LIDAR Studies of Small-Scale Lateral Dispersion in the Ocean

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LONG-TERM GOALS

Our long-term goal is to better understand lateral mixing processes in the ocean on scales of 10 m to 10 km, i.e., the “submesoscale”. We aim to understand the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. The research will contribute to fundamental knowledge of ocean dynamics at these scales, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

OBJECTIVES

One objective of our work is to determine the extent to which shear dispersion – the interaction of vertical mixing with vertical shear – can explain lateral dispersion at scales of 10 m to 10 km. A second objective is to determine whether slow but persistent vortices enhance the stirring attributable to shear dispersion. We also share the overall objectives of the Lateral Mixing DRI to try to determine the extent to which submesoscale stirring is driven by a cascade of energy down (in wavelength) from the mesoscale versus a propagation of energy upwards from small mixing events (e.g., via generation of vortices). A key technical goal of our work is to develop the use of airborne LIDAR surveys of evolving dye experiments as a tool for studying submesoscale lateral dispersion.

This annual report marks the end of year 3 of a 5 year study as part of the “Scalable Lateral Mixing and Coherent Turbulence” (a.k.a., LatMix) DRI. The main effort of the present work is a collaboration between J. Ledwell and E. Terray (WHOI), M. Sundermeyer (UMass Dartmouth), and B. Concannon (NAVAIR). This project is also being performed jointly with a collaborative NSF grant to J. Ledwell, E. Terray, and M. Sundermeyer (see “Related Projects” below). ONR is providing support for the airborne LIDAR operations and for a substantial part of the field operations and analysis.

APPROACH

Our approach is to release dye patches on an isopycnal surface in the seasonal pycnocline, and to survey their evolution for periods of 1 to 6 days, in collaboration with other investigators in the DRI.

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Drogues released with the dye not only help with tracking, but also give valuable measurements of the shear/strain field on the outer scale of the patches. Lagrangian floats released with the dye patches give measurements of vertical shear and strain following the patch (D'Asaro). The dye patches are sampled not only with towed instruments from ships (Sundermeyer; Levine) but also, as mentioned above, with airborne LIDAR (Concannon, Terray, Sundermeyer). Because of the scope of the DRI, of which our work is a part, the hydrographic and dynamic setting of the dye dispersion studies have been well measured with profiling towed bodies from two other ships (Lee and Klymak), with a swarm of EM-APEX floats (Sanford, Lien, Shcherbina), and a flotilla of gliders (Shearmann), as well as with satellite remote sensing (Harcourt) and ultimately with numerical models (Mahadevan, McWilliams, Molemaker, Ozgokmen, Tandon). Members of the DRI field team have also studied fine structure and microstructure with a heavily instrumented AUV (Goodman) and towed system (Kunze). Theory will be applied to our observations by all of the DRI PI's and their students and post-docs.

In the context of the DRI modeling efforts, M. Sundermeyer is also collaborating closely with M.-P. Lelong in support of her DRI grant, "LES Modeling of Lateral Dispersion in the Ocean on Scales of 10 m – 10 km." As part of this, numerical simulations and analysis are being performed under the present effort in preparation for, and to aid interpretation of, the main field studies. These numerical simulations are also being coordinated with modeling efforts of other DRI participants.

WORK COMPLETED

A planning meeting for the DRI was held at UCLA 15-16 February 2011, chaired by Ledwell. The main objective of this meeting was to plan a 3-week field operation in June 2011. This field program involved three research vessels: *Cape Hatteras*, *Endeavor* and *Oceanus* and a Navy P3 *Orion* Aircraft with the LIDAR system. Ledwell served as nominal overall coordinator of the experiment, dealing with preparations that were common to all three ships, with much help from Eric D'Asaro and Ramsey Harcourt on ship-to-ship communications, from Tom Sanford as chief scientist for *Endeavor*, from Craig Lee as chief scientist for *Oceanus*, from Brian Concannon as NAVAIR PI for P3 operations, from Ramsey Harcourt on information flow, and indeed from all the PIs involved in the field work.

