Contributions

1. Most Significant Contributions to Research and/or to Practical Applications

My research area is **stratified fluid dynamics** with a focus on internal gravity waves. These waves propagate both vertically and horizontally in fluids such as the ocean where the density increases with depth. The generation, propagation, and breaking of internal waves are important in the transport and mixing of energy and momentum. Modern numerical climate models are unable to explicitly resolve these waves and the mixing. The development of efficient, accurate mathematical **parameterizations** that capture the overall physics of such small-scale processes is an active area of research in the oceanographic community. Much of my research has been to perform **laboratory experiments** and **numerical simulations** that provide experimental foundations to develop those parameterizations. I also have been involved in hydrodynamic modeling for development of industrial applications.

A) Internal waves from flow over topography

It is a classical result to examine the generation of internal waves over smooth, two-dimensional periodic topography. I have examined the generation of internal waves by tidal flow over **three-dimensional topography** using a hydrostatic numerical model. I explored how asymmetric ridges as compared to symmetric seamounts, were significantly more efficient at converting energy from the barotropic tides to internal waves. My journal article on that work (*Munroe & Lamb, 2005*) was included in a 2007 review article on internal tide generation and has been cited a total of 23 times in the literature.

Internal waves can also be generated by flow over **rough topography**. In this case, boundary layer separation can lead to a turbulent wake from the topography. I prepared a paper (*Munroe & Sutherland, 2008*) exploring the forcing of a rectangular wave shaped topography model towed along the surface of a stratified fluid. When the **towing speed** is slow, waves are generated with a frequency directly related to the speed of the towing and the wave number of the rectangular waveform as predicted by linear theory. At higher speeds, where linear theory does not predict the generation of freely propagating internal waves, our experiments showed the internal waves propagating downwards with a characteristic frequency 0.7 of the buoyancy frequency. This **characteristic frequency** was independent of the towing speed. For moderate towing speeds, there was a transition in the dominant frequency from the linear prediction to this characteristic frequency. This result was previously seen for a rough topography towed in a linearly stratified fluid. My work demonstrated that a stratification with a **mixed layer** of homogenous density on top, and a linear stratified fluid beneath, did not change the frequency of the observed waves for high towing speeds.

J. R. Munroe and K. G. Lamb. (2005) Topographic amplitude dependence of internal wave generation by tidal forcing over idealized three-dimensional topography. Journal of Geophysical Research - Oceans. 110, C02001, 10.1029/2004JC002537.

J. R. Munroe and B. R. Sutherland (2008) Generation of internal waves by sheared turbulence: experiments. Environmental Fluid Mechanics. 10.1007/s10652-008-9094-3.

B) Generation of internal waves by turbulence

Internal waves can also be forced by **turbulent flows**. I designed and performed a series of lab experiments to model the generation of **non-hydrostatic internal gravity waves** in the upper ocean by the forcing of **wind-driven turbulent eddies** in the surface mixed layer. The turbulence in the shear layer was characterized using **particle image velocimetry** (PIV) to measure the kinetic energy as well as length and time scales. Internal waves were measured using **synthetic schlieren** to determine the amplitudes, frequencies, and energy density of the generated waves. Synthetic schlieren is a non-intrusive optical technique based on the variation of index of refraction with density which can detect small-amplitude internal gravity waves.

I determined the fraction of energy leaked by a shear turbulent layer into a density stratified ambient as internal gravity waves and found that the total kinetic and potential energy density of the internal waves in the lower stratified fluid was approximately **2%** of the **turbulent kinetic energy** density of the well-mixed, turbulent upper layer. This **fixed ratio** of energy densities appears independent of the forcing for the range of parameters studied.

To corroborate the laboratory experiments, I performed two-dimensional **direct numerical simulations** of a turbulent shear layer of mixed fluid above a stratified, initially quiescent layer. Internal waves were again generated. In this case, the turbulent eddies coalesced into coherent **vortical structures** as is expected for two-dimensional turbulence. These vortices interacted with the stratified layer beneath and internal waves radiated away. Interestingly, again expressed as the ratio of the energy density of the **radiated internal waves** to the turbulent kinetic energy density of the **turbulent eddies**, the fraction was roughly **2%**. More significantly, I estimated that **8%** of the total work done on the fluid was being radiated away as internal wave energy. There are important implications to the energy budget of the upper ocean mixed layer if these estimates are supported by future studies. This research was published in Physics of Fluids (*Munroe and Sutherland, 2014*).

