2013 Annual Report for Project on Isopycnal Transport and Mixing of Tracers by Submesoscale Flows Formed at Wind-Driven Ocean Fronts

Leif N. Thomas
Department of Environmental Earth System Science
School of Earth Sciences, Stanford University
473 Via Ortega
Stanford, CA. 94305
phone: (650) 721-1140 fax: (650) 489-5099 email: leift@stanford.edu

Grant Number: N00014-09-1-0202
http://pangea.stanford.edu/~leift/

LONG-TERM GOALS

This project is part of the DRI on Scalable Lateral Mixing and Coherent Turbulence that aims to characterize lateral mixing in the ocean on scales of 10m-10 km, the submesoscales. Lateral mixing at the submesoscales is not accounted for in present-day ocean models. This deficiency is a potential source of error in the numerical prediction of the distribution of temperature, salt, nutrients, phytoplankton, pollutants, etc. in the upper ocean. The goal of the DRI is to develop parameterizations for submesoscale processes to improve the simulation of lateral mixing in ocean models.

OBJECTIVES

Winds blowing along ocean fronts are highly effective at energizing flows on the submesoscale. The process involves three stages: a frontal mixing stage where small scale gravitational and symmetric instabilities homogenize properties in the mixed layer, a subduction phase where three-dimensional baroclinic mixed layer instabilities exchange fluid along isopycnal between the mixed layer and pycnocline, and a phase in which the mixed layer instabilities evolve into coherent vortices that drive lateral stirring along surfaces of constant density. Near-inertial waves (NIWs) can be generated as well that are strongly modified by fronts. The objective of this research is to characterize and parameterize the submesoscale physics involved in each of these steps and in the generation, propagation, and dissipation of NIWs, and evaluate the lateral mixing characteristic of the flows. Dynamical insights gained from the research have been used for planning, interpreting, and analyzing observations collected during the two field programs that were conducted as part of the DRI.

APPROACH

The approach taken in this project is to use a combination of theory, process-oriented numerical experiments, and analysis of observations of wind-driven submesoscale flows to study the governing physics of these flows. Analysis and diagnostics of the simulations and observations will be used to construct parameterizations for coarser resolution numerical models that cannot explicitly resolve the submesoscale.

WORK COMPLETED

In this fifth year of the project I have analyzed the observations from the LatMix 2012 field campaign showing evidence for the interaction of inertial motions and symmetric instability in the boundary layer. I developed a simple theoretical model for this interaction and in collaboration with John Taylor (DAMPT, University of Cambridge) have been analyzing output from large eddy simulations (LES) configured to study the process. Under my supervision, my graduate student, Dan Whitt, has been analyzing the observations from the LatMix 2012 field campaign evidencing strong NIWs in the thermocline of the Gulf Stream and their potential for mixing.

In addition to this observational work, John Taylor and I have completed a theoretical study that illustrates how inertial motions can be rapidly damped by a parametric subharmonic instability that forms in fronts as a consequence of frontal horizontal density gradients. This study is in review in the Journal of Fluid Mechanics. Elements of both the theoretical and observational analyses have been presented at the Fall AGU meeting in December of 2012 and at a meeting on Ocean Turbulence in Santa Fe, NM in June 2013 organized by Los Alamos National Laboratory.

RESULTS

Most of the LatMix 2012 cruise was organized around a series of drifts following Eric D'Asaro's Lagrangian float in the proximity of the North Wall of the Gulf Stream. On these drifts we observed evidence for the generation, propagation, and dissipation of NIWs. On one drift that took place between March 5-8, the wind stress was particularly strong and variable (Fig. 1a) resulting in the generation of an inertial oscillation (IO) in the boundary layer, as evidenced in the vertical shear of the velocity (blue circles in Fig. 1b-c) oscillating at near the inertial frequency. A comparison of the shear to the output of a slab mixed layer model forced by the observed winds is shown in Fig 1b-c (red lines). Before yearday 65.6, the oscillations in the model and observations share a similar phase relation and amplitude. Further evidence of an IO can be seen in the time variability of the boundary layer stratification. For example, between yeardays 65.3-65.6, while the shear in the cross-stream direction was negative, isopycnals steepened, as would be expected from advection of density by inertial currents (Fig. 2c-e).