During the actual experiment our part of the DRI was conducted from R/V *Cape Hatteras*, with Ledwell serving as chief scientist, and organizing dye releases, with assistance from Brian Guest and Leah Houghton at WHOI. The drogue program was led by Sundermeyer, with assistance from Pascale LeLong from NWRA and Gualtiero Badin of BU. The dye patches were sampled with a Moving Vessel Profiler by Murray Levine and Stephen Pierce from OSU and David Ciochetto from WHOI, and with an Acrobat towed CTD/Fluorometer by Sundermeyer and Daniel Birch of UMass Dartmouth. LIDAR surveys of the dye patches were conducted by Brian Concannon of NAVAIR and flight crews from Patuxent River Naval Air Station, with on-site support from WHOI personnel Gene Terray and Cindy Sellers. Inherent and Apparent optical properties of the water column in the vicinity of the dye patches were measured from the R/V *Cape Hatteras* by Ledwell and Houghton using profiling instruments. These measurements will aid in the inversion of the measured fluorescence intensity to estimate dye concentration.

The roles of the three ships were as follows. Besides the dye and drogues, Lagrangian Floats were deployed by Eric D'Asaro and Mike Ohmart of APL/UW from *Cape Hatteras*. A swarm of EM-APEX floats was deployed and tended by Tom Sanford of APL/UW and his group from R/V *Endeavor*. *Endeavor* was also the platform for 10-km scale surveys of the hydrography around the dye patches and the dye itself, by Jody Klymak and his group of U. Victoria during much of the experiment, and was the platform for tending gliders launched by Kipp Shearmann from OSU. Surveys at 30-km scale were conducted with a towed instrument array (*Triaxus*) by Craig Lee of APL/UW and his group on R/V *Oceanus*. Oceanus also tended an AUV (*T-REMUS*) operated by Lou Goodman of UMass Dartmouth for 8-hour deployments during which a towed body with CTD and temperature microstructure sensors (*Hammerhead*) was deployed by Eric Kunze of U. Victoria. All of these efforts by the various PIs were tightly coordinated during the field program, as will be the interpretation of the results during the analysis phase of this work; hence the entirety of the effort warrants mention here.

The studies were focused on the upper ocean. Mixed layer depths were typically 10 to 20 meters, but varied from virtually nil to as much as 25 m, depending on wind and radiative conditions and on location with respect to ocean fronts. Except for one venture in the mixed layer, the dye patches were always released in the stratified layer below the mixed layer on isopycnal surfaces whose depths were from 20 m to 35 m. Drifters with surface buoys and drogues set for approximately the depth of the dye patches were also released with the dye. Nine drifters were deployed in a cross pattern centered on the dye streak for the longer-term (~140-hour) rhodamine experiments, and two or three along the streak for each of the short-term (~30-hour) fluorescein experiments, giving as many as 18 drogues in the water at any given time.

Two rhodamine experiments were performed, one in each of the areas mentioned above, which will be called Site 1 and Site 2. Both experiments lasted about a week. The Site 1 rhodamine release was a low strain region, selected based on in situ surveys, models, and satellite images. This prediction was borne out by the surface drifters, whose separation with time was consistent with a strain rate of approximately $1\text{x}10^{-6}\ \text{s}^{-1}$. The Site 2 rhodamine release was chosen as a higher strain region. The drifters at Site 2 initially separated at a rate that was consistent with a strain rate of approximately $1\text{x}10^{-5}\ \text{s}^{-1}$. After about two days, the rate of separation decreased and the drifters actually moved closer together. Within each of the one-week experiments, a set of 3 or 4 fluoresecin patches were released, intended for surveying by the aircraft and for intensive study with *T-REMUS* and *Hammerhead*.

The dye patches were surveyed from *Cape Hatteras*, usually in regular radiator patterns with boundaries set during surveying by the incoming data. Surveys were guided by the integrated ship's ADCP velocity in the bin near the depth of the dye release (a "virtual float"), and by the drogued drifters. As noted above, the dye was also sampled by several of the vehicles deployed from the other ships as they executed their preset survey patterns designed to measure the hydrographic and velocity fields in the study areas. Figs. 1 and 2 summarize two of the surveys.

Work to date on the Lidar data has been to evaluate the quality of the data, and to calibrate and geo-register the fluorescence and backscatter intensities using the on-board INS. We have also written software to advect the dye patch over time using the shipboard ADCP measurements of the current so that the evolution of the patch can be studied by comparing shape between successive flights. This initial phase of the data analysis is close to completion. The next phase will be to invert the intensity profiles to recover the dye concentration. An algorithm to do this by optimally combining the fluorescence and backscattered intensities was previously developed by us (Terray et al., 2005) and successfully applied to airborne Lidar observations (Sundermeyer et al., 2007). We will extend that approach to permit inclusion of *a priori* information such as the shipboard measurements of the water column optical properties, as well as the *in situ* towed observations of the dye. We are also working on an improved forward model connecting the dye concentration to the observed intensities.

