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AESOP DRI:
An Integrated Modeling and Observational Study of Three-Dimensional Upper Ocean Boundary Layer Dynamics and Parameterizations

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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
- 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 do not address the dynamics of unresolved submesoscale horizontal mixing processes below their O(0.1)-O(10) km horizontal resolution scale. Modeling work carried out as part of this AESOP DRI has focused on surface boundary layer horizontal mixing processes in regions of significant horizontal variability, as commonly found in frontal regions. This study seeks to quantify the coupling between mixed layer vertical fluxes and the dynamics of lateral mixing by submesoscale coherent structures.

APPROACH

Resolution of 3D large-eddy turbulence in boundary layers of depth 10m< H_{ML}<100m enables 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. The Large Eddy Simulations (LES) have been done in close collaboration with E. A. D'Asaro and C. M. Lee, whose AESOP field experiments measured 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 (Fig. 1). A new line of inquiry has also been pursued in this year to examine

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relationships between small-scale dissipation measurements and the baroclinic environment in Gulf Stream measurements obtained in the CLIMODE experiment by M. C. Gregg (also in AESOP) with post-doc R. Inoue. The opportunity to examine this data with an eye to frontal effects was pursued due to similarities between the Kuroshio and Gulf Stream environments, and because there is a need, in the context of a very rich set of submesoscale mixing phenomena, to consider a broader set of observational results. (R. Harcourt is not a member of the NSF CLIMODE experiment.)

