# Collaborative Proposal: Studies of Stirring and Mixing at the Submesoscale in the Ocean

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## LONG-TERM GOALS

The long term goal of the "Scalable Lateral Mixing and Coherent Turbulence" DRI, under which the PIs are funded, is to understand the processes that stir and mix tracers in the ocean on lateral scales of 100 kilometers to 10 meters, the so-called submesoscales. The specific long term goals of the PIs are to understand the influence of mesoscale strain in driving stirring and mixing at the submesoscale, and to develop a robust theoretical framework through which to interpret the observations.

## OBJECTIVES

The objective of the DRI group is to devise and execute field experiments, supported by numerical simulations, that will distinguish between potential mechanisms of submesoscale stirring and mixing. The many interacting processes occurring at the submesoscales present a serious challenge to this effort. In order to focus the team work, potential mechanisms were distilled into three core hypotheses: (**H1**) Isopycnal mixing at scales of 10 m -10 km in the stratified ocean is the result of stirring by coherent vortices generated by mixing events associated with gravity wave breaking (the so-called vortical modes); (**H2**) Isopycnal mixing at the submesoscale is effected by motions resulting from a cascade of tracer and potential vorticity (PV) variance from the deformation scale (where baroclinic instability generates mesoscale eddies) to smaller scales; (**H3**) Both diapycnal and isopycnal mixing in the upper ocean are enhanced by ageostrophic instabilities along lateral density fronts generated at the submesoscale.

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Hypothesis H2 followed directly from research published recently by the PIs (Smith and Ferrari 2009, hereafter SF09). Our specific objectives are to work together with the other modeling teams, as part of a collective effort, to provide theoretical direction to, support for and analysis of the observational effort. Specifically, the work completed, underway and planned by the PIs seeks to address hypotheses H2 and H3

## APPROACH

Turbulent motions act to redistribute oceanic tracers like temperature, salinity, and chemical compounds and various biological forms. The traditional view is that these fluxes are dominated by geostrophic eddies at the mesoscale and three dimensional eddies at the microscale. Our research is focused on understanding the interactions between these two classes of motions, with the goal to provide guidance to the experimental design, and to develop a theoretical framework through which to interpret the observational results. Our approach is to use a hierarchy of numerical process models, with precisely controlled mean shear and stratification, systematically run over a wide range of parameters. We use both a balanced quasigeostrophic (QG) model (developed by PI Shafer Smith) and a nonhydrostatic Boussinesq (NHB) model (developed by postdoc John Taylor), each run at a resolution of O(500 m) horizontally and O(10 m) vertically.

There are three major components to our current and planned DRI-related research:

1. Simulations designed to aid in the development of a theory for the three-dimensional stirring of tracers in the ocean interior by a realistic geostrophic field.
2. Simulations designed to illuminate the nature of geostrophic stirring near the surface, where submesoscale density fronts can be amply produced by geostrophic straining.
3. Sister simulations using the NHB and QG models in nearly identical configurations, designed to expose precisely what effects involve true loss of balance, as opposed to processes in which the unbalanced modes are slaved to the balanced flow.

The **key personnel** involved are the two PIs, **Raffaele Ferrari** and **Shafer Smith**, and a postdoctoral researcher, **John Taylor**. Taylor will run most of the NHB numerical simulations, and Ferrari will directly advise and oversee Taylor's efforts. PI Smith will design and run the QG simulations. All three researchers will work closely with one another to analyze and compare the simulated results, to relate the results to parallel efforts by other DRI modeling teams, and to provide guidance and interpretation to the observational efforts.

## WORK COMPLETED

### Stirring and mixing in the ocean interior

In SF09, the PIs considered the generation of T/S gradients in the Eastern North Atlantic at the submesoscale, using the QG model, run at O(1 km) horizontal and O(50 m) vertical resolution, and forced with the large scale shear, stratification and T/S gradients found in the North Atlantic Tracer Release Experiment (NATRE – see Ledwell et al. 1998) region.

The mean flow is baroclinically unstable and generates a vigorous eddy field. The resulting eddy stirring of the large scale thermohaline gradients results in compensated T/S filaments with variability that is quantitatively consistent with the NATRE observations (see Fig. 7 of SF09), despite the lack of unbalanced turbulence. This result was explained in detail in last year's report. Geostrophic stirring generates T/S filaments with a small slope close to f/N, i.e. much thinner in the vertical than in the horizontal. The implication is that geostrophic stirring generates sharp vertical gradients which are often referred to as T/S finescale structure. Geostrophic stirring appears to be the dominant mechanism for the generation of T/S finescale structure below the thermocline, contrary to the common view that ascribes the generation of T/S finestructure primarily to internal wave or double diffusive turbulence.