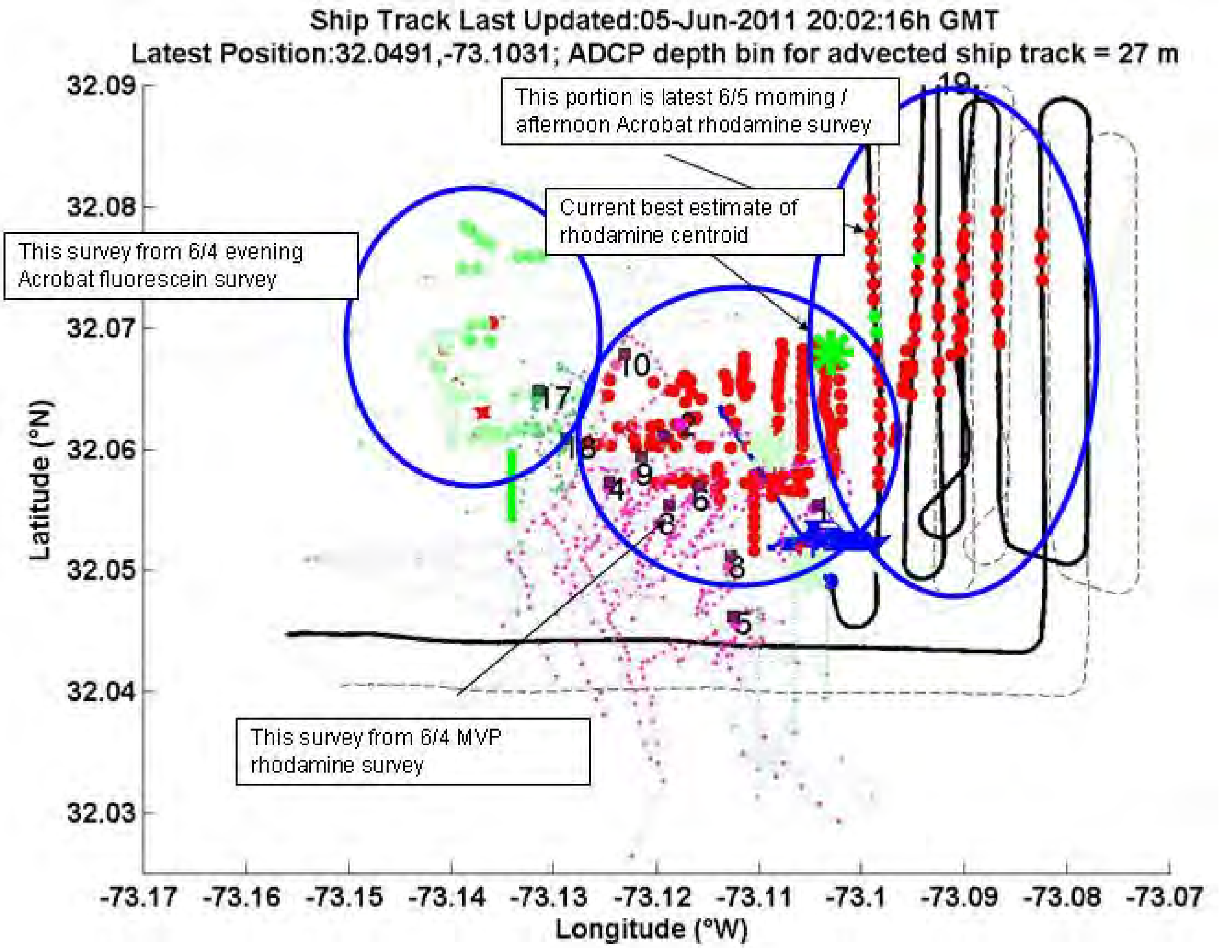

Fig. 1. Example annotated real-time map of selected surveys for the Site 1 experiment. Red dots are rhodamine hits on 5 June; pale green dots are fluorescein hits from 4 June; magenta and green dots are fixes for drifters released with the rhodamine and fluorescein, respectively; magenta and green squares with numbers are latest predicted positions for rhodamine and fluorescein drifters, respectively; dashed and bold solid black lines are R/V Hatteras ship track in Earth and advected coordinates; ship icon indicates R/V Hatteras position at time of the map.

