Collaborative Research: Internal Waves Across the Pacific

M. Alford, J. MacKinnon, W. Munk, R. Pinkel, and K. Winters

Intellectual Merit:

The wind and the tides input the overwhelming majority of the energy into the internal-wave field, whose breaking is the primary driver of turbulent mixing in the ocean. It has recently become clear that much of the input energy takes the form of low-mode internal waves, which can propagate far (> 1000 km). It follows that, in principle, *The global magnitude and distribution of turbulent mixing depends primarily on the sources and subsequent evolution of the propagating, low-mode internal waves.* New interpretation of historical moorings, new observations from the Hawaii Ocean Mixing Experiment, and new numerical modeling results suggest that long-range wave propagation is strongly modulated and, at times, completely disrupted, by interactions with 1) other internal waves (most dramatically, Parametric Subharmonic Instability, which can drain energy from the M_2 tide at latitudes equatorward of 28.9°), 2) topography, and 3) the mesoscale background.

We propose a collaborative project between five PIs (W. Munk unfunded) to better understand the processes that govern long-range internal-wave propagation, with an ultimate long-range goal of determining the global distribution, magnitude and time-dependence of internal-wave driven mixing. Though near-inertial and tidal internal waves appear to be of comparable importance, our present focus is the long-range propagation of the mode-one M_2 tide northward from the Hawaiian Ridge. The proposed work will integrate three principal activities:

- *Observational Study of Long-range Propagation.* A line of 6 McLane Moored Profilers extending northward from Hawaii, spanning 26N-37N, will measure velocity and density from 100-2600 m down to 2-m scales, for 50 days. *R/V Revelle* will measure upper-ocean shear and density along this track, obtaining 2 broad snapshots and three spring-tide 5-day time series at three latitudes. Energy, energy flux, and dissipation rate (from overturning scales) will be computed at all measurement locations. This experiment will enable a coherent picture of the long-range propagation of the tide over ≈ 1200 km.

- *Numerical simulations.* A series of hypothesis-driven, controlled numerical experiments willl be conducted to optimally design the observations, and to investigate dynamical processes that can drain energy from a propagating internal tide.

- *Historical Data Analysis* of moored records and upper-ocean shear from R/V Revelle. We aim to 1) characterize the spatial dependence of internal-wave shear, ray slopes, energy and flux, and 2) provide large-scale observational context for the above simulations.

Broader Impacts:

This work has four vital implications for the broader community. First, a dynamical understanding of the resultant geography of mixing is required for accurate understanding and modeling of the large-scale circulation in past, present and future climates. The combination of observations and process-oriented modeling will contribute to the knowledge required to construct physically-motivated mixing parameterizations that are dynamically coupled to the large-scale circulation. Second, satellite altimetry has been increasingly seen as an important community resource for monitoring global internal-wave fields. Careful comparison of altimetric results and subsurface observations will help interpretation of altimetric data. Third, our 50-day, 1200-km array is a prototype observing system for long-term monitoring not only of the internal tide and associated turbulence, but of many other mesoscale phenomena. Fourth, the proposed work will contribute to education by providing support and mentoring for two post-docs, and at-sea experience for several graduate students. Results will be shared at national and international workshops and conferences.

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1 Motivation

Recent evidence from satellite altimetry, shipboard Doppler sonar, and numerical process studies suggests that long-range propagation of the internal tide may be strongly modulated or completely disrupted by very efficient, highly latitude-dependent instabilities (Fig. 1). Numerical results predict a rapid Parametric Subharmonic Instability (PSI) near 28.9° - the critical latitude where the local inertial frequency is exactly half the M_2 tidal frequency. Remarkably, there is indeed an order of magnitude drop in observed shear variance and altimetric mode-one tidal amplitude over a similar latitude range. In perplexing contrast, higher-latitude moorings record substantial northward tidal fluxes, though with highly variable magnitude and phase (Fig. 2). The proposed experiment will investigate the fate of the long-range propagating internal tide in order to shed light on these observations.

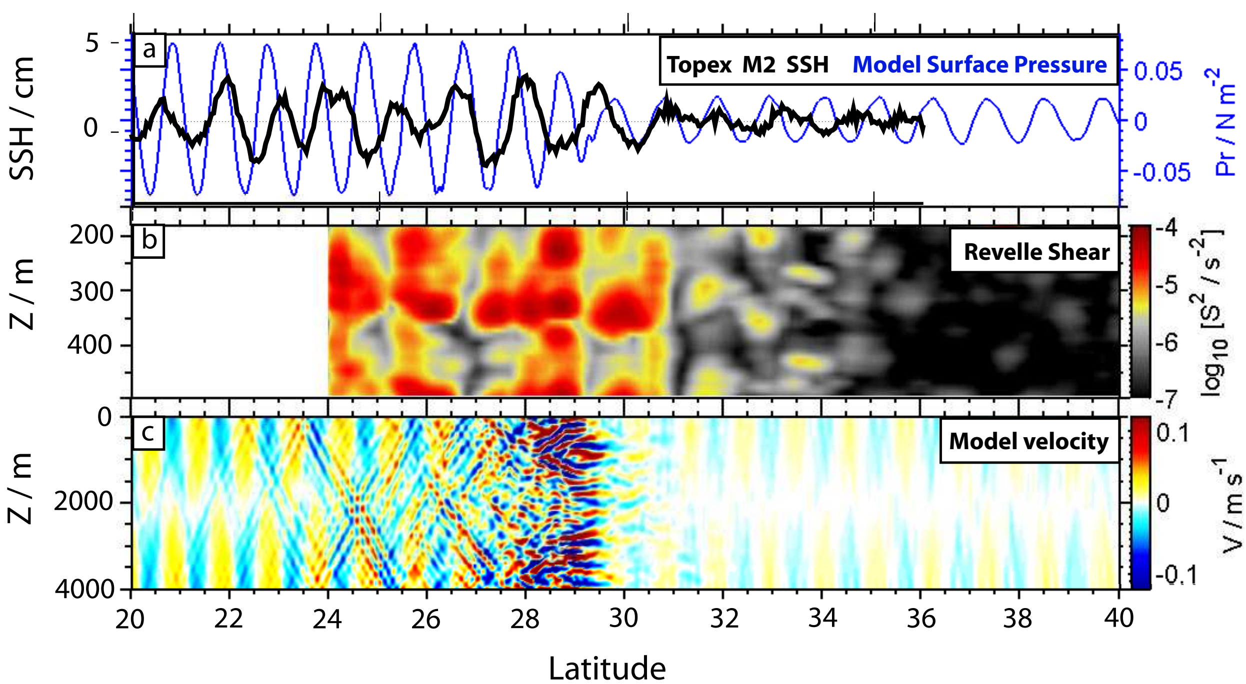

Figure 1: Observed and modeled catastrophic behavior of the northward propagating internal tide near the critical latitude 28.9 °. From top to bottom: 10-year-averaged M_2-tidal-frequency sea-surface height from Topex/Poseidon altimetry, track 36 (black, left axis, R. Ray pers. comm., Sec. 1.3.2) and modeled surface pressure (blue, right axis, Sec. 1.3.4), a transect of upper-ocean shear variance measured by a Doppler sonar on the R/V Revelle (Sec. 1.3.3), and modeled full-depth meridional velocity (Sec. 1.3.4).

