Lateral Mixing DRI: Turbulence-Resolving Simulations of Upper-Ocean Lateral Mixing

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior
- Frontal dynamics, in particular the role of surface forcing in lateral mixing
- The interaction of finescale and submesoscale upper-ocean mixing at fronts.

OBJECTIVES

The focus of modeling in this study is to quantify relationships between surface fluxes of heat, energy and momentum, the available baroclinic potential energy, the resultant vertical mixing and geostrophic imbalance, and the ensuing dependence of lateral mixing at successively larger scales on atmospheric forcing.

APPROACH

Large Eddy Simulations of 3D large-eddy turbulence in boundary layers of depth 10m< H_{ML}<100m have enabled model-data comparisons against measurements of turbulence and dispersion. Such comparisons can critically assess the role of mixed layer dynamics and surface-driven vertical mixing in the cascades of baroclinic potential energy into submesoscale lateral mixing processes. Large Eddy Simulations (LES) have been done in close collaboration with E. A. D'Asaro and C. M. Lee, whose AESOP field experiments measure upper ocean mixing processes in the strong lateral density gradients of the Kuroshio and in a weaker front of the California Current off Monterey, during periods of varying wind and wave forcing. Field experiments for the LatMix DRI will provide further basis for realistic modeling efforts. These simulations incorporate virtual Lagrangian Floats, gliders and drifters, to provide a basis for interpreting these small-scale mixing measurements. In addition to LES modeling and parameterization of observed and simulated frontal regimes, Harcourt has been participating extensively in the field component of the LatMix DRI by providing a steady stream of remote sensing and regional model data to scientists in the field through the information flow (INFLO) subgroup of the DRI.

WORK COMPLETED

Providing remote sensing and ocean model imagery and data in compact form to ships during field experiments constitutes a significant effort in this year. Dubbed information flow (INFLO), a system for archiving and serving images to ships with low bandwidth capabilities, was developed out of Harcourt's prior roles in the field work of E.A. D'Asaro and Lee during the AESOP DRI. While there are many sources of data and imagery available from multiple agencies, the requirements of field program are more specific, and a consistent and unified system for framing and downloading data to scientists was necessary. This has been a service activity to the DRI carried out with important assistance from J. Molemaker in the June 2010 pilot program under J. Ledwell.

Analysis of new and previous LES model results has focused on parameterizing horizontal fluxes and TKE components in simulations of field observations made during the AESOP DRI. Results of this analysis are described in greater detail below. In addition, a collaborative paper (D'Asaro et al, 2010) on observations of a sharp front in the Kuroshio is in nearly final form for submission. Another paper still in review (Inoue et al., *submitted*) examines mixed layer TKE budget discrepancies in wintertime Gulf Stream observations, and the possible impacts of submesoscale dynamics and the forward cascade of energy to small scales on this budget.

RESULTS

Work on LES modeling and parameterization in FY 2010 has sought to formulate effective parameterizations for simulated mixed layer fronts. Working along the lines of second moment closures, an equilibrium model was developed for how lateral mixing depends on vertical fluxes of heat and momentum. The equilibrium model neglects transport divergence and planetary rotation terms in the covariance budgets, but provides a useful tool for picking apart different processes contributing to lateral fluxes in complex mixed layer simulations. It relates down-front and cross-front turbulent kinetic energy (TKE) components $\overline{v'^2}$ and $\overline{u'^2}$, corresponding scalar fluxes $\overline{v'\theta'}$ and $\overline{u'\theta'}$, as well as $\overline{u'v'}$ and $\overline{\theta'^2}$, to vertical momentum and scalar fluxes $\overline{u'w'}$, $\overline{v'w'}$ and $\overline{w'\theta'}$ in mixed layer shear and stratification and the dissipation length scale that may be diagnosed in the LES.

