OSM-PS11A

- # PS11A: Interaction Between Internal Waves and Multiple-Scale Dynamics I

  - nternal waves in the ocean, including inertial internal waves, internal tides and nonlinear internal waves, co-exist with other oceanic phenomena with multiple-scales, such as general circulations, fronts, mesoscale and sub-mesoscale eddies. Since such phenomena have different temporal and spatial scales from internal waves, their dynamics have usually been studied separately. However, more and more evidences reveal apparent interactions between them. Background currents and tilted thermocline associated with geostrophic circulation or mesoscale eddies affect the generation and propagation of internal waves, including reflection, refraction, formation of higher modes and non-linear evolution. As a feedback, internal wave breaking or scattering changes local mixing, thus influencing the genesis and evolution of general circulation and mesoscale eddies. This feedback may be especially important for long-term variations of ocean circulation and climate change, and also provides a roadmap to understand and estimate appropriate dissipation rates for numerical models. This session invites presentations that report recent progress on interactions between internal waves and other dynamical phenomena in the ocean, so as to clarify the energy and momentum route between these processes in different scales. Observational, theoretical and numerical investigations are all welcome.

Primary Chair

- Qiang Li
  - *Tsinghua University*

Co-Chairs

- Xueen Chen
  - *Ocean University of China*
- John Huthnance
  - *National Oceanography Center*

Moderators

- Xueen Chen

- *Ocean University of China*

- John Huthnance

- *National Oceanography Center*

- 08:00 AM**PS11A-01** Assessment of finescale parameterizations of deep ocean mixing in the presence of geostrophic current shear : Results of microstructure measurements in the Antarctic Circumpolar Current Region***Anne Takahashi**, The University of Tokyo, Earth and planetary Science, Tokyo, United States and Toshiyuki Hibiya, The University of Tokyo, Department of Earth and Planetary Science, Graduate School of Science, Tokyo, Japan*
- The Southern Ocean is thought to be one of globally significant mixing hotspots. In this study, we carry out simultaneous measurements of microscale turbulence and finescale shear/strain in the south of Australia to assess the validity of the existing finescale parameterizations of deep ocean mixing in the Antarctic Circumpolar Current (ACC) region where geostrophic shear flows coexist with the background internal wave field.
- It is found that turbulent dissipation rates and the derived diapycnal diffusivities are overall small but the internal wave field is more energetic than the Garrett-Munk (GM) wave field. Finescale shear/strain ratio (R_ω) well exceeds the GM value in the deep layer south of Southern ACC Front, suggesting that the local internal wave spectra are significantly biased to lower frequencies. Through the comparison of the turbulent dissipation rates directly measured with those inferred from finescale parameterizations, we find that the Gregg-Henyey-Polzin (GHP) and Ijichi-Hibiya (IH) parameterizations, both of which take into account the spectral distortion in terms of R_ω can well predict the turbulent dissipation rates at many observed locations, whereas the shear-based parameterization (the strain-based parameterization) tends to overestimate (underestimate) the directly measured turbulent dissipation rates. However, at the observed locations where the vertical shear associated with the geostrophic current is enhanced, both the GHP and IH parameterizations tend to overestimate the turbulent dissipation rates by up to a factor of 3. Using the observed data, we discuss several possible mechanisms by which the geostrophic vertical shear brings about these overestimates (e.g., critical layer absorption, further distortion of the background internal wave field).

- 08:15 AM**PS11A-02** Internal wave propagation and scattering in presence of non-trivial background currents, varying stratification and arbitrary topography*Stefan G Llewellyn Smith, University of California San Diego, La Jolla, CA, United States and **Noe Jules-Antoine Lahaye**, LOPS, IUEM, University of Brest, Brest, France*
- The propagation of internal waves in an inhomogeneous ocean is investigated using normal mode analysis. The present framework allows the presence of a vertically-sheared background current and arbitrary topography. We derive generalized orthogonality conditions, thus extending the range of application of normal-mode decomposition.
- Using perturbation theory, a coupled-mode equation describing the horizontal variations of the mode amplitudes is derived that allows analytical investigation of mode propagation and modal energy transfer through horizontal inhomogeneities (e.g. varying stratification or topography). In addition, the linear generation and subsequent propagation of tidal beams by weak topography can be included in the same framework. The coupled-mode equation can be solved numerically and different approximate solutions of lower computational complexity can be derived, recovering an equivalent-WKBJ solution (horizontal rays) at the lowest order of approximation.
- The present study provides a convenient framework for both theoretical investigation of mode scattering and numerical solution of mode propagation in an inhomogeneous ocean at low computational cost.
- 08:30 AM**PS11A-03** Stimulated generation: extraction of energy from balanced flow by near-inertial waves ***Cesar B Rocha**, Scripps Institution of Oceanography, La Jolla, CA, United States, Gregory LeClaire Wagner, MIT, Cambridge, MA, United States and William R Young, University of California, La Jolla, CA, United States*
- Primitive-equation numerical simulations and analysis of reduced models suggest that stimulated generation—the transfer of energy from balanced flows to existing internal waves—is a leading contender for an ocean mesoscale energy sink. Here we study stimulated generation using an asymptotic model that couples barotropic quasi-geostrophic flow and near-inertial waves with exp(imz) structure on the f-plane. A detailed description of the conservation laws of this vertical plane-wave model illuminates the mechanism of stimulated generation associated with vertical

vorticity and lateral strain. In particular, there are two sources of wave potential energy, and corresponding sinks of balanced kinetic energy: (1) the refractive convergence of the wave action density into anti- cyclones (and divergence from cyclones) and (2) enhancement of wave-field gradients by geostrophic straining.

- We quantify the energy conversion and describe the phenomenology of stimulated generation using numerical solutions of decaying ocean macroturbulence modified by near-inertial waves. The initial conditions are a uniform inertial oscillation and a two- dimensional turbulent field emergent from random initial conditions. In all solutions, stimulated generation co-exists with a transfer of balanced kinetic energy to large scales, which is associated with vortex merger. And geostrophic straining accounts for most of the generation of wave potential energy, which represents a sink of 10-20% of the initial balanced kinetic energy. But refraction is fundamental because it creates the initial eddy- scale lateral gradients in the near-inertial field that are then enhanced by advection. In these quasi-inviscid solutions, wave dispersion is the only mechanism that upsets stimulated generation: with barotropic balanced flow, lateral straining enhances the wave group velocity; the waves accelerate and thus rapidly escape from the straining regions. Because of this wave escape, the wave field does not suffer a direct cascade to dissipative scales.
- 08:45 AM**PS11A-04** Internal Waves, Their Amplification, and Potential to Break***Andrei Natarov**, University of Hawaii at Manoa, Honolulu, HI, United States and Kelvin John Richards, Univ Hawaii, Honolulu, HI, United States*
- We study the mechanisms of internal wave amplification in the interior of rotating stratified quiescent fluids by calculating two heuristic stability measures: the isopycnal steepness (for overturning instability) and the Froude number (for shear instability) as functions of wave energy density and phase to determine the regions where fast perturbation growth and subsequent wave breaking are more likely to occur. For purely inertial waves, the Froude number field is uniform, and wave breaking is equally probable at any point. We show that for non-inertial waves the locations of the minimal convective and shear stability always coincide, but the onset of shear instability almost always occurs at lower energy densities than the onset of convective overturning for all wave frequencies. At high frequencies, the critical energies for convective and shear instability nearly coalesce. In a

nonrotating fluid, in contrast, the two critical energies coalesce at all frequencies. After completing the analysis for a uniform medium, we describe the transformation of various fields when a wave travels through a jump in stratification. We show that waves amplify in both steepness and Froude number when they enter stronger stratification. Under the hydrostatic approximation, the amplification factors for both stability measures are a monotonic function of the ratio of the two buoyancy frequencies. In addition, the Froude number amplification factor is a nonlinear function of the wave energy density: waves entering a region with a stronger stratification with larger initial energy amplify to larger Froude numbers than waves with smaller initial energy. On the other hand, more energetic waves entering weaker stratification lose a larger fraction of their Froude number than less energetic waves. When the hydrostatic approximation is relaxed, we find that amplification upon refraction becomes stronger in both steepness and Froude number. The difference is especially pronounced when the incident waves have frequencies close to the buoyancy frequency. Our results extend previous studies to include rotation, and both hydrostatic and fully nonhydrostatic cases, and are also valid when the buoyancy frequencies are lower than the rotation frequency.

