Turbulent Mixing Parameterizations for Oceanic Flows and Student Support

Subhas Karan Venayagamoorthy
Department of Civil and Environmental Engineering
Campus Delivery 1372
Colorado State University
Fort Collins, CO 80523-1372
phone: (970) 491-1915 fax: (970) 491-7727 email: vskaran@colostate.edu

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LONG-TERM GOALS

The long-term goal of these two closely related research projects is to formulate robust turbulence parameterizations that are applicable for a wide range of oceanic flow conditions.

OBJECTIVES

The primary objectives of these projects are to bridge the gap between parameterizations/models for small-scale turbulent mixing developed from fundamental direct numerical simulations (DNS) and grid turbulence experiments to geophysical scale models with an emphasis on making progress towards improved turbulent parameterizations in the ocean and (ii) to develop a quantitative understanding of the impact of obstacles on the lateral mixing of momentum and scalars in oceanic flows.

APPROACH

Our main approaches are to use theoretical modeling efforts to formulate parameterizations and then use model-data comparisons, to test our formulations. We are also performing highly-resolved two-dimensional and three-dimensional simulations of flow around obstacles to investigate and elucidate the fundamental mechanisms responsible for turbulent mixing; and improve the efficacy of existing parameterizations for turbulent mixing.

WORK COMPLETED

In FY2013, most of our effort has been on formulating a general framework for parameterizing stably stratified shear-flow turbulence and carrying out model-data comparisons to study small scale turbulence and mixing. We have performed direct numerical simulations (DNS) of homogeneous stably stratified turbulence to carry out some fundamental studies on the relationships between well known length scales. Furthermore, through a collaboration that the PI has forged with Dr. Louis St. Laurent at WHOI. Benjamin Mater (the PhD candidate on this project) has began to perform extensive analysis of turbulence measurements in an effort to examine classical overturning length scales (e.g. Thorpe and Ozmidov scales) and their relationships to kinetic energy dissipation rate especially in strong turbulent forcing environments such as slope convection. These comparisons will be used to flesh out the underlying physics in order to develop improved parameterizations. In particular, the PI's collaboration with Dr. St. Laurent has provided Mr. Mater with a unique opportunity to examine turbulence measurements made in internal wave dominated environments using free-falling microstructure profilers. The PI joined the scientific team in July 2011 for a 3-week long research expedition to the Luzon Passage in South China Sea to conduct microstructure study as part of the ONR sponsored Internal Waves in Straits Experiment (IWISE). This is one of most energetic internal wave induced mixing regions with overturns of the order of hundreds of meters high (Alford *et al.* 2011). Data from this cruise has been our starting point to compare the pertinent turbulent scales.

RESULTS

The first set of results that we present are from the DNS study on the relevancy of the Thorpe scale that has been recently published as Mater *et al.* (2013) in Physics of Fluids. Our main goal was to compare the Thorpe overturn length scale, 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). The main findings from this study is that the utility of the Thorpe scale lies in its ability to provide a measure of the turbulent kinetic energy, rather than the rate of its dissipation when stratification is relevant. This is of practical pertinence from the standpoint that the turbulent kinetic energy can be inferred from density profile measurements alone.

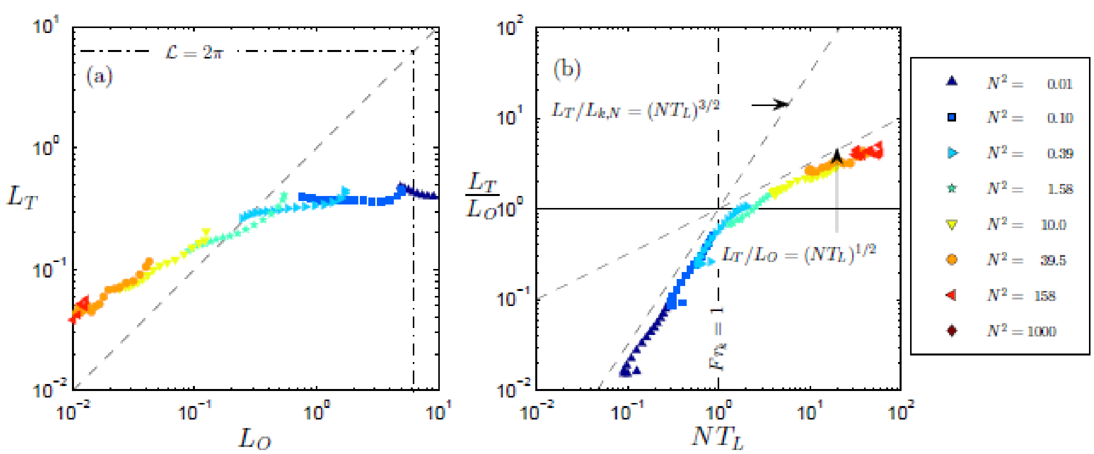

Figure 1: Ozmidov length scale, L_O, versus Thorpe length scale, L_T: (a) direct comparison, and (b) plotted against the dimensionless stratification parameter, NT_L.