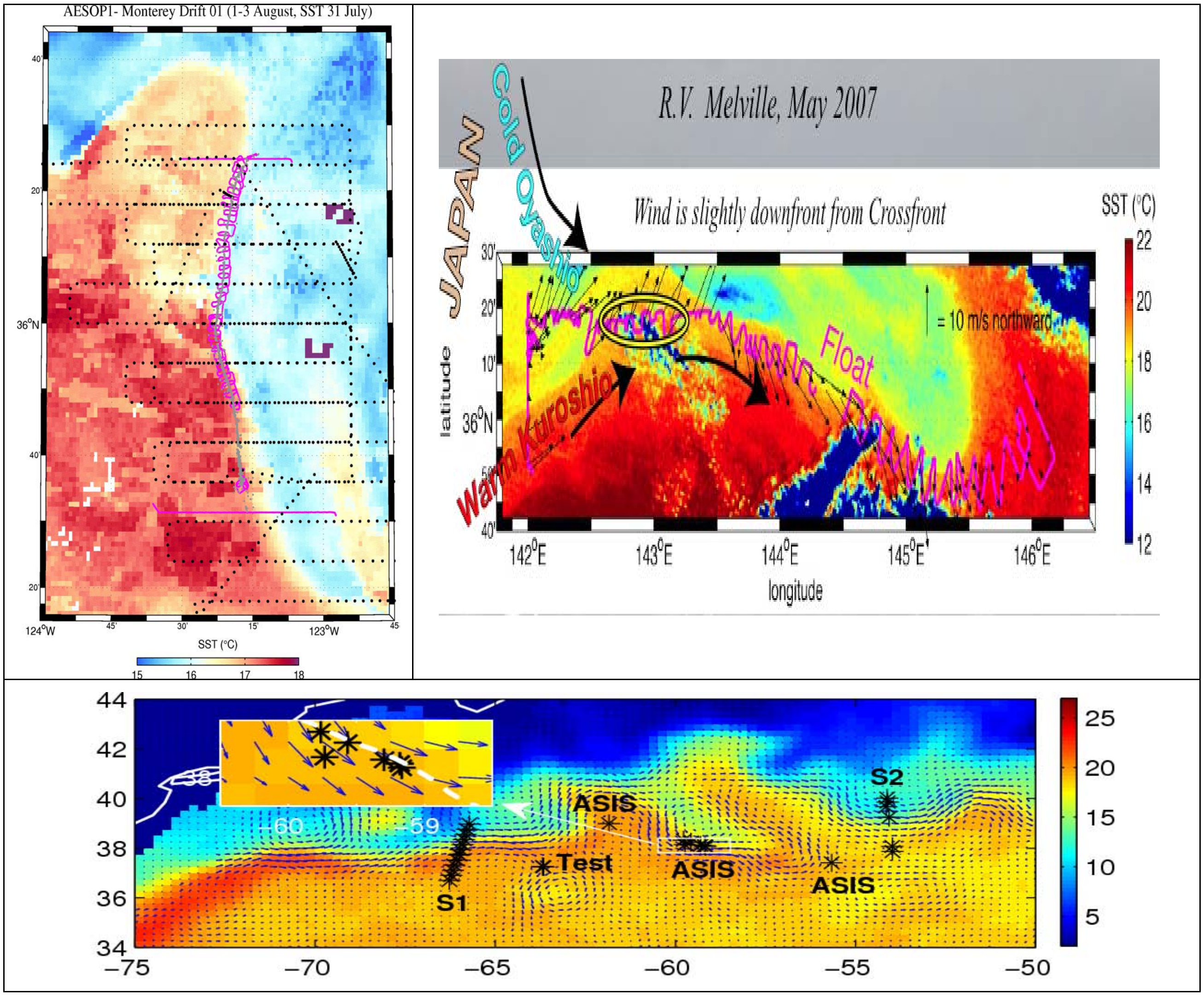

Figure 1: LES modeling has focused on two AESOP DRI field experiments, where rapid towed body surveys (magenta tracks) were used to measure the submesoscale environment of a Lagrangian float (gray tracks) deployed into a moderate strength front off Monterey (left) and a very strong frontal segment of the Kuroshio extension off Japan (above). Microstructure dissipation measurements from baroclinic mixed layers at CLIMODE wintertime Gulf Stream stations ('*' on SST map below) complements the AESOP data.

WORK COMPLETED

A suite of numerical simulations has been carried out for each of the two geographic field experiment components. For the California Current component, LES cases have been based on a particularly well-sampled front off Monterey measured during 2006. A period of wind-driven mixing was followed by rapid restratification as the wind let up. Horizontal stratification M^2=db/dx=-6×10^{-7} s^{-2} due to gradients of temperature and salinity within the front are incorporated as uniform backgrounds in otherwise periodic realizations of the dynamics between O(1) and O(10^3) m length scales. Kuroshio case simulations are based on observations in stronger lateral density gradients (M^2=db/dx=-1.6×10^{-6} s^{-2}) where Lagrangian float measurements recorded a large departure in mixed layer turbulence energy from Lagmuir turbulence scaling. Surface forcing combined ship-based meteorological observations with surface wave spectra simulated using Wave Watch III (courtesy of NRL Monterey & FNMOC).

Comparisons between LES model results and AESOP observations continued this year, although they have been delayed by the need to further analyze data from both Kuroshio and Monterey observations. This has moved forward with the hire of researchers L. Rainville and A. Shcherbina to work on data from the Kuroshio and Monterey cases, respectively. A manuscript (D'Asaro et al., in prep) on the elevated mixing observed in the sharpest front is mostly written, but further analysis is still needed. Furthermore, a sense of myopia due to the singular nature of these two rare (and incongruous) observations at fronts has in part motivated the examinations of microstructure dissipation in other frontal mixed layers that are described in RESULTS below.

Analysis of dissipation measurements from the wintertime Gulf Stream (Fig. 1c) complements the Monterey and Kuroshio results with significantly different small-scale sensitivities to the baroclinic mixed layer environment. Instead of indicating unaffected 3D-turbulence cascades as encountered in the Monterey front, or enhanced turbulence as found briefly in the Kuroshio measurements, Gulf Stream mixed layer dissipation levels were generally smaller than predicted by empirical scalings based on layer depth and surface forcing. The interesting contrast to AESOP observations under different surface forcing conditions motivated an analysis of mixed layer TKE budgets. Two manuscripts (Inoue et al., 2009a, 2009b, both in prep.) on this work are approaching submission, with the first complete and pending finalization of results from the second.

In addition, significant progress has been made in accounting for the impact excess float buoyancy on Lagrangian float measurements. A prescription 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, *submitted*). This study also reflects ONR-sponsored work under the Typhoons and AESOP DRI's. These results, and their relevance to the observation of Lateral Mixing by Lagrangian floats, are described in the Lateral Mixing DRI report.

RESULTS

Analysis of observed dissipation rates from the CLIMODE experiment in the wintertime Gulf Stream (GS) was pursued as complementary to AESOP measurements of small-scale turbulence in and below baroclinic mixed layers, as the latter were made under predominantly wind-driven surface forcing conditions.