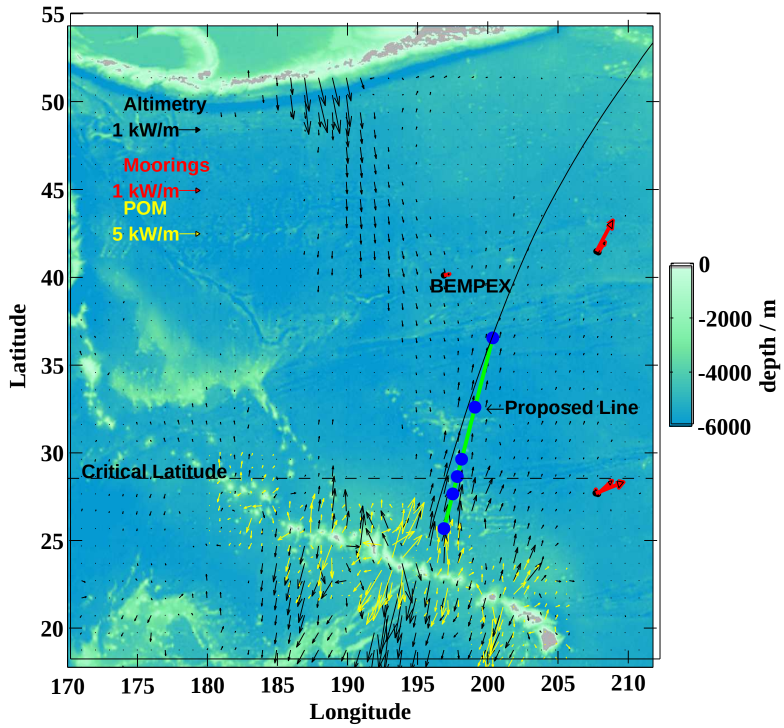

Figure 2: Bottom depth (color) and energy-flux vectors from three sources: a POM model (yellow, *Merrifield et al.* [2001]), altimetry (black, *Ray and Cartwright* [2001]), and historical moorings (red, *Alford* [2003]). The location of the planned ship track (green) and moored profiler time series (blue) overlie a ray path (L. Rainville, pers. comm.) emanating from the Hawaiian Ridge. The POM fluxes are scaled down by a factor of 5.

1.1 Internal-wave-driven mixing: its geography and significance

It is now clear that mixing in the ocean is strongly spatially and temporally variable [*Polzin et al.*, 1997; *St. Laurent et al.*, 2002]. It has long been suspected that this inhomogeneity may have profound implications for the large-scale circulation (e.g. *Samelson* [1998]). Recent modeling studies [*Simmons et al.*, 2004a; *Hasumi and Suginohara*, 1999] have investigated the effects of such localized mixing, concluding that the resulting global and basin-scale flow patterns differ significantly from those calculated with uniform diffusivities. In fact, predictions of deep circulation patterns from models with patchy mixing are much more in accord with recent WOCE findings that meridional abyssal flow (and by implication upwelling fueled by turbulent downward heat diffusion) is spatially localized [*Webb and Suginohara*, 2001a].

Breaking internal waves, whose primary sources are the wind and the tides, are the dominant source of deep-ocean mixing. *Munk and Wunsch* [1998] suggest that 2 TW of power may be required to maintain the deep-ocean stratification (this view has been challenged by [*Webb and Suginohara*, 2001b], who argue that the value may be closer to 0.7 TW). The combination of tidal models and satellite altimetry [*Egbert and Ray*, 2001] show that energy is extracted from the oceanic surface tide and converted to the internal tide at an integrated rate of ≈ 1 TW (0.7 TW for M_2). Comparable power is input by the wind into near-inertial motions [*Alford*, 2003], but the focus of the proposed study is the tides.

A portion of the energy lost from the barotropic tide dissipates locally through scale transformations leading to turbulence. For example, the Hawaii Ocean Mixing Experiment (HOME) and the Brazil Basin Experiment [*Polzin et al.*, 1997] both find turbulence elevated by orders of magnitude within several wavelengths of internal-wave generation sites. Since the spatial distribution of the barotropic tidal losses is now well known [*Egbert and Ray*, 2001], such observations of elevated mixing above rough topography have stimulated the development of new mixing parameterizations suitable for use in large-scale models (see e.g. *Simmons et al.* [2004a], and references therein).

However, between 50% and 95% of the energy lost by the barotropic tide escapes the nearfield to propagate up to thousands of kilometers across ocean basins in the form of a low-mode internal tide (Fig. 2, *St. Laurent and Garrett* [2001], *Althaus et al.* [2003], *Alford* [2003]). The fate of these propagating internal tides remains unclear: **We do not know how the O(0.5-1 TW) of power from the internal tide feeds the internal wave continuum or where the energy dissipates.**

1.2 Fate of the internal-tide: governing processes

This proposal seeks to identify the processes responsible for the variability in Figures 1 and 2. Here we briefly discuss the three major candidates that may significantly alter the magnitude or phase of a propagating internal tide. We are especially interested in processes that can transfer low-mode energy to the small scales at which enhanced shear and strain lead to turbulent mixing.

Wave-wave interactions. Nonlinear wave-wave interactions [*Müller et al.*, 1986; *Henyey et al.*, 1986; *Sun and Kunze*, 1998] transform internal wave energy from large to small scales. The particular wave-wave interaction most likely to affect the internal tide is known as Parametric Subharmonic Instability (PSI); it involves energy transfer from a primary wave of relatively large scale to two 'recipient' waves of smaller vertical scale and approximately half the primary frequency. For the internal tide, energy can be drained through PSI only when the half-frequency recipient waves are still within the internal wave band ($M_2/2 \geq f$), a criterion only satisfied equatorward of 28.9°. *Olbers and Pomphrey* [1981] concluded that PSI was an inefficient method of transferring energy out of a mode-one internal tide, with a characteristic interaction timescale of months. On this basis, internal tides were 'disqualified' from playing a significant role in the overall energy balance of propagating low-mode waves. However, we suggest that this disqualification may be premature: on the contrary, it appears that PSI can be very efficient under certain circumstances (Fig. 1, Sec. 1.3). We suspect the crux of the discrepancy is the random phase assumption made in resonant interaction theory - an assumption which may not be appropriate for a coherent internal tide.

