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

PI: Raffaele Ferrari
54-1420
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139-4307 USA
phone: (617) 253-1291 fax: (617) 253-4464 email: rferrari@mit.edu

PI: K. Shafer Smith
Courant Institute
New York University
251 Mercer Street
New York, NY 10012 USA
phone: (212) 998-3176 fax: (212) 995-4121 email: shafer@cims.nyu.edu

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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. At the Mediterranean Outflow Water level, the generation of temperature variance by geostrophic stirring, χ_{eddy} is remarkably close to the measured temperature variance dissipation χ (see diamonds in Figure 1). This is an example of hypothesis H2 at work. Nearer to the surface, the weak lateral gradients of T and S provide insufficient eddy variance generation to explain the observed dissipation rates, consistent with the importance of turbulent stirring at these levels.

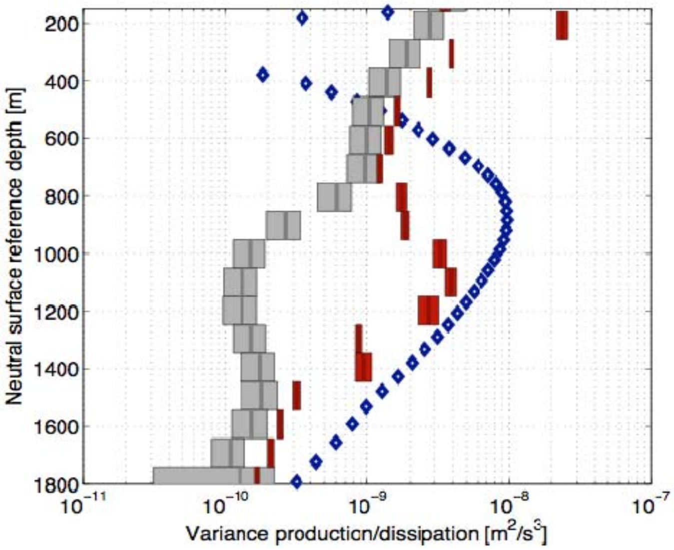

Figure 1: Temperature variance budget analysis in the NATRE region. Microstructure measurements provided direct estimates of molecular dissipation of thermal variance, χ (red bars), and of turbulent generation of thermal variance, χ_{turb} (grey bars). The production of thermal variance by eddy stirring, χ_{eddy} (diamonds), is estimated by running a QG model forced with the observed shear and stratification in the NATRE region.

The filaments of T and S are teased in the horizontal by the lateral stirring field and, at the same time, they are tilted in the vertical by the geostrophic eddy shear. This results in a three-dimensional forward cascade of tracer variance, generating sharp, small-scale gradients both in the vertical and in the horizontal, as can be seen in the salinity snapshots shown in Figure 2. The slope of the tracer filaments is proportional to the ratio of the inertial and buoyancy frequencies, f/N (the white line in the right panel). The tracer filaments are therefore much thinner in the vertical than in the horizontal, and so the cascade of variance is arrested once the thickness, not the width, of the filaments shrinks to the scale of the isotropic turbulence that characterizes internal wave breaking. This conjecture is supported by simulations in which vertical diffusion alone acts to absorb the tracer variance cascade.

A suite of similar numerical experiments, with increasing mean state complexity, are currently underway. 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.