- 09:00 AM**PS11A-05** The Demise of Semidiurnal Internal Tides in the Equatorial Pacific: Incoherence or Dissipation?***Maarten C Buijsman***[1]*, Brian K Arbic*[2]*, James G Richman*[3]*, Jay F Shriver*[4]*, Alan J Wallcraft*[5] *and Luis Zamudio*[3]*, (1)University of Southern Mississippi, Stennis Space Center, MS, United States, (2)University of Michigan, Ann Arbor, MI, United States, (3)Florida State University, Tallahassee, FL, United States, (4)Naval Research Lab Stennis S, Stennis Space Center, MS, United States, (5)Naval Research Laboratory, Stennis Space Center, MS, United States*
-

Equatorward propagating semidiurnal internal tides from Hawaii and the French Polynesian Islands do not appear to cross the equator in sea-surface height amplitude maps computed from altimetry. In this study we investigate if this apparent demise can be attributed to dissipation and/or phase incoherence associated with the time variability of the equatorial jets. In this talk we will report on analyses performed on realistically-forced global model simulations with a horizontal resolution of 1/12.5° and 1/25°. The analyses for the 1/12.5° simulations have been conducted while the analyses for the 1/25° simulations are under way. The jets in the equatorial Pacific Ocean cause a strong loss of phase coherence in semidiurnal internal tides in the 1/12.5° simulations. This loss of coherence is quantified with a baroclinic energy analysis, in which the semidiurnal-band terms are separated into coherent, incoherent, and cross terms. For time scales longer than a year the coherent energy flux approaches zero values at the equator. The time-variability of the incoherent energy flux is compared with the internal-tide travel-time variability, which is based on along-beam integrated phase speeds computed with the Taylor-Goldstein equation. On monthly time scales, the loss of phase coherence in the equatorward beams from the French Polynesian Islands is attributed to the time variability in the vertically-sheared background flow associated with the jets and tropical instability waves. On an annual time scale, the effect of stratification variability is of equal or greater importance than the shear variability is to the loss of coherence. The low-frequency equatorial jets do not noticeably enhance the dissipation of the internal tide in the 1/12.5° simulation. We will investigate if this is also true for the higher resolution, 1/25° simulation.

DOI:10.1002/2016JC012590

09:15 AM**PS11A-06** Observed eddy - internal wave interaction in the Southern Ocean
Jesse Martin Cusack, *National Oceanography Centre, Southampton, United Kingdom, J. Alexander Brearley, British Antarctic Survey, Cambridge, United Kingdom, Alberto Naveira Garabato, University of Southampton, Southampton, United Kingdom and David Smeed, National Oceanography Center, Soton, Southampton, United Kingdom*

Mesoscale eddy motions dominate the kinetic energy budget of the ocean at mid and high latitudes. It has been suggested that interaction of the eddy field with the internal wave field may result in a transfer of energy from eddies to waves. The importance of this potential sink of eddy energy remains unknown due to the limited amount of previous observational work on the subject. We treat the interaction as a viscous coupling and characterise the process in detail using data from an array of 5 moorings deployed in the Southern Ocean for 439 days. The magnitude of the energy sink is found to be of order $2 ¥times 10^{-9}$ W kg^{-1} above 2000 m and not statistically different from zero below this depth. Significantly, this value is the same order of magnitude as other sinks of energy estimated at the same site, including lee wave generation and bottom boundary layer friction, implying that eddy - wave interactions are of first order importance in the local energy budget.

09:30 AM**PS11A-07** Observations of near-inertial internal waves in the southeast Indian Ocean***Ajitha Cyriac***[1], *Helen Elizabeth Phillips*[2], *Nathaniel L. Bindoff*[1] *and Ming Feng*[3], *(1)University of Tasmania, Institute for Marine and Antarctic Studies, Hobart, Australia, (2)University of Tasmania, Institute for Marine and Antarctic Studies, IMAS, Hobart, Australia, (3)CSIRO, Oceans and Atmosphere, Crawley, Australia*

Mixing is important in transporting energy and materials throughout the ocean and also plays a major role in the evolution of large scale circulation. In the stratified ocean, most of the mixing is caused by internal wave breaking. The global estimates of mixing vary from place to place and also with depth which is attributed to the spatial variability of the internal wave field. This study presents the characteristics and the spatiotemporal structure of the near-inertial waves (NIW), the dominant mode in the internal wave spectra and their interaction with the Leeuwin Current eddies in the southeast Indian Ocean (SIO) using EM-APEX floats. These floats can provide data with a resolution high enough to resolve the internal waves, which are difficult to analyse using limited ship-based observations. The floats measured ocean velocity and water mass properties up to a depth of 1200m with a resolution of 3-4m in the vertical. NIWs are mainly generated by winds near the ocean surface and they propagate down in to the ocean interior. Using linear wave theory, the characteristics of the beams at different depths are estimated. The impact of mesoscale vorticity on the characteristics and propagation of the observed NIWs is also investigated. The cyclonic eddy shifts the near-inertial frequency by half of its vorticity near the surface. The increased near-inertial shear variance in the region of anticyclonic eddy shows that the NIWs are trapped in it. At depth, high inertial shear variance can be attributed to bathymetric roughness and cyclonic background vorticity. These observations of NIWs can be used to estimate the contribution of SIO internal wave field in to the global ocean mixing.

- 09:45 AM**PS11A-08** Propagation and Dissipation of Nonlinear Internal Tides on the Australian Northwest Shelf***Jeffrey W Book***[1], *Nicole L Jones*[2], *Ana E Rice*[1], *Gregory N Ivey*[3], *Silvia Matt*[1] *and Scott R Smith*[1], *(1)U.S. Naval Research Laboratory, Stennis Space Center, MS, United States, (2)University of Western Australia, Crawley, WA, Australia, (3)University of Western Australia, Crawley, Australia*

- The Australian Northwest Shelf is characterized by strong and intense nonlinear internal tide driven oscillations with isotherm fluctuations that have been observed to fluctuate over 60 m in less than 100 m water depth due to the passing of internal tide wave packets. A series of collaborations between U.S. and Australian funded projects resulted in the deployment of moorings at 23 different sites on the shelf between November 2011 and August 2012 to capture both internal tide variability and connectivity of shelf currents with the Leeuwin Current. Moorings were divided between four different observational clusters that spanned the southwestern most portion of the shelf and were located inshore of both broad and steep portions of the continental slope where these wave packets are generated. These measurements were complimented by over 300 vertical microstructure profiles that were taken in and around the moorings, as well as other shipboard and ocean glider data measurements. Together, these arrays of measurements are used to analyze the propagation and dissipation of these wave packets as they travel onto the shelf. Propagation and phasing of the tide packets was sensitive to the wind and coastal current circulation induced stratification changes, leading to complete blocking of shoreward propagation under certain mesoscale conditions.
- 10:30 AM**PO12A-01** Progress in understanding the roles of rough topography and its interactions with the bottom flow(Invited) ***David S Trossman***, *University of Texas at Austin, Institute for Computational Engineering and Sciences, Austin, TX, United States and Brian K Arbic, University of Michigan, Ann Arbor, MI, United States*
- This presentation is about the interaction between oceanic bottom flows and the underlying topography. A parameterization (Garner, 2005) that accounts for the drag associated with the generation of internal lee waves and topographic blocking arising from geostrophic flow impinging upon rough topography is assessed using observations in two Southern Ocean regions where internal tides are small. The parameterization is inserted into the momentum equations of an eddying global ocean model at two different horizontal resolutions. Model results with and without the theory included as a parameterization are compared to satellite altimetry and current meter observations. An energy budget analysis is performed to address a hypothesized mechanism for the dynamical changes in the simulations. There are relatively small impacts on sea surface height variance and kinetic energy in contrast to larger decreases in abyssal kinetic energy, but even the small surface

changes are well above the level of seasonal variability. In another set of simulations, motivated by the strong sensitivity of idealized geostrophic turbulence models to bottom drag strength, we vary bottom drag strength in global eddying general circulation simulations, and find a relatively small sensitivity of eddy statistics to bottom drag strength as compared to idealized model results. Underlying reasons for the relatively small magnitude of the impacts on the sea surface when bottom drag is varied by orders of magnitude and when the Garner (2005) parameterization is introduced in the model are further explored in an ensemble of quasi-geostrophic turbulence simulations. Results are presented to motivate future studies that can address the following questions: 1) Does the presence of rough topography short-circuit the inverse cascade to large-scale, barotropic, energetic flow and if so then how? 2) How is the geography of baroclinic instability altered with additional abyssal energy sinks? 3) Does topographic blocking contribute to large amounts of turbulent kinetic energy dissipation only in isolated hotspots, primarily in the Southern Ocean, or globally? 4) What fraction of lee-wave energy is lost to turbulent dissipation and mixing, as opposed to redistributed via reabsorption into the mean flow or generating higher-frequency harmonics?