Topographic interactions. Propagating low-mode waves may also lose energy through scattering and reflection from topography [*Müller and Liu*, 2000]. *St. Laurent and Garrett* [2001] predict that a mode-one internal tide will slowly bleed energy to smaller scales as it propagates over deep rough topography. Though this mechanism may be dominant in some situations, it cannot explain abrupt decreases in tidal amplitude away from sharp topographic features (Figs. 1, 2).

Interaction with the Mesoscale. Changes in propagation speed due to encounters with time-variable currents, eddy fields and meandering fronts may produce time-varying phase shifts in the tide. These affect not only the inherent dynamics of propagating low-mode waves, but also our ability to observe them, since the resultant "phase smearing" renders the tide invisible to altimetry (but not to moorings). Therefore, moored observations of variable phase (Sec. 1.3.5), and of strong northward fluxes at 42N (Fig. 2), where altimetric fluxes are zero, argue for strong interactions with the mesoscale field.

1.3 Fate of the internal tide: evidence to date

Recent observations and modeling show 1) strong parametric instability (energy transfer to $M_2/2$), 2) dramatic latitudinal variations in tidal amplitude and shear variance, and 3) large variability in the energy flux, amplitude and phase of the internal tide in moored records. We present these results here.

1.3.1 HOME results

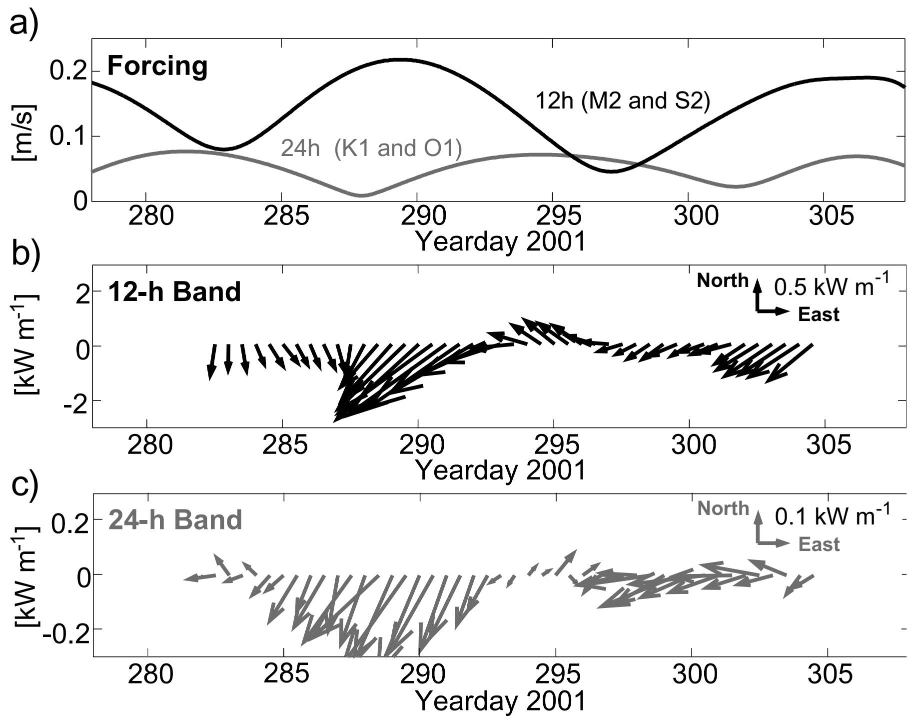

Figure 3: Depth-integrated (80 to 720 m) energy fluxes associated with the internal waves in the semidiurnal (b) and diurnal (c) frequency bands, 430 km southwest of the Hawaiian Ridge (HOME Farfield, 18N). The magnitude of the cross-Ridge currents in the Kauai channel (forcing) in both bands is shown in (a). The semidiurnal flux (b) varies with the spring/neap tidal cycle. The diurnal energy flux (c, note smaller y-axis), which contains both $M_2/2$ and K1, also shows a strong cycle. Its magnitude is related to the semidiurnal (panel a, black) rather than the diurnal (panel a, gray) spring-neap cycle, arguing that the motions are $M_2/2$ rather than K1. (L. Rainville, personal communication).

Luc Rainville and Rob Pinkel (manuscript in preparation) calculated energy fluxes associated with the internal wave field at the HOME Farfield site (18 N) from the cross-spectra of p' and (u', v'), the perturbation pressure and velocities recorded from R/P FLIP. Although the semidiurnal energy flux dominates, significant fluxes (20% of the semidiurnal fluxes) are also seen in the half-frequency 24-h band (Figure 3). The 24-h band waves have high vertical wave number and vary with the strength of the 12-h band waves, not with the strength of 24-h barotropic tidal forcing. This suggests that the 24-h band waves are fed by PSI, leaching energy from the M_2 internal tide.

1.3.2 Altimetry

Ray and Cartwright [2001] constructed a spatial map of long-term-mean, mode-one, M_2 energy flux (Figure 2) in the North Pacific. These altimetric estimates are based on averages over many M_2 cycles, and therefore only detect phase-locked signals. As indicated by previous altimetric results [*Cummins et al.*, 2001; *Dushaw et al.*, 1995], a mode-one flux is detectable over 1000 km north of the Hawaiian Ridge as well as southward from the Aleutian chain. One of the most notable results is that at most longitudes there is a relatively abrupt drop in the magnitude of northward flux at or within a few degrees of the critical latitude for PSI - 29° (Figs. 1 and 2). There are two possible reasons for such an abrupt signal decrease: either the tide is rapidly losing energy through dynamical instabilities at this latitude, or it experiences a strong enough phase shift to render it invisible to altimetric techniques.

1.3.3 Revelle sonar sections

The 50 kHz Pinkel Sonar has been installed on the R/V Revelle since 2000, and operated as often as possible. The data shown in Figure 2 (second from top) was collected during a transit from Astoria, Oregon (13 Aug, 2000, 46 14' N, 124 3' W) to Honolulu, Hawaii (25 Aug, 2000, 24 01'N, 156 50' W), with a roughly direct route. Velocity data was collected in 8 m vertical bins, smoothed with a 30-minute window and first differenced to estimate shear. A 0.4 degree smoothing was then applied to the shear-squared data. The observed shear variance is strong south of 30° , with a characteristic horizontal scale similar to the horizontal wavelength of the mode-one internal tide. Yet north of 30° , the shear variance drops sharply. The same pattern also occurs over a similar latitude range in the south Pacific (not shown).