The winds, while variable, had a component in the downstream direction, i.e. in the sense to destabilize the front by lowering the potential vorticity (PV) of the current to negative values. Negative PV was indeed observed in the boundary layer in cross-stream sections (Fig. 2) and was associated with stable stratification and cyclonic vorticity, telltale signs of a symmetrically unstable flow. Symmetric instability (SI) is a submesoscale phenomenon that acts as a source of turbulence at ocean fronts. Unlike other forms of boundary layer turbulence, SI derives its energy from frontal currents as opposed to winds, cooling, or surface waves. It is thus an important process because it represents a sink of kinetic energy for the ocean circulation. Theories for SI developed in the past by myself and others have studied SI under conditions of steady forcing, neglecting the effects of IOs. The forcing experienced during the drift was far from steady and lead to strong IOs, implying that these existing theories could not be applied to this data set. To fill this gap in knowledge, I developed a theory for the interaction of SI with IOs.

The theory involves a linear stability analysis of a flow based on the conditions present during the drift: negative PV, a horizontal density gradient, an inertial current, and oscillating stratification. In contrast to SI in a steady flow, SI in the presence of an IO experiences periods of explosive growth that occur a little less than half an inertial period after the peak in stratification (Fig. 3a). LESs configured with a flow similar to that used in the linear stability analysis illustrate that during these periods, SI develops secondary shear instabilities that enhance turbulence. The observed dissipation, as estimated from the Lagrangian float (Fig. 3c), shows that consistent with the theory, turbulent motions were intensified near yearday 65.5, a little less than half an inertial period after the peak in stratification.

A striking finding from the observations, is the disappearance of the IO after yearday 65.6 (Fig. 1b-c). We posit that this rapid damping of the IO is caused by the downward radiation of near-inertial energy out of the boundary layer. The evidence supporting this hypothesis is the bands of strong vertical shear observed in the Gulf Stream thermocline that oscillate at near-inertial frequencies (Fig. 4a). These shear bands were characterized by upward propagating phase, suggesting downward propagating energy. While consistent with our hypothesis, what was puzzling was the rapidity of the energy propagation. A theory for NIWs in strong fronts that my graduate student Dan Whitt and I developed suggests that this fast propagation is a consequence of the intense horizontal gradients in density and vorticity found in the North Wall. A ray tracing calculation based on this theory shows that rays of NIWs are anomalously steep at the front, leading to a funneling of near-inertial energy down from the surface. The theory also predicts that the group velocity of NIWs decreases in the thermocline, suggesting that wave shoaling and amplification should be found there. The high shears and low Richardson number of the NIWs seen in the observations (Fig. 4a-b) are consistent with this prediction. The amplitude of the NIWs in the thermocline was large enough for wave breaking to occur, as evidenced by the bands of elevated dissipation and diapycnal mixing inferred from Kipp Shearman's glider-based microstructure measurements. Given the combination of enhanced diapycnal mixing and strong shear, these NIWs would be expected to drive lateral mixing via shear dispersion with a lateral diffusivity that we estimate to be of order 1 m^2s^{-2}.

Motivated in part by the observational findings of the DRI, John Taylor and I have performed theoretical calculations and numerical simulations that illustrate a new damping mechanism for vertically-sheared inertial motions involving an inertia-gravity wave (IGW) that oscillates at half the inertial frequency, f, and that grows at the expense of inertial shear. This parametric subharmonic instability (PSI) forms at fronts where thermal wind shear, by reducing the PV, allows for IGWs with frequencies less than f. For a flow with uniform shear and stratification, PSI develops when the Richardson number of the frontal flow nears 4/3. When this criterion is met, IGWs with a frequency $f/2$ and with flow parallel to isopycnals amplify, extracting kinetic energy from the inertial shear. The solutions of the numerical simulations are consistent with these predictions and additionally show that PSI when of finite amplitude both damps inertial shear and is itself dampened by secondary shear instabilities (Fig. 5). In this way, PSI opens a pathway to turbulence where kinetic energy in inertial shear is transferred to small scales and dissipated.

