LatMix 2011 and 2012 Dispersion Analysis

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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. This 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

This project is a 1-year supplement to continue analysis and publication of results obtained during the "Scalable Lateral Mixing and Coherent Turbulence" (a.k.a., LatMix) DRI. The initial effort was a collaboration between M. Sundermeyer (UMass Dartmouth), J. Ledwell and E. Terray (WHOI), and B. Concannon (NAVAIR). This project was performed jointly with a collaborative NSF grant to M. Sundermeyer, J. Ledwell, and E. Terray (see "Related Projects" below). ONR support for this work included the airborne lidar operations as well as a substantial part of the field operations and analysis.

A primary objective of our LatMix work was to directly measure rates of submesoscale lateral dispersion in the upper ocean and pycnocline using dye and drifter release studies. Within this, we sought 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. Additionally, we sought to determine whether slow but persistent vortical motions enhance the stirring attributable to shear dispersion. Throughout this work, we also shared the overall objectives of the Lateral Mixing DRI 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 was to develop the use of airborne light detection and ranging (lidar) surveys of evolving dye experiments as a tool for studying submesoscale lateral dispersion.

Numerous papers by our group relating to the LatMix field and modeling efforts are either published, submitted, or in preparation and nearing completion (see list of references). Our analysis to date relating to the LatMix dye results have contributed significant insight into the underlying mechanisms responsible for isopycnal and diapycnal mixing and cross-frontal transport during both the 2011 and 2012 field campaigns. Despite the many manuscripts already resulting from the LatMix dye / drifter / lidar effort, however, there are additional aspects of the data and analysis that are beyond the scope of these already-in-progress manuscripts, but which we believe also represent significant contributions warranting publication. These include a manuscript describing our inversion approach for determining absolution dye concentration from raw waveforms collected during the LatMix 2011 airborne lidar surveys, and completion of the analysis and write-up of major results stemming from the LatMix 2012 dye release experiments. Publication of these two additional manuscripts, as well as ancillary analysis associated with this effort, has the potential to significantly enhance the impact of the LatMix field efforts. An additional benefit of the proposed effort is that it will also further strengthen the results of multiple manuscripts already published or in preparation by our group as well as other LatMix PIs.

APPROACH

In the primary LatMix field effort, our approach was to release dye patches on an isopycnal surface in the seasonal pycnocline, and along the Gulf Stream front, and to survey their evolution for periods of 1 to 6 days, in collaboration with other DRI investigators. Two major field experiments were conducted under LatMix, one 21-day experiment in the Sargasso Sea in June 2011, and one 25-day experiment along the north wall of the Gulf Stream in Feb/Mar 2012. Both efforts were multi-ship, multi-investigator efforts, of which the dye, drifter, and lidar work under this project were one part. Analysis of data from these field efforts was a collaborative effort between the field PIs, numerical modelers, and theoreticians.

Both the LatMix 2011 and 2012 field programs represent unique data sets, providing a wealth of new information and insight into the dynamics of submesoscale mixing under a range of environmental and forcing conditions. Close coordination of both field efforts and extensive collaboration throughout the planning, execution and analysis phases of these experiments has resulted in a data set that is much greater than the sum of its parts. The combination of the numerous measurements made during the LatMix field campaigns together with the dye tracers in particular together provide a unique opportunity to evaluate underlying mechanisms responsible for observed submesoscale dispersion.

Under LatMix funding, we completed a significant field effort and associated analysis relating to the dye release experiments, and we already have a core set of manuscripts published or in preparation reporting on our major findings. Nevertheless, there are still many important key results that remain to be written up that also have the potential of having significant impact on the field. The primary objective of the current effort is to complete the analysis and write-up for two additional primary manuscripts relating to the LatMix 2011 and 2012 field experiments, and to further strengthen the results for one manuscript already in preparation. New manuscripts anticipated to result from this effort are:

- Sundermeyer, M. A., J. R. Ledwell, J. Klymak, C. M. Lee, E. D'Asaro, D. Birch, S. Pierce. Dispersion Studies in the Gulf Stream During Winter Forcing Conditions, *J. Phys Oceanogr*.

  Subject: Detailed description of the four dye experiments performed during LatMix 2012, including transport and fate of the patches, and inferred diapycnal and isopycnal dispersion rates.

- Sundermeyer, M. A., J. R. Ledwell, B. Concannon, E. A. Terray. A Lidar Inversion for Oceanic Dye Release Experiments, *J. Applied Optics.*

  Subject: Lidar inversion technique to compute absolute dye concentration as a function of depth over the penetration depth of the lidar, as applied to LatMix 2011 lidar dye surveys.

WORK COMPLETED

The first of two field efforts under our prior LatMix funding was conducted in June 2011, ~250 km southeast of Cape Hatteras, NC, in the Sargasso Sea east of the Gulf Stream. The field program involved three research vessels: R/V *Cape Hatteras*, *Endeavor* and *Oceanus* and a Navy P3 *Orion* Aircraft, which operated the lidar system used to survey the dye release experiments. Since the application of the NAVAIR lidar system was new to this purpose, an engineering test cruise was also performed in September 2008, well in advance of the main field effort. A second engineering test cruise focusing on the ship based observations and the land-based data system was conducted in August, 2010 in collaboration with two other groups participating in the ONR LatMix DRI, M. Levine's dye group, and R. K. Shearman's glider group, both from Oregon State Univ. (OSU).