- doi:10.1016/j.ocemod.2013.08.006, doi:10.1002/2015JC010892, doi:10.1016/j.ocemod.2015.10.013, doi:10.1175/JPO-D-16-0229.1

- 10:45 AM**PO12A-02** The lee wave Froude number and its intuition***Eric Mayer**, Stanford University, Civil and Environmental Engineering, Stanford, CA, United States and Oliver B Fringer, Stanford Univ-Civil/Envir Engg, Stanford, CA, United States*
-

There is a longstanding debate in the literature of stratified
flows over topography concerning the correct dimensionless
number to refer to as a Froude number. The most relevant nondimensional number for lee waves generated by hills in deep water is $J=U/(N h_0)$, where U is the flow speed, N is the buoyancy frequency, and h_0 is the topographic amplitude. Although J is commonly referred to as an inverse Froude

number, such an interpretation is incorrect. By nondimensionalizing the stratified Euler equations describing the flow of an infinitely deep fluid over topography, we show that J is in fact the square of an internal Froude number because it can identically be written in terms of the inner variables as $Fr_{¥delta}^2=J=u_0^2/(g'¥delta)$, where u_0, g', and $¥delta$ are, respectively, inner scales for the perturbation velocity, buoyancy, and vertical wavelength, following Winters and Armi (2012). Our scaling also identifies J as the ratio of the vertical velocity scale within the lee wave to the group velocity of the lee wave, which we term the vertical Froude number, $Fr_{vert}=J=w_0/c_g$. This identification of J as a Froude number offers intuition for the evolution of the lee wave from the linear ($J<<1$) to the supercritical regime ($J>J_c$). Using an iterative solver of Long's nonlinear lee wave equation (Long 1953, Laprise and Peltier 1989), we demonstrate this evolution with increasing J as a progression from a system in which the wave radiates energy away from the disturbance without any local loss, to a weakly nonlinear regime, where increasingly first-order accelerations within the wave field result in a deviation of the form drag from the prediction of linear theory that the form drag, $F_d ¥propto J^2$ (Lilly and Klemp 1979), and finally to the critical point, analogous to hydraulic control, where the nonlinear accelerations overwhelm the buoyant response and initiate wave breaking.

11:00 AM**PO12A-03** Observations of internal waves generated at a steep submarine ridge***Celia Yun Ou***, *University of California San Diego, Scripps Institution of Oceanography, La Jolla, CA, United States and Shaun Johnston, Scripps Institution of Oceanography, La Jolla, CA, United States*

As quasi-steady currents flow over topography, internal lee waves transfer energy and momentum to smaller scales. Where barotropic tides flow over topography, internal tides also transfer energy and momentum to smaller scales, either locally or after propagation of low modes over long distances. We observed internal waves propagating in quasi-steady stratified flow over tall, steep topography. Associated energy and momentum fluxes may have measurable effects on the quasi-steady flow. The observed oscillations may be due to either lee waves or internal tides, and we will discuss how both cases are plausible. Shipboard velocity and towed CTD measurements (SeaSoar) were made around a steep submarine ridge in the North Equatorial Countercurrent. We observed a strong, vertically sheared mean flow from $1.0~¥mathrm{m~s}^{-1}$ at the surface to $0.3~¥mathrm{m~s}^{-1}$ at 400 m. Energy flux was directed away from the ridge, and

momentum flux indicates upward transport of westward momentum. Energy flux divergence is the equivalent to a dissipation rate of $O(10^{-7}~¥mathrm{W~kg^{-1}})$. Momentum flux divergence is the equivalent to a change in the mean current of 3--4 $¥mathrm{cm~s^{-1}}$ per day.

11:15 AM**PO12A-04** The role of lee waves for dissipation of transient eddies in the Southern Ocean***Luwei Yang***[1], *Maxim Nikurashin*[1], *Andrew M. Hogg*[2] *and Bernadette Sloyan*[3], *(1)University of Tasmania, Institute for Marine and Antarctic Studies, Hobart, Australia, (2)Australian National University, Research School of Earth Sciences, Canberra, ACT, Australia, (3)CSIRO, Oceans and Atmosphere, Hobart, Australia*

Transient mesoscale eddies play an important role in the Southern Ocean by transferring momentum, heat, and tracers horizontally and vertically. While the generation mechanisms for mesoscale eddies are well-understood, the processes governing their dissipation and energy transfer to mixing remain uncertain. A potential route to dissipation may occur in the deep ocean where deep-reaching eddies interact with small-scale topography, generating internal lee waves. These lee waves have been suggested to extract energy from eddies to sustain mixing in the deep Southern Ocean and apply drag on the time-mean flow of the Antarctic Circumpolar Current (ACC).

In this study, we evaluate the role of lee waves for the dissipation of transient mesoscale eddies in the Southern Ocean using a 1/10° eddy-resolving model and linear lee wave theory. The results show that the energy dissipation of the total flow due to lee wave generation is comparable to its dissipation due to turbulent bottom boundary layer drag, accounting for 0.16 TW and 0.07 TW respectively, and that lee waves make a stronger contribution to the dissipation of transient eddies (0.12 TW) than to the dissipation of the time-mean ACC (0.04 TW). We find that the lee wave generation by transient eddies is also more sensitive to the anisotropy and orientation of small-scale topography than the wave generation by time-mean flows. Our results imply that lee waves should be parameterized in the eddy-resolving ocean models in order to improve the modeled eddy and mixing representation in the Southern Ocean and hence the response of the Southern Ocean to changes in winds.

11:30 AM**PO12A-05** The role of turbulence from highly sheared tidal and low-frequency flows in modulating topographic drag and flow separation near Palau***Jennifer A MacKinnon***[1], *Matthew H Alford*[2], *Gunnar Voet*[2] *and Ali Mashayek*[3], *(1)University of California San Diego, La Jolla,* *CA, United States, (2)Scripps Institution of Oceanography, La Jolla, CA, United States, (3)Massachusetts Institute of Technology, Cambridge, MA, United States*

Where strong steady or oscillatory flows encounter abrupt topography, a rich panoply of wake dynamics may result, including internal gravity waves, flow separation and lee eddies. Such wakes are important not only for their ability to extract appreciable energy and momentum from the incident flow, but also their tendency to significantly enhance local stirring and mixing rates. Here we investigate the nature of turbulence and flow separation using a series of towed body, shipboard sonar, and microstructure studies near Velasco Reef, at the northern end of the Palau island chain. Our observations focus on detailed measurements of turbulence near the flow separation point, and the ensuing lee wake eddies. While sharing many similarities with previous wake studies, the present work adds two additional levels of complexity. First, most previous studies of wake eddies have either concentrated on purely oscillatory (generally tidal) flows, or looked at separation of low-frequency currents, where the role of tides was not considered. In the present work, and perhaps in reality at many if not most coastal headlands, tides and low-frequency flows are comparable in magnitude. The tidal flows play a first order role here both in controlling the strength of turbulent drag at the separation point, and in contributing to the vorticity variance that evolves into a larger scale wake. The second complexity of the current work is the multi-layered, sheared nature of the incident flow in this region, with near-surface currents and oppositely flowing under-currents creating wakes on opposing sides of the same headland.