Microstructure profiles taken in February 2007 across the Gulf Stream (GS) measured the temporal and spatial variability of the intense mixing that forms Eighteen Degree Water (EDW). Strong winds, gusting to 60 kt, and heat fluxes up to 1000 W m^{-2} produced moderate-to-strong mixing in the surface mixed layer and the entrainment zone, as well as in the thermocline. Below the mixed layer near the GS, diapycnal diffusivities in the thermocline averaged about $O(10^{-4})$ m^2 s–1, and are approximately 10 times the levels previously observed in the GS during other seasons. Banded shear structures in velocity profiles, dominated by shoaling phase coherence and clockwise rotation, indicate that downward-propagating near-inertial waves are responsible for much of this enhanced subsurface mixing.

The main involvement of AESOP funding in analyzing this data has focused on relating variations and generally low levels of dissipation to aspects of the GS frontal environment. In this line of investigation, the Turbulent Kinetic Energy (TKE) budget of the surface mixed layer is evaluated in the vicinity of the strong Gulf Stream (GS) jet with varying degrees of upper ocean baroclinicity. The non-local K-profile parameterization (KPP) of vertical fluxes was combined with observed hydrography and meteorology to diagnose boundary layer depth and TKE production. In baroclinic regions indicated by strong shear, boundary layer depths predicted by the bulk Richardson number criteria of KPP tend to be significantly deeper than indicated by observed dissipation rates. Even after correcting this diagnosis of mixed layer depth, KPP-based layer-averaged TKE production estimates $\langle \Psi_{KPP} \rangle$ exceed observed dissipation rates $\langle \boldsymbol{\varepsilon}_{obs} \rangle$ by up to an order of magnitude. Several factors could cause KPP predictions to be high, particularly in the presence of strong thermal wind shear that does not figure into the diagnosis of vertical eddy diffusivities. However, comparisons with empirical dissipation scalings $\langle \boldsymbol{\varepsilon}_{emp} \rangle$ (Lombardo and Gregg, 1989) showed observed levels to be similarly lower than expected, indicating that 1D vertical TKE budgets do not close locally for more fundamental reasons that we evaluate with reference to the mean shear (Sh) in the central half of the layer, taken as a proxy for baroclinicity when large compared with mixed layer surface forcing scales.

One theory bearing on the level of small scale dissipation in frontal zones suggests that submesoscale structures and centrifugal instabilities triggered by negative potential vorticity carry energy through O(0.1-10) km length scales in a forward cascade bringing energy from mesoscale and frontal structures down into the 3D turbulence scales and into dissipation. This is at least superficially at odds with the GS microstructure measurements, which show not only generally reduced levels but also that strong mixed layer shears due to baroclinicity or submesoscale energy are associated with some of the lowest levels of dissipation, relative to empirical and KPP-based predictions. Ratios to predictions $\langle \boldsymbol{\varepsilon}_{obs} \rangle / \langle \Psi_{KPP} \rangle$ and $\langle \boldsymbol{\varepsilon}_{obs} \rangle / \langle \boldsymbol{\varepsilon}_{emp} \rangle$ are ~0.2-0.3 when mid-depth mixed layer shear is largest, implying that small scale dissipation is decreased, not increased, when potential vorticity ($\sim f(N^2\text{-}Sh^2)$) is most negative. In Figure 2, the positive values of differences $\Delta\boldsymbol{\varepsilon}$ between predictions and expectations are plotted against mid-layer shear, although the scatter is large, as expected for such comparisons.

The positive trend in Figure 2 corresponds roughly with the rate at which the geopotential energy is released by in the bolus-velocity based parameterization of submesoscale lateral fluxes of Fox-Kemper et al. (2008). This coincidence suggests that while the observations are only superficially at odds with the expectation of elevated small-scale dissipation, that locally released energy propagates away laterally in submesoscale structures or downward by internal waves, leaving behind restratified mixed layers that are only remixed at the expense of the atmospherically-driven mixed layer budget.

