The Role of Scale in the Development and Evolution of Stratified Shear Turbulence, Entrainment and Mixing

Daniel G. MacDonald, PI
Associate Professor
Department of Civil and Environmental Engineering
University of Massachusetts Dartmouth
285 Old Westport Road
North Dartmouth, MA 02747
phone: (508) 910-6334 fax: 508-999-8964 email: dmacdonald@umassd.edu

Mehdi Raessi, Co-PI
Assistant Professor
Department of Mechanical Engineering
University of Massachusetts Dartmouth
285 Old Westport Road
North Dartmouth, MA 02747
phone: (508) 910-6334 fax: 508-999-8964 email: dmacdonald@umassd.edu

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LONG-TERM GOALS

The goal of the research effort is to use existing field and laboratory data, along with direct numerical simulation (DNS) models to explore the variation of turbulence parameters across significant spatial scales. This work will allow better communication between laboratory studies and observations of stratified-shear turbulence in the oceans, and will lead to better parameterizations of turbulence in ocean models, and more effective predictions of ocean processes.

Most studies to date have assumed that stratified-shear turbulence is essentially independent of Reynolds number, $\boldsymbol{Re}$, once a specific critical value of $\boldsymbol{Re}$ is exceeded. Rather, observed variability is typically interpreted as a function solely of the local Richardson number, $\boldsymbol{Ri}$, or bulk Richardson number, $\boldsymbol{Ri_B}$. Recent comparisons of field and laboratory data suggest otherwise. This is a potentially significant realization that could have profound implications for our understanding of stratified-shear turbulence and the development of robust turbulence closure models.

OBJECTIVES

This project will utilize a combination of field data, laboratory data, and DNS simulations to provide a robust view of various turbulence parameters across at least 4 to 5 orders of magnitude in $\boldsymbol{Re}$. These data will first be used to validate proposed equations relating entrainment (e.g. Ellison and Turner 1959; Christodoulo 1986; Yuan and Horner-Devine 2013) and buoyancy flux (e.g., Smyth et al 2001; MacDonald and Chen 2012) across Reynolds number space, then to assess the behavior of $u_*/\Delta u$ as a function of ***Re***, starting with the simplistic relationship $u_* / \Delta u \sim f\left(\mathrm{Re}^{-1/3}\right)$, assuming constant $\boldsymbol{Ri_B}$, and then considering more complicated (and realistic) scenarios of varying stratification. A significant challenge in compiling the necessary data will be in developing enough high quality, reliable estimates of turbulence quantities across the desired range of ***Re***. Field data will generally support the high end of the range, while existing laboratory datasets will be supplemented with new DNS simulations to fill in the low end of the range.

The goal with this approach is to develop and test simple parameterizations, initially resulting in quasi-empirical relationships between turbulent quantities and ***Re***, which may force a reanalysis of existing parameterizations based $\boldsymbol{Ri_B}$. Thus, one objective of the project will be to develop a universal multi-variate parameterization for shear-stratified turbulence quantities as a function of both ***Re*** and $\boldsymbol{Ri_B}$. Once these quasi-empirical parameterizations are in hand, they can be used in future efforts to guide more mechanistic studies focused on delineating the physical processes responsible for the observed variability.

APPROACH

This project will utilize existing data from a variety of sources, including field and laboratory data, as well as new DNS simulations that will be used to corroborate and extend the existing laboratory and other data at the low end of the anticipated ***Re*** range. Initial tasks (approximately August 2015 – January 2016) will involve the collection of data from disparate sources, and the definition of reanalysis tasks. Specifically, we will gather data from the Merrimack, Columbia, and Fraser River plume studies, as well as the 2011 LATMIX experiment. We will also mine laboratory data from existing and relevant studies in the literature, as well as collect and organize laboratory data from recent experiments (i.e. Yuan and Horner-Devine 2013). Collectively this data will be consolidated into similar formats for comparative purposes and derived values will be checked for consistency. We will also focus on setup of the DNS model during this period, and perform initial DNS simulations.

