Scalable Lateral Mixing and Coherent Turbulence

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Participants: Terri Paluszkiewicz (ONR), Scott Harper (ONR); Ayal Anis (TAMU), Burkard Baschek (UCLA), Eric D'Asaro (APL/UW), Raffaele Ferrari (MIT), Lou Goodman (UMass Dartmouth), Eric Kunze (U. Victoria), Jim Ledwell (WHOI), Pascale Lelong (NWRA), Murray Levine (OSU), Amala Mahadevan (Boston Univ.), Jeroen Molemaker (UCLA), Shafer Smith (NYU), Miles Sundermeyer (UMass Dartmouth), Amit Tandon (UMass Dartmouth, John Taylor (MIT), Gene Terray (WHOI)

1. Abstract

Lateral stirring is one of the most basic oceanographic phenomena affecting the distribution of physical and biological fields throughout the ocean. Yet, it is poorly understood. Presently, there are no parameterizations for numerical models that handle both biological and physical dynamics at the submesoscale. Furthermore, observed rates of lateral mixing are typically larger by several orders of magnitude than expected from classical shear dispersion models. In fact, the classical Fickian diffusion model itself does not work in typical ocean conditions, and a new formulation, which takes into account the strong scale dependence of dispersion is needed. The present document outlines the major outstanding questions regarding lateral mixing at scales of 10 m – 10 km, and describes a framework for a coordinated, multi-year effort to address these via field observations, numerical modeling studies, and theory.

2. Introduction / State of the Science

Oceanic mixing on lateral scales of 10 m – 10 km and temporal scales ranging from hours to days are poorly understood. This is due in part to our limited understanding of the dynamics at this range of scales, which is transitional between the better studied geostrophic mesoscale and turbulent microscale, and in part to the paucity of observations in this regime due to technological difficulties. Particular interest in lateral mixing at these scales stems from observations of rapid tracer dispersal in the coastal and open ocean. While stirring may be induced by mesoscale and larger scale processes, little is known about the processes that lead to the formation of sharp horizontal and vertical gradients all the way down to scales where molecular dissipation takes over. In the submesoscale regime, the traditional paradigm of separating motions into geostrophic eddies that dominate lateral transport and microscale turbulence that dominates vertical mixing is no longer appropriate. Horizontal stirring and vertical mixing are inextricably linked. Several processes have been proposed as contributing to the generation of submesoscale processes and stirring: frontal processes at multiple scales, loss of balance through ageostrophic instabilities, generation of thin potential vorticity filaments by geostrophic turbulence, and vortical mode generation by breaking internal waves.

In the stratified interior, the coupling of horizontal strain and vertical shear tends to generate sharp tracer filaments with small vertical scales that are eventually arrested by vertical mixing in numerical experiments. A question arises as to whether vertical mixing is coupled to the generation of filaments. In the passive picture, mixing is due to breaking internal waves. In the active scenario, the generation of potential vorticity filaments leads to loss of balance and sudden bursts of mixing. The passive and active hypotheses make different predictions for the width of tracer and potential vorticity filaments and could be tested versus in situ fine-structure observations in different parts of the ocean.

In the pycnocline, another set of processes may act to create mixing. When internal waves break, they generate patches of mixed fluid that help arrest the downscale cascade of variance via straining. On longer timescales, the mixed patches of fluid slump under the combined action of gravity and rotation and form coherent eddies. It has been speculated that these vortical eddies contribute to stirring and homogenization of tracers on scales of O(1-10) km. So far, this is a hypothesis waiting to be tested, because direct observations of vortical modes in the field have not been made.

In the upper ocean, the presence of a free surface allows for the formation of sharp lateral density gradients and alteration of potential vorticity through atmospheric forcing. The presence of the surface boundary supports frontal intensification and the formation of negative potential vorticity leading to ageostrophic and "unbalanced" dynamics, in contrast to the approximately balanced flows in the ocean interior. Numerical simulations show that unbalanced dynamics associated with zero or negative potential vorticity can drive intense diapycnal motions. These motions can lead to strong vertical fluxes of biologically active tracers, such as nutrients, as well as lateral diapycnal tracer fluxes at specific locations.

