Environmental and Geophysical Fluid Dynamics
Dynamique des fluides en environnement et en géophysique
(Org: **Kevin Lamb**, **Francis Poulin** and/et **Marek Stastna** (University of Waterloo))

TRIANTAPHYLLOS AKYLAS, MIT
*On the interaction of an internal wavepacket with its induced mean flow and the role of streaming**

The coupled nonlinear interaction of three-dimensional gravity-inertia internal wavepackets, in the form of beams with nearly monochromatic profile, with their induced mean flow is discussed. Unlike general three-dimensional wavepackets, beam wavepackets are not susceptible to modulation instability from their inviscid, purely modulation-induced mean flow. However, streaming – the induced mean flow associated with the production of mean potential vorticity by the combined action of dissipation and nonlinearity – can cause cross-beam bending, transverse broadening and increased along-beam decay of the beam profile, in qualitative agreement with earlier laboratory experiments. For non-beam wavepackets, by contrast, streaming does arise, but plays a less prominent role in the interaction dynamics

*Joint work with Boyu Fan (MIT) and Takeshi Kataoka (Kobe University, Japan)

PETER BARTELLO, McGill University
Spontaneous imbalance in rotating stratified turbulence

While it is well-established that the frequency disparity between vortical and wave motion is key to understanding the quasi-geostrophic limit, i.e. strong rotation and stratification, the starting point for this work is that it has recently been established that there is no such frequency disparity in stratified turbulence without rotation. It remains to ask what happens in between these two limits, long held as the prevailing dynamics between deformation-scale eddies and the microscale where isotropy is recovered. To do this, ideas from numerical weather prediction were borrowed in order to explore numerically the nonhydrostatic Boussinesq equations starting from initial conditions that are close to our current fuzzy notions of balance for a variety of Rossby and Froude numbers. It is found that evolution is spontaneously away from this balance in the small scales, and from steep to much more shallow spectra. It will be argued these results are robust to uncertainties in the definition of balance and are similar to observations of both atmosphere and ocean. This is joint work with Hossein Amini Kafiabad.

NICOLAS GRISOUARD, University of Toronto
Inertial-Symmetric Instability Energetics.

Submesoscale oceanic density fronts are structures in which stratification and rotation play an important role, while being only typically 10 km wide and evolve over the course of a few days. They are prone to ageostrophic instabilities called inertial-symmetric instabilities. We argue in this article that drainage of potential, rather than kinetic, energy from the front is a leading-order source of their growth. We illustrate our point with two-dimensional Boussinesq numerical simulations of oceanic density fronts on the f-plane. A set of two-dimensional initial conditions covers the submesoscale portion of a three-dimensional parameter space consisting of the Richardson and Rossby numbers, and a measure of stratification or latitude. Because we let the lateral density gradient decay with depth, the parameter space map is non-trivial, excluding low-Rossby, low-Richardson combinations. Dissipation effectively selects the largest growing mode, and inertial-symmetric instability in a confined unstable region creates flow cells that recirculate outside the unstable region, disturbing isopycnal locations. As the ageostrophic flow grows in amplitude, isopycnals eventually get significantly displaced. Systematically, such isopycnal displacements correspond to a drainage of available potential energy from the geostrophic fronts to the ageostrophic perturbations. In the majority of our experiments, this energy drainage is at least as important as the drainage of kinetic energy from the front. Various constraints, some physical, some numerical, result in our experiments to behave like inertial rather than symmetric instabilities. Our results depend very weakly on the Richardson number and more on the Rossby number and relative stratification.

NICHOLAS KEVLAHAN, McMaster University
Variational data assimilation for the shallow water equations

The shallow water equations (SWE) are a widely used model for the propagation of surface waves. In particular, the SWE are used to model the propagation of tsunami waves in the open ocean. We consider the associated data assimilation problem of optimally determining the initial conditions for the one-dimensional SWE equations from a small set of observations of the sea surface height. We derive variational data assimilation methods for both the linear and nonlinear SWE and implement them numerically. In the linear case we solve the assimilation equations analytically and prove a theorem giving sufficient conditions for convergence to the true initial conditions. At least two observation points must be used and at least one pair of observation points must be spaced more closely than half the effective minimum wavelength of the energy spectrum of the initial conditions. We confirm our analysis in numerical implementations of the both the linear and nonlinear SWE assimilation problems. At least three observation points are required for the practically useful results. This paper is a first step in understanding the conditions for observability of the SWE for multiple observation points in more physically realistic settings.