A rough scaling implies that this is a relevant process that needs to be parameterized in numerical ocean models. The work, based on laboratory experiments and a 2D numerical simulation, provides an order of magnitude estimate of this energy scaling which should provide the basis for future studies.

C) Experimental measurement of parametric subharmonic instability of internal waves

Internal waves are inherently unstable and exhibit an instability by forming a nonlinear **resonant triad interaction** with two other waves with frequencies near subharmonics of the initial waves. Although the theoretical mechanism is understood and has been demonstrated in numerical experiments, my work is the first laboratory measurement of the **growth rate** of this instability. As we reported in *Joubaud et al. (2012)* the laboratory results are consistent with the theoretical prediction but are very sensitive to the magnitude of the wave undergoing the instability. This research was performed during my post-doctoral work and was supported by ANR (France's national research agency) through a grant led by Dr. Thierry Dauxois on the "Physics of Internal Waves in the Ocean". The work also resulted in two international conference presentations and one conference proceeding (*Odier et al. 2011*).

D) Intrusive gravity currents and internal waves

Gravity currents are density-driven horizontal flows. During my PhD I published a paper based on **intrusive gravity currents** and internal waves (*Munroe et al., 2009*) based on experiments performed by an undergraduate summer student in our research group and myself. This paper also included collaboration with another research group who performed numerical simulations of our experiment. I examined the interactions of intrusive gravity currents with a stratified ambient and found that, in the regime of parameters between a **symmetric intrusion** traveling down the middle of a tank and **bottom propagating** gravity current, internal waves are generated which substantially changes the dynamics causing the intrusion to slow and momentarily stop. This arresting of an intrusive flow is an important consideration for future modeling of pollution transport in strongly stratified environments.

J. R. Munroe, B. R. Sutherland, C. Voegeli, V. Birman, and E. H. Meiburg (2009) Intrusive gravity currents from finite-length locks in a uniformly stratified fluid. Journal of Fluid Mechanics. Volume 635, pg 245-273.

E) Design and validation of a large hydrofoil for an AUV

I was a co-investigator on the REALM project (Responsive AUV Localization and Mapping) funded by the Atlantic Innovation Fund and aims to improve a deep-water **autonomous underwater vehicle** owned by Memorial University. This was a large project ($3.2 million) with several industrial partners. My role was to provide research guidance on the development and testing of the **hydrodynamics** of a large wing to the AUV to deploy a large commercial instrument suspended beneath the vehicle. We used **computational fluid dynamics** (CFD) and **particle image velocimetry** (PIV) measurements in a large flume tank to validate the design. Field trials in April 2012 demonstrated that the wing design only minimally affects performance of the AUV. We prepared a technical report (*Mouland et al., 2012)* on the work documenting the success of the project. As well, a paper (*Allston et al., 2012)* drafted by a student under my supervision on the comparison between the CFD and PIV results and on the nature of the turbulent wake behind the wing was published in Methods in Oceanography.

2. Research Contributions and Practical Applications

Published in Refereed Journals

J. Munroe and B. Sutherland (2014) Internal wave energy radiated from a turbulent mixed layer. Physics of Fluids. Volume 26.

T. Allston, J. Munroe, R. Lewis, J. Xu, D. Mouland. (2014) PIV Experiments to Validate CFD Predicted Wake around an AUV Hydrofoil. Methods in Oceanography. Volume 10. 166-177.

S. Joubaud, J. Munroe, P. Odier, T. Dauxois. (2012) Experimental parametric subharmonic instability in stratified fluids. Physics of Fluids. Volume 24, 6 pages.

Submitted or in Revision

S. Tadavani, J. Munroe and A. Yethiraj (2016). Electrohydrodynamics-driven droplet dynamics in an oil-in-oil emulsion.

F. Lin and J. Munroe. (2015). Drifting sphere in an internal wave field.

D. Xu and J. Munroe (2015). Anthropogenic CO2 emission shifts species composition in seaweeds.

Theses Supervised

F. Lin. (2014). Internal Wave Drift of a Neutrally Buoyant Sphere. Msc. Thesis.

P. Kurtakoti. (2014). Experiments on Internal Waves: Propagation and Reflection. Msc. Thesis.

Extended Conference Abstracts and Proceedings

K. Macpherson, D. Walker, R. Devillers, N. Kennedy, P. King, R. Lewis, J. Munroe, A. Vardy. (2014). The Memorial Explorer: Developing AUV survey strategies for multidisciplinary use. Ocean's 2014. St. John's, Newfoundland. 15pp.

