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

For FY2014, we have focused on formulating and testing a simple turbulence parameterization for stably stratified flows in the proximity of boundaries and working on setting up and running process-oreinted simulations. We have also focused on extending the findings from our direct numerical simulations (DNS) of homogeneous stably stratified turbulence (see Mater *et al*. 2013) to field scale observations. 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.

RESULTS

We use both a simple zero-equation turbulence closure scheme as well as the standard k-ε model to highlight the improvements obtained from a new parameterization for the turbulent Prandtl number that we have derived. The turbulent Prandtl number (Pr_t) is the linking bridge between the turbulent momentum and scalar fluxes in the context of Reynolds-averaged Navier-Stokes (RANS) simulations. The proposed parameterization for Pr_t takes into account (for the first time to our knowledge) the inhomogeneity caused by the wall coupled with the effects of density stratification. This formulation is given in equation 1 below as:

$$\mathrm{Pr}_t = \left(1 - \frac{z}{D}\right)\frac{Ri_g}{R_f} + \left(1 - \frac{z}{D}\right)\mathrm{Pr}_{twd0} + \mathrm{Pr}_{t0}, \qquad (1)$$

where Ri_g is the gradient Richardson number, R_f is the flux Richardson number, z is height measured from the bottom, D is the total water depth, Pr_{twd0} is the difference between the neutral Prandtl number at the wall and the neutral turbulent Prandtl number for a homogeneous shear flow (Pr_{t0}).

The comparisons (as shown in figures 1 and 2) of the one-dimensional simulations results for both the mean velocity profile and the mean density profile with direct numerical simulation (DNS) of stably stratified channel flow results show remarkable agreement. Also shown in these figures are the turbulent Prandtl number formulations proposed by Munk and Anderson (1948) and a homogeneous formulation given in equation (2) below.

$$\mathrm{Pr}_t = \frac{Ri_g}{R_f} + \mathrm{Pr}_{t0}\,. \qquad (2)$$

Further details can be found in a published article in *Journal of Geophysical Research* (see Karimpour and Venayagamoorthy 2014a).

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.

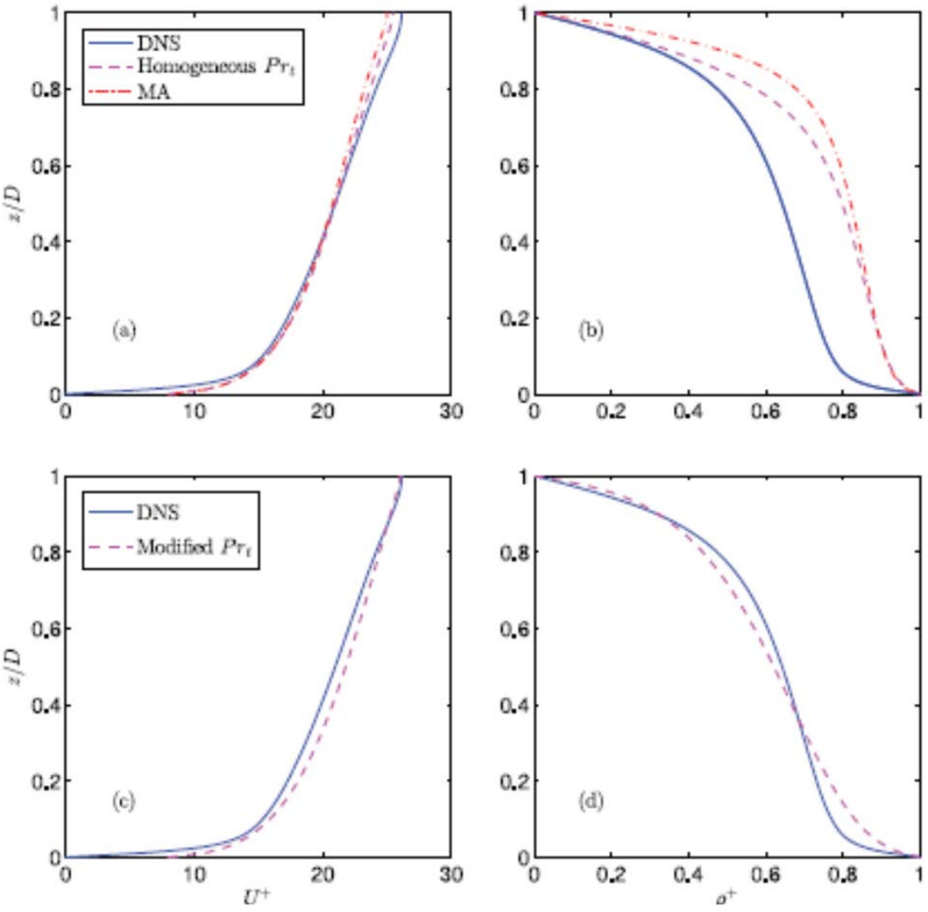

Figure 1: (left) Velocity profiles and (right) density profiles for Ri_τ= 60 obtained from the zero-equation closure scheme using (a, b) the Prt formulations given by equation (2) and the formulation of Munk and Anderson (1948) and (c, d) the modified Prt formulation (equation (1)) compared with the channel flow DNS data of Garcıa-Villalba and del_Alamo (2011).