1.3.4 Numerical Results

An exploratory set of numerical experiments were performed to develop insight into the nonlinear transformations that might be possible as energetic, low-mode waves propagate meridionally on a β-plane. The experiments were run using a fully nonlinear, parallel spectral model [*Winters et al.*, 2004], thereby avoiding the dynamical simplifications required in theoretical models.

The experiment consisted of a steadily forced mode-one internal tide propagating north from about 18N with an energy flux roughly matching that observed near the Hawaiian Ridge [*Rudnick et al.*, 2003]. In addition, random low-level (<< 1 cm/s) noise was excited throughout the domain, and sponge layers were activated near the north/south ends. Away from the forcing and sponge regions, waves are free to propagate and interact according to the fully nonlinear equations of motion. Results from a two-dimensional run are shown in Figure 1. Similar results were obtained in three dimensional runs and in higher resolution experiments run to verify numerical convergence.

The most striking result is the instability and consequent generation of small-scale shear with half the tidal frequency ($M_2/2$) that occurs between 28 and 30° . We refer to this feature as a 'subtropical catastrophe'. It is catastrophic in the sense that northward energy flux carried by the low-mode tide essentially vanishes due to a latitude-dependent instability that transfers energy to small scales which propagate only slowly and dissipate locally. The efficiency and latitude dependence of the instability suggest a *rapid Parametric Subharmonic Instability* is at work. A small fraction of the $M_2/2$ energy propagates to the south as increasingly superinertial waves, visible as beams between 24° and 28° (Fig. 1). However, the bulk of the M_2 flux is dissipated near the critical latitude, resulting in a local diffusivity elevated several orders of magnitude above background levels.

1.3.5 Historical Moorings

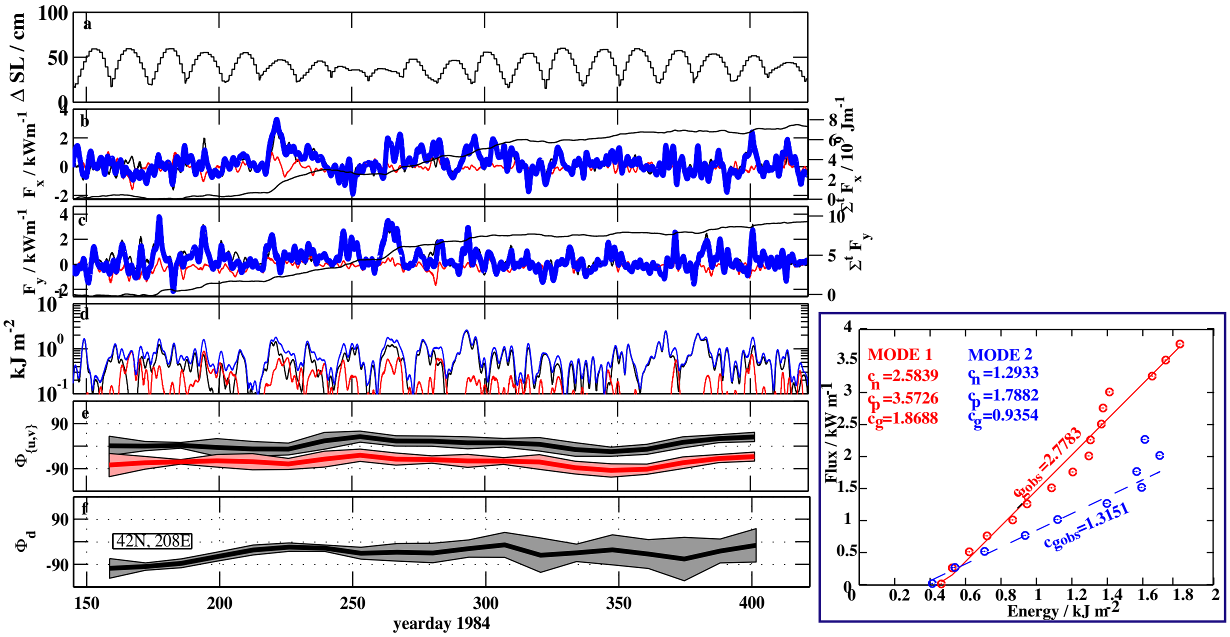

Figure 4: Left: Time series of moored semidiurnal flux, energy and M_2 phase at 42N, 152W (Fig. 2). (a) Low-passed barotropic tidal height from TPXO.5, indicating the spring/neap cycle. (b,c) Zonal and meridional flux in mode 1 (black), mode 2 (red), and the total (blue). The time integral is also indicated (axis at right). (d) Kinetic (black), potential (red) and total energy (blue). (e): Harmonic M_2 phase of mode-one u (black) and v (red), computed over 28-day windows. (f) As in (e) but for mode-one displacement, η. The observed variability of energy, flux and phase implies strong refraction by the mesoscale field. Right: Scatter plot of binned flux magnitude versus energy (left, panels b-d) at the same mooring, for modes 1 (red) and 2 (blue). The group velocity, given by the best-fit slope, agrees well with expected values (indicated at upper left) for both modes.

In contrast with altimetric results, fluxes estimated from historical moorings (Fig. 2, red arrows) reveal strong yet highly variable northward tidal fluxes extending to at least 42 N. Passage of the low-mode internal tide can be reliably detected for a number of available historical moorings [*Alford*, 2003]. For modes 1 and 2, estimated group velocities (the ratio of energy flux to energy) and horizontal wavenumbers (calculated from group speed) are in line with expected values computed for each mode using the observed stratification profile and the linear dispersion relationship (Fig. 4, right). Note the small net flux at the BEMPEX mooring, consistent with tomographic measurements [*Dushaw et al.*, 1995], which we interpret as nearly-equal northward and southward fluxes canceling each other. Unlike altimetric measurements, estimates from historical moorings do not require a phase-locked signal. Hence, the larger magnitude of the moored fluxes suggests that at times the tide may be getting past the critical latitude, but with a shift in phase. Such a shift may be due to strong refraction by time-varying mesoscale stratification and currents. Since POM model fluxes (yellow arrows, *Merrifield and Holloway* [2002]) exceed the altimetric values even in the nearfield, even when smoothed appropriately, refraction appears to occur immediately.