KEVIN LAMB, University of Waterloo
Internal Wave Generation by Tide-Topography: Effects of a Mean Background Current

Tide-topography interactions are the source of approximately half the internal wave energy and of most internal solitary waves in the oceans. In this talk the effects of a surface trapped uni-directional current on the generation of internal waves by tidal currents over a symmetric ridge will be discussed using idealized linear and two-layer stratifications. The current introduces an asymmetry in the background state that results in asymmetries in energy fluxes and internal solitary waves and makes kinetic energy fluxes a leading-order contribution to the total energy flux. A linear theory for the wave generation process will be presented along with results from two-dimensional numerical simulations. Using linear stratifications the dependence on the ridge width is explored. For wide ridges the downstream energy flux is larger than the downstream energy flux while the opposite is true for narrow ridges. Using continuous two-layer stratifications internal solitary waves can be generated. Broader waves form in the downstream direction and in extreme cases internal solitary waves in the downstream direction can be waves of elevation while internal solitary waves in the upstream direction are waves of depression.

ADAM MONAHAN, University of Victoria
Regime Dynamics of the Stably Stratified Atmospheric Boundary Layer

Flow, stratification, and turbulence in the atmospheric boundary layer are dynamically coupled: turbulent intensity and fluxes are influenced by the character of the eddy-averaged state, which in turn is itself influenced by the turbulent fluxes. This interplay is of particular interest in the stably stratified atmospheric boundary layer, which is observationally found to exist in distinct regimes. The first, the weakly stable boundary layer (wSBL), is characterized by weak bulk shear, a modest inversion, and sustained turbulence. The second, the very stable boundary layer (vSBL), has strong bulk shear, a strong inversion, and turbulence which is weak and intermittent.

This talk will present recent observational and idealized modelling results regarding these regimes and the transitions between them. First, the regimes will be separated in data using a Hidden Markov Model (HMM) analysis of long time series of tower observations. Idealized physical models will then be used to elucidate the physical mechanism resulting in these regimes. Equilibrium and linear stability analyses will be presented and compared with time-dependent model behaviour. Finally, these ideas will be combined in a stochastic model of the bulk boundary layer momentum budget which provides a physically-based, if idealized, model for the probability distribution of near-surface winds.

DAVID MURAKI, Simon Fraser University
Cloud-Edge Dynamics and Mysterious Holes in the Sky

A holepunch cloud is a curious phenomenon where a disturbance in a thin cloud layer, as can be caused by aircraft penetration, leaves behind a growing circular hole of clear air. Observed since the dawn of aviation, only in 2011 was the holepunch feature simulated in a full-physics numerical weather model. Although the initiation process has been clearly attributed to ice crystal formation, we explain that the continued expansion of the hole is a travelling front between two phases of moist air — unsaturated and weakly-stratified (clear) intruding into saturated and moist-neutral (cloudy). Our investigations into this phenomenon are leading us toward the development of a more general free-boundary theory for the evolution of cloud edges by gravity wave motions.

This work is in collaboration with R Rotunno (NCAR), H Morrison (NCAR) and R Walsh (SFU).

KEISUKE NAKAYAMA, Kobe University

Mass transport velocity in a three-layer system

In lakes and the ocean, organic matter and nutrients tend to remain within the pycnocline due to the suppressed diapycnal mixing by the strong density gradient. Stokes velocity within the pycnocline can cause significant isopycnal mass transport. Therefore, isopycnal mass transport due to Stokes velocity within the pycnocline can be important for long-term processes in the ecology and biogeochemistry. Under the vertically symmetric stratification conditions, mass transport velocity has been investigated in the previous studies. However, studies on mass transport velocity under internal solitary waves are scarce. In this study, Fully nonlinear and strongly Dispersive Internal wave (FDI) equation based on a variational principle in a three-layer system was proposed, and the FDI equation was applied to investigate mass transport velocity due to both sinusoidal and solitary internal waves. The validity of the FDI equations was done by using an analytical solution for mass transport velocity due to sinusoidal waves under vertically symmetric stratification. Mass transport velocity in the middle layer under internal solitary waves is revealed to be more positive than that under sinusoidal internal waves. In addition, the applicability of the FDI equations was confirmed from the analysis of "breathers".

FRANCIS POULIN, University of Waterloo

Modelling Wind-Driven Oceanic Gyres

The atmospheric winds drive the oceans from above and create gyre dynamics and western boundary currents throughout the World's oceans. The Quasi-Geostrophic (QG) model is a very simple model for ocean dynamics that has clearly demonstrated that it is the winds and dissipation at the large scale that are essential for creating these gyres. One limit of the classical theories of wind-driven gyres focused on linear dynamics in very simple geometries.

In this work, we investigate wind-driven gyres in the context of a one-layer QG model that includes complex geometries, something that is relatively easily done using the Finite Element library Firedrake. First, we present wind-driven gyre solutions to the QG model that can include bottom drag, lateral viscosity and nonlinear advection. Second, we compute the basin mode solutions that exist in the context of these numerical solutions. One of the motivations of this research is to bridge the gap between idealized models and realistic real-world calculations. We have written software that is freely available that we hope will enable researchers and students alike to more easily investigate the dynamics of wind-driven gyres.

