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Structure, Energetics and Variability of the Non-Linear Internal Wave Climate over the New Jersey Shelf

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ABSTRACT

Non-Linear Internal Wave (NLIW) packets are ubiquitous features of the coastal ocean, producing significant changes to its acoustics, optics and biogeochemistry, and influencing its dynamics. While they arrive like clockwork in some regions like the South China Sea, they occur with a high degree of variability on most continental shelves. And even in regions where they form at regular intervals, their amplitudes can vary dramatically from packet to packet, and there are strong seasonal changes. Through this grant, we have

- described the 3D structure, energy and timing of the ~100 NLIW packets that propagated through the SW06 mooring array;
- quantified the external factors (seasonal/mesoscale/tidal) that control NLIW energetics and variability in the coastal environment; and

Together, these will improve our ability to detect, predict and quantify the effects of NLIWs in an arbitrary coastal environment.

LONG-TERM GOALS

This work is part of a goal to obtain a more complete and fundamental understanding of the hierarchy of processes which transfer energy and momentum from large scales, feed the internal wavefield, and ultimately dissipate through turbulence. This cascade significantly impacts the acoustic, optical, and biogeochemical properties of the water column. Non-Linear Internal Waves (NLIWs) represent one such pathway.

APPROACH

Using data we collected during shipboard surveys and from an extensive array of moorings deployed during the Shallow Water 2006 experiment, we compute the 3D wave structure, propagation direction, baroclinic energy density and energy flux. Data integration between wave-tracking experiments and mooring time-series are used to confirm moored energy/flux estimates. Divergences of energy flux indicate the generation locations and conversion efficiencies; phasing of baroclinic signals (and their relationship to the barotropic tide) elucidates mechanisms. In-house numerical model studies

performed by Sam Kelly using MITgcm have been used to assess the magnitude of baroclinic generation and the influence of mesoscale stratification; model-data comparisons aid interpretation.

WORK COMPLETED

A full census of NLIW timing, structure, propagation direction, and wave energetics at all SW06 ADCP moorings has been completed (SW29, SW30, SW32, SW34, SW37, SW38, SW39, SW41, SW42 & SW43). This forms a wave inventory database used for higher-order calculations. This database, CTD-ADCP mooring data (w/ Duda) and ADCP/P-pod bottom lander data (w/ Moum) are available for use by SW06 collaborators. Ten (10) peer-reviewed manuscripts have been supported by this and its prior award, most of which are now in print.

RESULTS

Analysis of NLIW timing, 3D structure and energy at SW06 reveals that this site is highly complex – typical of coastal internal wave climates. Not only was the amplitude, timing and propagation direction highly variable, but the NLIW energy was found to be unrelated (or inversely related?) to the strength of the shelfbreak barotropic tide (Figure 1). Instead, NLIW energy levels are found to be highly correlated to the strength of the internal tide. The complex NLIW climate at SW06 site dramatically contrasts the regularity of waves and timing in the South China Sea. This contrast may simply be a reflection of the relative complexities of the internal tide in these two regions.

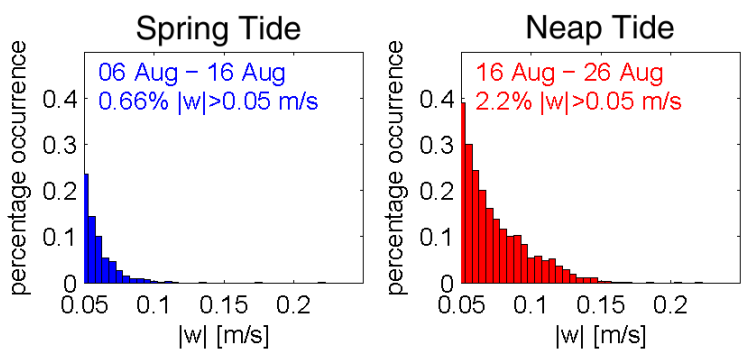

Figure 1: Distribution of vertical velocity at SW37 (70-m isobath) during spring (left) and neap (right) August 2006 tides. The average vertical velocity and energy of NLIW packets during the August 2006 spring tide was about 25% of that during the following neap tide. In contrast, barotropic velocities during spring tides were almost a factor of 2 stronger than the neap.