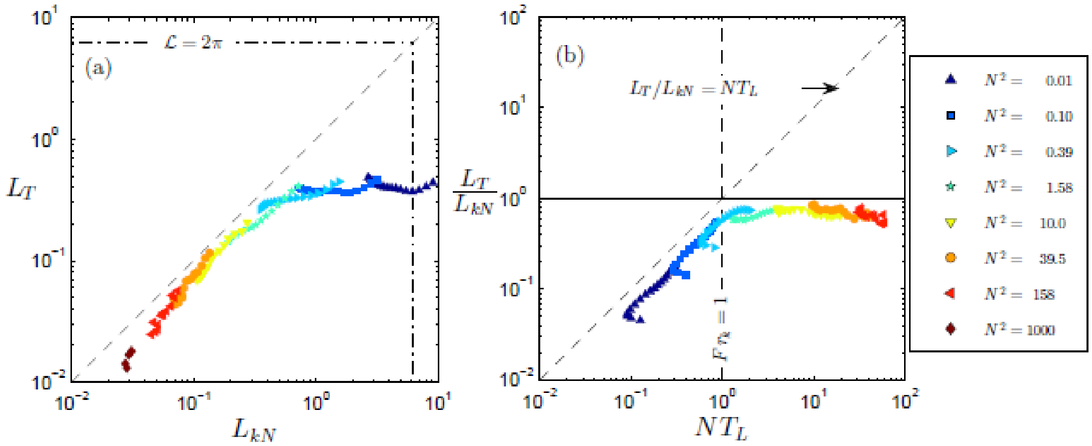

Figure 2: Turbulent kinetic energy length scale, L_{kN}, versus Thorpe length scale, L_T: (a) direct comparison, and (b) plotted against the dimensionless stratification parameter, NT_L.

As a direct extension to the work published in Mater *et al.* (2013), we include mean shear S to bring the discussion closer to the realm of oceanic flows in which turbulence can be decaying or growing. Hence, we now have to consider additional regimes using the shear parameter ST_L, where $T_L = k/\varepsilon$ is the turbulence time scale and/or the gradient Richardson number Ri. In the limit of high Reynolds numbers, we can conceptualize the flow in an NT_L - ST_L space as shown in Figure 3 through which lines of constant Ri can be constructed. Within this conceptual framework, we have assumed critical values in NT_L, ST_L and Ri so that the two-dimensional space is de-lineated into the well-cited regimes of shear and buoyancy dominance, but also a regime in which these background influences are absent or minimal that we entitle the "unforced" regime. In this regime the flow trends toward isotropy in that any sustained "forcing" by shear or stratification is not felt. Therefore, in such a state, Ri becomes an irrelevant concept. A common example of this kind of flow is unstratified turbulence generated by a grid. Critical values in the parameters are initial estimates informed from classical studies on flow stability and stationarity. The choice of $Ri_c \approx 0.25$ follows from classic shear layer stability analysis (Miles 1961) and has been shown to be a criterion for stationarity in homogeneous shear flows (e.g. Rohr et al. 1988). Choice of a critical value in the shear parameter follows from findings that $ST_{L,c} \approx 3.3$ in the log layer of unstratified channel flow where production and dissipation are in approximate balance (see Pope (2000)) and at mid-depth in stationary wind tunnel turbulence (Saddoughi and Veeravalli 1994). Recently, Chung and Matheou (2012) published data suggesting this value is approached in the unstratified limit of stationary homogeneous turbulence. The typical values chosen for Ri_c and $ST_{L,c}$ imply $NT_{L,c} = O(10^0)$ which is in agreement with our earlier findings as discussed in Mater *et al.* (2013) regarding Thorpe scale behavior in the stratified, shear-free limit.

We are now examining various numerical simulations and laboratory/field datasets to show their distribution on the parameter space shown in Figure 3 and to determine the relationships between the overturning scale (i.e. the Ellison/Thorpe length scales) and related fundamental length scales such as the Ozmidov length scale L_O and the turbulent kinetic energy shear and buoyancy length scales L_{kS} and L_{kN}, respectively. While this work is currently still in progress, our preliminary findings indicate that the overturning scale appears to be strongly correlated with the turbulent kinetic energy length scales scales L_{kS} and $L_{kN.}$ We are also working on an alternative formulation for the diapycnal mixing (i.e. diapycnal diffusivity K_d) based on the premise that we can infer the turbulent kinetic energy from overturns. The second thrust of our work is to investigate the impact of obstacles on the flow dynamics and lateral mixing of scalars as well as momentum. To this end, we are performing highly resolved numerical simulations to quantify the lateral mixing and transport of a passive scalar around porous cylindrical obstacle in uniform and oscillatory flows with/without density stratification.