3. Recommendations for the DRI Research Plan

The above processes are believed to occur to varying degrees throughout the ocean. However progress in understanding these dynamics has stalled largely due to lack of direct observations and high resolution numerical simulations. The goal of the present DRI is to provide an understanding through observations, modeling and theoretical studies, which can be translated into parameterizations and formulae that are applicable under a variety of forcing conditions.

1. DRI Objectives

Based on what is presently understand about vertical and horizontal mixing processes at large and small scales, there are a number of specific questions that should be a priority for the DRI to better understand lateral mixing at scales of 10 m – 10 km. In terms of guiding the field program, the three main hypotheses that emerged from discussions of the DRI working group were:

Primary Hypotheses:

1. Inhomogeneous IW mixing creates PV anomalies that are responsible for significant isopycnal mixing.

2. Mesoscale straining leads to a cascade of both tracer and PV variance to submesoscales that is responsible for significant submesoscale isopycnal mixing.

3. Non-QG, submesoscale instabilities feed a forward cascade of energy, scalar and PV variance which enhances both isopycnal and diapycnal mixing.

The mechanisms associated with the above three hypotheses are distinct, and would be expected to lead to potentially different rates of lateral dispersion in different regions of the ocean. However they are also potentially linked. For example, the mesoscale straining of hypothesis 2 is presumed to be the primary source of energy for the imbalance of hypothesis 3. Meanwhile, the PV anomalies of hypothesis 1 may, through an up-scale energy cascade, interact with the PV variance associated with both 2 and 3. Associated with each of the above three hypotheses, or in some cases relevant to all of them, there are thus a number of additional hypotheses that should also be addressed in the DRI.

Additional Hypotheses:

Relevant to hypotheses 1 – 3, is the additional hypothesis:

4. Submesoscale variability is associated with coherent structures: mixing is inhomogeneous and anisotropic and submesoscale processes are inherently vertical as well as horizontal.

Relevant to hypothesis 3:

5. "Fronts are not barriers to transport". Specifically, we hypothesize that submesoscale processes facilitate cross-density-front exchange (Here, the point is to understand how a collection of

submesoscale processes add up to give a cross-front transport at the mesoscale; i.e. bolus transport, not mixing that leads to irreversible mixing - diffusion).

Relevant to hypothesis 2:

6. Filaments develop a slope of f/N at scales dominated by geostrophic dynamics. (What sets the width and thickness of filaments?)

Relevant to both hypotheses 2 and 3:

7. The lateral downscale variance cascade is absorbed by vertical (as opposed to lateral) mixing processes. How does filamentation interact with vertical processes, e.g., double diffusion, Kelvin-Helmholtz, internal wave breaking?

2. Field Experiments

The above hypotheses can be addressed through a combination of observations, numerical modeling, and theory. A number of considerations can help guide such efforts. For example, hypotheses 1 and 2 may be considered opposed as follows: does the mesoscale generate small eddies that are then erased by small-scale mixing events, or do small-scale mixing events generate submesoscale eddies directly (and if the latter, what gets rid of them?) Second, while the surface mixed layer is rife with submesoscale phenomena, it is also strongly forced, in contrast to the stratified interior. Hence, comparing processes in the surface mixed layer with those in the stratified interior could help clarify the contribution of various processes. Finally, the link between vertical and lateral mixing necessitates studying the exchange between the surface mixed layer and upper pycnocline, and its role in lateral spreading.

Site Selection (general):

The strategy for selecting a field site is to identify key features of the mechanisms of interest, and determine in a general sense what regions of the ocean would provide the strongest signal and the highest probability of exhibiting those phenomena. Considering the above hypotheses, it is recommended that two sites be studied as part of the DRI, to obtain a contrast between regions of low and high eddy energy. This will in effect provide end-points for the mechanisms of interest, from which modeling and numerical studies can determine the role of each process under varying intermediate conditions. Site 1 should be in the midst of a mesoscale eddy field of moderate eddy kinetic energy, away from the influence of the coast and persistent fronts. Areas for such a site abound in the open ocean. In choosing such a site, one might want to avoid the equator, where the horizontal Coriolis acceleration vanishes, and the boundaries of the ocean, where topography and fronts are likely to play a strong role. Site 2 should be at a location with a high likelihood of strong frontal activity, and associated high available potential energy. While it may be difficult to locate a single persistent front well in advance of the field effort, satellite and aerial observations combined with operational modeling can be used to inform the in situ field program of more immediate conditions.