Further evidence for this hypothesis is seen in typical time-series of flux, energy and mode-one M_2 phase from the mooring at 42N, indicated in Figure 4. To compute these quantities, records at 6 discrete depths were semidiurnally band-passed and mode-one and -2 amplitudes of u, v and displacement, η, computed by inverse. Flux and energy were then computed by standard methods [*Alford*, 2003]. Both flux (b) and flux (c) vary by an order of magnitude. During some periods, energy displays a spring/neap cycle, lagged by about 7.5 days relative to the barotropic forcing (a). This lag is approximately consistent with the travel time expected from the Hawaiian Ridge at the expected group velocity. Furthermore, phase varies $\pm$ 45° , indicating that the phase is not coherent at these latitudes, and thus these energy fluxes are missed in the altimetric estimates.

1.4 Summary of motivating questions and hypotheses

We believe that the fate of propagating low-mode waves at semi-diurnal and inertial frequencies holds the key to the spatial and seasonal distribution of $O(1)$ TW of dissipation and mixing in the world oceans. The behavior of these low-frequency, low-mode waves may be easier to observe or explicitly include in large-scale numerical models than the full internal-wave continuum used in previous internal-wave driven mixing parameterizations. The recent work reviewed above strongly suggests that predictable nonlinear interactions or instabilities are capable of tapping the large reservoir of energy in propagating low-mode waves. Evidence includes:

- An $M_2/2$ signal is observed in both the near- and far-field observations obtained during the Hawaii Ocean Mixing Experiment (HOME). The $M_2/2$ signal is highly correlated with the intensity of the semidiurnal tide but occurs at much smaller vertical scales (Fig. 3).
- Altimetry data shows that the *coherent* M_2 signal north of the Hawaiian Ridge ($\approx$22N) is strongly attenuated near 28-31° for several (but not all) tracks (Figs. 1, 2). Marked attenuation of upper-ocean shear is also evident near this latitude range in previously-unanalyzed Revelle transects (Fig. 1).
- A unifying dynamical framework for these observations is provided by numerical simulations, which show that a northward propagating internal tide is susceptible to rapid Parametric Subharmonic Instability (PSI), a process that is capable of transferring energy from M_2 to $M_2/2$ frequency motions equatorward of 28.9° (Fig. 1).

On the other hand, substantial but variable northward tidal fluxes with large deviations in phase are a common feature of time series obtained from historical mooring records (Fig. 4). The correct resolution of these complex observations is not obvious, but will require further focused numerical and observational experiments. At stake are at least two issues of interest to the broader community. First, a dynamical understanding of the spatial variability of wave-driven mixing is required to predict the evolution of earth's climate. Such an understanding is needed for development of either mixing parameterizations to be directly included in existing types of GCMs (following *Simmons et al.* [2004a]), or parallel global internal-wave models (P. Müller, pers. comm.). Second, satisfactory resolution of the discrepancies between tidal fluxes measured by altimetry and moorings is required for future confidence in results from either of these valuable community resources.

2 Proposed Work

We propose to explore the questions presented in the previous section using a combination of new observations, numerical modeling, and historical data analysis. Our immediate objective is to observe and understand the processes affecting the energetic, low mode internal tide propagating northeast from the Hawaiian Ridge, across 28.9° to latitudes where the altimetric M_2 signal is very weak. In addition to this and to the broader benefits described above, the proposed experiment will serve as an exploratory prototype for a global observing system. In particular, confidence continues to grow in knowledge of the generation sites and initial propagation direction of the internal tide [*Egbert and Ray*, 2001; *Simmons et al.*, 2004b]. With the selective monitoring of a finite number of strategic points, future observing systems can contribute to a fundamental improvement in the way that internal waves and associated turbulent dissipation and diffusivities are incorporated into numerical models. The experiment proposed here will help bound the necessary observational parameters, and elucidate the relative contributions that shipboard and moored measurements can make to such a system. A future global observing system that evolved from the proposed experiment would be invaluable for improving our understanding not only of internal-waves and mixing, but also of time-varying mesoscale features such as the subtropical front

2.1 Field Study

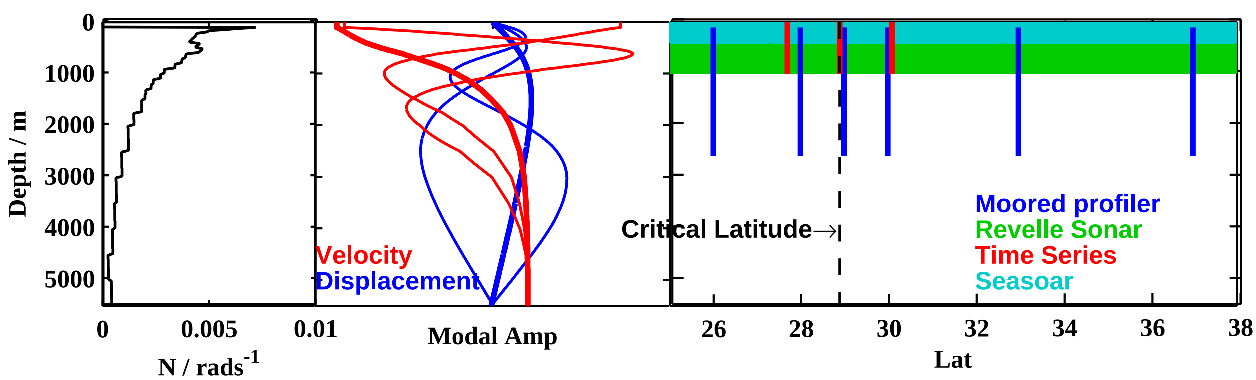

Figure 5: (left) Levitus buoyancy-frequency profile at the study region (35 N, 200E). (center) First (solid), second and third (thin) modes of velocity (red) and displacement (blue). (right) Depth-latitude coverage of the proposed profilers (blue), intensive sonar/CTD time series (red), seasoar (lt. blue; sawtooths too tight to be visible), and Revelle sonar (green).

We aim to measure the long-range propagation characteristics of the mode-one internal tide by:

1. Deploying a line of 6 Moored Profilers spanning 26-37° N (Fig. 5, blue), positioned in the primary internal-tide "beam" established from POM and altimetric flux estimates (Figure 2). These will measure u, v, T, and S from 100-2600 m every three hours for 50 days, sufficient to capture 3 complete spring/neap cycles. Energy, energy-flux, group velocity, intrinsic frequency, and horizontal wavelength will be computed. In addition, turbulence quantities will be inferred using the Gregg-Henyey scaling [*Gregg*, 1989], and computed more directly from overturning scales [*Thorpe*, 1977].