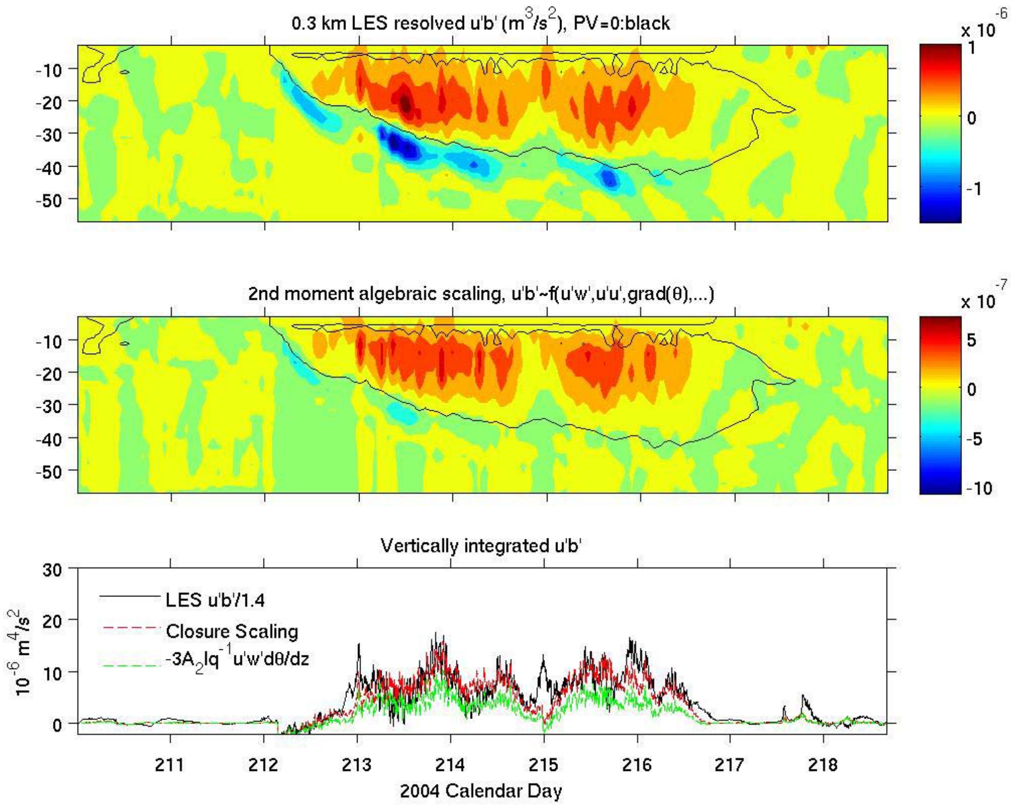

Fig.1. The evolution of profiles of small domain (288m x 288m) LES model cross-frontal buoyancy flux $\overline{u'b'}$ of a down-front wind event observed in a California current front (top) is compared with predictions (middle) from an equilibrium closure model based on LES vertical fluxes (middle). The comparison (bottom) of the integrated closure scaling to LES results (scaled uniformly by 1.4) also shows the dominant term contributing to $\overline{u'b'}$ production.

Figures 1-2 illustrate the ways in which this horizontal boundary layer closure both works and fails. This LES model run of the California Current observations made by E.A. D'Asaro, C.M. Lee and R.R. Harcourt (as shore support) in 2004 is carried out at 3m resolution over a week period spanning paired Lagrangian float and Triaxus towed body surveys. The model was forced by in situ fluxes, radiation and winds, and using Stokes drift from modeled wave spectra to include Craik-Leibovich forcing terms. The distinction between the comparisons to the horizontal equilibrium model closures in Fig. 1 and Fig. 2 is that the LES domain in Fig. 1 is 288m x 288m, while the one in Fig. 2 is 1152m x 1152m. In both figures the evolution of the cross-frontal buoyancy flux $\overline{u'b'}$ is averaged horizontally and compared with the corresponding horizontal closure equilibrium model both in the evolving profile and in its vertical integral.

For the smaller domain (Fig.1) the second moment closure equilibrium model predicts lateral fluxes that very closely track vertically integrated $\overline{u'\theta'}$ through the experiment (Fig. 1 bottom), after an overall adjustment in the return-to-isotropy closure constant for momentum-scalar covariance A_2 from its customary value in second moment closure models for vertical fluxes. Similar adjustments also appear in close tracking between other LES horizontal TKE levels and fluxes and the equilibrium closure model. In Figure 2, however, it is clear the skill of the equilibrium model is limited in the much larger LES domain to early phases of the downfront mixing event, to the period before inverse cascade or mixed layer instability processes populate O(300-600m) scales more than an order of magnitude larger than the mixed layer depth. These features have now also been reported by E. Skyllingstad in this DRI for fronts forced by both wind and the Craik-Leibovich vortex force due to surface wave Stokes drift. While the equilibrium model does not work well in the Larger LES domain when these submesoscale structures develop, it fails specifically because of identifiable problems in the closure assumptions used, particularly the assumptions for pressure-shear and pressure-stratification covariances that are expected to drive boundary layer turbulence towards isotropy. Further modeling efforts are under way to more carefully look at these pressure fluctuation covariances and develop new closure assumptions to improve the skill of second moment closures for lateral mixing problems.