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.

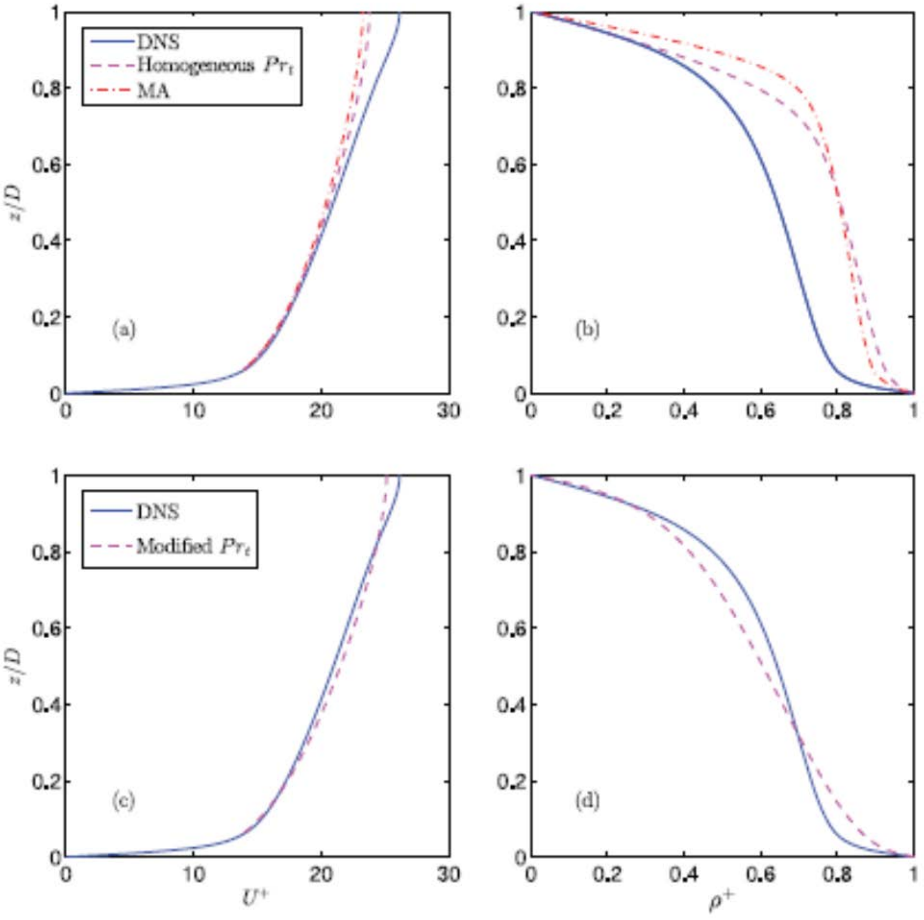

Figure 2: (left) Velocity profiles and (right) density profiles for $Ri_\tau = 60$ obtained from the standard k-ε closure scheme using (a, b) the Prt formulations given by equation (2) and the formulation of Munk and Anderson (1948) and (c, d) the modified Prt formulation (equation (1)) compared with the channel flow DNS data of Garcıa-Villalba and del_Alamo (2011).

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. Our findings have been recently published in two articles in the Journal of Fluid Mechanics (see Karimpour and Venayagamoorthy 2014b, 2013). We have extended this work to wall-bounded stratified flows and therefore the efforts are synergistic to this project.