In this past year we run a suite of similar numerical experiments, with increasing mean state complexity. All simulations advect two tracers: one forced by a mean gradient, brought to equilibrium through an appropriate dissipation operator (vertical diffusion or other parameterized effects), and the other as an initial value problem form a point release. The goal is to unravel the complexities that remain from the study of SF09 such as a more accurate, quantitative prediction for tracer slopes, their equilibrated filamentary scale and structure, and to provide the basis for a theory of point-release in a three-dimensional field of geostrophic turbulence (i.e. extending the results of Garrett 1983 to a full 3D geostrophic field). The current simulations have domains of size 500 x 500 $km^2$ with a horizontal resolution of about 1/2 km and vertical resolution of about 20 m.

**Stirring and mixing at the ocean surface**

PI Raffaele Ferrari and postdoc John Taylor examined the influence of density fronts, generated by geostrophic eddy stirring, on upper ocean turbulence. This work focused on the influence of a horizontal density front on turbulent convection and mixed layer growth using turbulence-resolving numerical simulations. The code used for this study is the NHB model developed by postdoc John Taylor.

Starting with uniform horizontal and vertical buoyancy gradients in balance with a constant thermal wind shear, convection is driven by imposing a heat loss or a de-stabilizing wind-stress at the upper boundary. The forcing creates a turbulent layer with reduced vertical stratification that deepens in time. For weak fronts, the density in the turbulent layer is nearly homogeneous, while for strong fronts, horizontal and vertical density gradients persist in the turbulent layer. Regardless of the strength of the front, the mean potential vorticity (PV) in the turbulent layer is nearly zero. Using the PV budget, scalings for the depth of the turbulent low-PV layer and its growth rate are derived. These compare well with the numerical simulations. The derived expression for the low-PV layer depth is more general than the classical expression for the growth of a mixed layer in upright convection, because it accounts for the effect of lateral density gradients.

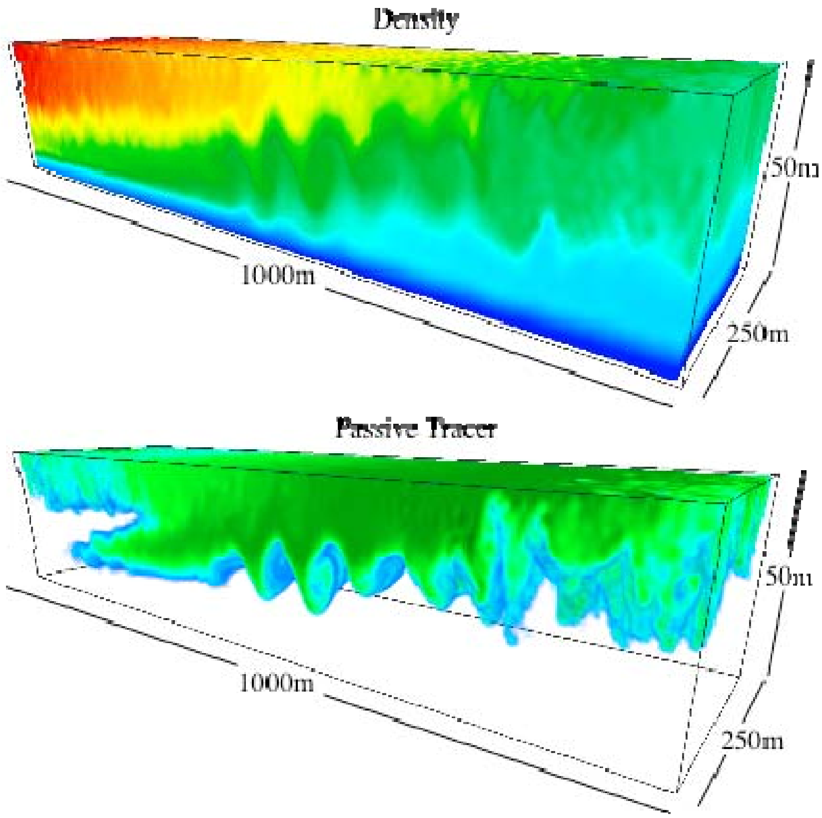


***Figure 1: Density and passive tracer concentration in a simulation of convection at a mixed layer density front. The passive dye was initially released uniformly in the upper 10m and was allowed to evolve for 20 hours.***

