Internal Wave Driven Mixing and Transport in the Coastal Ocean

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LONG-TERM GOALS

The long-term goal of this research is to develop improved parameterizations of internal wave driven mixing in global circulation models where such small-scale processes are not resolved (i.e. occur as subgrid-scale processes).

OBJECTIVES

The main objectives are: (1) to perform a series of high-resolution "numerical" microstructure profile studies using representative field scale flows in the coastal ocean to investigate the relationship between relevant length scales and time scales for mixing of both momentum and scalar (density); (2) to formulate parameterizations for diapycnal (irreversible) mixing driven by internal waves; and (3) to explain the fate of nonliner internal waves (NLIWs) that propagate into shallower seas as a result of the interaction process and determine whether they contribute significantly to mixing and transport.

APPROACH

This research takes a take multi-pronged approach that involves high-resolution numerical simulations, theoretical analysis and model-data comparisons. The first major thrust of this work is to perform highly resolved idealized simulations to conduct a process-oriented study since they allow for specific internal wave induced turbulent mixing processes to be isolated and examined. Furthermore, they will also permit the exploration of a broad flow and environmental parameter space. The second major thrust of this research project is to perform representative field-scale simulations that will require subgrid-scale modeling to resolve the turbulence. Based on the insights gained from the process-oriented simulations and model-data comparisons, it will be possible to evaluate the performance of the subgrid-scale parameterizations in the field-scale simulations.

WORK COMPLETED

The PI has recruited a PhD student in Fall 2012 (Ms. Amrapalli Garanaik) to begin her dissertation research on turbulent mixing processes in the coastal ocean. Another PhD student, Mr. Jian Zhou has joined Dr. Venayagamoorthy's research group in January 2013. His research will be directly related to this YIP project.

Since Fall 2012 (FY2013), we have focused our attention mainly on performing a high-resolution "numerical" microstructure study using direct numerical simulations (DNS) of homogeneous stably stratified turbulence as well developing a theoretical framework for parameterizing mixing in stably stratified flows. The idealized conditions used in DNS is akin to a breaking internal gravity wave or other intermittent disturbance leading to turbulence that is isolated from boundaries. The laboratory equivalent is the grid-tow experiment in which a bi-lateral mesh is towed through a stratified bath.

RESULTS

We briefly discuss some preliminary results from the DNS study in what follows. A journal article on this work has recently been published in *Physics of Fluids* journal (Mater *et al.,* 2013). Our main goal was to compare the Thorpe overturn length, L_T, with other length scales of the flow that can be constructed from large-scale quantities fundamental to shear-free, stratified turbulence. Quantities considered are the turbulent kinetic energy, k, its dissipation rate, ε, and the buoyancy frequency, N. Fundamental length scales are then the Ozmidov length scale, L_O, the isotropic large scale, $L_{k\varepsilon}$ and a kinetic energy length scale, L_{kN}. Behavior of all three fundamental scales, relative to L_T, is shown to be a function of the buoyancy strength parameter NT_L, where $T_L = k/\varepsilon$ is the turbulence time scale. When buoyancy effects are dominant (i.e., for $NT_L > 1$), L_T is shown to be linearly correlated with L_{kN} and not with L_O as is commonly assumed for oceanic flows (see Figures 1 and 2).

Agreement between L_O and L_T is only observed when the buoyancy and turbulence time scales are approximately equal (i.e., for the critical case when $NT_L \approx 1$). The relative lack of agreement between L_O and L_T in strongly stratified flows is due to anisotropy at the outer scales of the flow where the energy transfer rate differs from ε. The key finding of this work is that observable overturns in strongly stratified flows are more reflective of k than ε. In the context of oceanic observations, this implies that inference of k, rather than ε, from measurements of L_T is fundamentally correct when $NT_L = 1$ and most appropriate when $NT_L > 1$.