As part of the modeling efforts in collaboration with M.-P. Lelong, we also continue to conduct numerical simulations pursuant to one of the hypotheses of the LatMix DRI, involving localized internal wave breaking and subsequent lateral stirring by the relaxation of diapycnal mixing events. One manuscript on this work has been published in *Physics of Fluids*, a second has been submitted to *J. Physical Oceanography*, and a third is in preparation, with major results completed. We are also continuing to examine the effects of large-scale shears and strains, and of intermittency, on the vortical mode stirring mechanism. These simulations will guide our interpretation of the field in distinguishing among different possible lateral mixing processes.

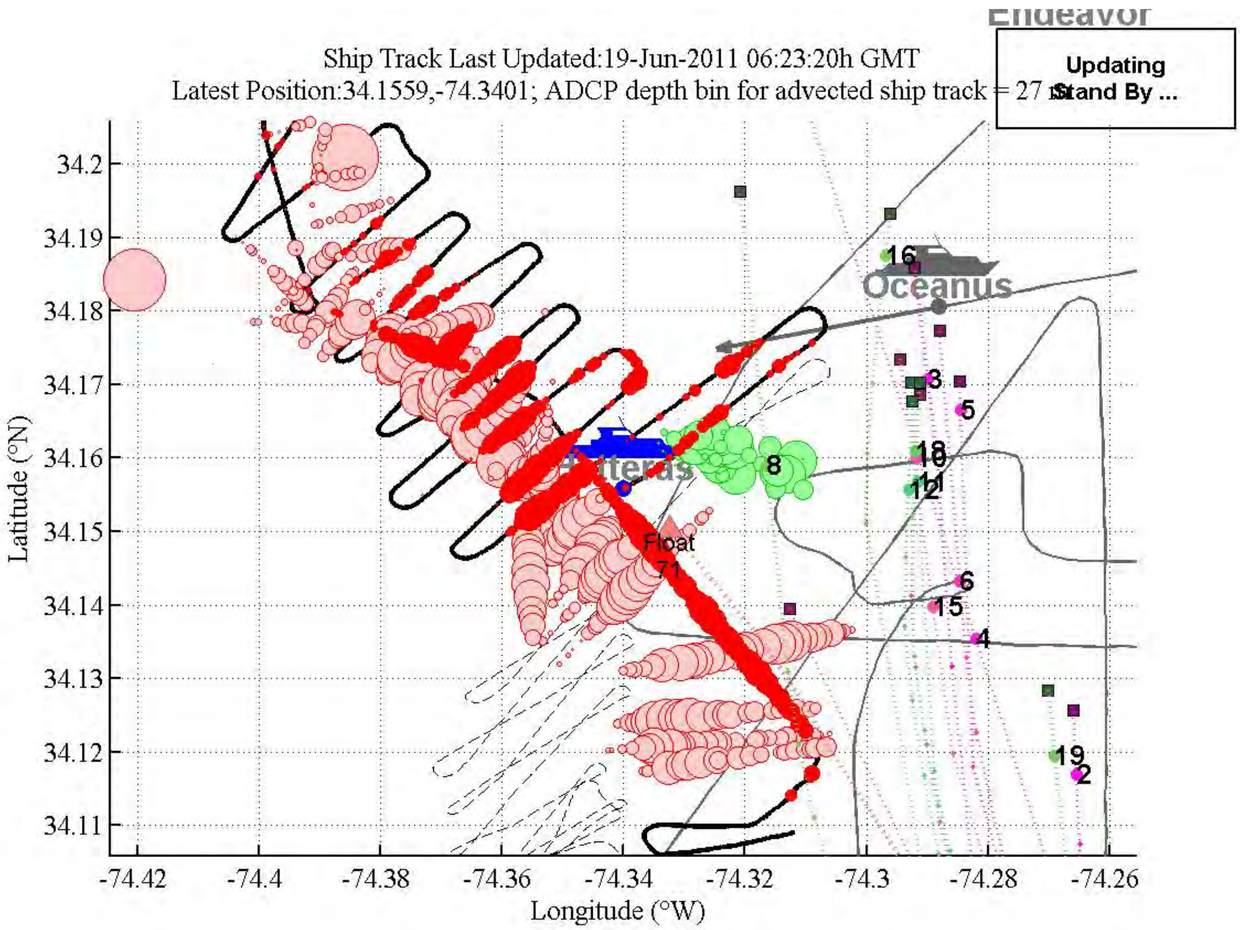

Fig. 2. Similar to Fig. 1, except that here size of circles indicates relative size of peak dye concentration along track. Red circles are dye hits from survey in progress, pink circles are advected positions of dye hits from previous survey, green circles are hits from most recent fluorescein survey. Grey line and grey ship icon are track and latest position of coordinated R/V Oceanus survey, with a portion of grey line also indicating R/V Endeavor survey (ship just North of image at time of snap-shot).

RESULTS

