

## **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

# Report Documentation Page

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boundary layer turbulence and facilitated detailed separation of vertical and horizontal processes. These measurements were specifically designed to allow direct comparison with Large Eddy Simulations and thus have direct application to assessing regional model subgrid parameterizations.

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. 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. 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

This project funds D’Asaro’s role in the analysis of the 2011 and 2012 Lateral Mixing experiment and, with Craig Lee’s project, supports Andrey Shcherbina’s analysis work on this same data.

## **WORK COMPLETED**

A paper comparing the submesoscale structures in the ‘submesoscale soup’ has been published.

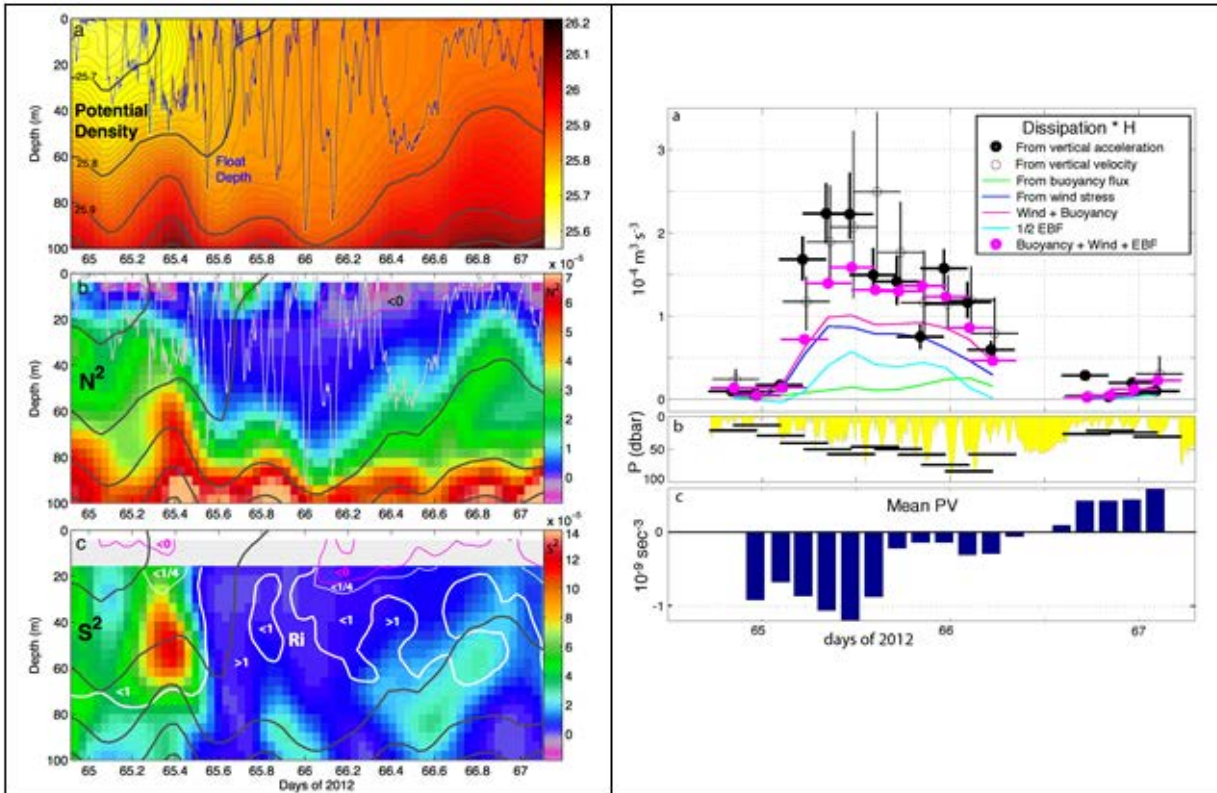
A LATMIX 2011 overview paper is accepted in BAMS.

A second analysis, lead by Leif Thomas at Stanford, has focused on the North Wall and the associated mixing processes. Preliminary results from this are described below.

## **RESULTS**

Fig. 1 summarized the conditions within the Gulf Stream North Wall during a period of strong forcing and mixing. These were computed by combining turbulence data from the float with survey data from the *R.V. Knorr* during the LATMIX 2012 experiment, averaged over a region close to the float. The upper 80m of the front undergoes a rapid and dramatic transition at about yearday 65.5 (left panel). Before this, strong winds blowing down the front, set up the conditions for symmetric instability. The boundary layer becomes strongly stratified and sheared, as seen from the survey data, but still allows

continuous mixing, as seen from the float trajectory. The potential vorticity becomes strongly negative (right panel c) and the kinetic energy dissipation is larger than that expected from meteorological forcing alone (right panel a). This is similar to what was seen in our 2007 observations of the Kuroshio under much weaker forcing. At yearday 65.5, the stratification and shear abruptly disappear, so that the upper 60m becomes well-mixed in density and velocity. The transition is associated with a peak in vertically integrated dissipation and strongly negative values of potential vorticity (right panel).



**Figure 1. Evolution of vertical structure within the North Wall of the Gulf Stream during the 2012 winter experiment. Left: a) potential density (contoured and colored) and float depth (blue line). b) Vertical density stratification expressed as buoyancy frequency squared (colored). Boundary of unstable regions are indicated by the magenta lines. Float trajectory is repeated from panel a. c) Vertical shear squared (colors) and Richardson number = buoyancy frequency squared over shear squared (white contours). Selected density contours as in panel a. Right: a) Time series of boundary layer integrated dissipation estimated from float acceleration spectrum (black solid symbol) and from float vertical kinetic energy (black opensymbol). Expected dissipation from various forcings: buoyancy flux (green line), wind stress (blue line), their sum (red line), Ekman Buoyancy flux (cyan line) and the sum of all forcings (magenta symbol). b) Float depth during Lagrangian drifts (yellow filled) and boundary layer depth for each time window (heavy black) estimated as twice the mean float depth. c) Mean potential vorticity in the boundary layer.**

Theory and modelling of this transition show that it is due to strong inertial oscillations set up by the wind forcing. The oscillations first enhance the stratification and shear, but then, at the transition time, erase them entirely by strongly advecting heavy water over light, thereby mixing the upper ocean by

convection. LES simulations confirm this interpretation and further show that symmetric instability is more efficient at extracting kinetic energy from geostrophic currents when inertial oscillations are present. Thus inertial oscillations are a key component of boundary layer physics in the presence of lateral density gradient, just as they are in the absence of such gradients.

## **IMPACT/APPLICATIONS**

The 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. Our results indicate that these theories can yield parameterizations of the submesoscale for use in larger scale models.

## **PUBLICATIONS**

Shcherbina, A., E. A. D'Asaro, C. M. Lee, J. M. Klymak, M. J. Molemaker, and J. C. McWilliams, 2013, Statistics of vertical vorticity, divergence, and strain in a developed submesoscale turbulence field, *Geophys Res Lett*, 40, 4706–4711, DOI: 10.1002/grl.50919.

Shcherbina, A. et al., 2014, The LatMix Summer Campaign: Submesoscale Stirring in the Upper Ocean., *Bull. American Meteorological Society*, in review

## **HONORS/AWARDS/PRIZES**

Eric D'Asaro was elected to the National Academy of Sciences, the first experimental physical oceanographer so honored in many years. This undoubtedly reflects scientific contributions made possible by ONR support over the last 30 years.