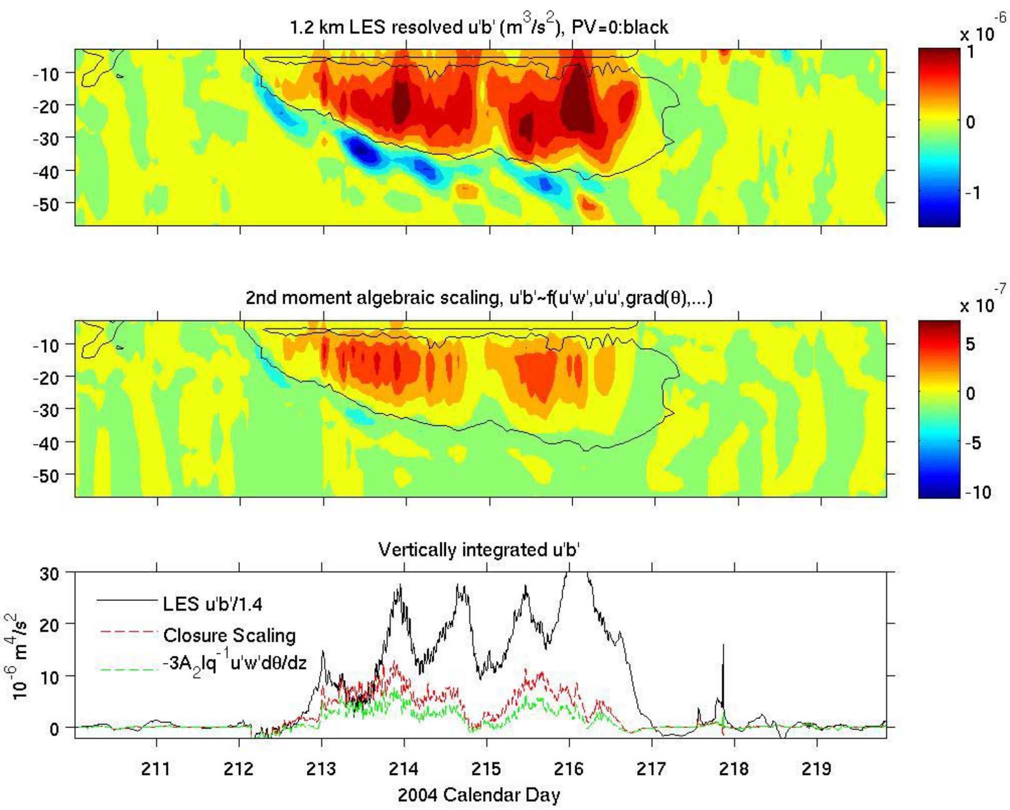

Fig.2. The evolution of profiles of the large domain (1152m x 1152m) LES model as described otherwise in Fig.1 . Departure in the integrated $\overline{u'b'}$ (bottom) from the net closure scaling and it's largest component coincides with the development of submesoscale features at more than O(10) times the mixed layer depth.

Significant progress has been made in accounting for the impact excess float buoyancy on Lagrangian float measurements. This problem is important in the context of Lateral Mixing observations because floats traversing density fronts under submesoscale lateral mixing can become significantly more or less dense than their environment, and although corrective ballasting is possible this capability is limited. A perscription for removing systematic errors due to float buoyancy from turbulence statistics of vertical velocity has been developed for a wide set of wind and wave-driven mixed layer cases (Harcourt & D'Asaro, *in press*). This study also reflects ONR-sponsored work under the Typhoons and AESOP DRI's.

IMPACT/APPLICATIONS

Lateral Mixing DRI results bear on the predictive skills of regional scale models with O(1-10) km resolution. At these scales the parameterizations of both vertical and lateral fluxes are not well understood or tested, especially in energetic frontal environments, or in subsurface environment where lateral mixing is driven by the relaxation of stratification anomalies produced by turbulent mixing events.

RELATED PROJECTS

One focus of the Lateral Mixing DRI is to continue a focus of the AESOP DRI to improve our understanding of mixed layer instabilties and associate lateral mixing process in a close collaboration between modeling and observations, and in particular on the combination of LES modeling and Lagrangian float observations. Typhoons DRI relies similarly on LES and LES-based models for the interpretation of Lagrangian float data, particularly where density changes along the float path due to lateral gradients can impact the relationship between Eulerian and Lagrangian turbulence statistics.

REFERENCES

D'Asaro, E. A., C. M. Lee, L. Rainville and L. Thomas 2010: Enhanced mixing and dissipation at an ocean front *in preparation*.

Inoue, R., M. C. Gregg and R. R. Harcourt, 2010: Mixing rates across the Gulf Stream, Part 2: Implications for non-local parameterization of vertical fluxes in baroclinic surface boundary layers, *submitted to J. Mar. Res.*.

PUBLICATIONS

Harcourt, R.R., and E.A. D'Asaro, 2010: Measurement of Vertical Kinetic Energy and Vertical Velocity Skewness in Oceanic Boundary Layers by Imperfectly Lagrangian Floats *submitted to J. Ocean. Atmos. Tech.* [in press, refereed]