The second major field experiment of the LatMix DRI occurred February/March, 2012. Again this was a multi-ship, multi-investigator effort, with R/V *Knorr* as the "lead" ship, focused on hydrographic and dye surveys around Lagrangian float deployments (C. Lee and E. D'Asaro, APL/UW, and L. Thomas, Stanford Univ.), and R/V *Atlantis*, conducting hydrographic and glider surveys, and coordinating dye and drifter releases (J. Klymak, Univ. Victoria; M. Sundermeyer and D. Birch, UMass; and R. K. Shearman, OSU).

As noted above, numerous publications have already resulted from this work, as listed in the reference section of this report. Detailed descriptions of the major results can be found in our annual and final report for the primary DRI effort, and will not be repeated here. For the present 1-year supplemental grant, notification of funding arrived in early August. Since then, work completed includes an additional manuscript (Kunze and Sundermeyer, in press) examing the shear dispersion hypothesis during the LatMix 2011 field campaign. This manuscript was in review for publication, and as of Sept. 2015, has now been revised and accepted for publication. A second manuscript (Klymak et al, in preparation) on the LatMix 2012 field campaign, is also now complete, and is about to be submitted for publication.

RESULTS

The primary effort under the current 1-year funding supplement includes nominal support for PI summer salary, plus publication costs for two manuscripts. The following outlines the two additional publications planned as a result of this project.

a. LatMix 2011 Extended Analysis and Write-up

Our results to date relative to the LatMix 2011 field program have yielded 6 manuscripts that have already been published, 2 manuscripts submitted and/or in revision, and 4 manuscripts (the core LatMix dye dispersion papers) in preparation. An additional contribution relating to the LatMix 2011 work that could be completed with a relatively small amount of additional effort relates to the lidar inversion we have developed to infer absolute dye concentration from raw lidar returns. We anticipate that this manuscript would be submitted to *J. Applied Optics*. The main thrust of this effort would be as follows.

As part of our lidar dye analysis, we have already spent considerable effort to date developing a muli-variable nonlinear regression approach to solve for the dye concentration profile given a lidar backscatter and fluorescence return. Our approach solves the forward problem of a lidar pulse of known shape and duration, its propagation (including losses) through the air/sea interface, through the water column (potentially allowing for a depth dependent seawater attenuation), its absorption and re-emission by fluorescent dye (including 3-dimensional geometric effects), and the return path of the upward-bound fluoresced light through the water column and into the lidar receiver. Similar yet distinct equations are formulated for both the backscattered light associated with the original laser wavelength, and the fluoresced light associated with dye emission wavelength.

Using this forward model, we solve for the lidar backscatter and fluorescent waveforms assuming a hypothetical dye profile, and adjust the hypothetical profile using a nonlinear regression approach until the computed waveforms match the observed waveforms in a least squares sense. As the parameters associated with the dye distribution are relatively few compared to the total number of data points represented by the lidar returns (that is, the dye occupies only a fraction of the water column), the problem is formally over-determined, and hence is well posed. Thus, we can show for synthetic dye profiles where we start with a known dye profile and add noise, that the inversion is robust.

As we have already spent significant effort in developing this inversion approach in the course of our analysis of the LatMix 2011 lidar results, much of the work associated with coding and testing the inversion has been done. However, our manuscripts reporting on the technical aspects of the lidar dye measurement and on the inferred mixing characteristics gleaned from the lidar dye observations do not give full treatment to the lidar inversion procedure. Thus, an additional manuscript describing this inversion approach, including its strengths and associated uncertainties would be a valuable contribution to the field.

b. LatMix 2012 Analysis and Write-up

As described in previous LatMix reports, a total of four dye and drifter releases were performed during the 2012 field effort, two near the surface (~25 m depth), and two at depth (~55 m, and ~120 m depth). To date, analysis of the dye results has focused on identifying the pathways of transport and mixing of the dye (e.g., rapidly subducted along isopycnals due to symmetric instability, or pinched off the Stream during the formation of north wall filaments), as well as quantifying along and cross isopycnal dispersion in an environment where isopycnals vary from nearly vertical (outcropping) to nearly horizontal (main pycnocline). The primary data processing and coordination of the different data streams (flow through sensors from two ships, towed Triaxus measurements, Lagrangian float position) has been done. However, the majority of the analysis to date has been in support of analyses by other LatMix 2012 PIs. Again, we believe significant benefit could be realized with a relatively small amount of effort to write up the LatMix 2012 dye results in a separate, stand-alone publication. The thrust of the resulting manuscript would be as follows.