For both sites, a number of factors should be taken into account when choosing a specific geographic region and time of year. Such factors should include, but are not limited to: overall water depth, mixed layer depth, large scale spice gradients to track isopycnal stirring, wave height, mean currents, predictability of submesoscale features, distance to lateral boundaries, internal wave activity, presence/absence of significant internal tide, eddy kinetic energy, wind, chlorophyll signal, presence/absence of significant mesoscale and/or submesoscale energy, water clarity, existing or feasibility of proposed moorings, availability of other supporting data such as CODAR, and/or satellite data (e.g., fog- and cloud-free), existing regional or process modeling efforts, proximity to port, proximity to airport, and feasibility of conducting small boat surveys.

With these considerations in mind, some further characteristics of two observational field sites are given below, together with a description of suggested field efforts that will address the above hypotheses.

Open Ocean Site: Site 1

Many of the hypotheses stated earlier apply to an open ocean site, in particular, the primary hypotheses 1, 2, and 3. A site and season should be chosen with the above scientific goals as well as practical considerations in mind. Almost any site with a well developed eddy field will suffice, so practical and technical constraints will help determine the final choice. Once a site is chosen, the external parameters appropriate for the site can be built into numerical process models designed to examine the hypotheses to be tested. These models will be used to guide and to interpret the experiments. It is likely that different models will be needed for the different hypotheses.

A patch of water about 200 km across, accessible by ship and aircraft, most likely from an island, will be chosen. A field campaign of 3 to 4 weeks duration, in the second year of the DRI, would be mounted at this site. The overall site, at 200-km scale should be characterized with satellite observations, and possibly with aerial and ship surveys and/or AUVs. Study sites, on the order of 10 km across, will be chosen within the general area for testing of the hypotheses. Intensive surveys with towed instruments and/or AUVs of the velocity, spice, density, and turbulence fields of the study site would be made to span scales of 1 m – 1 km. A series of dye releases would then be done within the study site to examine the actual lateral mixing events at scales of 10 m – 10 km, and to estimate mixing parameters such as diffusivities and Lyapunov coefficients. Measurements of the velocity, density, internal wave, and turbulence fields, as well as the dye field, would continue during these dye experiments. The measurement program should be designed with guidance from the numerical process studies such that together with theory, they can adequately test the various hypotheses for the dynamics of lateral mixing.

Processes at scales of 10 m – 10 km are expected to unfold rapidly. Their study will benefit from recently developed tools to obtain rapid and high resolution surveys. These tools include gliders, self-propelled AUVs and towed instruments equipped to measure turbulent dissipation rates as well as standard hydrography and optical properties, profiling floats that can measure currents and possibly turbulence as well as hydrography at fine scales, and airborne LIDAR, which can rapidly survey a dye patch. Appropriate use should be made of satellite data on sea surface height, sea surface temperature and upper ocean chlorophyll fluorescence.