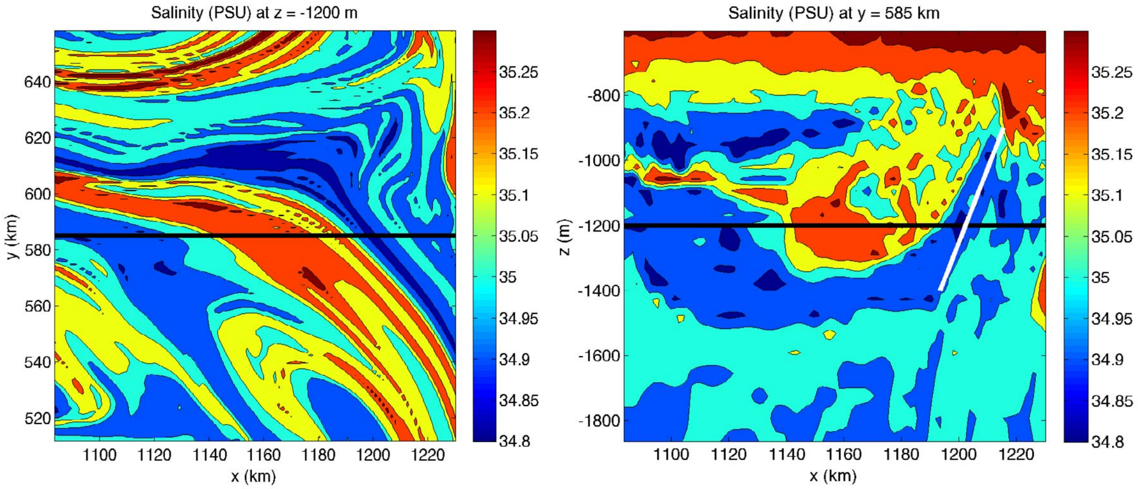

Figure 2: Lateral (left) and vertical (right) slices of the eddy salinity field in a subregion of a high resolution QG simulation of the NATRE region. The lateral slice is taken at 1200m depth, and the vertical slice is taken from the center of the lateral slice region, over depths from 600 m to 1900 m. The white line in the right panel has slope f/N, and so indicates the steepness of filaments of salinity.

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.

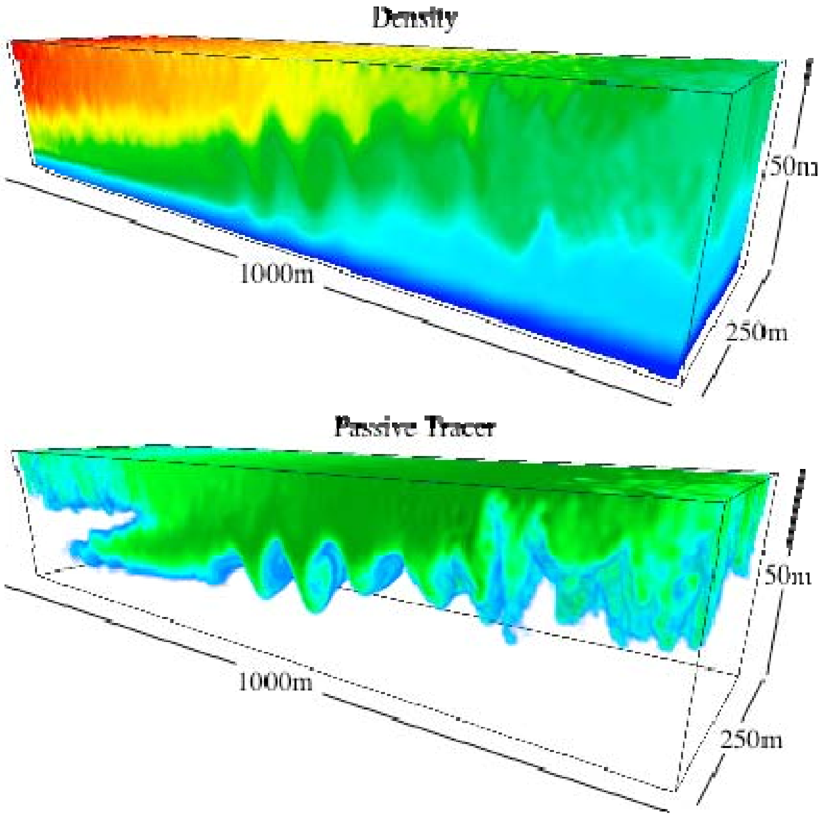

Figure 3: Density and passive tracer concentration in a simulation of convection at a mixed layer density front. The passive dye was initially released uniformly in the upper 10m and was allowed to evolve for 20 hours.

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, characterized by along-isopycnal motion. Injecting a passive tracer into the upper 10m of a 50m deep low PV layer (Figure 3) illustrates the along-isopycnal spread by the forced symmetric instability.

This work is reported in two papers. The first paper (Taylor and Ferrari 2009a) has already appeared in the Journal of Fluid Mechanics and the other (Taylor and Ferrari 2009b) has been just been submitted for consideration to the Journal of Physical Oceanography.

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. 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, but which is nevertheless characterized by low PV, (2) mixing in this low-PV turbulent layer is maintained by a forced symmetric instability, characterized by along-isopycnal motion, and (3) that 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.

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Taylor, J., and R. Ferrari, 2009b: Turbulent convection at a mixed-layer front. *J. Phys. Oceanogr.* [submitted, under review]

HONORS/AWARDS/PRIZES

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