11:45 AM**PO12A-06** Island wake variability from High-Frequency radar***Sophia Merrifield***[1], *Eric J Terrill*[2], *Travis Allen Schramek*[1], *Thomas Cook*[1], *Mark P Otero*[1], *Carlos Garcia-Moreno*[1], *Eric Gallimore*[1] *and Myles Syverud*[1], *(1)Scripps Institution of Oceanography, La Jolla, CA, United States, (2)SIO, UCSD, La Jolla, CA, United States*

High-frequency (HF) radar systems were installed at Kayangel, Melekeok, and Angaur in the main island group of Palau to study surface current variability. Operational since July 2016, the network provides hourly surface currents with 6km horizontal resolution and offshore coverage out to 175km on the eastern side of Palau. Captured in the spatial time series are near-field and offshore variability associated with both upstream and wake conditions as the synoptic geostrophic flow interacts with the island group.

Strong tidal (dominant K1, M2 constituents) and inertial flows are observed in the near-field and offshore. The relative vorticity is elevated relative to the local planetary vorticity both upstream and in the wake. During wake conditions, submesoscale eddies are prevalent with strong vorticity signatures. The vorticity in the wake is elevated over a broad range of frequencies, sub- to super-inertial, suggesting that tidal and near-inertial generation at topography contributes to the wake signature downstream. Harmonic analyses and filtering methods applied to the data highlight the role of internal tides in influencing the total variance of the surface currents.

12:00 PM**PO12A-07** Vortex dynamics and wake turbulence in stratified flow past three-dimensional obstacles: LES results***Sutanu Sarkar***, *Masoud Jalali, Jose Luis Ortiz Tarin, Karu Chongsiripinyo and Geno R Pawlak, University of California San Diego, La Jolla, CA, United States*

Low-frequency and tidal motions past deep, three-dimensional obstacles lead to distinct flow features: internal gravity waves, separated boundary layers, coherent wake vortices, and turbulence. We perform LES of flow past a conical obstacle to examine the dynamics in the regime where topographic Froude number, Fr_h , is less than O(1). Boundary layer separation and the energetic scales of turbulence are resolved. The flow separation and coherent vortices in the lee of the obstacle are found to change qualitatively with increasing stratification and decreasing Fr_h. The excursion number of the tidal constituent is also found to have a strong influence on the properties of the wake. We will present results that quantify the coherent vortices and turbulence levels.

- 12:15 PM**PO12A-08** Flow and Turbulence in Wakes of Abrupt Topography***Louis St Laurent***, *Woods Hole Oceanographic Institution, Physical Oceanography, Woods Hole, MA, United States, Harper L Simmons, School of Fisheries and Ocean Sciences, Fairbanks, AK, United States, Sophia Merrifield, Scripps Institution of Oceanography, La Jolla, CA, United States and Eric J Terrill, Scripps Institution of Oceanography – UC San Diego, La Jolla*

- **PO14B** Multiscale Topographic Effects on Large-Scale Flow: From Wakes and Lee Waves to Small-Scale Turbulence and Mixing III Posters
- *Oregon Convention Center*
- *- Poster Hall*
    - **PO14B-2170** Interaction of the North Equatorial Undercurrent (NEUC) Jets with the Palau Ridge***Shuiming Chen***[1], *Bo Qiu*[2], *Daniel L Rudnick*[3] *and Shaun Johnston*[3], *(1)University of Hawaii at Manoa, Honolulu, HI, United States, (2)Univ*

Hawaii Manoa, Honolulu, HI, United States, (3)Scripps Institution of Oceanography, La Jolla, CA, United States

- To elucidate how large-scale wind-driven circulation interacts with the Palau Ridge in the Philippine Sea Basin, we collected available temperature-salinity and velocity data in the region from historical hydrographic, International Argo, as well as from ONR OKMC and FLEAT projects, and constructed a 3-D circulation field around Palau with a mesoscale-resolving spatial resolution. We found the Palau Ridge interacts differently with the large-scale circulation in the vertical. Within the ventilated thermocline of upper ocean (sigma-theta < 26.8), the Palau Ridge acts as the classical cylindrical obstacle to the westward-flowing North Equatorial Current (NEC), generating downstream wakes to the west of the Ridge. In the subthermocline layer of sigma-theta = 26.8-27.4 (depth = 300-1,200m), the Palau Ridge interacts with the two NEUC jets centered along 6N and 9N, respectively, at its southern and northern edges. A southward-flowing western boundary current, dubbed the East Palau Ridge Current (EPRC), exists to the east of the Palau Ridge. The EPRC is simulated favorably in the eddy-resolving OGCM for the Earth Simulator (OFES) model. An examination of eddy momentum dissipation from the OFES model output reveals that the eddy momentum dissipation at the southern edge of the Palau Ridge exceeds that at the northern edge. Based on Kelvin's circulation theorem, we argue that this differential eddy momentum dissipation at the southern versus northern Palau Ridge edges is the mechanism underlying the EPRC formation.
- **PO14B-2171** On the Energetics and Structure of Seamount Wakes***Brad Perfect**, University of Washington Seattle, Seattle, WA, United States, James J Riley, University of Washington Seattle Campus, Seattle, WA, United States and Nirnimesh Kumar, University of Washington Seattle Campus, Civil and Environmental Engineering, Seattle, WA, United States*
- Seamounts are one of the ubiquitous topographical features on the sea floor. Internal wave generation from seamounts has been extensively investigated. However, the dynamics of hydrodynamic wakes created by seamounts, and their

role in extracting energy from the ambient current are poorly understood. In general, the physics governing wakes in a stratified, rotating environment are not yet well-studied. Rotation and stratification may be significant factors in the overall effect of seamount wakes on the ocean currents and density structure. Here a set of idealized numerical ocean model simulations are conducted in order to gain insight into the structure and energetics of seamount wakes.

- Constant (non-tidal) flow past a 2500m Gaussian seamount in a stratified ocean with Coriolis forcing is simulated using ROMS (Regional Ocean Modeling System), a three-dimensional, primitive equation model. The hydrodynamic wake associated vortex structure is investigated qualitatively and quantitatively. As the diameter of the seamount varies with the vertical level in the water column, the vortex shedding frequency changes in order preserve a Strouhal number $¥text{St}¥equiv ¥frac{fD}{U} ¥approx 0.2.$ These vertical variations in the vortex shedding frequency lead to strongly tilted vortex lines, which eventually break apart, creating regions of high shear. These structures facilitate the transfer of kinetic energy from the mean flow into submesoscale motion. A kinetic energy budget, consisting of mean flow, eddy scale motions, and sub-grid scale turbulence kinetic energy is presented in order to trace the pathways from mean flow kinetic energy to turbulent dissipation and vertical mixing. Other preliminary results suggest that the mechanisms described above may vary substantially as the relative strengths of rotation and stratification are modified.
- **PO14B-2172** Asymmetrical flow response in a shelf valley to along-shelf winds of opposite directions – A lee-wave mechanism***Weifeng Zhang**, Woods Hole Oceanographic Institution, Department of Applied Ocean Physics & Engineering, Woods Hole, MA, United States and Steven J Lentz, Woods Hole Oceanographic Inst, Woods Hole, MA, United States*
- This study investigates the wind-driven flow in shallow shelf valleys and is motivated by observations in Hudson Shelf Valley showing stronger up-valley than down-valley flows. It explains the mechanism of the asymmetrical response of the valley flow to along-shelf winds of opposite directions: i) flow tends to follow the isobath and generates weak down-valley transport when the wind is in the same direction as coastal-trapped wave (CTW) propagation (*downwelling* regime); and ii)

flow turns onshore in the valley under wind in the opposite direction and generates strong up-valley transport and standing meanders upstream (CTW sense) of the valley (*upwelling* regime). Our analysis reveals that the flow asymmetry results from CTWs being arrested by the shelf flow that opposes CTW propagation and that the upstream meanders are coastal-trapped lee waves. Essentially, the valley bathymetry drives an initial up-valley flow, which excites CTWs. Arresting of the CTWs by the shelf flow sustains the onshore flow in the valley. For wind-driven flow in the opposite direction, disturbances generated in the valley propagate away. Scalings of the along-valley flow and transport in both regimes are developed based on potential vorticity conservation and the lee-wave dynamics. Because of the similarity in the physical setup, the basic mechanism of arresting CTWs is expected to be applicable to the asymmetrical flow response in slope canyons.

