Research Activities

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Abstract

This document is a brief summary of current and recent research projects and principal results as of May, 2014. Publication details, links to online journal versions, and abstracts for the papers referenced can be found at *http://scrippsscholars.ucsd.edu/kbwinters/publications*.

Stratified flow over topography

Stratified flow over topography is a fundamental aspect of oceanic motion characterized by a wide range of phenomenology. The processes that produce internal gravity waves that radiate to the far field can coexist and be dynamically coupled to near-field phenomena such as upstream jets, hydraulic control, intensified down-slope flow, internal hydraulic jumps, dissipation and mixing. Understanding the physics linking these local and global responses is an important precursor to understanding the variability of barotropic to baroclinic energy conversion and thus to the variability of internal wave and topographically induced mixing in the ocean.

In Winters and Armi (2012), analytical theory for single-layer, reduced-gravity hydraulics was extended to continuously-stratified flows at low $Fr = U/Nd$. By linking the concepts of hydraulic control, blocking and upstream influence, and bifurcation of streamlines to produce a stagnant isolating layer and an uncoupled flow aloft, we were able to derive a nonlinear theory linking Fr to the speed and thickness of the asymmetric, jets that are drawn up over an obstacle and accelerated to form supercritical, down-slope flow in the lee. The theory was tested against numerically reproduced data from the classic stratified towing experiments of Browand and Winant (1972).

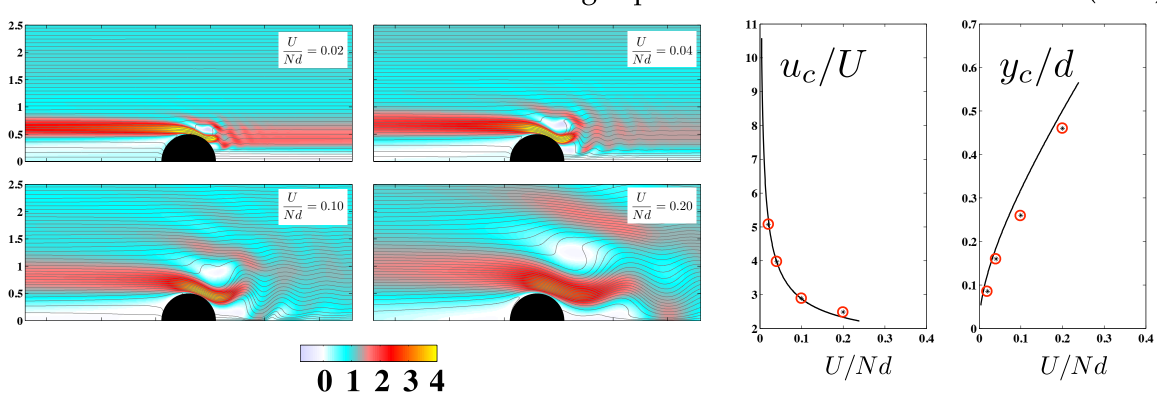


Figure 1: Direct simulation of Browand & Winant (1972) stratified towing experiments. Left: Shown is rightward flow relative to a stationary cylinder at different, small values of the outer Froude number U/Nd where U is the towing speed, N is the buoyancy frequency and d is the diameter of the towed cylinder. Right: Bulk flow properties at the obstacle crest predicted by the theory in Winters and Armi (2012), solid lines, and observed in the numerical solutions, red circles.

When the stratified flow is not steady but rather oscillates in time, *e.g.* like tidal flows in the ocean, a second dimensionless parameter $\mathcal{E}$ becomes important. This parameter is the ratio of the horizontal excursion length U/ω to the near-crest horizontal scale σ of the topography. Here U and ω are the characteristic velocity and frequency of the total flow in the vicinity of the obstacle and σ is the width at the a distance U/N. In Winters and Armi (2013), we introduce this second parameter into a scaling analysis and show why it is the fundamental measure of nonlinearity in the near-crest flow and demonstrate that the flow is characterized by linear wave radiation and excitation of internal wave beams when $\mathcal{E}$ is small, and by steady, hydraulically controlled flows like those in Figure 1 when $\mathcal{E}$ is order one or greater. We also show that the intermediate regime when $\mathcal{E} = O(1)$ exhibits both wave-like behavior as well as near-crest hydraulic phenomena and enhanced dissipation and mixing. These theoretical results were verified and illustrated via direct numerical simulation.