MAREK STASTNA, Waterloo

A re-examination of the gradient Richardson number criterion for the instability of stratified fluids

The gradient Richardson number is perhaps the aspect of classical hydrodynamic stability theory with the farthest reach in the natural sciences. This is because the so-called Richardson number criterion is often used as both a proxy for instability and mixing in the natural environment, as well as in parametrizations in large scale ocean and atmosphere models. Yet at the same time, it is well know that the Richardson number less than 0.25 is a necessary, and not sufficient, criterion for instability of stratified, parallel shear flow. Moreover, examples exist in the published literature of the inadequacy of the Richardson number in determining whether a flow remains stable, or undergoes instability and transition to turbulence. In this talk I will begin by reviewing several relevant examples from the literature related to the Richardson number. I will then present results of relatively simple simulations of the stratified adjustment process. These reveal the complex manner in which long waves, such as internal solitary waves, coexist with short wave instabilities in situations for which the Richardson number of the background state remains higher than 0.25. The initial perturbation acts to dynamically modify the background state, leading to significant short wave activity, and for long times, the breakdown of some of the internal solitary waves present.

DAVID STRAUB, McGill

Near-inertial damping of geostrophic flows

Recent work examining balanced-to-unbalaned energy transfers in the low to moderate Rossby number regimes typical of the atmosphere and ocean have suggested that, although spontaneous loss of balance is weak, balanced-to-unbalanced energy transfers can nonetheless be significant when near-inertial (unbalanced) motion is either externally forced or present in initial conditions. Here, we review recent literature and attempt to disentangle the messy jargon that it has introduced. Further, we present examples from a range of numerical settings: i) an unstratified wind-driven primitive equation ocean basin, ii) a wind-driven primitive equation (ocean) channel and iii) decaying turbulence near an idealized, Bousinesq tropopause. In all cases, the total flow includes geostrophic and near-inertial components, and our interest is in describing energy exchanges between the two. We will also comment on idealisations in which the total flow is considered to be the sum of geostrophic and weakly nonlinear near-inertial components (e.g., as in recent models by Xie and Vanneste (2015) Wagner and Young (2016). We find this idealization to be reasonable at large horizontal scales, and that it is at these scales where the bulk of the energy transfer occurs.

BRUCE SUTHERLAND, University of Alberta

Lagrangian Transport by Horizontally Modulated Internal Modes

Using perturbation theory for quasi-monochromatic internal gravity wavepackets, we consider flows induced by horizontally modulated vertical modes. In uniform stratification, a mode-n wavepacket induces a mode-2n flow whose amplitude varies spatially on the scale of horizontal modulations of the wavepacket. The flow is a combination of the Stokes drift and the Eulerian induced flow, which combined give the Lagrangian flow induced by the waves, as determined previously by McIntyre (J. Fluid Mech., 1973) through consideration of the conservation of the wave impulse. In particular, horizontally long waves in a wavepacket induce a Stokes drift and Eulerian flow of comparable magnitude. For horizontally modulated vertical modes in non-uniform stratification, the induced flow is significantly more complicated. Both the Stokes drift and Eulerian induced flows exhibit strong shear where the stratification varies rapidly in the vertical. Superharmonic disturbances are also excited. In constructing of the Lagrangian flow, the Stokes drift and Eulerian flows can superimpose constructively or destructively depending upon the horizontal wavenumber of waves in the wavepacket relative to the characteristic length scale of the stratification.

MIKE WAITE, University of Waterloo

Random Forcing of Slow Modes in Rotating-Stratified Turbulence

This talk will discuss the details and implications of random forcing of geostrophic motion in idealized simulations of rotating stratified turbulence. Random forcing accounts for the injection of energy into large-scale vortices by unresolved large-scale processes (e.g. baroclinic instability or interactions with larger scale vortices). White noise is a popular choice because it is simple and is unbiased in that it excites all frequencies equally. However, white noise includes frequencies much higher than the natural frequencies of large-scale vortices, which such forcing is meant to represent. The effects of these unrealistic high frequencies in the forcing are investigated and discussed here. Geostrophic modes are forced with red noise over a range of decorrelation time scales τ, from a few time steps to the large-scale vortex time scale. Fast forcing, (short τ, i.e. nearly white noise) results in about 40% more gravity wave energy than slow forcing (longer τ), despite the fact that wave modes are never forced directly. This effect is explored by analyzing wave-vortex interactions, through which the high frequencies in the forcing excite waves at their natural frequencies. These results suggest that white noise forcing of slow geostrophic modes should be avoided when a careful representation of wave-vortex energy exchange is required.