IMPACT/APPLICATIONS

The observations of symmetric instability in the Gulf Stream shed light on a new form of turbulence in the upper ocean that we are calling SI-turbulence. It forms at wind-forced fronts and compared to other forms of upper ocean turbulence, such as wind-driven shear instabilities and Langmuir circulations, SI is new and unique in that it derives its energy from fronts as opposed to the wind or waves. It thus represents a sink of energy for the general circulation and is also quite efficient at lateral mixing as evidenced by the rapid dispersion of dye during the surveys. The trapping of strong near-inertial waves at fronts that has been observed in the Gulf Stream and modeled by Whitt and Thomas (2013) also represents an efficient mixing mechanism. A large fraction of the kinetic energy (KE) in the ocean's inertia-gravity wave (IGW) spectrum is contained in NIWs and inertial motions. While the generation mechanisms of inertial motions, i.e. time-variable winds, is relatively well-understood, the manner in which their KE is lost is less certain. The parametric subharmonic instability that John Taylor and I have discovered represents a sink of KE for inertial motions and a source of small-scale turbulence and mixing that could be important at ocean fronts.

PUBLICATIONS

Thomas, L. N., 2012. On the effects of frontogenetic strain on symmetric instability and inertia–gravity waves. *J. of Fluid Mech.*, 711, 620-640.

Thomas, L. N. and J. R. Taylor, 2013. Damping of inertial motions by parametric subharmonic instability in baroclinic currents. *Submitted to the J. of Fluid Mech.*

Thomas, L. N., E. D'Asaro, J. Taylor, C. Lee, J. Klymak, 2013. The interaction of inertial oscillations with symmetric instability in the Gulf Stream. *In internal review*.

Whitt, D. and L. N. Thomas, 2013. Near-inertial waves in strongly baroclinic currents. *J. of Phys. Ocean*. 43, 706–725.

Whitt, D., L. N. Thomas, J. Nash, K. Shearman, C. Lee,J. Klymak, E. D'Asaro. 2013. Near-inertial mixing in the Gulf Stream thermocline. *In internal review*