We have now extended this theoretical work to predict not only the bulk properties of the controlled flow drawn over an obstacle but also the vertical profiles of velocity and density both upstream and downstream of crest. This is a major advance in the theory of stratified flows interacting with topography. While the theoretically derived, nonlinear solution is stable upstream of the blocking point, and thus can be observed in a variety of settings, it is unstable downstream and thus gives insight into the nature of the instabilities and turbulence in the lee.

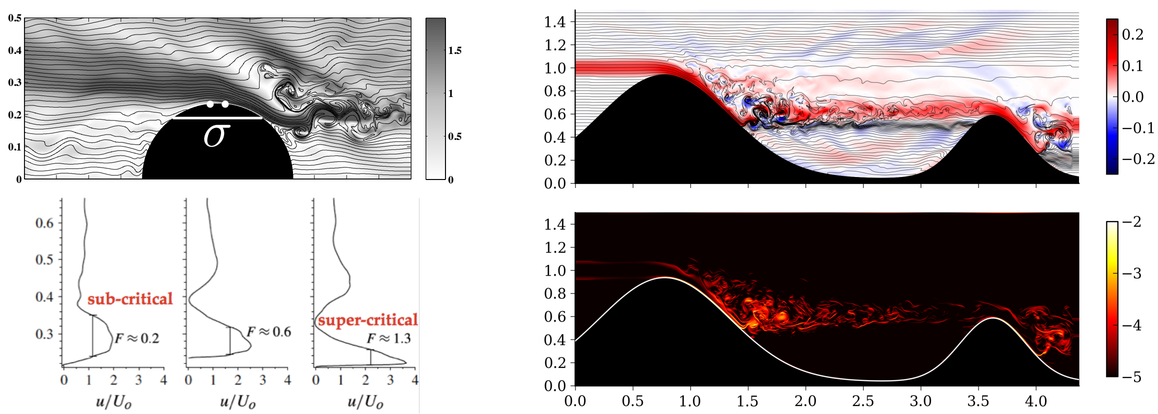


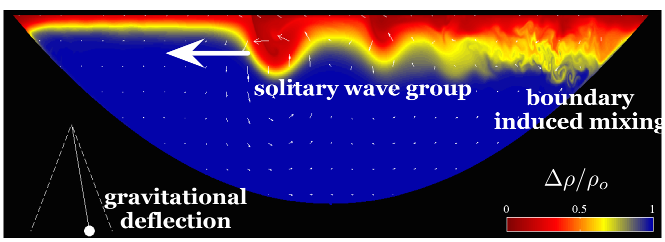
Figure 2: Left: Oscillating stratified flow over an obstacle when $\mathcal{E} = O(1)$ from Winters & Armi (2013). Like the steady case, controlled asymmetric jets form with bulk properties that are predictable from the outer Fr. The flow separates in the lee and spawns shear instabilities. Right: Stratified flow over two obstacles. Upper: Horizontal speed and isopycnals. Lower: Log of the dissipation rate of kinetic energy. The strength of the flow is specified as an outflow boundary condition on the right boundary. Also specified is the (uniform) density gradient of the upstream reservoir. Because the "inflow" conditions a finite distance upstream of the left obstacle are determined by the upstream influence of waves emanating from the obstacle, imposed inflow conditions that do not match these outgoing signals will require a strong flow adjustment. Here we impose our theoretically derived solution and demonstrate that it is exactly that required for the given stratification, obstacle height and flow rate. The separation point for the down-slope flow over the left obstacle, and thus the strength of the internal hydraulic jump, is set by the blocking depth and upstream influence of the right obstacle. Note that the flow over the second obstacle is similar to the jet like flow over the first obstacle but differs in detail owing to the altered stratification produced by the turbulence in the jump upstream.

Funding: U.S. National Science Foundation, Physical Oceanography.
Collaborator: Larry Armi (SIO, University of California San Diego)

Tidally forced internal gravity waves in closed basins

The behavior of the barotropic tide in a closed ocean basin is well understood: in plan view the basin modes appear to rotate around the periphery of the basin as Kelvin waves, in the counter-clockwise sense in the northern hemisphere. In this research we investigate whether the coupled baroclinic response, internal basin modes of much smaller wavelength than the surface tide, can be responsible for the large internal tides that are often observed on the continental shelf. This study combines theoretical analyses, idealized and realistic simulations and analyses of previously collected data to study the generation and behavior of along-coast propagating internal tides.