- **PO14B-2173** Flow Encountering Abrupt Topography: Observations of flow separation and mixing in the vicinity of a deep ocean island and ridge***Joel C Wesson****, Hemantha W Wijesekera and David W Wang, Naval Research Laboratory, Stennis Space Center, MS, United States*
- Flow encountering complex topographic features connected with the Velasco Plateau and Palau-Kyushu ridge off northern Palau in the western equatorial Pacific Ocean, were examined using both long-term moored observations and short-term ship-based observations, as part of the ONR sponsored research initiative, Flow Encountering Abrupt Topography (FLEAT). The main goals are to observe, understand and quantify low-frequency currents and high-frequency fluctuations of velocity, vorticity and hydrography, and turbulent mixing, when the north equatorial currents interact with the Palau Islands and submarine ridges. Here we describe a 10-day long ship-based microstructure and velocity survey conducted in November/December 2016. Microstructure surveys using a Vertical Microstructure Profiler (VMP) were conducted in the upper 250 m of water around the reef and over the ridge. We collected eight sections (5-8 nm in length) over the Velasco slope where water depths ranged from 50 m to 3000 m, and one east-west section over the ridge. The VMP profiles were collected by steaming slowly either toward or away from the reef. Currents were as high as 1 m/s, and there was intense mixing around the reef and also over the ridge. Turbulent overturns as large as 20 m were observed. Strong currents flowing along the eastern side of the reef separated at

the northern edge of the reef, while generating strong vorticity. The relative vorticity estimated at 5-10 km scales, was about 3-4 times larger than the planetary vorticity. Strongly sheared currents, energetic mixing, 10^{-5} to 10^{-4} W/kg, and large eddy diffusivities, 10^{-4} to 10^{-2} m^2/s, were found. The Velasco reef and the connected submarine ridge is a mixing “HOT SPOT”.

- **PO14B-2174** Energetics of the Brazil Current in the Rio Grande Cone region***André Lopes Brum**, Universidade Federal do Rio Grande, Pelotas, Brazil, José Luiz Azevedo, Federal University of Rio Grande, Instituto de Oceanografia, Rio Grande, Brazil, Leopoldo Rota de Oliveira, FURG, Rio Grande, Rio Grande do Sul, Brazil and Paulo Henrique Rezende Calil, Universidade Federal do Rio Grande, Institute of Oceanography, Rio Grande, Brazil*
- The energetics of the Brazil Current (BC) in the region of the Rio Grande Cone (RGC, 30-35.5°S), a topographic rise in the southwest portion of the Brazilian continental margin, are analyzed using 16 years of numerical data from the Ocean General Circulation Model (OGCM) for the Earth Simulator (OFES). The main focus of this study is the eddy-mean flow interactions of the BC and the local energy budgets. The kinetic and potential energy balance equations are derived for mean and eddy flows, and the resulting terms are presented and discussed. The eddy-mean flow interactions exhibit complex spatial distributions, and the intensities of the energy budgets decrease with increasing depth. However, only the mean potential energy budget decreases southward. Eddy kinetic energy (EKE) and eddy potential energy exhibit similar horizontal distribution patterns. Additionally, the baroclinic and barotropic conversion rates increase downstream of the bump, where the eddy energy field exhibits along-stream variability that increases southward. Barotropic conversion is more intense between 50 and 200 m, where mean kinetic energy (MKE) and EKE are concentrated, and it exhibits a horizontal cross-stream variation pattern, with mean-to-eddy energy conversion observed on the offshore side of the BC. Generally, baroclinic conversion exhibits a greater influence on the eddy-mean flow interaction than does the barotropic conversion. The RGC directly affects the local dynamics of the BC by increasing the eddy field as soon as the BC reaches the bump. The energy diagrams illustrate a stream characterized by evolving barotropic and baroclinic instability processes throughout the water column. This result indicates an intrinsically unstable jet in the study

region. Moreover, baroclinic instability is the main source of EKE in the RGC region.

- **PO14B-2175** Glider Observations of Elevated Velocity Variance and Recirculation in the Lee of NEC Interaction with Palau***Kristin Fitzmorris*** *and Daniel L Rudnick, Scripps Institution of Oceanography, La Jolla, CA, United States*
- In an effort to examine the dynamics of large-scale basin flow encountering steep topography, a 2.5 year timeseries of velocity, temperature and salinity profiles to 1000 m from meridional glider surveys is used to study the interaction of the North Equatorial Current with the northernmost ridge of the archipelago Palau. Objectively mapped into time and space, mean sections of zonal velocity suggest a recirculation pattern in the lee of the island during periods identified as having mean westward incident zonal flow, as well as distinctly elevated variance throughout the water column downstream and exactly north of the ridge extent. In contrast, periods identified as having mean eastward incident flow demonstrate a similar elevated variance at a latitude south of the ridge extent, and no clear recirculation. These observed asymmetries in the response of the mean flow to the ridge may support the predictions of quasi-geostrophic theory, in which incident westward flow results in vortices being shed in the lee of the island, and eastward flow may become arrested by westward propagating rossby waves. Also explored are asymmetries in temperature and salinity, as well as OSCAR UV products from the same time period. The latter are used to illuminate the larger-scale context and to explore other possible explanations for the observed mean patterns and asymmetries in zonal velocity.
- **PO14B-2176** Small-scale internal tides drive balanced flow in the upper ocean***Callum James Shakespeare****, Australian National University, Research School of Earth Sciences, Canberra, Australia and Andrew M. Hogg, Australian National University, Research School of Earth Sciences, Canberra, ACT, Australia*
- Internal waves are thought to be responsible for driving deep ocean mixing and sustaining the overturning circulation. One of the major mechanisms of internal wave generation is the flow of barotropic tides over the rough ocean bottom. In this talk I will present results from idealised regional-scale simulations with realistic tidally generated internal wave fields. The wave energy budget for these

simulations shows that less than 50% of the energy going into the generated waves is lost to dissipation and mixing. The majority of the wave energy is returned to the mean flow in the surface 100m of the model ocean. Furthermore, the internal tides transfer net momentum from the ocean bottom to the surface and drive a large-scale upper ocean flow. Both the energisation and acceleration of the upper ocean by the internal tide is contrary to the current paradigm that internal tides flux energy downscale towards dissipation. As such, these results fundamentally change our understanding of internal tides, the wave energy budget, and the ocean circulation.

- **PO14B-2177** What makes the Deep Western Boundary Current "leak"?***Aviv Solodoch***[1], *James C McWilliams*[2], *Andrew Stewart*[3], *Jonathan Gula*[4] *and Lionel Renault*[3], *(1)University of California Los Angeles, Los Angeles, CA, United States, (2)UCLA, Los Angeles, CA, United States, (3)University of California Los Angeles, Atmospheric and Oceanic Sciences, Los Angeles, CA, United States, (4)Laboratoire de Physique des Océans, Brest, France*
- We investigate the mechanisms underying the "leakiness" of the Deep Western Boundary Current (DWBC) in the North Atlantic using a high resolution (2.5 km horizontal grid spacing) regional model simulation in the vicinity of the Grand Banks of Newfoundland. The modeled DWBC leakiness, characterized by a relatively rapid along-stream change in its properties due to exchanges with the open ocean, is qualitatively similar to previous observations derived from floats (Bower et al 2009) and tracers (Rhein et al 2002).