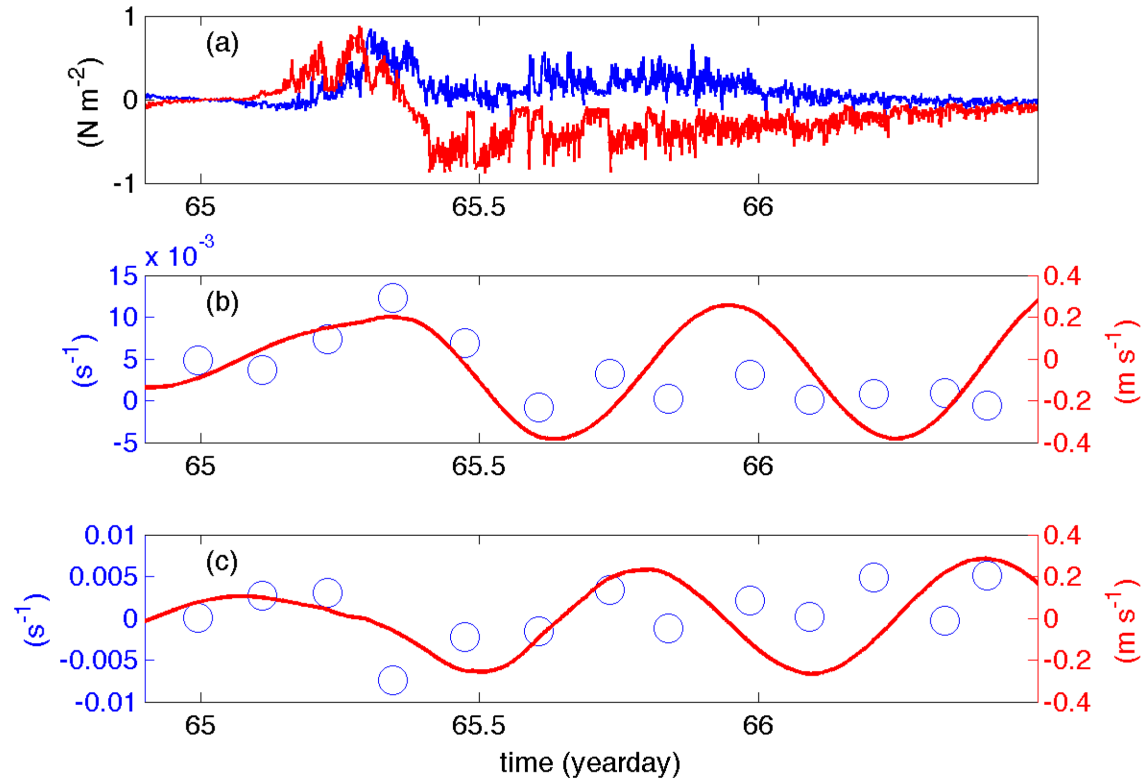

Fig. 1: Time series of the downstream (blue) and cross-stream (red) components of the wind stress (a), where downstream is defined to be in the direction of the float's drift. The down-stream and cross-stream components of the vertical shear (blue circles in (b) and (c), respectively) averaged across the top 60 m and horizontally over a cross-stream transect. The solution from a slab mixed layer model forced by the observed winds for the velocity in the downstream and cross-stream directions is indicated by the red lines in panels (b) and (c), respectively, and is scaled by the axis to the right in red. Before yearday 65.6 the observed vertical shears exhibit an inertial oscillation with similar phase and amplitude to the solution from the slab mixed layer model. After yearday 65.6, however, inertial oscillations are not evident in the observations, apparently having been dampened.

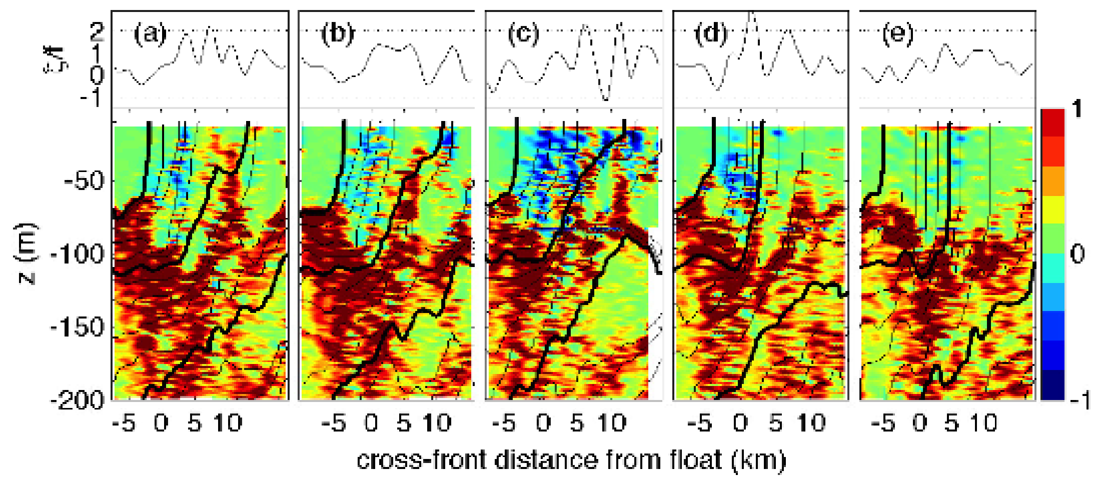

Fig. 2: A sequence of the vertical vorticity averaged over the top 60 m normalized by the Coriolis parameter (top panels) and cross-stream sections of density and potential vorticity (bottom panels). The sections were made on the \R/V Atlantis around yearday 65.11 (a), 65.23 (b), 65.35 (c), 65.47 (d), and 65.61 (e). Density is contoured every 0.1 kg m^{-3} and the thicker contours denote the 25.5, 26.0, and 26.5 kg m^{-3} isopycnal surfaces. The presence of negative potential vorticity in a stably stratified boundary layer with positive vorticity indicates that the flow is symmetrically unstable. Note the steepening of isopycnals in the upper 60 m from yearday 65.35-65.61.

.