The LatMix 2012 dye manuscript will provide a detailed description of the four dye experiments, including transport and fate of the patches, and inferred diapycnal and isopycnal dispersion rates. Analysis will be similar to that of the LatMix 2011 experiments, except that in this case, movement of the dye relative to the front is the main concern. This movement will be estimated from the position of the center of mass of the dye relative to the position of the front, with the latter estimated with help from satellite data and in situ data collected by other LatMix 2012 investigators. Second moments of dye concentration along isopycnals will give integral estimates of isopycnal diffusivity. Similarly, second moments of the relative to vertical distribution of isopycnals, but transformed into an appropriate distance coordinate, will provide estimates of diapycnal diffusivity.

Major results to be described in the LatMix 2012 dye manuscript will include:

- Detailed description of the four dye experiments, including transport and fate of the patches.
- Estimates of diapycnal and isopycnal dispersion for the four dye experiments, including careful distinction of where such dispersion corresponds to vertical vs. lateral mixing processes.
- Primary inferences from the dye observations (in collaboration w/ D'Asaro, Thomas and others) regarding mechanisms responsible for observed dispersion; e.g., symmetric instability, intra-thermocline eddies, and/or formation of north wall filaments.

Again, we anticipate one additional publication stemming from this effort reporting on the primary results of the LatMix 2012 dye experiments performed in the Gulf Stream under winter forcing conditions. Aside from being a valuable contribution in its own right, this manuscript will provide a valuable reference and back-drop for numerous manuscripts already in preparation or published by other LatMix 2012 PIs relating to the underlying mechanisms responsible for the observed dispersion and cross-frontal mixing.

IMPACT/APPLICATIONS

The present work used a novel approach – remote sensing of dye using airborne lidar – to study mixing in the ocean. Our research contributes 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 enhances 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 follow on 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).

REFERENCES

Birch, D. A., M. A. Sundermeyer, 2011. Breaking internal wave groups: Mixing and momentum fluxes. *Phys. Fluids*., **23** (9), DOI: 10.1063/1.3638155. [published, refereed]

Brunner-Suzuki, A.-M. E. G., M. A. Sundermeyer, M.-P. Lelong, 2012. Vortex Stability in a Large-Scale Internal Wave Shear. *J. Phys. Oceanogr.*, **42**, 1668–1683. doi:10.1175/JPO-D-11-0137.1. [published, refereed]

Brunner-Suzuki, A.-M. E. G., M. A. Sundermeyer, and M.-P. Lelong, 2014. Upscale Energy Transfer by the Vortical Mode and Internal Waves. *J. Phys. Oceanogr.*, **44.9**, 2446-2469. [published, refereed]

Klymak, J.M., R.K. Shearman, J. Gula, C.Lee, E.A. D'Asaro, L.N. Thomas, R.R. Harcourt, A.Y. Shcherbina, M.A. Sundermeyer, M.J. Molemaker, J.C. McWilliams, 2015. Submesoscale streamers exchange water on the North Wall of the Gulf Stream. To be submitted to: *J. Phys. Oceanogr.* [in preparation, refereed]

Kunze, E., J.M. Klymak, R.-C. Lien, R. Ferrari, C.M. Lee, M. A. Sundermeyer, and L. Goodman, 2015. Submesoscale Water-Mass Spectra in the Sargasso Sea. *J. Phys. Oceanogr.*, **45**, 1325–1338. [published, refereed]

Kunze, E., and M. A. Sundermeyer, 2015. The Role of Intermittency in Internal-Wave Shear Dispersion. In Press, *J. Phys. Oceanogr*. [in press, refereed]

A.Y. Shcherbina, M.A. Sundermeyer, E. Kunze, E. D'Asaro, G. Badin, D. Birch, A.M.E.G. Brunner-Suzuki, J. Callies, B.T. Kuebel Cervantes, M. Claret, B. Concannon, J. Early, R. Ferrari, L. Goodman, R.R. Harcourt, J.M. Klymak, C.M. Lee, M.-P. Lelong, M.D. Levine, R.-C. Lien, A. Mahadevan, J.C. McWilliams, M.J. Molemaker, S. Mukherjee, J.D. Nash, T. Özgökmen, S.D. Pierce, S. Ramachandran, R.M. Samelson, T.B. Sanford, R.K. Shearman, E.D. Skyllingstad, K.S. Smith, A. Tandon, J.R. Taylor, E.A. Terray, L.N. Thomas, and J.R. Ledwell, 2015: The LatMix Summer Campaign: Submesoscale Stirring in the Upper Ocean. *Bull. Amer. Meteor. Soc.,* **96**, 1257–1279. doi:10.1175/BAMS-D-14-00015.1.

Sundermeyer, M. A**.**, E. Skyllingstad, J. R. Ledwell, B. Concannon, E. A. Terray, D. A. Birch, S. D. Pierce, B. Cervantes, Observations of Large-Aspect Ratio Large Eddy Circulation in the Ocean Surface Mixed Layer. *Geophys. Res. Lett.*, **41**, 7584–7590, doi:10.1002/2014GL061637, 2014. [published, refereed]

PUBLICATIONS

None to report.