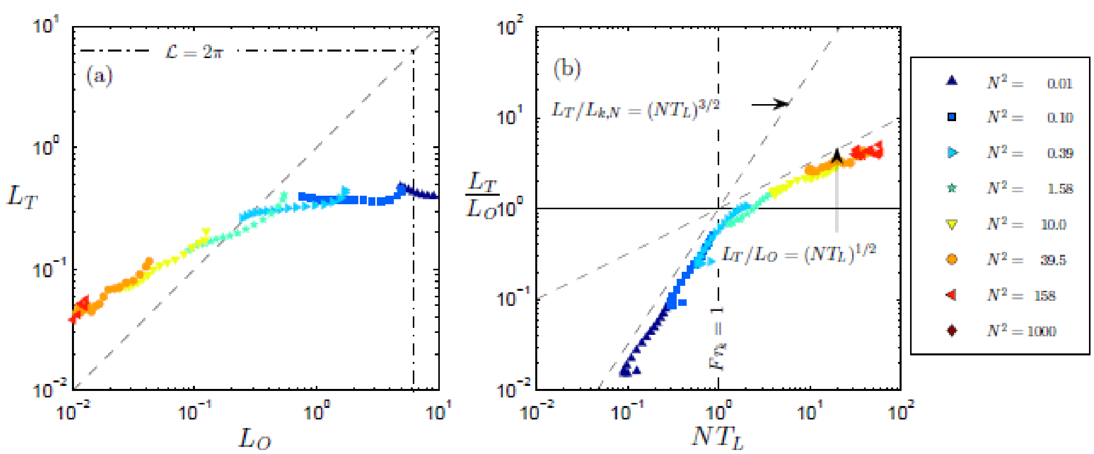

Figure 1: Ozmidov length scale, L_O, versus Thorpe scale, L_T: (a) direct comparison, and (b) plotted against the dimensionless stratification parameter, NT_L.

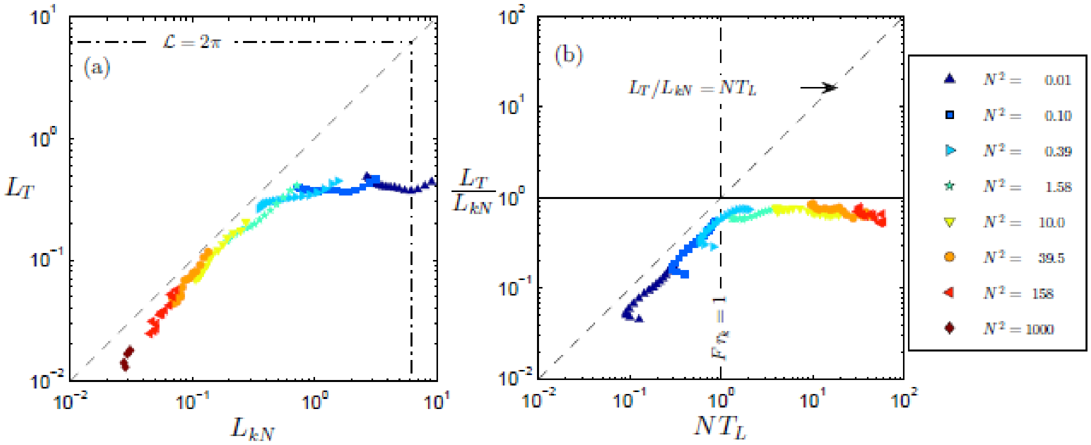

Figure 2: Turbulent kinetic energy length scale, L_{kN}, versus Thorpe scale, L_T: (a) direct comparison, and (b) plotted against the dimensionless stratification parameter, NT_L.

Extension of this published work is now in progress to investigate the trends in ocean turbulence data. This work is in collaboration with Dr. Lou St. Laurent at WHOI. The next phase of our work on this project is on mixing driven by breaking internal waves using highly resolved numerical simulations. As an example, Figure 3 shows a time sequence of the density field (with superimposed velocity vectors) obtained from a preliminary high-resolution laboratory scale simulation of the interaction of a nonlinear first-mode internal wave interaction with a steep ridge topography. The rich dynamics of the interaction process is evident with steepening of isopycnals at the leading edge of the wave leading to local kinematic instabilities that cause wave breaking as well as ejection of denser fluid over the ridge crest. At the rear end, the formation of a hydraulic jump occurs leading to enhanced mixing and release of lee waves. These initial results provide some qualitative insights on phenomena associated with strong wave forcing over steep topography such as the double ridge system in Luzon Strait (e.g. see Alford *et al.* 2011). Field measurements from the ONR DRI on Internal Waves in Straits Experiment (IWISE) cruises in 2010 and 2011, respectively indicate overturning length scales of the order hundreds of meters in the Luzon Straits at certain locations and times (e.g. see Alford *et al.* 2011 and Louis St. Laurent – personal communication). It is not clear whether such large overturns are indicative of actual local mixing or indicate signatures of dense water uplifted higher into the water column by slope convection under strong wave forcing. Our ongoing process-oriented simulation study will provide insights on this issue.