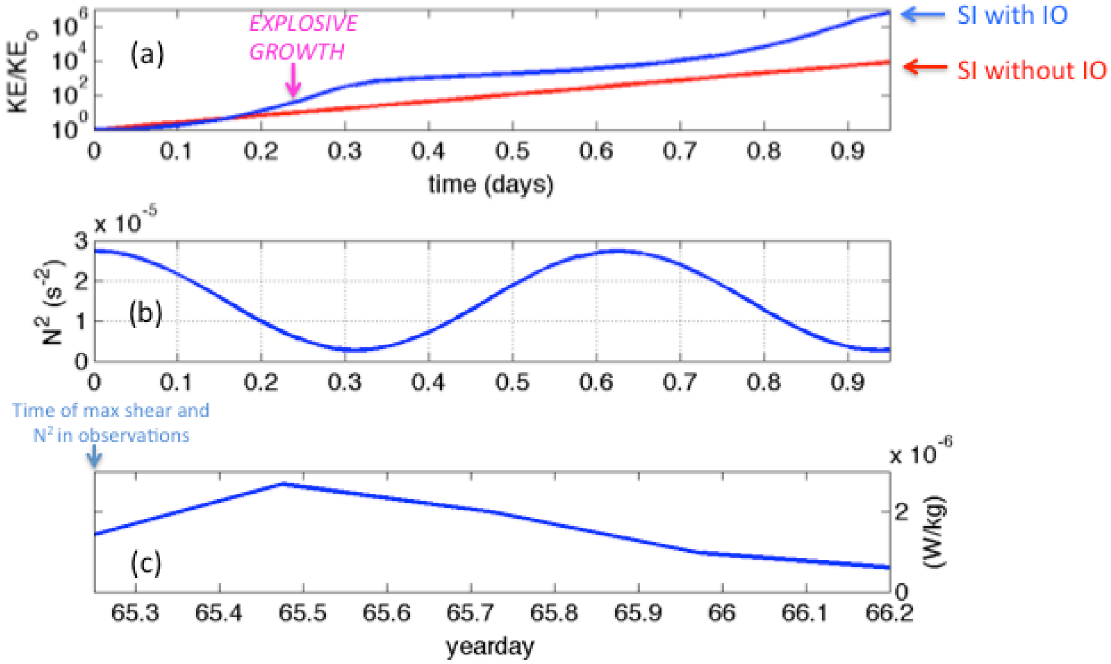

Fig. 3: (a) The KE of symmetric instability (SI) as predicted by a linear stability analysis (blue line) in flow field with similar characteristics to the observations, i.e. with negative potential vorticity, an inertial oscillation, and stable yet time variable stratification (shown in panel (b)). The KE of SI in a flow field without an inertial oscillation but with the same PV is also shown in the panel (red line). The interaction of SI with the inertial oscillation leads to periods of explosive growth that occur a little less than half an inertial period after the peak in stratification. Large eddy simulations configured with a flow similar to that used in the linear stability analysis illustrate that during these periods, SI develops secondary shear instabilities that enhance turbulence. (c) The observed dissipation as estimated from the Lagrangian float indeed shows that turbulent motions are intensified near yearday 65.5, a little less than half an inertial period after the peak in stratification.