In the limit of a vanishing horizontal density gradient, the low-PV layer is convective in the traditional sense: plumes descend to the base of the mixed layer and the vertical buoyancy flux decreases linearly with depth. When the horizontal density gradient is large, upright convection is confined to a very thin layer near the surface, while in most of the low-PV layer, mixing is maintained by a forced symmetric instability (SI), characterized by along-isopycnal motion. Injecting a passive tracer into the upper 10m of a 50m deep low PV layer (Figure 1) illustrates the along-isopycnal spread by the forced symmetric instability.

One of the important characteristics of forced SI is that it extracts energy from the front instead of the surface forcing. Figure 2 shows the turbulent kinetic energy budget for upright convection (a) and forced SI (b). Both simulations are forced with the same surface heat loss; the only difference is the presence of a horizontal density gradient in the simulation with forced SI. In the absence of a front, upright convection derives its energy through the buoyancy flux as available potential energy generated by the surface heat loss is converted to kinetic energy. When forced SI is active at a front, turbulent kinetic energy is generated primarily through a shear production term acting on the thermal wind. Since the thermal wind is needed to balance the hydrostatic pressure gradient associated with the front, extracting energy from the thermal wind will ultimately weaken the front.

Even for strong fronts, when the surface heat loss is sufficiently, convective plumes can be seen in a thin surface layer, and these plumes are associated with a significant buoyancy flux as seen in Figure 2

(b) in the upper 5-10m. We have derived a scaling for the depth of the convective layer that depends only on the observable external parameters: the frontal strength, surface buoyancy flux, and boundary layer depth. The scaling for the convective layer depth is particularly useful when used in combination with the predicted low-PV layer depth to predict when forced SI will occur. Since forced SI can only develop inside the low-PV layer but beneath the convective layer, it requires that $h<H$, where $h$ is the convective layer depth and $H$ is the low-PV layer depth.

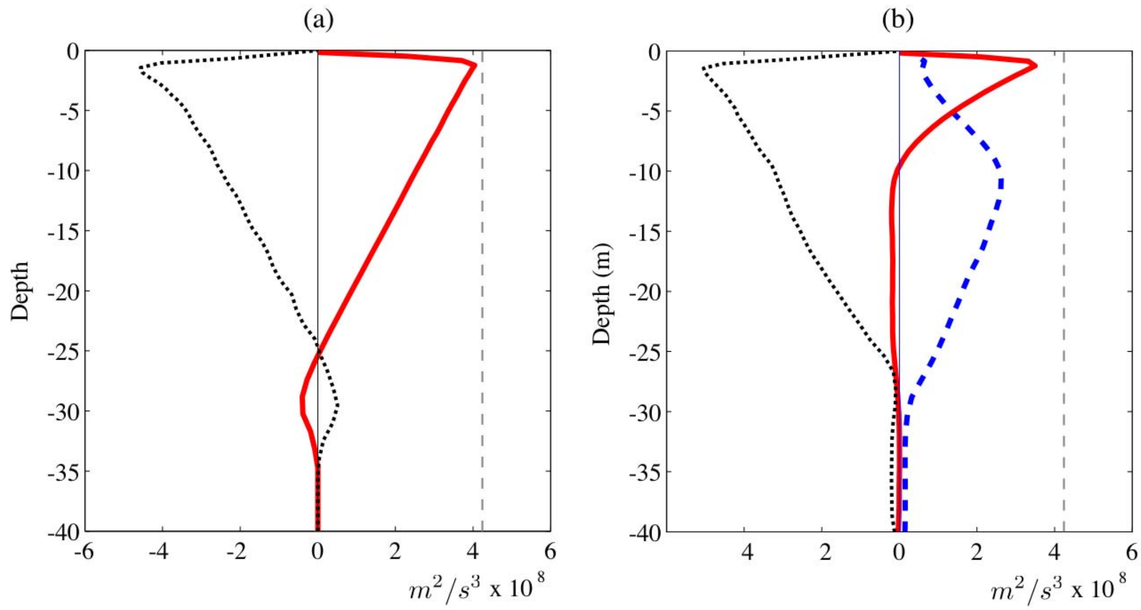


***Figure 2: Turbulent kinetic energy budget for (a) upright convection and (b) slantwise convection. Red lines show the buoyancy flux, the dashed blue line shows the geostrophic shear production, and black dotted lines show the sum of all other terms.***

