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Scalable Lateral Mixing and Coherent Turbulence (LatMix) DRI: Turbulence-Resolving Simulations of Upper-Ocean Lateral Mixing

Ramsey R. Harcourt
Applied Physics Laboratory
University of Washington
Seattle, WA 98105
phone: (206)221-4662 fax: (206) 543-6785 email: harcourt@apl.washington.edu

Award Number: N000140910174
http://opd.apl.washington.edu/~harcourt

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

Physically-based parameterizations of vertical mixed layer fluxes in ocean models characterize turbulent mixing at length scales smaller than the layer depth, but neglect the dynamics of unresolved horizontal mixing processes below their O(1)-O(10) km horizontal resolution scale. Numerical modeling can be used to test new and existing scaling predictions of surface boundary layer horizontal mixing processes in regions of significant horizontal variability, as commonly found in major ocean fronts and coastal regions. The goal of numerical modeling work in in this year of the DRI 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. The objective in simulation analysis and model-data comparison is to develop dynamic scalings for the horizontal and vertical components of turbulent kinetic energy and fluxes in baroclinic upper ocean environments. These scalings will be used to compare with observations of lateral mixing and to tune modifications of existing upper ocean boundary layer models.

APPROACH

Large Eddy Simulation techniques are employed in the context of a background lateral density gradient where perturbations are doubly periodic. This baroclinic column geometry is used to simulate the response of turbulence on scales smaller that the domain, and simulations of 3D large-eddy turbulence in boundary layers of depth 10m< H_{ML}<100m can be compared with *in situ* measurements of turbulence and dispersion. Model forcing cases encompass mean buoyancy gradients $4\text{x}10^{-7}\text{s}^{-}$

$^2<M^2<2x10^{-6}s^{-2}$, destabilizing surface buoyancy losses to 100 W/m^2, and winds 5m/s$<U_{10}<$18m/s both with and without wave forcing through the Craik-Leibovich mechanism. Domains are 1-3 km wide across fronts, 0.4-1 km across-front, and 50-100m deep to accommodate mixed layers 40<H<80m, and isotropically resolved to 1-2 m using viscosity based on an advected subgrid TKE budget. Simulations can incorporate virtual Lagrangian Floats, gliders and drifters, to provide a basis for interpreting these small-scale mixing measurements.

WORK COMPLETED

Numerical modeling in this year has been motivated by differences between the ~400-600*m* scales of coherent lateral structures in prior simulations of baroclinic mixed layer turbulence in a front of the California current observed during the AESOP DRI (Fig. 1), and the 1-3*km* scales predicted for the lateral length scales in wind-driven turbulence with symmetric instabilities (SI) by in results for similar LES cases of Thomas and Taylor (2010) and of Taylor and Ferrari (2010). Numerical simulations carried out this year include forcing and domain cases to reproduce those reported in these studies, and additional cases at higher and lower wind stress and surface buoyancy loss forcing, as well as at larger and smaller imposed background baroclinic density gradients. Ongoing simulations are testing the effect of the short down-front dimensions of the oblong domain geometry on realized submesoscale instabilities.