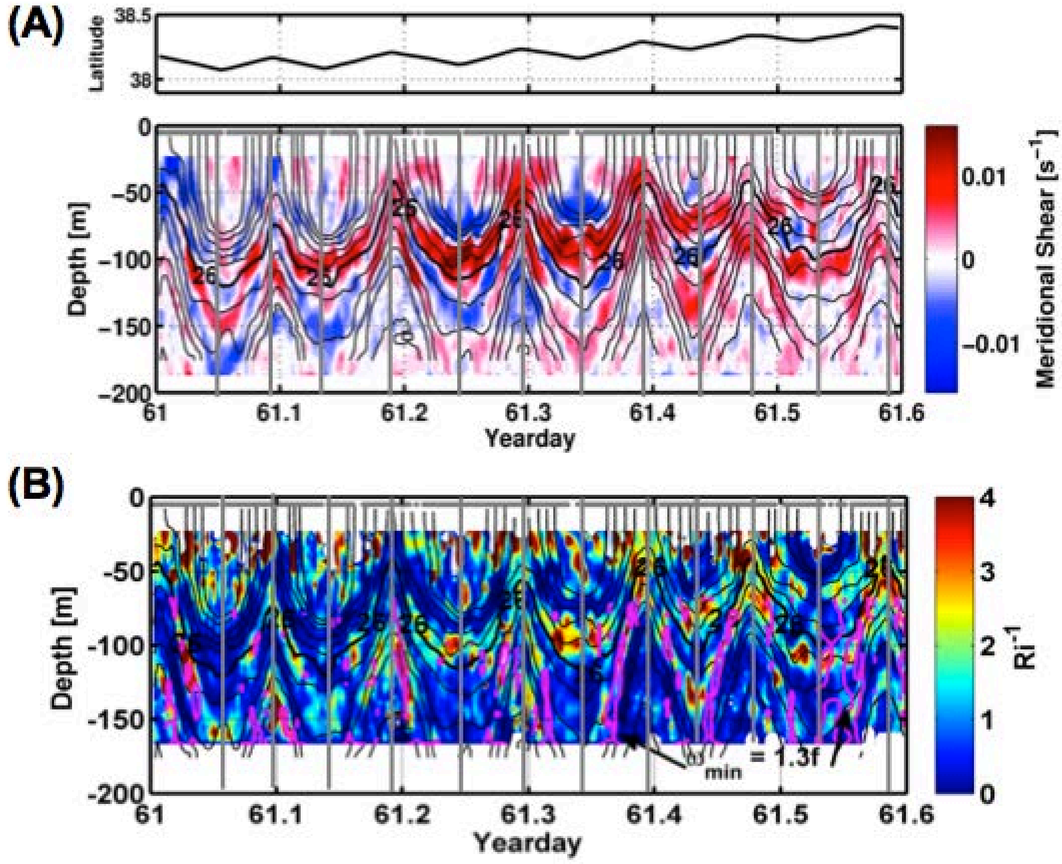

Fig. 4: Evidence of NIWs in the thermocline of the Gulf Stream and their potential for breaking. Depth-time series of density (contours), vertical shear of the meridional velocity (a) and the inverse Richardson number, Ri^{-1}, (b) on a Lagrangian drift from March 2-3 (yearday 61-62). The bowl like structure of the fields is a consequence of the ship track (plotted at the top of (a)) crossing the front multiple times. Bands of strong shear, running nearly parallel to isopycnals and that oscillate at a frequency 1.2f are observed in the thermocline. At certain phases of these NIWs Ri^{-1} approaches a value of 4, i.e. the threshold for breaking.

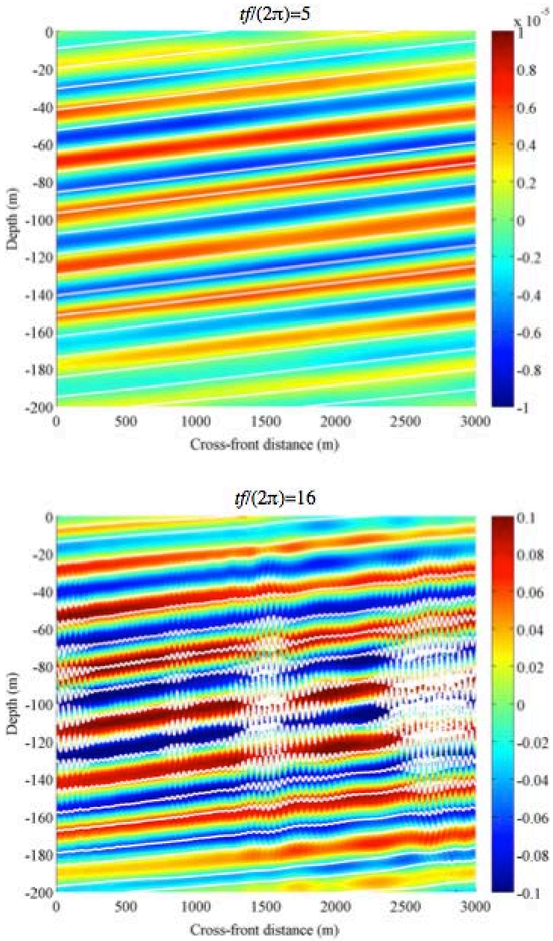

Fig. 5: Visualizations of the cross-front velocity (color shading) and isopycnals (white contours) from a numerical simulation illustrating the parametric subharmonic instability that can grow off of an inertial oscillation in a front. The upper row shows a time during the linear phase of the instability, with nearly along-isopycnal motion, and at times of maximum (left) and minimum (right) stratification. The bottom row again shows times corresponding to minimum and maximum stratification, but now at a later time immediately following the onset of a secondary shear instability.