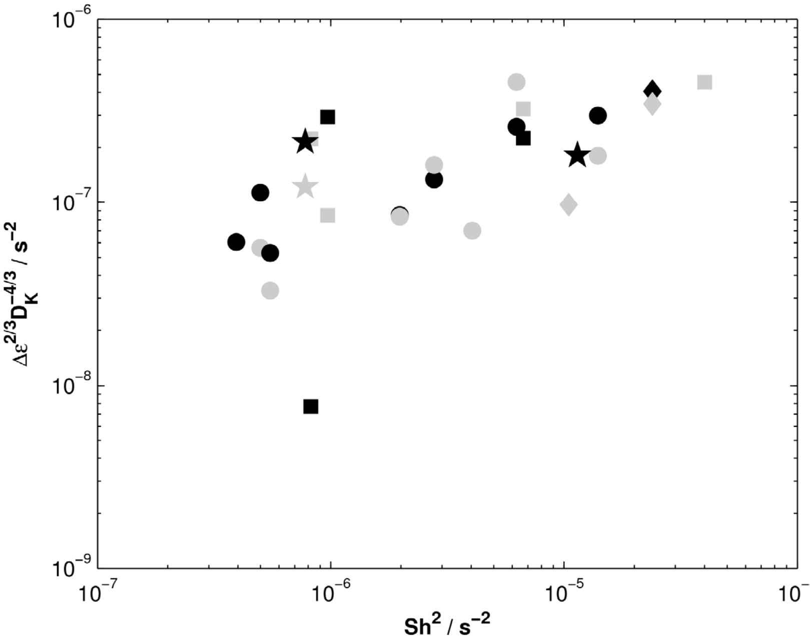

Fig. 2. Dependence of dissipation rate differences on mid-layer mean shear squared (Sh^2), with -$\Delta\boldsymbol{\varepsilon}_{KPP} = \langle\Psi_{KPP}\rangle - \langle\boldsymbol{\varepsilon}_{obs}\rangle$ in black, and -$\Delta\boldsymbol{\varepsilon}_{emp} = \langle\boldsymbol{\varepsilon}_{emp}\rangle - \langle\boldsymbol{\varepsilon}_{obs}\rangle$ in gray. Only $\Delta\boldsymbol{\varepsilon} > 0$ is shown, normalized to homogeneous (s^{-2}) dimensions as $(|\Delta\boldsymbol{\varepsilon}|/D_K^2)^{2/3}$ using mixed layer depth D_K.

The second theory impacting small-scale dissipation predicts that near-surface Ekman-driven advection at surface fronts can increase or decrease mixed layer TKE production by either stabilizing or destabilizing the water column, leading to increased or decreased vertical buoyancy fluxes (Thomas, 2005). In KPP-based TKE production predictions, this is partially included through the use of observed stratification, and only the indirect effect on vertical diffusivities remains. Using observed winds and lateral density gradients at ~20km spacing to modify the convective velocity scale w* through an additional effective surface flux J_b^{Ek} did not produce changes in diffusivity that were significant compared to the TKE budget deficit, since they only impact w* with a power of 1/3.

If we turn again to mid-layer shear as a proxy for baroclinicity, Fig. 3a shows how $\langle\boldsymbol{\varepsilon}_{obs}\rangle / \langle\Psi_{KPP}\rangle$ and $\langle\boldsymbol{\varepsilon}_{obs}\rangle / \langle\boldsymbol{\varepsilon}_{emp}\rangle$ vary with the angle between the wind vector and surface front direction (angle 0 is a down-front wind). The dissipation levels relative to predictions seem to cluster around wind directions blowing toward 90 degrees to the left of down-front, while the Ekman advection hypothesis predicts enhancement of dissipation when winds are blowing toward the down-front direction. The additional surface buoyancy flux due to Ekman advection relative to mid-layer shear appears unrelated to the TKE budget deficit, but the corresponding additional flux J_b^{non-Ek} that is largest when winds and waves, without Coriolis effects, are pushing surface water down the density gradient, does appear related to reduced dissipation levels and has the same scale.

While both of these results are at odds with predictions, it is also possible that together they provide a consistent picture, with downfront winds increasing dissipation from levels to which they are reduced by submesoscale instabilities that release geopotential energy but restratify the mixed layer locally. In relating this hypothesis to the AESOP data from Monterey, the suggestion would be that increased vertical mixing by destratifying winds was roughly countered by restratification by frontal instabilities, with TKE transport divergence by submesoscale vortices or internal waves. The GS and Monterey downfront wind cases stand in contrast to the strong but brief elevation of small-scale mixing in the Kuroshio front, probably due to the unbalanced nature of the strongly confluent and frontogenetic mesoscale flow there.

IMPACT/APPLICATIONS

AESOP 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.