The simulations that have been discussed so far have considered a background density gradient that is constant in space and time. This `frontal zone' configuration is ideal for developing an understanding of how turbulence changes in response to horizontal density gradients since the frontal strength can be controlled. However, this setup does not allow the front to freely evolve in time. In order to test our predictions in a more realistic environment where the front is allowed to evolve in response to the turbulence, we have recently conducted simulations of an isolated front forced by surface cooling. In order to separate the front from the lateral computational boundaries, a much larger horizontal domain is used 16km compared to 1km in the previous simulations. Figure 3 shows an instantaneous snapshot from this simulation. A streak of dye was released spanning the domain at a depth of 20m and its concentration is shown in color about 14 hours later. Away from the front, the dye is well-mixed throughout the mixed layer by convection, while at the front, the along-isopycnal streaks characterizing symmetric instability are clearly visible. Black contour lines indicate the *predicted* PV layer and convective layer depths given the instantaneous vertically-averaged horizontal density gradient and the surface forcing. The depth of the mixed layer is very well-captured by the theoretical prediction, as is the depth of the low PV layer at the front. The location where the low PV layer is deepest is shifted compared to the prediction due to the tilt of the front. The location where symmetric instability occurs is also well-captured by the region where the predicted convective layer depth is shallower than the low-PV layer depth.

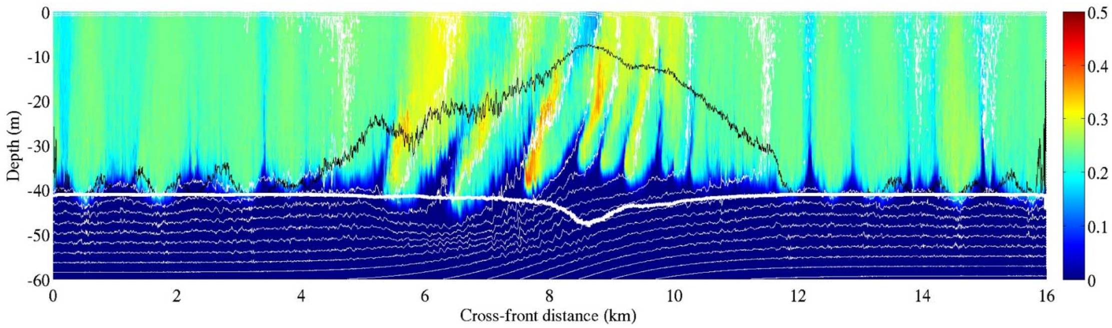


***Figure 3: Symmetric instability at a forced isolated front. Passive dye was released in a cross-front streak centered at 20m and its concentration after about 14 hours is shown in color, normalized by the maximum initial concentration. Isopycnals are shown in thin white lines. The thick white line shows the predicted low PV layer depth using the instantaneous vertically-averaged density gradient, and the black line shows the predicted convective layer depth.***

This work is reported in two papers. The first paper (Taylor and Ferrari 2009) was published in the Journal of Fluid Mechanics and the other (Taylor and Ferrari 20010) was recently published in the Journal of Physical Oceanography.

**NHB vs. QG simulations**

Quasi-geostrophic (QG) theory has been a foundation for our understanding of ocean dynamics for decades. Several assumptions are made in deriving the QG equations, one of which is that the Rossby number, $Ro=U/fL=\zeta/f$ is small. While this assumption generally works well for mesoscale eddies with scales O(100km), it is not expected to apply for sub-mesoscales O(1-10km) that are the primary focus of this DRI. One of the goals of this work is to identify processes that are not well-described by QG dynamics and to study their impact on the lateral stirring and mixing of tracers. In order to do this, we have conducted a series of simulations with the NHB and QG models in identical configurations.

The first problem that we have examined with the NHB and QG models consists of two pairs of opposing jets in a triply-periodic geometry. When applying periodicity in all three directions, we cannot explicitly apply boundary conditions. However, the initial condition that we use is anti-symmetric about two horizontal planes. As a result, the vertical velocity stays very close to zero on these planes, and the dynamics respond as if they were rigid surfaces. This allows us to examine both `interior' and `surface' dynamics in the same computational configuration. The domain size that we consider is 10km x 10km x 1km in the horizontal and vertical directions with 512 x 512 x 128 gridpoints. With this relatively small domain, sub-mesoscale eddies develop which violate the assumption of small Rossby number inherent in the QG model.