Scientific results from the field experiment are yet to come except for the following tentative one. Preliminary analysis on the decrease of the maximum rhodamine concentration with time suggests that the null hypothesis that “there is no mixing other than that by shear dispersion” can be rejected. The maximum rhodamine concentration at both sites appears to have decayed much faster than would be predicted from vertically sheared horizontal currents measured by the ADCP, combined with typically observed diapycnal diffusivity of order 10^{-5} m^2 s^{-1}. If this result is confirmed by further analysis, it indicates there are indeed other processes stirring the fluid, and a fruit of the overall DRI should be to find out what these are. Continued analysis of the dye data will include detailed estimates of the time rate of change of higher moments (e.g., 2nd moment) of the tracer patches, as well as other statistical measures of the patch evolution, and a more thorough examination of the shear dispersion hypothesis.

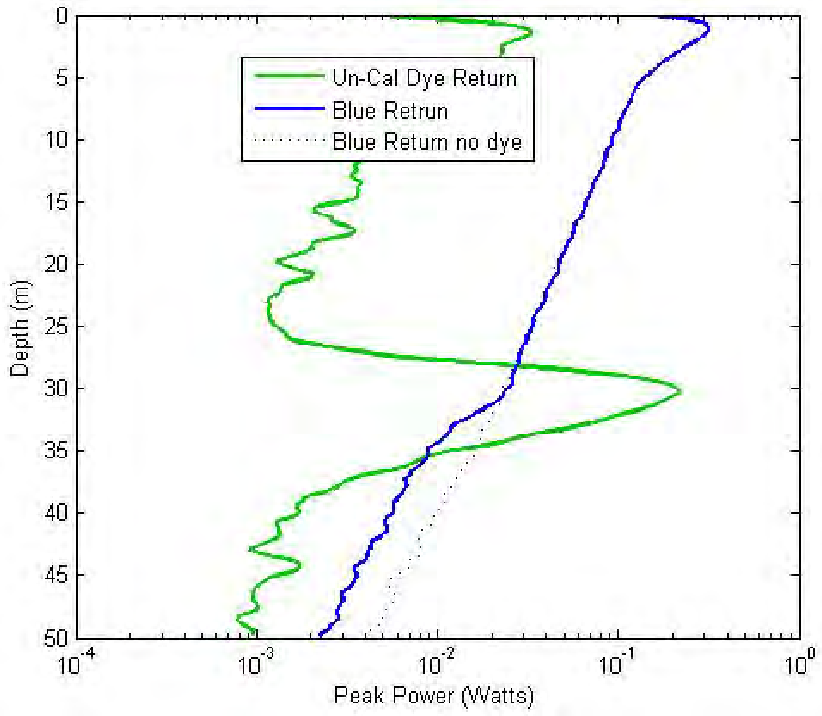

Fig. 3. Example of dye return signal (green) and lidar backscattered return signal (blue), sampling water with (solid) and without dye (dotted). The conversion of blue to green photons (i.e. fluorescence) within the dye patch can be seen as an increase in the absorption of blue light. From B. Concannon's report.