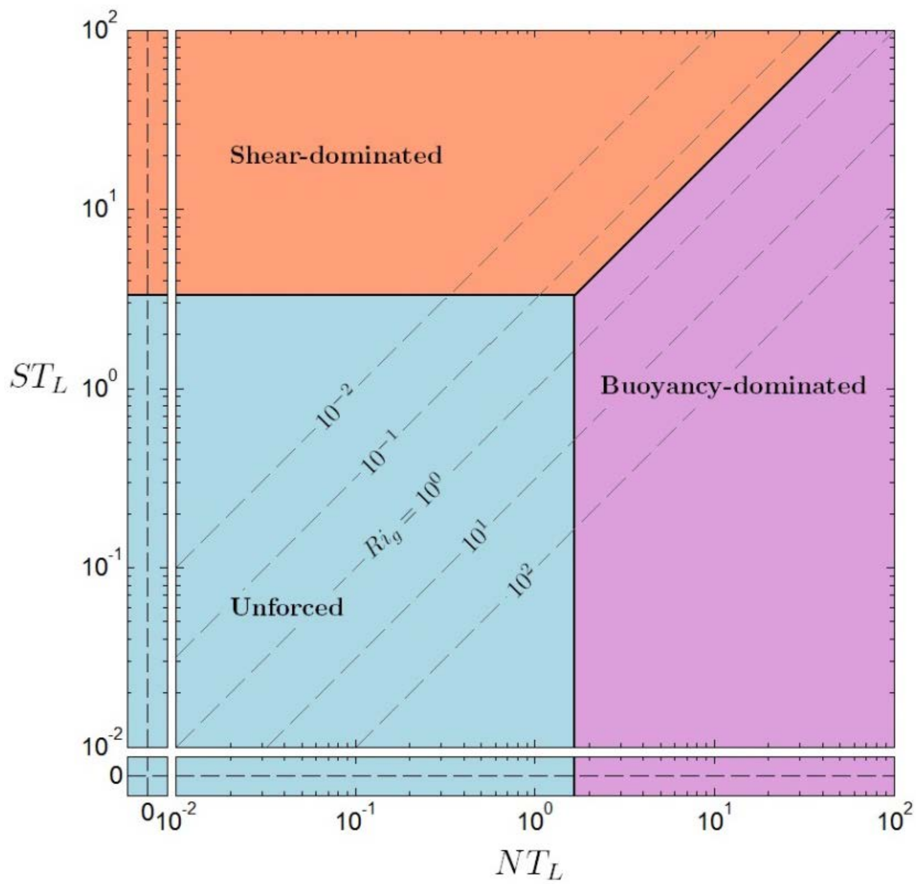

Figure 3: Conceptual parameter space for interpretation of high-Reynolds number shear-flow turbulence.

IMPACT/APPLICATIONS

Our work is motivated by oceanic studies of diapycnal mixing where observed overturns can be used to infer turbulent quantities that are pertinent to mixing but difficult to measure reliably.This project will contribute to an improved understanding of small-scale mixing processes and development of better parameterizations of such processes for applications in large-scale oceanic numerical simulations models where such processes are not explicitly resolved.

RELATED PROJECTS

Dr. Venayagamoorthy is collaborating with Dr. Amit Tandon (University of Massachusetts, Dartmouth) and Dr. Amala Mahadevan (Woods Hole Oceanographic Institution) to implement and test the proposed formulations for buoyancy effects in stratified flows for some oceanographically relevant flow (with coriolis and diurnal cycling included, for instance). We are currently working on comparing the results for 1-D oceanic scenarios and will then implement these schemes for sub-mesoscale flows.

Furthermore, the PI has another ONR funded project on internal wave driven mixing and transport in the coastal ocean where the goal is to investigate mixing from breaking internal waves interacting with topography. Hence there is some natural overlap between these two projects

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Saddoughi, S. G. and S. V. Veeravalli, 1994: Local isotropy in turbulent boundary layers at high Reynolds number. *Journal of Fluid Mechanics*, **268**, 333-372.

PUBLICATIONS

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. D. 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.

Manuscripts in Preparation

A framework for parameterizing stably stratified shear-flow turbulence, Mater, B. D. and Venayagamoorthy, S. K.

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.