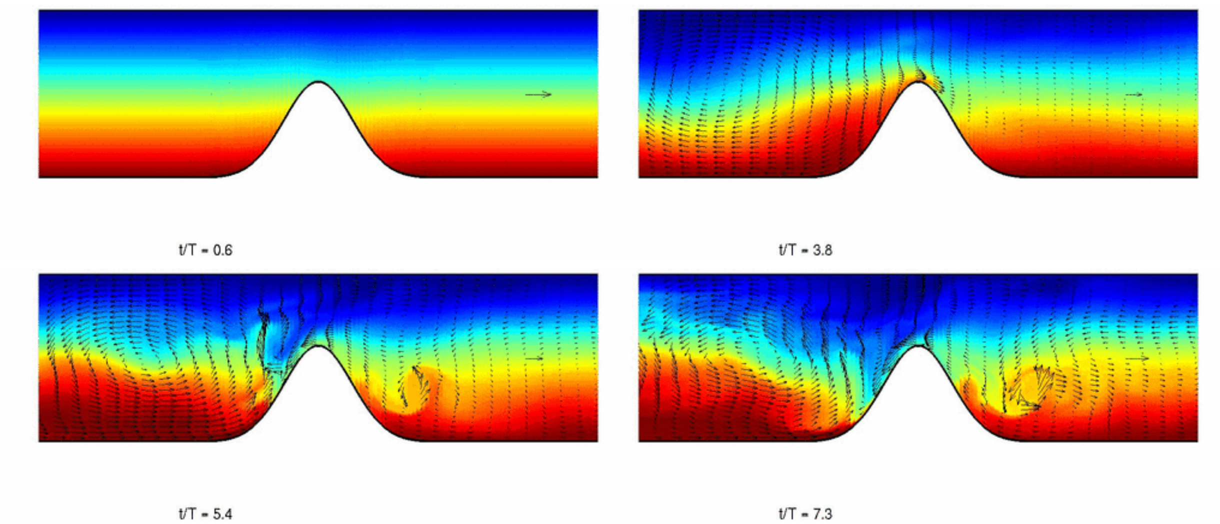

Figure 3: Time sequence of density field and velocity vectors from preliminary idealized numerical simulations to illustrate the rich flow dynamics that occurs when a low-mode internal wave impinges on a steep ridge. Note how dense fluid is advected up the ridge during the flood phase of the tide (wave 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.

REFERENCES

Alford, M. H., MacKinnon, J. A., Nash, J. D., Simmon, H. Pickering, A., Klymak, J. M., Pinkel, R., Sun, O, Rainville, L., Musgrave, R., Beitzel, T., Fu, K-H. and Lu, C-W. 2011. "Energy flux and dissipation in Luzon Strait: two tales of two ridges", *J. Phys. Oceanogr.*, doi: 10.1175/JPO-D-11-073.1.

García-Villalba, M. and del Álamo, J., 2011: Turbulence modification by stable stratification in channel flow. *Phys. Fluids, 23, 045104.*

Karimpour, F. and Venayagamoorthy, S. K. 2014a. "A simple zero-equation turbulence model for stably stratified wall-bounded flows, *Journal of Geophysical Research*, DOI: 10.1002/2013JC009332, pp: 1-11.

Karimpour, F. and Venayagamoorthy, S. K. 2014b. "A revisit of the equilibrium assumption predicting near-wall turbulence, *Journal of Fluid Mechanics*, ***in press***

Mater, B. D., Schaad, S. M. and Venayagamoorthy, S. K. 2013. "Relevance of the Thorpe scale in stably stratified turbulence", submitted to *Physics of Fluids*, 25, 076604 (2013); doi: 10.1063/1.4813809.

Munk, W.H., & Anderson, E.R. (1948). Notes on a theory of the thermocline. *J. Mar. Res.*, 7, 276-295

PUBLICATIONS

Karimpour, F. and Venayagamoorthy, S. K. 2014a. “A simple zero-equation turbulence model for stably stratified wall-bounded flows, *Journal of Geophysical Research*, DOI: 10.1002/2013JC009332, pp: 1-11.

Karimpour, F. and Venayagamoorthy, S. K. 2014b. “A revisit of the equilibrium assumption predicting near-wall turbulence, *Journal of Fluid Mechanics*, ***in press***

Karimpour, F. and Venayagamoorthy, S. K. 2013. “Some insights for the prediction of near-wall turbulence, *Journal of Fluid Mechanics*, **723**, pp 126-139.

Mater, B. D. and Venayagamoorthy, S. K. 2014a. “A unifying framework for parameterizing stably stratified shear-flow turbulence", *Physics of Fluids*, **26**, 036601 (2014)doi: 10.1063/1.4868142.

Mater, B. D. and Venayagamoorthy, S. K. 2014b. “The quest for an unambiguous parameterization of mixing efficiency in stably stratified geophysical flows", *Geophysical Research Letters*, DOI: 10.1002/2014GL060571.

Mater, B. D., Schaad, S. M. and Venayagamoorthy, S. K. 2013. “Relevance of the Thorpe scale in stably stratified turbulence", submitted to *Physics of Fluids*, 25, 076604 (2013); doi: 10.1063/1.4813809.

Mater, B. and Venayagamoorthy, S. K. 2012. “Abstract: M7.00007 : Parameterization of turbulent diffusivity in stratified flows using microstructure observations and DNS”, In Transactions of the 65th Annual Meeting of the Division of Fluid Dynamics American Physical Society, 18-20 November 2012, San Diego, California, USA.

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

2014 – Francois N. Frenkiel Award, American Physical Society, Division of Fluid Dynamics - in recognition of significant contributions to fluid mechanics that have been published in Physics of Fluids during the preceding year by young investigators. This award was given for an article published in the *Physics of Fluid Journal* the entitled “Relevance of the Thorpe scale in stably stratified turbulence” by Mater, B. D., Schaad, S. M. and Venayagamoorthy, S. K. 2013.

2014 - Faculty Excellence in Teaching Award, Department of Civil and Environmental Engineering, CSU.

2014 - Invited participant, Indo-American Frontiers of Eng. Symposium, National Academy Engineering.