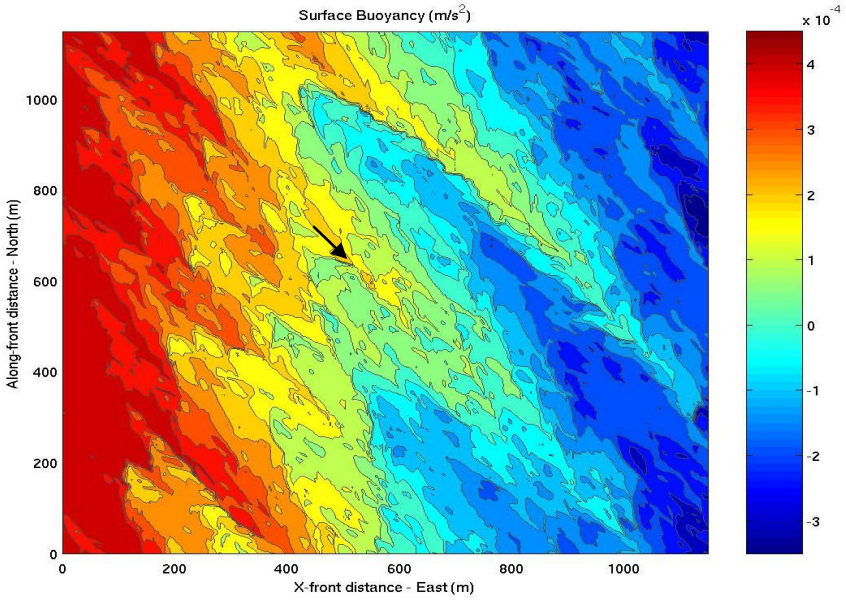

Figure 1: Surface buoyancy b from LES of baroclinic mixed layer in the California current with mean lateral stratification $M^2=6.3x10^{-7}s^{-2}$, x-y periodic perturbations, and time-dependent wind, waves and heat fluxes.

RESULTS

Results previously reported for baroclinic mixed layer cases forced by steady surface buoyancy loss or down-front wind stress were generally reproduced, but with significant quantitative differences. Cross-frontal length scales predicted to grow under the effect of SI to ~3km in wind-driven baroclinc layers with $M^2=6.3e^{-7}s^{-2}$ and surface stress 0.1 N/m^2 grew only to ~1km. For SI driven by buoyancy flux the slope of SI was reproduced, but with cross-frontal wavenumbers 2-3 times higher.

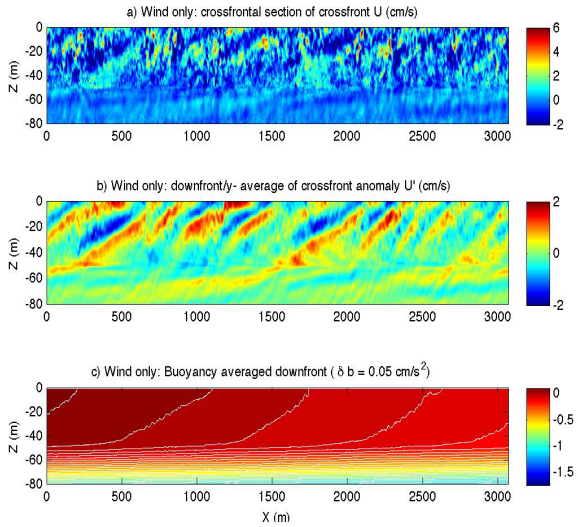

Figure 2: LES of baroclinic front forced by wind-only: a) Cross-frontal x-z section of cross-frontal velocity U; b) downfront (y-averaged) cross-frontal velocity anomaly $\langle U' \rangle_y$; c) contours of isopycnals and mean buoyancy and $\langle b-b_0 \rangle_y$ relative to central surface.

The slow growth of lateral length scales due to SI appears to account for the remaining differences between steady-state simulations and unsteady forcing cases. Figure 2 illustrates the cross-frontal velocity structures sloping along isopycnals, after a day of steady forcing, with ~500m lateral scales, comparable to those found for the California current with significant diurnal and higher frequency variability (Fig. 1).