J. R. Munroe and B. R. Sutherland. (2011) Energy radiated by internal waves from a turbulent mixed layer. 7th Intl. Symposium on Stratified Flows, Rome. 8 pages.

P. Odier, J. Munroe, S. Joubaud. T. Dauxois. (2011) Parametric Instability Growth Rates of Progressive Mode-1 Internal Wave. 7th Intl. Symposium on Stratified Flows, Rome. 8 pages.

Technical Reports

J. Munroe (2016) iOS App with Real-time Tx/Rx Data Display over a Network Socket Connection. Prepared for Solace Power, Inc.

J. Munroe (2012). A System for Dynamic Tuning. Prepared for Solace Power, Inc.

D. Mouland, N. Smith, **T. Allston**, J. Munroe, P. King. (2012) Technical Feasibility of Full SBI Integration. Responsive AUV Localization and Mapping (Activity 5). Submitted to Atlantic Canada Opportunities Agency.

Invited Talks

J. R. Munroe. Measuring Parametric Subharmonic Instability in Internal Waves. Canadian Symposium on Fluid Dynamics. Toronto, Ontario. June 25-37, 2012.

J. R. Munroe. Internal Wave Generation by Turbulence. Ecole Normale Superieure de Lyon, Laboratoire de Physique. Lyon, France January 12, 2010.

Conference Presentations and Posters

S. Tadavani, J. Munroe, S. Ghosh, and A. Yethiraj. Electrohydrodynamic behavior of droplets in a microfluidic oil-in-oil emulsion., 90th ACS Colloid and Surface Science Symposium, 2016.

J. R. Munroe, **F. Lin**, **P. Kurtakoti**. Nonlinear Effects in Internal Waves. Lab Experiments with Mode-1 Internal Waves. Ithaca, New York. June 9-12, 2014.

F. Lin and J. R. Munroe. Drift of neutrally buoyant spheres in an internal wave field. American Physical Society, Division of Fluid Dynamics. Pittsburgh, Pennsylvania. November 24-26, 2013.

P. Kurtakoti and J. R. Munroe. Propagating and reflecting mode-1 internal waves analyzed using the Hilbert transform. American Physical Society, Division of Fluid Dynamics. Pittsburgh, Pennsylvania. November 24-26, 2013.

J. R. Munroe. Parametric Subharmonic Instability: Mode-1 Internal Waves. American Physical Society, Division of Fluid Dynamics. Pittsburgh, Pennsylvania. November 24-26, 2013.

J. R Munroe. Energy Radiated by Internal Waves From a Turbulent Mixed Layer. 7th International Symposium on Stratified Fluids. Rome, Italy. August 22-25, 2011.

J. Munroe, P. Odier, and T. Dauxois. Parametric Instability Growth Rates of Mode-1 Waves. Internal Waves Workshop, Les Houches, France. February 2011 (*Poster*).

3. Other Evidence of Impact and Contributions N/A

4. Delays in Research Activity N/A

5. Contributions to the Training of Highly Qualified Personnel (HQP)

Since joining Memorial University in September 2010, I have contributed to the training of four master's students and five undergraduate students. My goal as a supervisor is to facilitate the research and progress of my students. I strive to equip them with excellent research tools and techniques and to encourage them to solve problems on their own. I work closely with my students both one on one and through weekly research group meetings. I encourage my students to share their research with each other and ask them to present their progress to the rest of the research group regularly. I make an effort, especially with my graduate students, to alert them to the next steps in their research careers and guide them toward becoming productive scientists. I share with them my own experiences with research when I was a grad student and often discuss with them research problems that I am working on independently to demonstrate collegiality.

I have explicitly requested funds in this proposal for travel for students. I think it is important for students to travel to conferences to gain experience in presenting their work, to learn the names and faces of the major players in the field, to be exposed to other aspects of their research area, and to be known by other as part of their future career advancement.

Advanced computer literacy, especially with Unix based systems, is a critical aspect of graduate students' education in the physical sciences. This includes a practical knowledge of software development. I teach and provide resources to my students to develop these valuable skills. I also invite contributions from my students on how to improve both the technological and sociological aspects of my research group. In spring 2016, I developed and taught an extra graduate course (32 registered students) on this topic to train graduate students from across the Faculty of Science.