A series of three-dimensional, direct numerical experiments in which a density-stratified fluid in a paraboloidal basin is continually forced by sinusoidally oscillating the deflection of the gravity force from vertical in order to mimic the temporally periodic forcing in a basin imposed by an equilibrium surface tide of planetary scale. The combined effects of gravity, rotation and the basin shape give rise to a rich collection of inertia-gravity waves. For a given basin, a key parameter is the ratio of the tidal forcing frequency ω to ω_i, the frequency associated with long internal waves "traversing" the basin. In the absence of rotation, waves traverse the basin in the plane of the gravitational deflections as seiching modes as shown on the left in figure 2. When such a flow is forced near resonance, the wave response is energetic and an initially basin-scale seiching mode transitions from a non-dispersive wave into a group of dispersive waves. When rotation is significant, cross-basin motions are restricted and waves are excited that "traverse" the basin by propagating around the edges as boundary trapped Kelvin waves. These waves coexist with a somewhat complicated pattern of approximately standing waves in the interior.



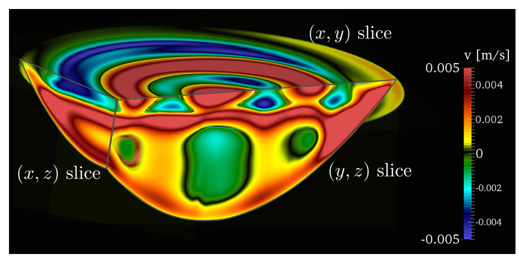


Figure 3: Left: Nonrotating basin subject to approximately resonant forcing. The large amplitude seich steepens and degenerates into a train of rank ordered nearly solitary waves. Strong boundary interactions result in mixing that alters the stratification and thus the traversal frequency of the waves. After several boundary interaction events, the system is no longer close to resonance and the wave response becomes muted. Right: Snapshot of three-dimensional flow in a rotating parabolic basin. Gravity is deflected in the $y - z$ plane. This view shows the connection between the mode-like nearly standing wave pattern in the interior with swirl-like patterns formed on the surface. Shown is the y component of the velocity.

Funding: U.S. National Science Foundation, Physical Oceanography.
Collaborators: Clint Winant (SIO, University of California San Diego), Jim Lerczak (Oregon State University)

Rotating horizontal convection

Horizontal convection is the generic name for a buoyancy driven flow when laterally varying heat or buoyancy flux is applied at a single horizontal surface. It is often used as a lowest-order model of the meridional overturning circulation of an ocean basin in which buoyancy is added at the surface in the equatorial regions and removed near the poles. The basic problem has been studied since the early experiments of Sandström in 1908 and progress was recently reviewed by Hughes and Griffiths (2008). Typical studies involve either non-rotating laboratory experiments or heavily parameterized numerical simulations using ocean circulation models applied at global scales. Winters and Young (2009) derived energetics constraints on the mixing that can occur in the classic problem of horizontal convection. Noting that the solutions for these flows have meridional motions that cannot exist in a rotating frame, we have turned our attention to the related problem of rotating horizontal convection. Our approach has been to use direct numerical simulations (DNS) in a rotating frame to quantify, without parameterization, the dissipation and mixing associated with the convective plumes and, in particular, to understand the role of baroclinic instabilities and eddies in controlling the lateral distribution of heat in closed, rotating basins subject to surface heating and cooling. Two manuscripts have now been published in the Journal of Fluid Mechanics; Winters and Barkan (2013) and Barkan, Winters and Llewellyn Smith (2013).

We are now investigating the influence of a surface wind stress on these flows and its effect on the generation of available potential energy and thus eddy formation via the upwelling induced by wind-stress curl. This problem is of interest because a large fraction of the kinetic energy in the ocean is stored in the quasi-geostrophic eddy field. Geostrophic turbulence theory suggests an upscale transfer of this energy. Instability mechanisms exist, however, that can break the approximate geostrophic balance of these eddying motions and produce a forward energy cascade and small scale dissipation. We are examining kinetic energy pathways in fully resolved direct numerical simulations of flow in a flat-bottomed re-entrant channel, externally forced by surface buoyancy fluxes and wind stress, a configuration that resembles the Antarctic Circumpolar Current. The flow is allowed to reach a statistical steady state at which point it exhibits both a forward and an inverse energy cascade. Flow interactions with irregular bathymetry are excluded so that bottom drag is the sole mechanism available to arrest the upscale eddy kinetic energy transfer. We have been able to show that eddy kinetic energy is dissipated preferentially at small scales near the surface. This pathway is regulated by frontal instabilities associated with loss of balance and a forward energy cascade rather than by bottom drag after an inverse energy cascade. This turns out to be true both with and without forcing by the wind. These results suggest that loss of balance caused by frontal instabilities near the ocean surface can provide an efficient mechanism, independent of boundary effects, by which eddy kinetic energy is dissipated in the ocean.