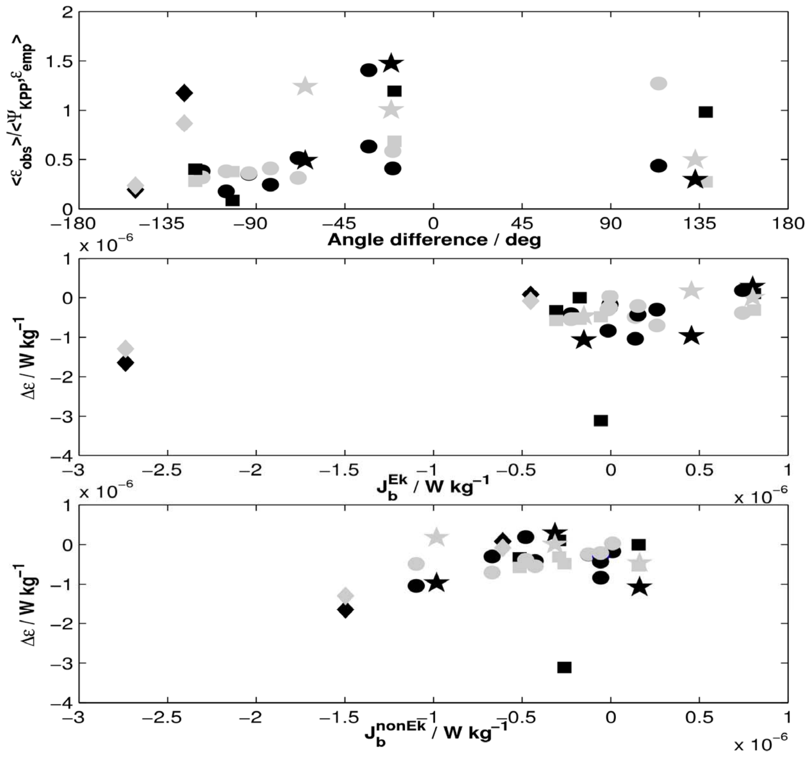

Figure 3: Comparison of $\langle \varepsilon_{obs} \rangle$ and the KPP TKE production prediction Black symbols compare $\langle \Psi_{KPP} \rangle$ (black symbols) and with the empirical $\langle \varepsilon_{emp} \rangle$ (gray symbols) of Lombardo and Gregg (1989). (top) The ratio of observed dissipation rate to predicted values vs. angle from front to wind vector direction. (middle) Differences between observed and predicted dissipations against buoyancy flux due to Ekman transport. (bottom) Differences between observed and predicted dissipations against buoyancy flux due to wind transport without earth rotation.

RELATED PROJECTS

AESOP results bear significantly on the concurrent new Lateral Mixing DRI, for which a new experimental site in the Gulf Stream is currently under serious consideration. 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 2009: Enhanced mixing and dissipation at an ocean front, *in preparation*.

D'Asaro, E. A. 2001: Turbulent intensity vertical kinetic energy in the ocean mixed layer, *J. Phys. Oceanogr.*, 31, 3530-3537.

Fox-Kemper, B., R. Ferrari, and R. W. Hallberg., 2008: Parameterization of mixed layer eddies. Part I: Theory and diagnosis. *J. Phys. Oceanogr*., 38, 1145-1165.

Inoue, R., M. C. Gregg and R. R. Harcourt, 2009a: Mixing rates across the Gulf Stream, Part 1: On the formation of Eighteen Degree Water, *in preparation.*

Inoue, R., M. C. Gregg and R. R. Harcourt, 2009b: Mixing rates across the Gulf Stream, Part 2: Implications for non-local parameterization of vertical fluxes in baroclinic surface boundary layers, *in preparation.*

Lombardo, C. P. and M. C. Gregg, 1989: Similarity scaling of viscous and thermal dissipation in a convecting surface boundary layer, *J. Geophys. Res*., 94, 6273–6284.

Molemaker, M.J. and J.C. McWilliams and X. Capet, 2008: Balanced and unbalanced routes to dissipation in an equilibrated eddy Flow, *submitted to J. Fluid Mech*.

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

PUBLICATIONS

Harcourt, R.R., and E.A. D’Asaro, 2008: Large-Eddy simulation of Langmuir turbulence in pure wind seas. *J. Phys. Oceanogr.*, **38**, 1542–1562. [published, refereed]

Harcourt, R.R., and E.A. D’Asaro, 2009: Measurement of vertical kinetic energy and vertical velocity skewness in oceanic boundary layers by imperfectly Lagrangian floats, *submitted to J. Ocean. Atmos. Tech.*