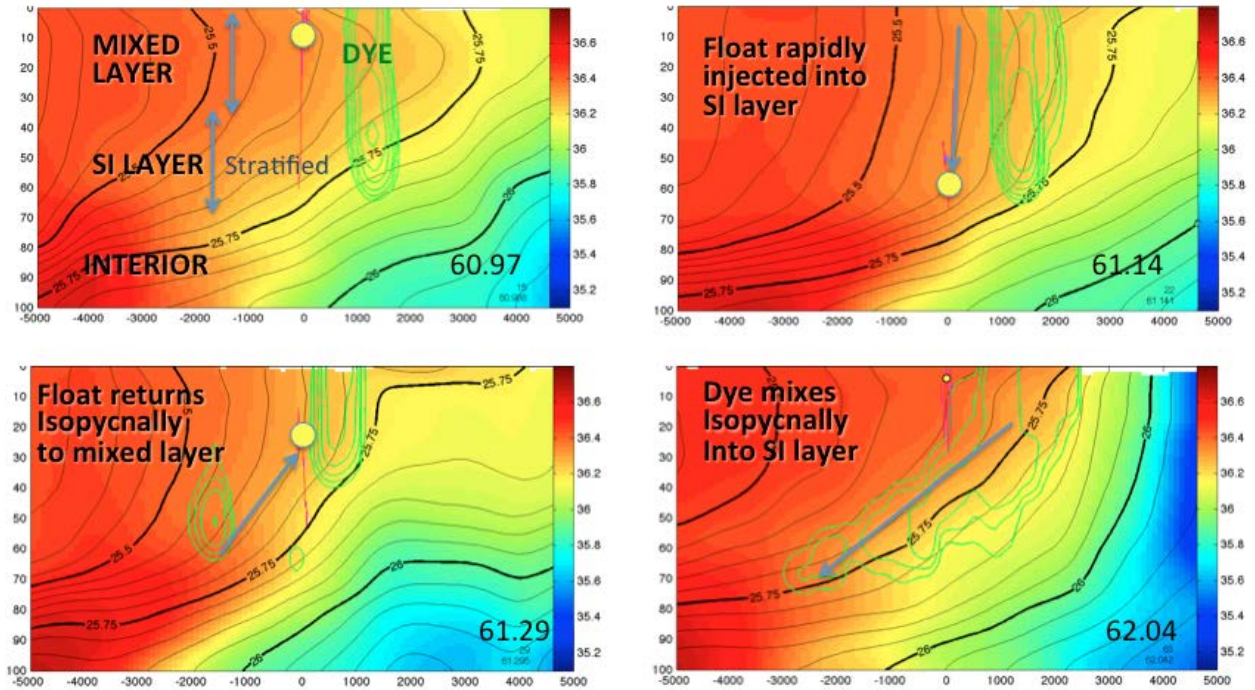


Figure 3. Evolution of the Gulf Stream front during the second survey of the LATMIX 2012 experiment as seen by the motion of a Lagrangian float (yellow dot), the evolution of density (black contours) and salinity (colors) in ship surveys surrounding the float and the evolution of dye (green contours) injected near the float. Time, in yeardays of 2012, is shown by the number in the lower right of each panel. The dye and float initially mix vertically to about 50m, despite the vertical stratification. The float eventually returns to the surface, demonstrating exchange between the interior and the surface, while the dye spreads out along the same isopycnal, showing how this exchange leads to deep subduction of some of the surface water. The boundary layer can thus be divided into an upper turbulent mixed layer and a lower symmetric instability (SI) layer with a new form of SI turbulence.