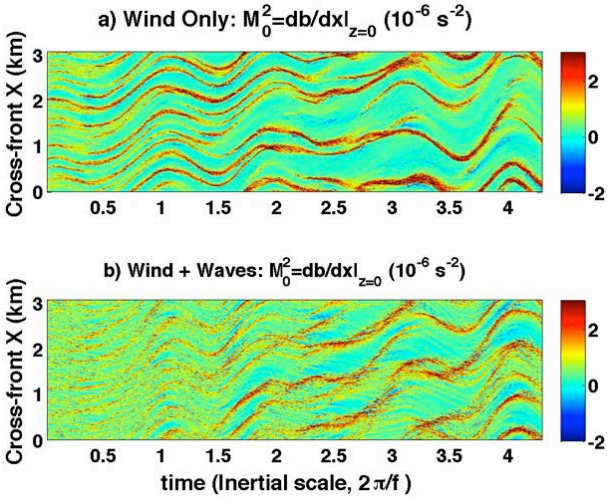

Figure 3: Evolution of front scales in cross-frontal surface stratification M_0^2 over the course of simulations forced by (a) 0.1 N/m^2 wind stress and (b) with additional forcing from a fully developed wave field.

The evolution of surface front structures mirrors that of cross-frontal circulations due to SI in the lower layer for simulation both with and without surface wave forcing. While the widths of individual fronts is altered by the Craik-Liebovich vortex force, the growth of inter-frontal scales (Fig. 3, 4a) and lower layer stratification remains very similar between the two cases. The growth to O(1) km scales of fully developed SI after 3 inertial timescales in both cases corresponds to lower the growth and equilibrium bulk Richardson numbers between 0.3-0.4 (Fig. 4b).

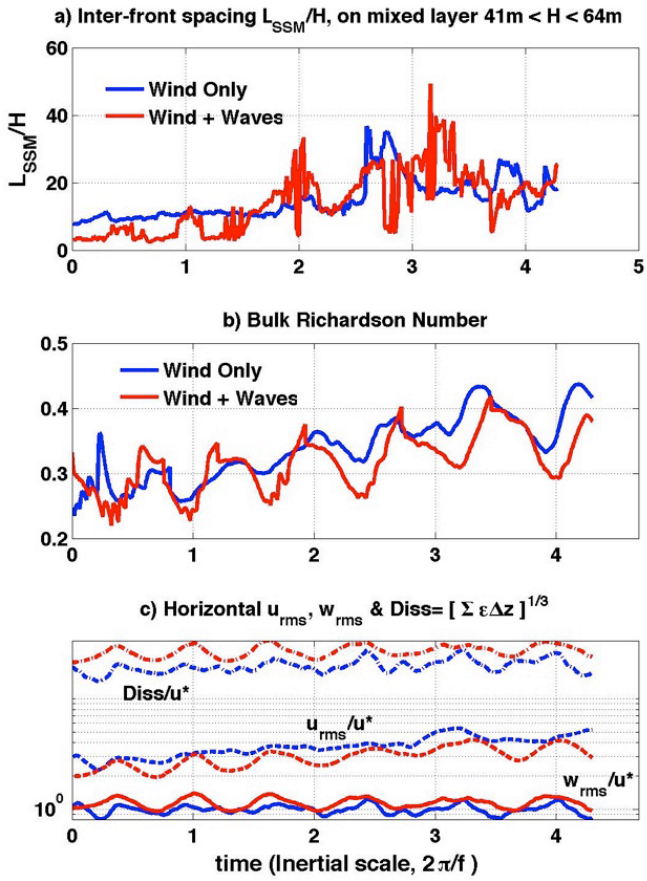

Figure 4: Evolution to steady-state of (a) inter-frontal length scale, (b) bulk Richardson number and (c) u*-scaling of horizontal (u_{rms}) and vertical (w_{rms}) TKE components and vertically-integrated dissipation ('Diss'), for LES cases with and without surface waves.

While mean dissipation (Fig 4c) is elevated several-fold by the additional TKE production from redistributing surface momentum flux down the geostrophic shear in the mixed layer, also known as the 'Ekman buoyancy flux'. Mean vertical TKE w_{rms}^2 is not correspondingly increased, except (Fig. 5) locally in rough correspondence to the variability in surface M^2, with a similar pattern for dissipation. Horizontal TKE components u_{rms}^2, v_{rms}^2 increase steadily to full SI levels.