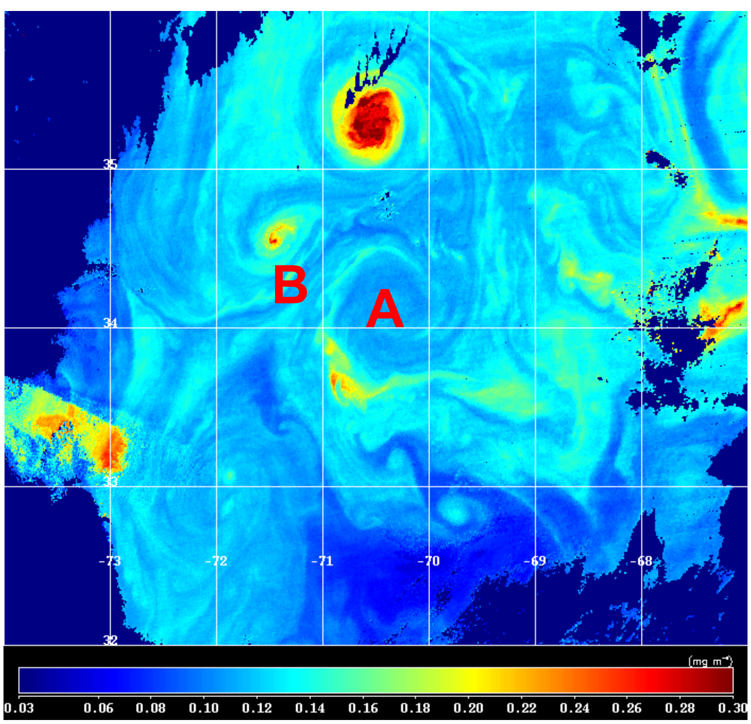

Figure 1: Sea surface chlorophyll distribution derived from sea surface color in the western Sargasso Sea on May 27, 2007 showing generic open ocean conditions that could be used to test hypotheses 1-3.

Figure 1 shows the effect of an eddy field on the surface chlorophyll distribution in a region of the western Sargasso Sea on May 27, 2007. This site is not near enough to an airport to be a possible candidate for the study, but it is useful as an illustration of how a campaign might be planned around such an image. Site A in the figure, within an anticyclonic eddy, would be a good study site to test hypotheses 1, and possibly hypothesis 3. Site B, along a front between eddies, would be a good site to examine hypotheses 2 and 3, involving mesoscale strain and submesoscale instabilities. Note the elevated chlorophyll concentrations and the cusps in the chlorophyll isopleths which suggest instabilities of the front at scales of 10 to 30 km.

Frontal Site: Site 2

A second study site focused on addressing primary hypotheses 2 and 3 will be chosen for the third year of the DRI. Again, a field campaign a 3 to 4 weeks in duration is envisioned. The primary focus of this field effort is to investigate how submesoscale instabilities at fronts result in cross-frontal transport, through both isopycnal and diapycnal mixing and enhanced energy dissipation. Near-zero or negative PV is the primary marker of this process. A key point regarding this field site is that very strong gradients and submesoscale instabilities abound, and in fact dominate, compared to the generic open ocean conditions of field site 1.

A number of criteria for field site 2 are pre-requisite. There must be a high probability of finding a sufficiently strong front. The site must be deep enough and far enough from the coast so that both the surface frontal instabilities and the resulting deep, cross-frontal transports occur. Fronts at the location must be strong enough to so that PV approaches zero or becomes negative. Internal waves must be sufficiently weak, particularly internal tide and inertial oscillations, to minimize contamination of the submesoscale frontal signal. There must be a strong cross-frontal spice gradient to provide a natural isopycnal tracer. There must be a mixed layer deep enough for submesoscale features to reliably form. There must be sufficient atmospheric forcing to maintain mixed layer and provide upfront and down-front wind orientation.