- We contrast the relative roles of baroclinic instability generated locally within the DWBC, bottom boundary layer separation around curving continental slopes, and mesoscale eddies generated in the open ocean adjacent to the Grand Banks. We assess the contribuions of coherent eddies vs. other less coherent (at submesoscale or mesoscale) mechanisms of exchange between the DWBC and the interior, using a combination of both eddy tracking and tracer particle advection.

- Bower, Amy S., M. Susan Lozier, Stefan F. Gary & Claus W. Böning. Interior pathways of the North Atlantic meridional overturning circulation. Nature 459, 243-247, 2009.

- Rhein, M., J. Fischer, W. M. Smethie, D. Smythe-Wright, R. F. Weiss, C. Mertens, D.-H. Min U. Fleischmann, and A. Putzka. Labrador Sea Water: pathways, CFC inventory, and formation rates. J. Phys. Oceanogr. 32, 648–665, 2002.

- ## Plain Language Summary
- Previous measurements of one of the major Atlantic ocean currents, the Deep Western Boundary Current, have shown that it exchanges water with its surroundings as it flows southward, especially near an underwater cape offshore of Newfoundland. We run and analyze a simulation of the western North Atlantic ocean to investigate the mechanism that produces this phenomenon. We investigate and contrast various exchange processes generated within the current itself, and processes that are powered by other, remote currents influencing the exchange in the Deep Western Boundary Current.
- **PO14B-2178** Non-propagating Form Drag and Turbulence Due to Stratified Flow over Large-scale Abyssal Hill Topography ***Jody M Klymak***, *University of Victoria, Victoria, BC, Canada*
- The problem of steady stratified flow over rough topography is important in some parts if the ocean, and in particular in the Southern Ocean. The drag and turbulence in such flows have been parameterized using linear theory over "abyssal hills" to estimate the energy radiated from the topography. The linear theory has no drag or energy loss due to large-scale bathymetry because waves with wavenumbers k < f/U_0 are evanescent (with f being the Coriolis frequency, and U_0 the mean flow speed; f=1e-4 rad/s, and U=0.1 m/s, corresponds to a lateral wavelength of 6 km), and previous numerical work supports this as a reasonable theory to apply for topography that is high-passed above f/U_0. Here we show that the large-scale "non-propagating" part of the internal wave field is actually highly non-linear and hence subject to blocking upstream and accelerated jets and turbulent rebounds downstream of prominent topographic features. The dissipation associated with the large-scale bathymetry in isolation is approximately twice that of the small-scale bathymetry. Simulations that contain both small and large-scale bathymetry have even more dissipation than just adding the large- and small-scale dissipations together, emphasizing the effect of local large-scale acceleration in increasing the small-scale internal wave generation. Unlike the small-scale dissipation, the large-scale turbulence is very localized, generally in the lee of large obstacles, presenting a substantial real-world sampling problem. Medium-scale regional or global models partially resolve the "non-propagating" wavenumbers, leading to the question of whether they need the large-scale drag to be

parameterized. A study of varying the resolution of the simulations indicates that if the ratio of gridcell height to width is less than the root-mean-square of the topographic slope, then the dissipation is over-estimated in coarse models (by up to 25% in our tests); conversely it can be greatly underestimated (by up to a factor of 2) if the ratio is greater than the root-mean-square slope. Most regional simulations are likely in the second regime, and should have extra drag added to represent the large-scale bathymetry as the deficit is at least as large as that parameterized for "abyssal hills".

- **PO14B-2179** Investigating flow features in vicinity of Palau using an array of Pressure-recording Inverted Echo Sounders***Thomas Peacock**, MIT, Cambridge, MA, United States, Ruth C Musgrave, Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA, United States, Jae-Hun Park, INHA, South Korea and Magdalena Andres, WHOI, Woods Hole, MA, United States*
- An array of five Pressure-recording Inverted Echo Sounders (PIES) was deployed to perform year-long monitoring of large scale flow features around the central and northern region of Palau as part of the ONR FLEAT program. These PIES were integrated with an additional array of four Current and Pressure-recording Inverted Echo Sounders (CPIES) to form a comprehensive monitoring configuration. In this region, the North Equatorial Current encounters the abrupt topography of Palau and we seek to better understand the key physical processes that consequently arise. We present some preliminary results on what can be inferred from the records of acoustic travel time and bottom pressure. Furthermore, regional models and SAR imagery suggest that large amplitude solitary waves may be present in the vicinity of Palua, and so two of the PIES were configured in a rapid mode in order to detect their presence. Consistent with this, data from early in our Rapid-PIES records reveal a period of seemingly strong internal wave activity.
- **PO14B-2180**
- Effects of the amplitude of tides and currents over a ridge on internal waves and turbulence***Masoud Jalali** and Sutanu Sarkar, University of California San Diego, La Jolla, CA, United States*
- Topographic features with steep slope on the ocean bottom are sites of large energy conversion from the oscillating tide to internal waves. Nonlinear waves and

overturns found in field observations and simulations are indicative of significant turbulence and large local energy loss at these sites. We have performed high-resolution 3D large eddy simulations (LES) of the flow over steep triangular obstacles. The results are used to characterize and understand the dynamics as the tidal amplitude, U_0 , changes and so does the excursion number and Froude number. With increasing values of tidal amplitude, the near-field of the internal waves looses its beam like character, the wave response becomes asymmetric and transient lee waves form while turbulence changes qualitatively. Turbulence is generated predominantly by shear in a downslope jet that originates at the ridge crest, shear in intensified boundary layers at near-critical flanks, convective instabilities during flow reversal and breaking of transient lee waves. Scaling laws for the amplitude and thickness of the layer of turbulent dissipation are inferred from the results. Simulations are also performed with a steady current. Results with various Ex from O(0.01) - O(1) are contrasted with those with a steady current.

- **PO14B-2181** Microstructure and mooring observations in the Kerama Gap***Ryuichiro Inoue***, *JAMSTEC Japan Agency for Marine-Earth Science and Technology, Kanagawa, Japan, Hirohiko Nakamura, Kagoshima Univ, Kagoshima, Japan, Takahiro Tanaka, Tohoku National Fisheries Research Institute, Japan Fisheries Research and Education Agency, Shiogama, Japan and Ichiro Yasuda, Atmosphere Ocean Research Institute, University of Tokyo, Kashiwa, Japan*
- The Kerama Gap, near the midpoint of the Ryukyu Island chain, dynamically controls the flow structures and modifies water mass distributions in the intermediate and deep layers of the Okinawa Trough. It has been suggested that a strong overflow at the Kerama Gap ventilated the deep water in the southern Okinawa Trough, and that upwelling is sustained by the strong mixing associated with the overflow. The strong mixing could also bring the nutrient rich Philippine Sea intermediate water to the lower thermocline below the Kuroshio. To prove existence of the strong mixing, we conducted microstructure and mooring observations around the Kerama Gap in December 2016. We observed the strong mixing near the topography, with vertical diffusivities of 10^{-2}~10^{-1} m^2s^{-1}, and found that tides are important to drive the strong mixing. To understand tidal processes,

we conduct two-dimensional numerical simulations and compare results with observed features.