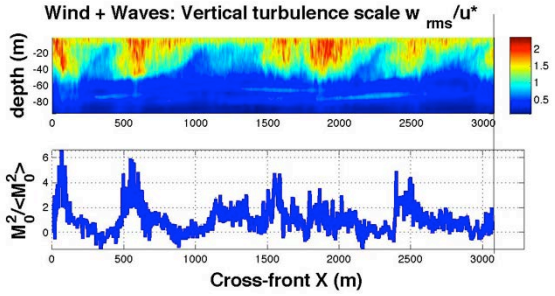

Figure 5: Top: Section of vertical TKE scale w_{rms}^2 from along-front averaging, fully developed SI state. Bottom: Surface cross-frontal buoyancy gradient M_0^2 scaled on its average value

The results from these and other completed simulations, and from those currently under way, are being analyzed to determine the scaling behaviors of lateral kinetic energy and flux components. While the behavior of LES-domain-averaged dissipation and vertical kinetic energy is not consistent with observations of SI-driven baroclinic boundary layer turbulence observed in the Kuroshio (D'Asaro et al, 2011) and in the Gulf Stream during LatMix 2012 field experiments, turbulence scaling based on conditional averaging at fronts in these LES results do appear consistent with the observations for downfront wind cases, provided that scaling front interior dissipation and w_{rms} with 'Ekman Buoyancy Flux' (EBF) forcing (Thomas, 2005) is not additive with forcing by wind stress and surface waves (Fig. 6). A case with wind and waves directed partially cross-front is notably not consistent with EBF scaling expectations.

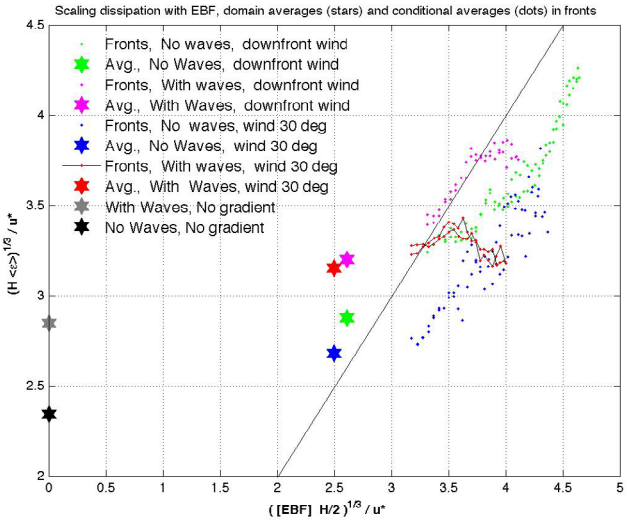

Figure 6: Scaling with EBF of layer-integrated dissipation <ε>H on surface friction velocity u*, domain-averaged (stars) and averaged conditionally on bins of surface horizontal buoyancy gradient (dots). EBF is the dot product of Ekman transport and surface buoyancy gradient. LES case with wind & waves directed 30 degrees toward the lighter side of front does not conform to 1:1 scaling line with EBF.

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.

REFERENCES

D'Asaro, E. A., C. M. Lee, L. Rainville R. Harcourt and L. Thomas 2011: Enhanced mixing and dissipation at ocean fronts. Science 15, 318-322.

Taylor, John R., Raffaele Ferrari, 2010: Buoyancy and Wind-Driven Convection at Mixed Layer Density Fronts. *J. Phys. Oceanogr.*, **40**, 1222–1242. doi:10.1175/2010JPO4365.1

Thomas, L. N., 2005. Destruction of potential vorticity by winds, J. Phys. Oceanogr., 35, 2457-2466.

Thomas, L. N., and J. R. Taylor, 2010. Reduction of the usable wind-work on the general circulation by forced symmetric instability, *Geophys. Res. Lett.*, 37, L18606, doi:10.1029/2010GL044680.