In early 2016, the two PIs will be joined by a Postdoctoral Investigator, who will be primarily responsible for the bulk of the DNS modeling over the following year. During the middle year of the project, data analysis efforts will focus on completion of the reanalysis priorities identified during the first phase of the project, and on generating robust comparisons between the various field and laboratory data sets developing more refined relationships between turbulence parameters and the governing non-dimensional groups (i.e., ***Re*** and $\boldsymbol{Ri_B}$). The field/laboratory data will also be compared closely with the DNS results to evaluate and redirect the DNS modeling, as necessary. The last six months of the project will primarily involve final comparisons between laboratory, DNS, and field data sources, including the refinement of identified relationships.

The overall effort will be managed by PI MacDonald, who will also be responsible for reanalysis of field and laboratory data, and for building and analyzing the database of turbulence values across $\boldsymbol{Ri_B}$ and ***Re*** parameter space. Co-PI Raessi will be responsible for DNS model development including both setup and simulations. The postdoctoral fellow will primarily be responsible for conducting the DNS simulations and initial analyses of DNS output. He or she will also provide assistance with the field and laboratory data compilation and analysis.

WORK COMPLETED

Work on this project commenced in August 2015. As such we have begun the initial tasks outlined above, including collection of existing data and setup of the DNS model. Construction of the database of existing data has begun with Merrimack and Fraser River plume data. PI MacDonald has also been in discussion with Lou Goodman (UMass Dartmouth) regarding 2011 LATMIX data, Joe Jurisa and Jonathan Nash (Oregon State University) regarding Columbia River plume data, and Alex Horner-Devine (University of Washington) regarding recent relevant laboratory experiments.

We have developed a plan for the DNS runs of this project, which will be performed by using NGA (Desjardins et al., 2008), an in-house flow solver for variable density low Mach number turbulent flows. DNS runs will be performed and analyzed over a range of $\boldsymbol{Re}$ values from 5000 to 20000 and $\boldsymbol{Ri_B}$ values from 10^{-2} to 10^{2}. The breadth of the $\boldsymbol{Ri_B}$ range will be accomplished by varying all three key variables (i.e., stratification, shear, and layer thickness) such that the complete range can be represented by changes in any one of the three variables. We anticipate 20 to 50 simulations will be performed to provide sufficient coverage of both the $\boldsymbol{Re}$ and $\boldsymbol{Ri_B}$ ranges. The DNS results will first be post-processed to justify and/or modify key assumptions used to relate the entrainment ratio and buoyancy flux. Then, the numerical output will be used to generate the necessary parameters to fully explore the Re and RiB dependence of entrainment and buoyancy flux within the larger context of the project.

RESULTS

Given the recent initiation of activities under this project, we anticipate that the most meaningful technical results will be generated during FY16 and FY17.

IMPACT/APPLICATIONS

Stratified-shear turbulence is a critical underpinning of ocean dynamics at many scales, both in the ocean mixed layer as well as in coastal regions. Specifically, the intensity of mixing can define the strength of density gradients and thickness of mixed layers, which in turn can have important impacts on sound speed, as well as transport and other ocean phenomena, and thus play a critical role in ocean forecasting. This effort will provide key insight into the nature of stratified-shear turbulence at geophysical scales, and enable linkages between geophysical scale turbulence and the wealth of detailed turbulent information available at laboratory, or DNS, scales, ultimately providing opportunities for improving existing turbulence closure techniques. Once relationships are established and tested, any Re dependencies may be incorporated into new or existing turbulence closure techniques. Improvement of ocean models will greatly enhance the Navy's capabilities to accurately forecast ocean conditions, which may be useful to acoustic monitoring, AUV operations, navigation, and other activities of interest to the Navy.

RELATED PROJECTS

Co-PI Raessi is an unfunded collaborator on a Large Eddy Simulation (LES) study of the dynamical evolution of ocean turbulence, where the properties of Richardson instabilities are examined at geophysically relevant Reynolds numbers. In this project, the LES capabilities of the NGA computational framework is used.

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