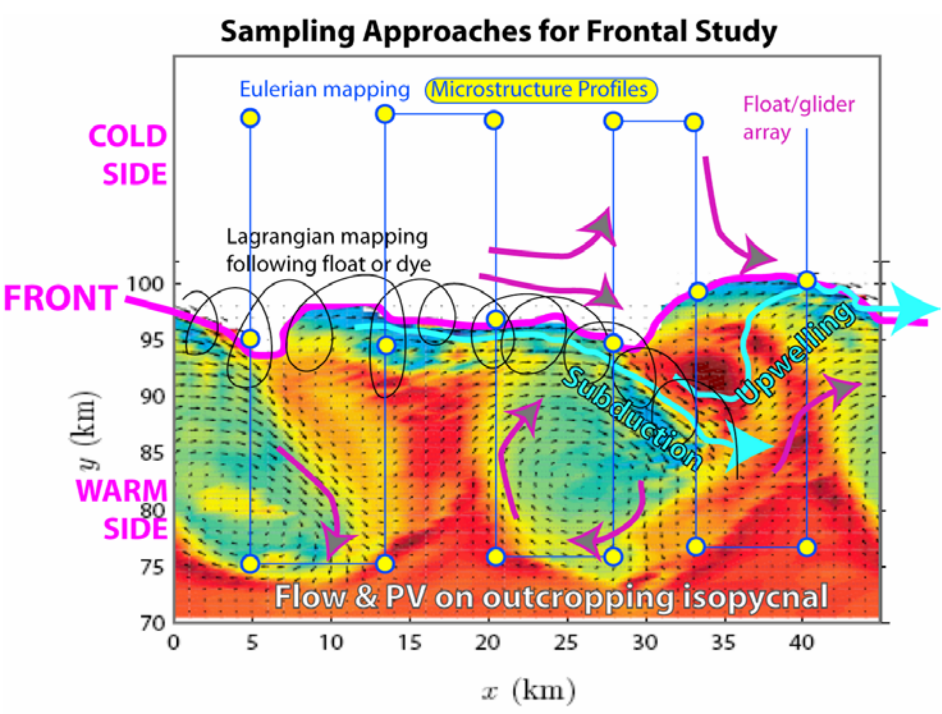

Figure 2: Schematic of possible sampling strategies for field site 2 superimposed on a simulation of a submesoscale frontal instability (from Thomas, 2007). Potential experimental elements are described in the text.

In advance of and during the second field effort, satellite and aerial remote sensing and model prediction will provide support for locating fronts. Shipboard surveys will be used to map the submesoscale temperature, salinity and velocity structure of the front, and from these deduce the PV and strain fields, and identify any coherent submesoscale eddies. Shipboard measurements will also be made of dissipation rates of turbulent kinetic energy, spice and potential density, both in the boundary layer and in the underlying stratification. All of these observations will be done in a manner so as to follow the evolution of the relevant frontal features downstream and as the meteorological forcing changes. The goal of the second observational program will thus be to measure, directly or indirectly, the fluxes across the front through some combination of a.) dispersion of natural or injected dye, b.) scalar variance budgets, and c.) direct estimation from mapped fields.

The following aspects are key components of the observational program for field site 2:

1. Lagrangian mapping. The kilometer scale structure of the front must be measured by a ship towing a profiling body while following a Lagrangian parcel, marked either by a float, dye or both. The rapid, repeated sampling provides accurate estimates of the potential vorticity, while the evolution of properties at the float or the dye dispersion provides estimates of the isopycnal and diapycnal mixing. The float and/or dye trajectories provide direct estimates of the expected intense upwelling and downwelling.

2. Eulerian mapping. The 10 km scale structure of the front is measured by a ship towing a profiling body in a regular pattern crossing the front and thereby mapping the submesoscale structure. This provides a context for the Lagrangian mapping and a means to best choose the location to inject the dye and/or float. The resulting maps provide estimates of the PV field and, using inversion techniques, the vertical velocity field for comparison with the direct estimates from floats and dye.

3. Float/glider mapping. An array of floats and/or gliders map the 10 km scale of the front.

4. Microstructure measurements. Microstructure profiles are made across the front to measure the dissipation rates of energy and scalars, thereby measuring both the local isopycnal mixing rates and contributing to variance budgets.

5. Remote sensing. Both satellite and aircraft remote sensing will be used to map the surface structure of the front in more detail than is possible using the above methods.

The complete plan outlined above for field site 2 (and likely also that for field site 1) will require two ships. It is anticipated that the 1-20 km frontal features of interest will evolve on time scales of many hours to days. These rapid changes will challenge the observational methods to provide sufficient space and time resolution. Also, both numerical modeling and theoretical studies/analysis will be required in support of the observational program. Detailed pre-measurement simulations of both realistic and idealized frontal scenarios will guide the experimental design. Operational forecast models, where already available, will guide the experimental execution. However, given the difficulty of predicting features such as frontal locations with sufficient accuracy, and in light of the widespread availability of remote sensing observations in near real-time, it is not anticipated that significant new operational forecast efforts would be worth the effort and resources to spin up.