2. To supplement these spatially- and temporally- discrete measurements, we also plan two quasi-synoptic spatial surveys with Seasoar (Fig. 5, lt. blue) and the Revelle sonar (green). These will provide a unique view of fully-resolved upper-ocean shear and strain along a tidal beam. For example, the spatial dependence of shear layers will be measured, allowing estimation of ray slopes. While these measurements will contain some temporal evolution as well as spatial information, we expect to be able to isolate frequency information with the aid of the simultaneous moored data. In addition, shear will be measured during transits between mooring sites on deployment/recovery.

3. Three 5-day intensive time series (10 M_2 cycles) will be conducted with a fast-profiling CTD and the Revelle sonar during spring tides, at sites equatorward, at, and poleward of the critical latitude (Fig. 5, red). During each period the Revelle will deploy two drifting, profiling "Wire-walkers" (each drogued at 500m) within about 20 km ($\approx$ 1/8 mode-one M_2 wavelength) of a U of W fixed mooring, and subsequently station itself 10-20 km east or west of the mooring. These will complement the Moored-Profiler measurements by 1) resolving the high-frequency motions 2) simultaneously resolving temporal and cross-track variability 3) measuring the internal-wave frequency/wavenumber spectrum bracketing the critical latitude. The goal is to document the cascade of energy at each of these three sites, and to identify the relative roles of mesoscale, ambient near-inertial waves and the tidal subharmonic in triggering mixing. For example, based on the exploratory modeling studies, we expect enhancement of high-wavenumber shear at 28.9, and reduced energy to the north.

Our observational tools are:

- *The McLane Moored Profiler (MMP)* is a newly-operational instrument capable of making repeated vertical traverses of the water column along a conventional subsurface mooring wire while carrying a Seabird Conductivity-Temperature-Depth (CTD) and a Falmouth Scientific Acoustic-Current-Meter. Originally developed by John Toole (WHOI), it now commercially available through McLane Research Labs (http://www.mclanelabs.com/mooredprofiler.html). Alford has purchased three with ONR-DURIP funds, and we plan to rent three more from the WHOI equipment pool. The profiler crawls at 25 cm/s, yielding vertical profiles of ocean temperature, salinity and velocity at 2-m vertical resolution. Profiling continuously, the batteries last 50 days.

- *The Revelle Hydrogaphic Sonar System (HDSS)* on the R.V. Roger Revelle will measure current (and shear). This system consists of nested 50 kHz and 140 kHz four beam Doppler sonars. The 140 kHz system profiles from near the surface to depths of 200-400 m with 4 m depth resolution. The 50 kHz sonar profiles to depths of 600-1000 m, depending on scattering strength, with 12 m depth resolution.

- *A new fast-profiling CTD,* developed for the 2005 ONR Non-linear Internal Waves Program, will be used from the Revelle to monitor the density field and to document overturning events. This device consists of a Seabird SBE-49 FastCat and a micro-conductivity cell packaged in a streamlined body. The package is suspended from a special-purpose shipboard profiling winch by an ultra-thin (5 mm) cable with several copper conductors. On descent, the profiling winch over-spools the wire slightly, so that the CTD falls uncoupled from the ship. The anticipated fall rate is 4 m/s, enabling down/up profile pairs to 800 m every 8 minutes. Though this system has not yet been tested, we emphasize that our goals can still be accomplished, albeit with lower temporal resolution, by yoyo-ing the shipboard CTD system.

- *Seasoar.* For spatial surveys, the SIO seasoar, now available as standard shipboard equipment, will be flown behind the Revelle while steaming at 7.5 kt. Seasoar measures T, S and density while cycling up and down between 50-400 m in a sawtooth pattern, every several minutes and several km.

- *Wirewalkers* (Rainville and Pinkel, 2001) Drifting instruments that profile from the surface to 500 m every 1-2 hours, depending on local sea conditions, while drifting. A Seabird CTD and a travel-time current meter (Falmouth Scientific, Nobska Instruments or equivalent) collect density and shear with a vertical resolution of order 2 m. The moorings are navigated by GPS and communicate their position via an Iridium link.

Detailed Methodology.

Alford will prepare, deploy and recover the moorings. Alford and Pinkel will together supervise the field component of the project, with Pinkel supervising the Revelle sonar, fast CTD and Wirewalkers. We will conduct the operations in two cruises planned for summer 2006 (Table 1). We anticipate several near-inertial "events" during this time, but expect near-inertial energy to be at a minimum, easing interpretation of the semidiurnal records. (A cabled-observatory node (B. Howe, APL, pers. comm.) is planned to be extended to the Hawaii Ocean Timeseries (HOT) site before then, which will deliver power to, and relay real-time data from, another full-depth Moored Profiler.)

SIO and UW postdocs and graduate students will go on both cruises. Depending on their qualifications, we anticipate that both postdocs will also aid in cruise planning, execution and data analysis.

At each mooring site, profiles of the semidiurnal perturbation pressure $p'(z)$ will be derived from vertical displacement $\eta(z)$ timeseries. The temporal resolution will allow near-inertial and semidiurnal frequency motions to be distinguished. Combined with semidiurnal fits to the two velocity components $[u(z), v(z)]$, we will obtain baroclinic semidiurnal energy-flux profiles ($\langle u'p' \rangle, \langle u'p' \rangle$; *Kunze et al.* [2002]; *Althaus et al.* [2003]), where the $\langle\rangle$ represent an average over wave phase. Though our measurements will not extend to the top and bottom, we will easily resolve the first two modes (Figure 5), which contain the overwhelming majority of the flux [*Kunze et al.*, 2002]. Higher-mode fluxes are still measurable, since errors in surface pressure are negligible for modes $\geq$ 3 [*Rainville*, 2004].

Phase will be estimated with standard harmonic-analysis techniques. The time-dependence of flux and phase will be compared to the (directly-measured) subinertial background density and velocity fields, to observationally determine the degree of mesoscale refraction of the internal tide.

Guided by altimetry and ray-tracing calculations, we have chosen a preliminary ship track (subject to further guidance from numerical simulations and historical analysis) that is aligned with the primary ray path of some of the strongest energy fluxes leaving Hawaii (Figure 2). The limited spatial and temporal resolution of the moorings will be augmented with the Seasoar surveys and time series, respectively. Though essentially 2-D, the combined space-time series of energy and energy-flux, spanning 1200 km, will provide the first fully-resolved ocean measurement of internal-wave propagation across basin scales.

Turbulent dissipation rates will be inferred from the moorings, the survey and the intensive time series using the Gregg-Henyey parameterization [*Henyey et al.*, 1986; *Gregg*, 1989; *Polzin et al.*, 1995], and via turbulent overturns [*Thorpe*, 1977; *Alford and Pinkel*, 2000]. At the proposed study site, we will be capable of detecting dissipation rates of 10^{-9} W kg^{-1} down to 1000 m and 10^{-8} W kg^{-1} down to 3000 m; below this, stratification is so weak that density noise can create spurious signals [*Alford and Gregg*, 2004]. Given 1) our focus on the initial transfer of energy from mode-one to higher modes, rather than the turbulence itself and 2) the expected success of the combination of the Gregg-Henyey scaling and overturns, we do not feel that the extra expense of microstructure measurements is warranted.