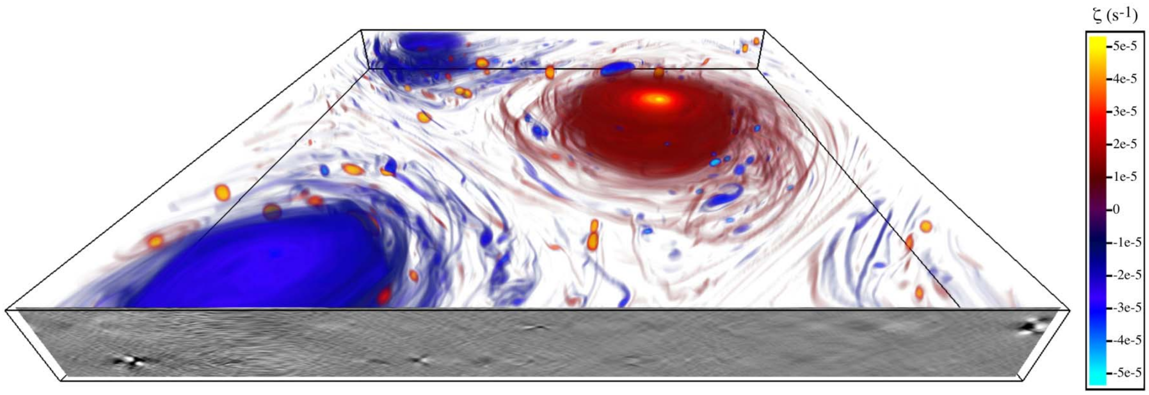


***Figure 4: Vertical vorticity (color shading) from the NHB model at t=146 days. At this time the large scales have coalesced into a dipole consisting of a strong cyclone, and a somewhat weaker anticyclone. Despite the inverse energy cascade, small-scale filaments and eddies are clearly visible. The front plane shows the vertical divergence field, dw/dz, which highlights the internal wave field and sub-mesoscale features.***

The initial condition consists of four jets in thermal wind balance, and this state is unstable to baroclinic instability. During the early phases of evolution, both models are very similar and in good agreement with linear stability theory. After a nonlinear eddy field forms, the NHB model develops a bias towards stronger cyclones than anticyclones, a feature not seen in the QG model. Both models show development of thin vorticity filaments and small eddies, as illustrated in Figure 4 (only the NHB model is shown). The small eddies tend to have high Rossby numbers with $\zeta=O(f)$=1e-4 ($s^{-1}$), and are therefore not well-described by QG dynamics.

The small-scale eddies and filaments are concentrated near the `surface' planes where $w$=0, while the vorticity and buoyancy are much smoother in the `interior' between the $w$=0 planes, as shown in Figure 5. In order to examine the influence of the small-scale structures on lateral mixing, we have also simulated a passive tracer. Tracer variance is generated from eddy motions acting on a background horizontal tracer gradient which is kept fixed in time. Unlike vorticity and buoyancy, the passive tracer exhibits fine-scale filamentation in the interior as well as at the surface. The spectral slope of the tracer variance is close to $k^{-1}$ at both planes (not shown) which is consistent with a field that is dominated by large-scale stirring.