Funding: U.S. National Science Foundation, Physical Oceanography.
Collaborators: Roy Barkan (Ph.D. student, SIO, University of California San Diego), Stefan Llewellyn Smith (MAE, University of California San Diego)

Numerical methods for rotating stratified flows

Much of my research utilizes process oriented scientific computation, using numerical models that I develop using high order numerical methods based on global differentiation schemes, primarily Fourier based spectral schemes (Winters et al 2000, 2003, Winters and de la Fuente, 2012). Such schemes have the advantage of excellent convergence properties that are useful for simulations of nonlinear waves and turbulence but require fundamentally different communications patterns on distributed-memory, parallel computing architectures. With support from a recent NSF SGER grant, this approach was recently shown to scale well to more than 1000 processors for a fixed, sufficiently large problem size. I couple this approach with immersed boundary methods to permit detailed simulations of rotating, stratified flow over topography or in irregular domains. When possible, the numerical methods are validated via comparison with laboratory experiments and collaborative research with laboratory experimentalists is actively sought (Echaverri et al, 2009, Winters and de la Fuente, 2012, Winters and Armi, 2012). While my approach to new problems is often based initially on numerical experiments, such efforts are almost always augmented by closely coupled theoretical work (e.g. Winters and DAsaro, 1995, Winters, 2008, Winters and Young, 2009, Winters and Armi, 2012, Winters and Barkan, 2012). This work is supported by grants from XSEDE, the San Diego Supercomputer Center and the Texas Advanced Computing Center.

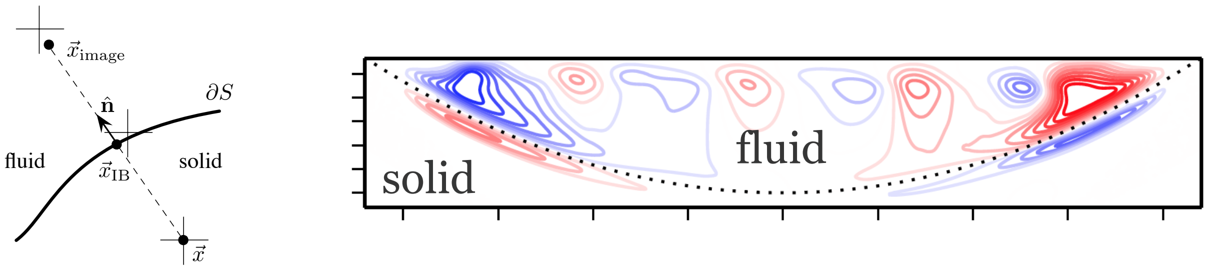


Figure 4: Left: Schematic showing a smooth immersed boundary surface ∂S separating fluid from solid regions within a computational domain. Also shown are a discrete grid point $\vec{x}$ and the corresponding nearest immersed boundary and image points, neither of which correspond to grid points. In general, neither the nearest immersed boundary point nor the image point necessarily reside on the same processor as the grid point $\vec{x}$. Right: Interpolation of information to the image points allows the fluid values to be reflected across the immersed boundary surface (dashed curve) with even or odd symmetry to impose Neumann or Dirichlet conditions on the immersed boundary itself. Tapering functions are then used to decay the reflected values in the solid region to zero so that simple Fourier boundary conditions can be applied at the computational domain boundaries. Shown is a snapshot of the vertical velocity in an irregular domain, reflected with odd symmetry across a curved no-slip, immersed boundary.