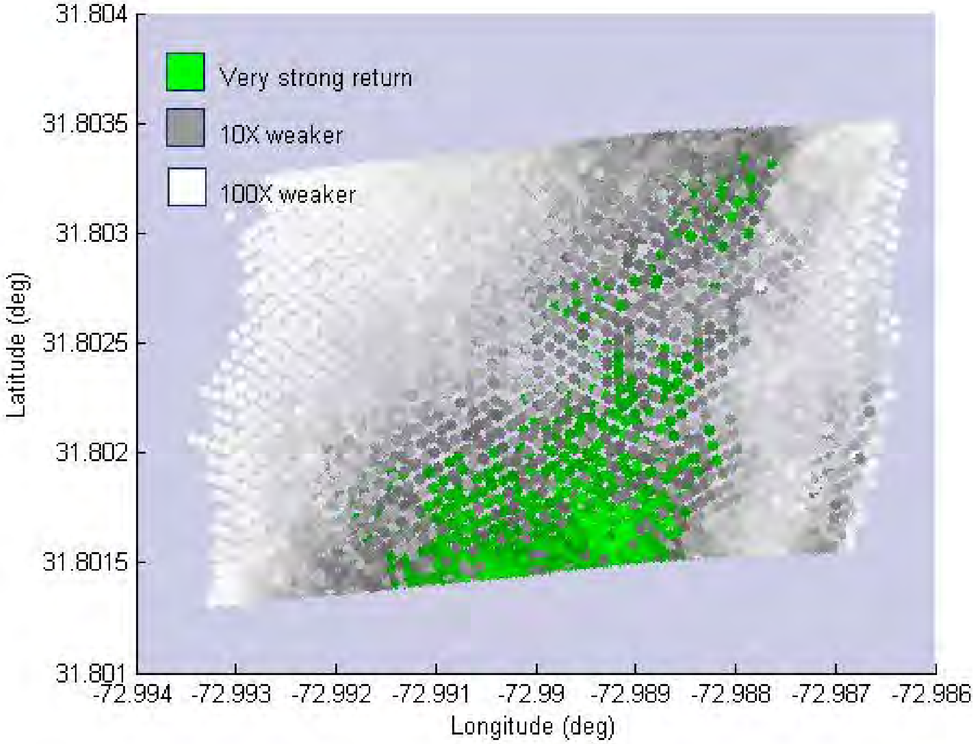

Fig. 4. Geo-registered fluorescein dye returns from a single flight pass. From B. Concannon's report.

In addition to the scientific importance, sensing of the dye patches by the LIDAR system is an area of technical advance important to oceanography. Our results so far are promising, though they also are at an early stage. The LIDAR observations are described more fully in the annual report by Brian Concannon (NAVAIR). However, at this stage, in summary, we have found strong returns in each flight from the fluoroscein patches. Although they were out of the main excitation band, we could also detect weak returns from the Rhodamine patches as well, but the extent and duration of those detections remains to be determined. A typical profile showing backscatter (blue) and fluorescence (green) is shown in Fig. 3. An example map of the strength of the return from a single pass over a dye patch is shown in Fig. 4.

Regarding our modeling work in collaboration with M.-P. Lelong, the major results of our numerical simulations examining the propagation, deformation, and breaking of a nonlinear wave packet through an ambient linear stratification are described in the recently published manuscript by Birch and Sundermeyer (*Phys. of Fluids,* 2011*)*. Regarding our simulations examining the effects of large-scale shears and strains on vortical mode generation and resultant stirring, our major findings to date are that low mode internal wave shears on vertical scales greater than the vortical modes can lead to both barotropic and baroclinic instabilities, which in turn lead to a break-up of the vortices. While this appears to indicate a forward cascade (break-up to smaller scales), when this break-up occurs in a field of vortical modes, the result instead is an inverse energy cascade, fed in part by the internal wave. Furthermore, our initial hypothesis that "low mode waves would arrest any inverse cascade by limiting the extent of vertical coupling of the PV field," appears to be incorrect. In fact, the internal wave feeds energy into the PV field via baroclinic instability, hence providing more energy to the inverse cascade at that scale. These results are detailed in manuscripts by Brunner-Suzuki, Sundermeyer and Lelong (J. Phys. Oceanogr., Submitted) and Brunner-Suzuki, Sundermeyer and Lelong (In Prep.). Additional findings on other aspects of the vortical mode stirring hypothesis in collaboration with M.-P. Lelong are detailed in her annual report.

IMPACT/APPLICATIONS

Our research will contribute to fundamental knowledge of ocean dynamics at the “submesoscale”, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

RELATED PROJECTS

The above work and findings represent a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively, and Brian Concannon (NAVAIR) under ONR award N0001411WX21010. Furthermore, our work is coordinated with all the other projects within the Lateral Mixing DRI.

Field instrumentation used in the 2011 field work was purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled “Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline”, NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI). The PIs efforts under the ONR LatMix DRI are being performed in coordination with the PIs efforts under the above mentioned NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

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