- **PO14B-2182** Turbulent mixing within the Kuroshio in the Tokara Strait***Eisuke Tsutsumi***[1], *Takeshi Matsuno*[2], *Ren-Chieh Lien*[3], *Hirohiko Nakamura*[4], *Tomoharu Senjyu*[2], *Xinyu Guo*[5] *and Jing Zhang*[6], *(1)Kyushu Univ, Research Institute for Applied Mechanics, Kasuga, Japan, (2)Kyushu Univ, Fukuoka, Japan, (3)Applied Physics Laboratory, Seattle, WA, United States, (4)Kagoshima Univ, Kagoshima, Japan, (5)Ehime University, Center for Marine Environmental Studies, Matsuyama, Japan, (6)Fac Sci, Univ. of Toyama, Toyama, Japan*
- Turbulent mixing due to Kuroshio-topography interaction is examined by observation using a microstructure profiler in the Tokara Strait, where many seamounts and small islands exist within the route of the Kuroshio in the East China Sea. Vertical structure and water properties of the Kuroshio were greatly modified downstream from shallow seamounts. In the lee of a seamount crest at 200 m depth, the modification made the flow tend to shear instability, and the vertical eddy diffusivity is enhanced by nearly 100 times that of the upstream site, to K_ρ ~ $O(10^{-3})$–$O(10^{-2})$ m^2 s^{-1}. Distribution of chemical tracers suggested a significant role of vertical mixing in the observed temperature-salinity modification. Analyses with one-dimensional diffusion model using the observed vertical eddy diffusivity reproduced the observed downstream evolution of the T-S profile. However, the estimated diffusion time-scale from the model experiment is at least 10 times longer than the observed advection time-scale. This suggests that the vertical eddy diffusivity reaches to $O(10^{-1})$ m^2 s^{-1} in the vicinity of the seamount.
- **PO14B-2183** Internal wave predictability over continental shelf seas***Anastasiia Domina***[1], *Matthew R Palmer*[2], *Vasiliy Vlasenko*[3], *Nataliya Stashchuk*[3], *Jonathan Sharples*[4] *and Mattias Green*[5], *(1)University of Liverpool, School of Environmental Sciences, Liverpool, United Kingdom, (2)NOCL, United Kingdom, (3)University of Plymouth, Plymouth, United Kingdom, (4)University of Liverpool, Earth, Ocean and Ecological Sciences, Liverpool, L69, United Kingdom, (5)Bangor University, School of Ocean Sciences, Menai Bridge, United Kingdom*

- In this research we aim to increase our understanding of internal wave (IW) dynamics over different topographies and varying stratification in continental shelf seas through a combination of observational (from moorings and ocean gliders) and modelling (MITgcm) methods. We used a new, high-resolution (50m horizontal) MITgcm configuration to generate a realistic internal wave field, which includes high-frequency internal waves and solitons. The model is used to identify regions of slope criticality and analyse the generation and propagation characteristics of IWs in shallow seas. These model results are compared to varying stratification scenarios from observations made during 2012 and 2015.
- Our model suggests that under increasing stratification, the IW field becomes more energetic at all frequencies, however, the increase in energy is not evenly distributed spatially or spectrally. While energy in the dominant tidal (M2) forcing frequency increased by 20-40 per cent, energy associated with higher frequency waves increases by as much as 90 per cent. These results are clearly divisible between on-shelf and off-shelf environments - off-shelf, the cascade of internal wave energy is analogous to that of the Garrett-Munk spectrum. On-shelf, the slope of energy cascade is shown to vary under changing stratification, with a disproportionate increase of energy across frequencies higher than M2 forcing resulting in a flatter spectral shape. These results are compared to observations. While realistic variability in tidal forcing and seasonal stratification makes direct comparison of results difficult, there is evidence of a similar reaction to the spectral cascade of IW energy. We investigate this changing spectral shape in continental shelf seas further using a unique 17-month time series of current velocity and vertical density structure and assess the predictability of internal wave energy under seasonally varying forcing.
- **PO14B-2184** Contribution of high and low frequency internal waves to boundary turbulence in a lake***Danielle Wain**, University of Bath, Bath, BA2, United Kingdom and Chris R Rehmann, Iowa State University, Ames, IA, United States*
- The interior of lakes is often quiescent and most of the mixing in a lake occurs at the sloping boundaries, where wind-induced internal waves create turbulence (which leads to mixing) through interactions with the lakebed. To predict the

occurrence and strength of turbulence in terms of meteorological forcing and stratification, we investigated the dependence of internal wave type, and their contribution to turbulence on the slope, on the Lake number, which compares the stabilizing tendency of stratification to the destabilizing tendency of the wind.

- Three thermistor chains and a meteorological station were deployed in West Okoboji Lake (length ~ 9 km, max. depth ~ 40 m) for two weeks. A wavelet analysis was conducted to determine time periods when different wave frequencies were excited, with particular focus on the first vertical mode seiche, the critical frequency with respect to the stratification and slope, and high frequency waves in the band of 1-10 times the buoyancy frequency. We measured the velocities in the bottom boundary layer (BBL) with a high resolution acoustic current profiler (2 MHz Nortek HR Aquadopp) and then computed the turbulent dissipation rate using the structure function method, which uses the spatial correlations of velocity along a beam to estimate the dissipation. This generated a two week time series of turbulent dissipation rate in the BBL which was then compared to the wavelet amplitudes.
- During the deployment, a strong daily wind forced near constant internal wave activity. The theoretical period of the first vertical mode seiche was ~17 hours, but the diurnal wind forcing interfered with free oscillation of this mode. Although not an obvious natural frequency of the lake, waves of the critical frequency (which had a period of ~11 hours) were activated throughout the measurement period. High-frequency waves were observed in the thermistor chain near the slope at the lowest Lake number wind events. The turbulence observed on the boundary was highest during these events, implying that the low frequency seiching was less important than higher frequency motions in driving turbulence on the slope.
- **PO14B-2185** Time-dependent Hydraulic Flow and Barotropic Tidal Energy Loss in the Canadian Arctic Archipelago***Kenneth Hughes***[1]*, Jody M Klymak*[1]*, William James Williams*[2] *and Humfrey Melling*[3]*, (1)University of Victoria, Victoria, BC, Canada, (2)Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, BC, Canada, (3)Inst Ocean Sciences, Sidney, BC, Canada*
- Detailed observations and high-resolution process-oriented modeling are presented for flow through a 13-km wide channel with a sill in the Canadian Arctic Archipelago, which is a key pathway for Arctic water outflow to the North Atlantic.

Both a tidal current and a mean current exist in the channel and together induce an internal hydraulic transition over the steeper eastern side of the sill where the tidal flow augments the mean during ebb. The sill is long relative to typical sills in fjords and other coastal areas. Consequently, the set up of a hydraulic transition, in this case a decelerating jet, takes a long time relative to a tidal period. We thereby interpret the hydrography as caused primarily by the mean flow and alternately enhanced and minimized by the tide. As our study region lies just poleward of the critical M_2 latitude, it is difficult to use analytical techniques to predict the response, in particular the partitioning of local to remote turbulent dissipation. Hence, we turn to numerical modeling. Idealized simulations in both two and three dimensions, together with a decomposition of energy into barotropic and baroclinic components, helps establish the extent to which energy radiates and the associated mechanisms such as internal Kelvin waves. This energy budget is therefore relevant to high-latitude fjords and other channels lying north of the critical latitude.

- **PO14B-2186** Topographic Enhancement of Diapycnal Diffusivity on the Continental Slope in the Northern Gulf of Mexico and Its Application to the Oil Droplet Dynamics***Zhankun Wang**, Cooperative Institute for Climate and Satellites, University of Maryland, College Park, MD, United States, Kurt L Polzin, WHOI, Woods Hole, MA, United States, Steven Francis DiMarco, Texas A & M University, College Station, TX, United States, John Toole, Woods Hole Oceanographic Institution, Woods Hole, MA, United States, Angel Ruiz Angulo, Centro de Ciencias de la Atmosfera, UNAM, Mexico D.F., Mexico, Miguel Costa Tenreiro, CICESE, Physical Oceanography, Ensenada, Mexico, Binbin Wang, Texas A&M University College Station, College Station, TX, United States and Christian Nygren, Texas A & M University, Oceanography, College Station, TX, United States*
- A tracer release experiment (Ledwell et al. 2016) has indicated that mixing was greatly enhanced over the slope in the northern Gulf of Mexico compared to the interior of the Gulf. To characterize the diapycnal diffusivity on the slope, we have conducted two research cruises specifically to measure turbulence in 2016 and 2017 and revisited the historical data collected during the Gulf Integrated Spill Response (GISR) cruises between 2013 and 2015. Diapycnal diffusivities are inferred from free-fall vertical microstructure profilers (VMP) that measure the rate

of dissipation rate of turbulent kinetic energy and give an independent measure of the small scale turbulence that controls diapycnal mixing. The mixing generated is quantified in terms of a turbulent diapycnal diffusivity, κ, which measures the rate at which the turbulence spreads a tracer across density surface over time. Indirect references of bottom mixing are also from the CTD tow-yo sections by estimating the buoyancy flux and from current meters on bottom-mounted moorings. Bottom enhanced mixing is found from both microstructure profiles and ctd tow-yos, which is likely associated with the local complex topography on the slope. We also relate turbulent velocity to the size and density of oil droplets by estimating the rising velocity of different size oil droplet due to balance between buoyancy and drag force.