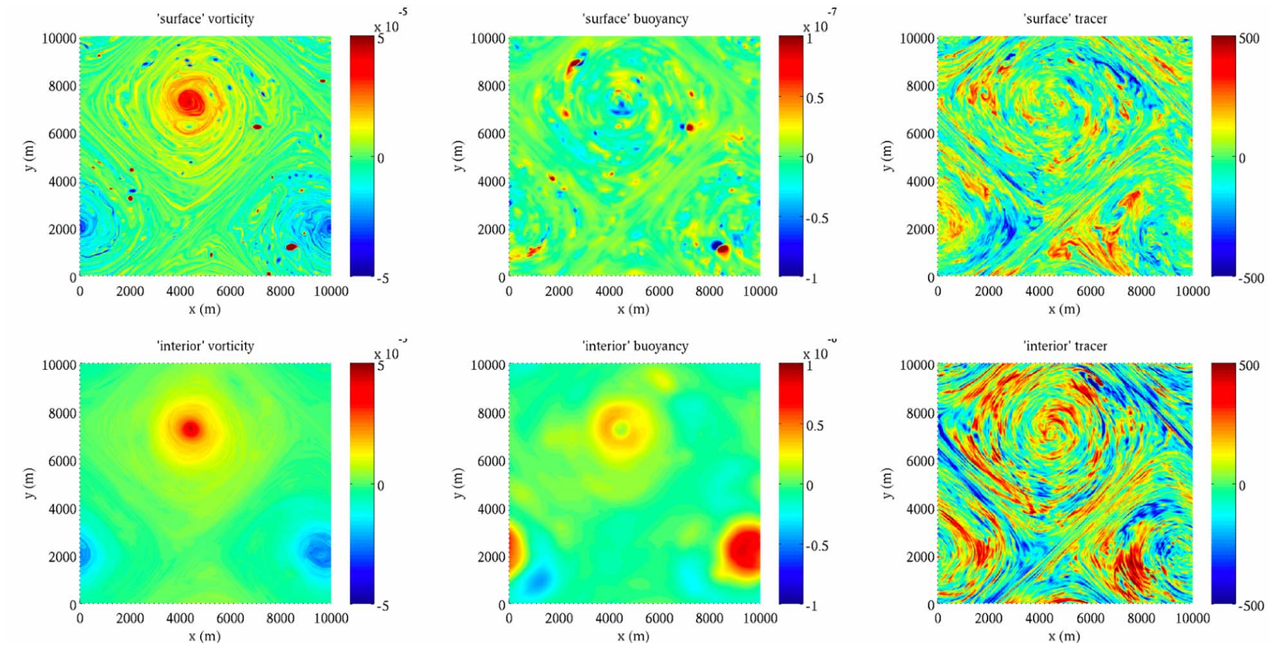


***Figure 5: Vertical vorticity, buoyancy, and passive tracer from the NHB simulation at t=156 days at two horizontal planes: a `surface' plane where w=0, and an 'interior' plane in the middle of the computational domain where w≠0.***

## RESULTS

The key results of our work so far can be summarized as follows. In the *ocean interior,* we found that (1) mesoscale eddies dominate generation of lateral tracer variance on scales between 100km and 100m, (2) the three-dimensional cascade of tracer variance produces significant vertical structure in the tracer field, resulting in tracer filaments with slopes of order f/N, far exceeding the isopycnal slopes, and (3) this vertical structure enables background vertical mixing to effectively absorb the variance generated by mesoscale stirring. We are now studying how non-quasigeostrophic effects modify this picture. So far we find that the quasi-geostrophic approximation captures well the overall energy and tracer variance cascades in the ocean interior. Near the *ocean surface,* our research has demonstrated that (1) surface-driven convection in the presence of a balanced lateral density gradient produces a turbulent layer in which horizontal and lateral density gradients persist, i.e. the layer remains stratified, (2) mixing in this turbulent layer is enhanced by a forced symmetric instability, when surface buoyancy loss is strong, and is suppressed by baroclinic instability, when the forcing is weak, (3) (3) a PV-budget based scaling provides a more complete theory for the turbulent layer growth rate and depth than the classic mixed-layer depth scaling.

## IMPACT/APPLICATIONS

The results presented in SF09 led to one of the driving hypotheses of the DRI effort, and in particular have shown the need to include measurement of the mean state and mesoscale forcing surrounding the experimental sites. The mesoscale forcing sets the rate of stirring at the submesoscale in the ocean interior, while it sets both the rate of stirring (through mesoscale strain) and mixing (through modifications of convection and shear instabilities at fronts) at the ocean surface. Our work demonstrates that the interpretations of T/S and other tracer distributions from past observational campaigns is marred by the lack of a detailed mapping of the local mesoscale field. Prompted by these results, the DRI observational strategy is now designed to span full range of scales from 100 km down to 10 m.

## RELATED PROJECTS

None.

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[published, refereed]

## HONORS/AWARDS/PRIZES

Raffaele Ferrari, Editors' Citation for Excellence in Refereeing for Geophysical Research Letters (2010).

Shafer Smith, Outstanding Reviewer, Journal of the Atmospheric Sciences (2010).

John Taylor, Andreas Acrivos Dissertation Award in Fluid Dynamics awarded by the American Physical Society (2008).