3. Numerical Modeling

Numerical modeling and theoretical studies have been fundamental to enhancing our understanding of submesoscale processes in the ocean. The findings from such studies have helped motivate many of the hypotheses laid out in this document. With the recent growth in computational modeling capabilities, a host of new phenomena have emerged in the 10 m – 10 km scale range that need to be investigated further. These include forced instabilities in the surface layer that can be captured through large eddy simulation, submesoscale instabilities and processes that arise in non-hydrostatic and primitive equation models with frontal dynamics, and boundary effects in quasigeostrophic (QG) dynamics seen in surface QG models.

To compliment the DRI field program, a multi-scale modeling approach should be used to cover a range of dynamical regimes and scales. This would enable more detailed study of various processes and their coupling on the along-isopycnal transport and spreading of tracers. As part of this, potential vorticity is a fundamental quantity that can be used to link the dynamics to tracers and buoyancy, and to make the connection with observations. Numerical modeling studies are also useful in that (i) they provide continual (though discretized) fields for analysis in multiple frameworks (e.g. Lagrangian vs. Eulerian, z-coordinate vs. isopycnal, spectral vs. physical), (ii) can be repeated numerous times with varying parameters to test theories and explore multi-parameter dependencies, and (iii) can isolate and assess the contribution of various competing physical processes.

To explore the role of the mesoscale strain field on tracer variance and its downscale cascade (hypothesis 2) QG models could be used. The applicability of surface-QG models to near-surface frontal dynamics should be investigated, particularly as the relative vorticity approaches the magnitude of the planetary vorticity at submesoscales. Submesocale processes and frontal intensification in the upper ocean (including the dynamics relating to hypotheses 3, 4 and 5) are well represented in primitive equation hydrostatic and non-hydrostatic models. These could be used to capture the generation of negative potential vorticity and the loss of balance, and examine the implications of the latter on filament formation, cross- and along-isopycnal transport, and mixing (hypotheses 6 and 7). Modeling internal waves and their nonlinear interaction with the eddy field, as well as the effects of internal wave breaking on submesoscale eddies and the upscale cascade associated with the vortical mode can also be studied with Boussinesq models (hypothesis 1). Surface instabilities leading to a loss of balance also suggest using large eddy simulation within the mixed layer. Using a series of hierarchical process studies and/or grid nesting, the models can span across various scales and dynamical regimes. Since no single model can capture all of these dynamics simultaneously, using a combination of models is necessary to study how these processes relate, and hence which of the three primary hypothesized mechanisms dominates when and where.

With the above goals in mind, the numerical modeling approach will be two-pronged. First, both regional and process study modeling in the years preceding the field experiments will help guide the field efforts in terms of designing measurements to test the hypotheses, and understanding conditions likely to exist in particular geographic locations at particular times of year. Second, following each of the field experiments, both realistic and process-study models will be used to interpret the observations, extend the hypotheses over a wider parameter range, examine in further detail the specific and statistical conditions at the study sites, and distinguish the different processes of interest. In addition, operational regional models can be used to both forecast and hindcast actual conditions in the field. They can also provide boundary conditions, both deterministically and statistically, for process study models. The overarching goal is to extend what is learned from the two contrasting field sites to other oceanic conditions, with the ultimate goal of developing parameterizations of the relevant processes.

4. Summary and Timeline

Lateral stirring and mixing along and across isopycnals are poorly understood. In contrast, diapycnal turbulent mixing in the stratified ocean interior has been successfully parameterized in terms of internal wave shear and strain. The goal of this program is to understand lateral mixing well enough to parameterize it in terms of larger-scale, more easily resolvable processes.

The envisioned timeline for the DRI consists of a three year initial effort, which includes a two-year field program plus numerical modeling studies. This initial effort will be followed by a two-year analysis, modeling and synthesis period. The open ocean (site 1) field program will take place in year 2, while the frontal (site 2) field program will take place in year 3. Modeling efforts will begin in year 1, and continue primarily in years 2-4, with time for synthesis in year 5.

Timeline:

FY09

- set up models
- continue instrument development
- initial field testing

FY10

- field studies (site 1)
- process modeling
- additional instrument development
- additional testing for year 3

FY11

- field studies (site 2)
- process modeling

FY12

- post experiment analysis
- process modeling

FY13

- analysis / synthesis
- report findings