Internal waves on a β plane

We have recently investigated the far-field dynamics and fate of the internal tide radiating from the Hawaiian Ridge. Previous theoretical work (MacKinnon and Winters, 2005) had predicted that these waves would experience a subtropical catastrophe as they reached the critical latitude of 28.8 degrees, where half the semi-diurnal tidal frequency matches the local inertial frequency. Numerical modeling suggested that the internal tide would suffer strong parametric subharmonic instability and transport only a fraction of its energy further poleward. Observations near the critical latitude, however, disproved this hypothesis, showing that, while parametric subharmonic instability did occur, there was no dramatic reduction of poleward flux. Revisiting the earlier work, we were able to show (Hazewinkel and Winters, 2011) why the original predictions were in error. They suffered from lack of inclusion of the spring-neap cycle of the tidal forcing, insufficient vertical resolution to resolved the preferred resonant triad scales and, most importantly, the lack of inclusion of observed levels of background turbulence which provides a weak damping mechanism that becomes significant over the spring-neap time scale.

Numerical work was also undertaken to investigate the fate of high-latitude internal tides approaching their critical latitude where their intrinsic frequency matches the local inertial frequency and traditional theories exhibit a change in the underlying equations from hyperbolic to elliptic type. We were able to demonstrate and confirm recent theoretical predictions suggesting that the inclusion of the horizontal component of the Coriolis term alters the waveguide substantially and permits the further propagation of these waves poleward into the deep ocean toward point attractors. We were able to confirm this behavior in the weakly nonlinear regime. This work was published in the Journal of Fluid Mechanics (Winters, Bouruet-Aubertot and Gerkema, 2010).

Collaborators: Pascale Bouruet-Aubertot (LOCEAN, University Pierre and Marie Curie, Paris), Theo Gerkema (Royal Netherlands Institute for Sea Research, NIOZ), Jeroen Hazewinkel (SIO post-doc)

Turbulence in the equatorial undercurrent

Understanding and quantifying the vertical fluxes of heat and momentum in the tropical Pacific equatorial undercurrent (EUC) system is one of the central problems linking the small-scale physics of flow instabilities and turbulent mixing to larger scale climatic variability such as ENSO. Significant progress was made in the last two decades, spurred primarily by simultaneous observations of "mean" profiles and microstructure combined with classical linear stability analyses. Nevertheless, significant uncertainty remains and, in particular, the mechanisms by which a unique mix of high-frequency internal waves and coherent turbulence patches is initiated and sustained at depths where the background shear is linearly stable are only poorly understood. We have recently undertaken a high-resolution numerical investigation to quantify the pathways through which energy sources- surface wind, buoyancy flux and mean kinetic energy of the jet-feed into turbulent dissipation. We are using both large-eddy-simulation (LES) and DNS to directly resolve the flow instabilities leading to turbulence and vertical fluxes. Our analyses focus on a physical interpretation of the finite amplitude, nonlinear mechanisms responsible for sustaining turbulence in regions of the flow where background conditions are linearly stable. This work has been published in a series of papers in the Journal of Physical Oceanography (Pham, Sarkar and Winters 2012a, 2013) and the Journal of Turbulence (Pham, Sarkar and Winters, 2012b).

Funding: U.S. National Science Foundation, Physical Oceanography.
Collaborators: Hieu Pham (MAE/SIO post-doc), Sutanu Sarkar (MAE, University of California San Diego),

Wind-driven Kelvin waves in large lakes

I am also collaborating on a combined field, laboratory and numerical study of nonlinear Kelvin waves generated by daily sea breezes in Lake Villarica, Chile. This study is motivated by a desire to better understand the mechanisms of vertical fluxes of oxygen and nutrients in an increasingly anthropomorphically stressed system. I spent a semester at the Universidad de Chile as a Fulbright research scholar and visiting professor. The objective of my visit was to set up a numerical investigation to couple closely with an ongoing laboratory experiment of large amplitude waves on a sharp density interface conducted on a 2m diameter rotating table. This work has continued with Ulloa-Sanchez, a Chilean Ph.D. student, visiting Scripps for six months. The numerical work examines the relationship between the nonlinearity of the Kelvin waves, their degree of rotational confinement to the boundary, and the vertical mixing and fluxes induced by small-scale instabilities. A conference paper documenting this work (Ulloa-Sanchez, Winters, de la Fuente and Niño, 2013) has been published.

Funding: U.S. Fulbright program, Universidad de Chile
Collaborators: Hugo Ulloa-Sanchez (Ph.D. student, Universidad de Chile), Alberto de la Fuente, Yarko Niño (Universidad de Chile)