IMPACT/APPLICATIONS

The relevance and broader scientific impacts of this research project come from the importance of turbulent mixing and transport processes in geophysical and environmental flows. The expected results from this research will enhance our basic understanding of turbulent mixing and transport in the coastal ocean induced by internal waves interacting with topography. This topic is a very active area of research in the oceanic research community. A major expected outcome of this research is the formulation of simple but yet accurate parameterizations of mixing and transport that will be valuable in developing better subgrid scale models for use in large scale numerical circulation models of the coastal ocean.

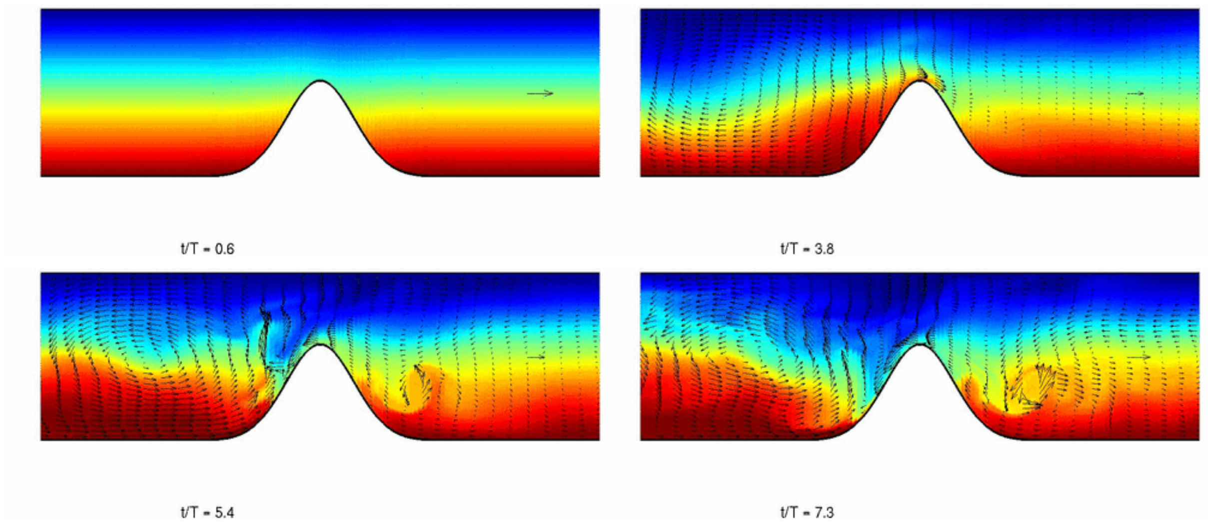

Figure 3: Time sequence of density field and velocity vectors from preliminary idealized numerical simulations to illustrate the rich flow dynamics that occurs when a low-mode internal wave impinges on a steep ridge. Note how dense fluid is advected up the ridge during the flood phase of the tide (wave forced from left end boundary which is truncated for clarity) and the generation of an internal hydraulic jump and the lee wave release during the ebb (slack) phase of the wave.

RELATED PROJECTS

The PI has another ONR funded project on improved turbulence parameterizations for oceanic flows where the goal is to develop, implement and test different turbulence parameterizations in numerical models. The emphasis of this work is on developing robust parameterizations that are applicable for a wide range of oceanic flow conditions. Hence there is some natural overlap between these two projects. Also, the PI (through a related topic funded partly through an NSF grant) has been able to investigate boundary-layer turbulence especially very close to the wall. This work has been recently published in the Journal of Fluid Mechanics (see Karimpour and Venayagamoorthy 2013). We will be extending this work to wall-bounded stratified flows and therefore the efforts are synergistic to this project.

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Venayagamoorthy, S. K. and Fringer, O. B. 2012. "Examing breaking internal waves on a shelf slope using numerical simulations", *Oceanography*, **25(2)**, pp 132-139.

HONORS/AWARDS/PRIZES

2013 – Invited by selection to attend the 2013 National Academy of Engineering Frontiers in Engineering Symposium held in Delaware from September 18-21, 2013.

2012 Young Investigator Award, Office of Naval Research.

2012 Outstanding Faculty Performance Award, Department of Civil and Environmental Engineering, Colorado State University

2012 Early CAREER Award, National Science Foundation.