Table 1: Preliminary Cruise schedules. Day 0 is June 23, 2006.

Day	**Spring/neap**	**What**
		Cruise 1: 25 days, June 23-July 18, 2006
0	NEAP	Leave Honolulu
0-4.5		Deploy moorings on a northward line.
4.5-5.5		Return to 32° N
5.5-10.5	SPRING	**Time series 1,** 31° N
10.5		Deploy SeaSoar, begin **spatial survey** to 25° N @ 7.5 kt
12.5		Arrive 25° N, turn around.
14	NEAP	
15.5		arrive 35° N, turn around
17.5		Arrive 27° N, recover Seasoar, deploy wirewalkers
17.5-22.5	SPRING	**Time series 2,** 27° N
24.5		Arrive Honolulu
		Cruise 2: 18 days, Aug 12 - Aug 29, 2006
45		leave Honolulu
47.5		Arrive 29° N, deploy wirewalkers
47.5-52.5	SPRING	**Time series 3,** critical latitude 28.9° N
52.5		Transit to 37° N.
55		Moorings stop profiling.
57	NEAP	Recover moorings.
63		return to Honolulu.

2.2 Numerical Modeling

A series of process oriented numerical experiments will be undertaken to explore the nonlinear dynamics and latitudinal dependence of low-mode internal tides. The experiments will be run on the Center for Observations Modeling and Prediction at Scripps (COMPAS) cluster. Winters and MacKinnon are both COMPAS members and together will have dedicated access to 128 processors. We will use a parallel spectral model [*Winters et al.*, 2004] that is currently running on the COMPAS cluster and other supercomputer centers. Dedicated access will allow us to do the production runs in three dimensions with significant computational bandwidth. For example, simulations of stratified wake instability are being run with 64 COMPAS processors with grids of 512x512x256 points. Simulations of this scale typically require 7-10 days to run.

The goals of the proposed numerical experiments are twofold − first to facilitate a physical understanding of the nonlinear dynamics affecting low-mode tidal propagation under a variety of conditions, and second to interactively support the design, analysis and interpretation of the ocean observations.

1. **Understand the essential dynamics of mode-one tidal energy loss.** We will both look at the details of the idealized subtropical catastrophe (Figure 1) and determine the influence of factors such as variable stratification, meso-scale eddies and time dependent forcing strength. High-priority questions will include:

   - Why is energy transfer out of the tide so much faster *at* the critical latitude than equatorward? We suspect the answer is related to the vanishing group velocity of the recipient half-frequency motions at this latitude (making them vulnerable to phase-locked energy transfers). We will start by analyzing energy transfers in a series of f-plane simulations at varying latitudes in terms of the rates predicted by both resonant wave triad interaction and linear-instability theory based on Floquet analysis [*Majda and Shefter*, 1998; *Winters*, 2004]).
   - What is the nonlinear tidal response to a spring/neap cycle? Observations from the HOME experiment (Figure 3) show that the strength of the subharmonic is highly sensitive to the tidal intensity. Is the response systematic or is there an intensity threshold? Do external factors, such as the presence of wind-forced near inertial waves, play a role?
   - Does a southward propagating internal tide (from the Aleutians, Figure 2) behave differently at the critical latitude?
   - Are there strong interactions between the internal tide and near-inertial waves? Near-inertial waves can be modeled using an impulse forcing of near-surface momentum, approximating the aftermath of rapidly passing storms. Preliminary results using this technique show that near-inertial waves do not disrupt the subtropical catastrophe, but in fact act as a catalyst, triggering the instability more quickly.
   - What effect do mesoscale features (fronts, eddies, variable stratification) have on the propagation or nonlinear interactions of the internal tide? Is it possible that interaction with mesoscale shear shifts the phase of the internal tide such that its energy flux is no longer visible to (phase-locked) satellite analysis but shows up in fixed moorings (Figure 2)? We have already implemented a procedure to initialize geostrophically balanced eddies with the parameter set (location, horizontal and vertical decay scales, velocity scale) for each eddy chosen randomly from prescribed distributions. We have previously used this scheme to study interactions between eddies and near inertial waves.

2. **Model / Field Work Comparison** Substantial and dynamic interaction between modeling and observational components of the proposed experiment will guide the evolution of both.

Several straightforward interactions are listed here, but we plan and expect close collaboration to allow the numerical and theoretical work to evolve in response to experimental discoveries.

- (years 1-2): Numerical simulation of proposed observational sampling strategies. While the proposed observations were designed to optimize spatial and temporal coverage, it is inherently difficult to interpret measurements of complex flows made at different points in space and time. We will compare the full numerical output with subsamples that would be measured by the numerical equivalent of moored profilers, shipboard sonar, and stationary time series.
- (years 2-4): As results from historical data analysis and new observations become available, observed tidal fluxes and mesoscale features (stratification and shear) will be incorporated into further numerical simulations. Some experiments will be run over limited domains at very high resolution to explore the small-scale dynamics of turbulence generation we expect to observe with the high frequency sonar.

2.3 Historical data Analysis

2.3.1 Moorings

Using funds from Alford's ONR-YIP award, we have begun examining near-inertial and tidal energy and energy-flux. We propose to continue the moored-data analysis we have begun, focusing here on the tide. Specific questions we still aim to address are 1) Can a spatial picture of low-mode tidal energy be obtained? To what extent does it agree with existing and ongoing numerical model simulations [*Hibiya et al.*, 1999; *Simmons et al.*, 2004b]? What can be learned about missing physics in the models? 2) Are the observed phase changes and group arrivals relative to barotropic forcing (Fig. 4) consistent with arrival-time differences from time-varying stratification? 3) Examining two simultaneous pairs of moorings at 28° N and 40° N, can any coherence be established between the low-mode records?

2.3.2 Revelle shear, and FLIP shear/strain

To optimally plan the fieldwork, two classes of existing data will be reanalyzed at Scripps. The first is a series of current profiles obtained from the Revelle sonar (HDSS), which are recorded whenever the ship is underway. HDSS data are publicly available.

There were six north-south transects in the Pacific across the latitudes of interest, four in the North Pacific and two in the south Pacific. A preliminary examination of transects across the critical latitude (Figure 1b) shows a marked increase in oceanic shear equatorward of ≈ 30 , consistent with our hypothesis that the instability of the M_2 tide is a phenomenon of global importance. Funds are requested for the further analysis of these data, to assure that all cases are examined and that biological (and other) artifacts are not influencing this finding.