- **PO14B-2187** Observations of a low frequency flow-generated oceanic lee wave and associated turbulent dissipation over a tall ridge***Gunnar Voet***[1]*, Matthew H Alford*[1]*, Jennifer A MacKinnon*[1]*, Ali Mashayek*[1] *and Jonathan D Nash*[2]*, (1)Scripps Institution of Oceanography, La Jolla, CA, United States, (2)Oregon State Univ, Corvallis, OR, United States*
- Oceanic lee waves, generated through the interaction of low-frequency flow and bottom topography, are thought to play an important role in the energy and momentum budgets of the global ocean circulation as they can break locally or radiate and dissipate their energy elsewhere. Here we present direct towed observations of lee waves generated over a tall ridge in the vicinity of the island group Palau in the tropical north Pacific. Our measurements focus on density, velocity and turbulent dissipation derived from thermal variance in the direct vicinity of the ridge. Lee waves were observed both during spring and neap tide. Turbulent dissipation over the ridge, associated with breaking lee waves, was stronger during spring tides. However, an asymmetry in the somewhat weaker dissipation of turbulent kinetic energy between the two sides of the ridge during neap tide, with stronger dissipation in the lee, shows that the low-frequency flow dominates lee wave generation and dissipation during weak tides.
- **PO14B-2188** Dissipation of Mesoscale Energy by Vortex-Topography Interaction***Siddhartha Bishnu****, Florida State University, Tallahassee, FL, United States and William K Dewar, Florida State Univ, Tallahassee, FL, United States*

- Energy is introduced into the oceans primarily at large scales by means of wind, tides and surface buoyancy forcing. This energy is transferred to the smaller mesoscale field through the geostrophic instability processes. The mesoscale field appears not to have accelerated appreciably over the last several decades, so we can assume that the mesoscale loses energy at roughly the same rate it receives energy. Interestingly, how the mesoscale loses energy is not quite clear. We have been exploring is topographic interaction as a pathway by which the mesoscale may lose energy to unbalanced forward cascading flows. To demonstrate this phenomenon, an approximate model theory is developed which consists of solving a reduced set of the momentum equations in density coordinates for any topographic configuration. The equations are solved using a high order spectral element technique and the results verified with MITgcm simulations.
- **PO14B-2189** Effects of a Dynamically Wide Submarine Canyon on Coastal Currents During an Upwelling Event***Idalia Alicia Machuca***, *University of British Columbia, Department of Earth, Ocean and Atmospheric Sciences, Vancouver, BC, Canada and Susan Elizabeth Allen, Univ British Columbia, Earth, Ocean and Atmospheric Sciences, Vancouver, BC, Canada*
- Submarine canyons disrupt the geostrophic equilibrium of incoming ocean currents, resulting in an unbalanced cross-shore pressure gradient that drives enhanced upwelling. Observational, laboratory, and numerical studies of narrow (less than 2 Rossby radii) canyons have shown that upwelling events not only exhibit complex dynamics within the canyon, but also alter the circulation patterns in the surrounding ocean. As flows move along the continental slope, a separation occurs at the canyon mouth where some flow turns into the canyon and some continues its trajectory downstream. A slow cyclonic structure forms between the canyon walls, and incoming flows are advected into the canyon and upwelled predominantly over the downstream rim. In the area upstream of the canyon, flows over the shelf and farther offshore experience reduced velocities compared to flows downstream. Additionally, flows over the shelf directly downstream of the canyon are steered offshore towards the shelf break.
- This work explores the impacts of a deep, dynamically wide canyon on coastal currents during an upwelling event. A regional configuration of the NEMO model

was developed to simulate the flow dynamics in Mackenzie Canyon and the circulation in the surrounding areas of the Beaufort Sea. The model used an idealized and realistic version of the local bathymetry, along with realistic Arctic stratification and upwelling-favourable wind conditions. Analysis of the results is provided through calculations and descriptions of volume transports, depths of upwelling, and form drag due to the canyon. Additionally, this discussion provides comparisons between the modelled circulation and real-world observations, and it highlights key differences to the flows through and drag due to narrow canyons. The findings of this research contribute to our understanding of the effects of steep topography on oceanic flow.

- **PO14B-2191** Submesoscale instability waves observed in the Kuroshio front***Yu-Hsin Cheng** and Ming-Huei Chang, IONTU Institute of Oceanography National Taiwan University, Taipei, Taiwan*
- Meanders are routinely observed in the Kuroshio in the Luzon Strait and along the east coast of Taiwan. This study analyze the instability waves that lead to the formation of submesoscale eddies in the Kuroshio front at the east coast of Taiwan using vertical profiling acoustic Doppler current profiler and high resolution satellite snapshots. The spectral analyses of moored current velocities reveal northward propagation of shear instability waves with 2-to-5-day periods. In addition, the wavelengths estimated from satellite snapshots of Chlorophyll-a concentration range from 40 to 80 km, which could be modulated by the variability of Kuroshio path and eastward mesoscale eddies. The Kuroshio would not only create the required ambient potential-vorticity gradient but would also transport the wave pattern.

- **PO14B-2192** The generation of Rossby waves and wake eddies in the lee of small islands***Ruth C Musgrave**[1], Glenn Flierl[2] and Thomas Peacock[2], (1)WHOI, Woods Hole, MA, United States, (2)MIT, Cambridge, MA, United States*
-

We examine the influence of small islands on zonal geostrophic currents in a two layer flow. We first derive an analytic solution for steady, inviscid quasigeostrophic flow under the assumption of no upstream influence, and then validate it numerically in a time-dependent quasigeostrophic model. Under these conditions, solutions are the sum of two eigenmodes, which are either arrested Rossby waves or evanescent depending on background flow conditions (layer speeds, stratification and latitude). Arrested Rossby waves can occur even when the depth mean flow is westward, and can be generated both to the east and west of the island. A third mode, Lighthill blocking, plays a role in time-dependent adjustments by the flow, altering the meridional structure of the zonal flow far upstream and downstream of the island. Finally, the influence of the quasigeostrophic modes on submesoscale island wake eddies is considered in a two-layer primitive equation model with no-slip boundary conditions at the island side walls. Wake eddy formation is inhibited in the presence of an arrested Rossby wave, and despite the contribution of wave drag in this case, the overall drag on the island is reduced compared to when no Rossby waves are arrested.

Plain Language Summary

Small islands in zonal currents can arrest planetary (Rossby) waves in their wake. We first use a two layer quasigeostrophic model to understand the flow conditions under which these waves are arrested in steady flows. We then consider the time dependent problem, where additional phenomena such as upstream blocking may appear. Finally, we examine the influence of arrested waves on the generation of island wakes by a frictional boundary layer, and evaluate the resulting drag by the island on the zonal flow.

- **PO14B-2193** Deep circulation in the eastern Chile Basin***Lena Schulze*** *and Kevin G Speer, Florida State University, Tallahassee, FL, United States*
  - Deep circulation in the Chile Basin is described using historic CTD and velocity observations. Hydrographic data from several ship-based sections show the location and structure of a deep southward current at the eastern boundary of the Chile Basin above the Peru-Chile Trench. It is centered at 2500 -- 3400 m and transports low PV, high silicate water south towards the Drake Passage. During the last Go-Ship P6 occupation the deep LADCP speed in the boundary current was recorded to be up to 15 cm/s. The hydrographic data, as well as PV and silicate distributions in the southeast Pacific Ocean, show that the major part of the current is comprised of recirculating flow from farther west. Thus, deep flow along the southern flank of Nazca Ridge feeds the eastern boundary current. At the southern edge of the Chile Basin the current interacts with the Chile Rise, turning offshore and crossing the rise in a complex region of passages and entering the broader

scale eastward flow above the southern flank of the Chile Rise; together, these waters flow to the eastern boundary before entering Drakes Passage.