Support is also requested to examine several historic FLIP data sets, where intensive CTD and Doppler sonar data have been co-collected. Our particular interests are the previous experiments:

- Patchex -34° N, 127° W. Open water, no wind-forced near inertial waves.
- Mildex - 34° N, 127° W. Drifting across the critical latitude. Strong wind forcing south of the critical latitude.

- SWAPP - 35° N, 124° W. Open ocean, stormy, wind forcing and nearby fronts.
- ARL -31.6° N, 118.6° W. Anchored on a strong tidal conversion site north of the critical latitude.

Both sonar-derived shear and the occurrence of overturns can be tracked in these historic data sets. While the shear data are readily accessible, significant data archaeology might be required to monitor overturns with precision.

In summary, we request support to document the dynamics of energetic, low-mode internal tides as they propagate thousands of kilometers from their generation sites. We propose a combination of historical data analysis, new observations and process oriented numerical modeling. We seek to better understand the dynamics underlying the spatial distribution of wave-driven mixing and the apparent paradox between altimetric and in-situ estimates of tidal flux. The processes to be observed and understood are coupled both to meso-scale variability and the global circulation. Our field observations will provide guidance toward the design of long-term monitoring of discrete tidal generation sites.

3 Results from Prior NSF Support

Hawaii Ocean Mixing Experiment
OCE 98-19529 (Pinkel, R.); 09/15/01-08/31/04,$683,069

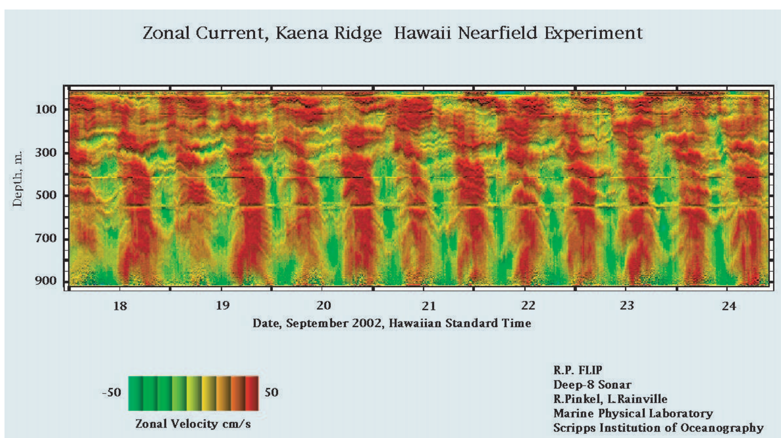

Figure 6: A representative record of zonal velocity, obtained from the Deep-8 sonar on the R.P.FLIP. The phase propagation of the long wavelength baroclinic tide is clearly downward, indicating upward energy propagation. The large near-inertial waves seen above 300m have a much shorter wavelength. They are radiating down from the surface, perhaps generated through a non-linear interaction with the reflecting tide.

As an aspect of the Hawaii Ocean Mixing Experiment, we collected an extensive set of CTD and Doppler sonar profiles on the Kaena Ridge, a strong tidal generation site, immediately west of the island of Oahu, Hawaii. The objective of this effort was to document the cascade of energy from the barotropic tides to the smallest baroclinic scales. Our group was one of 10 participating in the Nearfield component of the overall program. We worked from the Research Platform FLIP, which was anchored on the extreme southern edge of the ridge crest for a six-week period during September and October 2002. The water depth at the site is 1100 m. Over twelve thousand CTD profiles, from the surface to 800 m, were collected during the course of the cruise. Doppler sonar observations from the surface to 900 m were also obtained, with 3.5 meter vertical resolution and 30 second temporal resolution. A 6-day record of meridional velocity from the Doppler sonar is presented in Figure 6. The data reveal a dominant long vertical wavelength baroclinic tide propagating up from the sea floor. The direction of energy propagation is northward over much of the deep water-column and southward toward the surface. Perhaps surprisingly, the dominant shears, as indicated by shading, are associated with near-inertial (actually $M_2/2$), not tidal motions. These are seen most clearly near the surface and are perhaps associated with a non-linear interaction with internal tide. We conjecture that the dominant mixing at mid-depths is associated with this sub-harmonic, rather than tidal, activity. Using the micro-conductivity cell on the CTD, we can verify this conjecture. If true, we will have successfully documented an energy cascade from generation to dissipation scales.

Internal wave mixing near energetic sources
OCE-0242471 (Winters, K. B.); 8/1/02-7/31/04,$381,500
Numerical simulations are used to investigate nonlinear energy transfers in the near field of internal wave generation. Three idealized settings are being investigated: the near-field dynamics of moderate-to-small scale M_2 waves, similar to those observed above rough topography in the Brazil Basin, far field propagation of low-mode internal tides on a β-plane, and near-field dynamics of sheared inertial currents similar to those left after the passage of a rapidly moving storm. Results for internal tides indicate that rapid energy transfers occur via the PSI mechanism. The transfers have a time scale of days rather than months as predicted using random phase resonant interaction theory. Rapid transfers have implications for both near- and far-field dynamics and provide a mechanism for spatially variable wave-driven mixing. A new parametric instability was found for sheared inertial motions. The instability is rapid and leads to three-dimensional turbulence, mixing and dissipation. Though driven by shear, the instability occurs for Richardson numbers greater than 1/4. Publications include: *Winters et al.* [2004], *Winters* [2004], *MacKinnon and Winters* [2003], *Smyth and Winters* [2003]. Two manuscripts are in preparation, an invited talk and a poster were presented at the Portland 2004 AGU Ocean Sciences meeting.

Dimensional Evolution of Intrusions
OCE-00-95382 (M. Alford and M. C. Gregg); 03/01/2001 - 03/01/2004,$428,149
To understand the structure, evolution and dynamics of thermohaline intrusions in Puget Sound, we conducted two single-ship studies and a two-ship experiment using our towed body SWIMS, microstructure profilers, and acoustically-tracked Lagrangian floats (DAsaro). In addition, we deployed two McLane Moored Profilers for three months. From two ships, microstructure time series and repeated 3D surveys were conducted in a float-relative (Lagrangian) frame. We observed the structure and evolution of a cold, fresh, low-oxygen tongue of water centered at 70-m depth. Since turbulent fluxes were measured, and advective effects could be distinguished from intrinsic Lagrangian evolution, the warming of a float near the intrusions edge could be attributed to horizontal stirring there. Two manuscripts are in preparation.

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