Our original question "***What sets the intensity of NLIWs on the continental shelf?***" **has** evolved into… "***What sets the structure, intensity and direction of the internal wave energy flux at the shelfbreak?***"

While topography, seasonal stratification, and barotropic forcing are certainly important, these do not explain the low-frequency trends in baroclinic energy, nor do they account for the packet-to-packet variability in NLIW shape, amplitude or timing. A fundamental finding from this study is significant role of remotely-generated internal tides, which appear to control the on-shelf internal tides and nonlinear internal waves. The strength of shoaling internal tides from a remote, undetermined

location(s) is found to be the primary control on local on-shelf dynamics. However, subtle changes in the phasing of shoaling waves are found to play an important role in local generation (barotropic to baroclinic conversion) at the shelfbreak. In addition, the location of shelfbreak fronts, sub-tidal currents, near-inertial variability, and other factors play a role in setting the strength of the internal tide, its nonlinear steepening, and subsequent propagation of NLIWs.

The following summarizes our major findings:

1) NLIW Pressure p_w

In collaboration with Jim Moum, bottom pressure was directly measured on three bottom landers. Our analysis (Moum and Nash 2008) confirms that (1) we are correctly computing the wave-induced internal pressure $p_w = p_{surf} + p_{hyd} + p_{nhyd}$ and (2) wave amplitude, timing and sign (depression vs. elevation) can be measured from bottom pressure P-pods. This measurement provides a means for detecting and quantifying waves both waves of depression and elevation, which is significant, as the latter have no detectable sea surface signature.

2) NLIW Energy and Energy Flux

NLIW energy ($E = APE + KE$) and energy flux ($\boldsymbol{F_E} = \langle \boldsymbol{u_w}\, p_w \rangle + \boldsymbol{u_w}\, E$) have been computed for all waves during the experiment at all ADCP moorings; a summary from four inshore moorings is shown in figure 2. The nonlinear contribution to the energy flux ($\boldsymbol{u_w}\, E$) is found to be appreciable for most waves (usually >25% of $\boldsymbol{F_E}$), and that on average the flux is represented by $\boldsymbol{F_E} \approx \boldsymbol{c}\, E$, confirming our findings based on waves of elevation (Moum et al 2007). Moreover, for the first wave in each packet, energy is found to be equipartitioned ($KE \approx APE$) so that $\boldsymbol{F_E} \approx 2\, \boldsymbol{c}\, KE$, (Shroyer et al 2008). This result provides a simplified means of estimating NLIW energy and flux, if the result is indeed as universal as it appears to be.

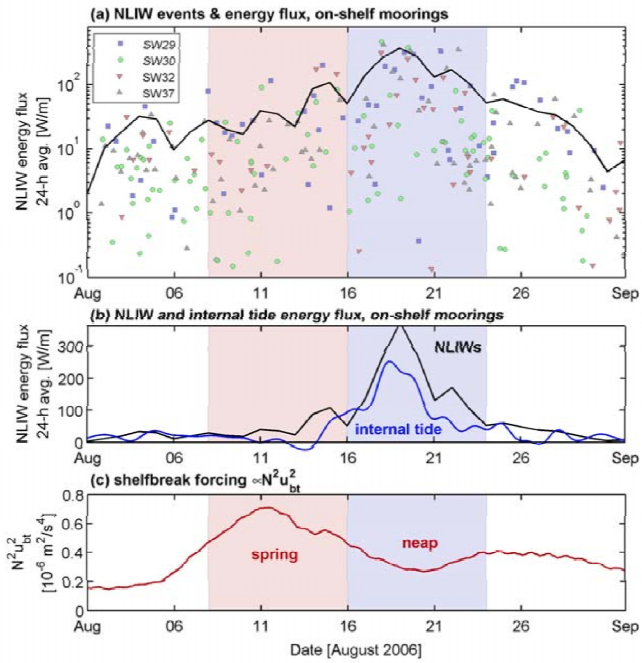

Figure 2: Time-series showing onshore transport of energy by NLIWs at 4 inshore moorings. Top panel represents the energy transport within individual wave packets, presented as 24-h averages on a logarythmic scale; the mean of the 4 moorings is in black. NLIW energy scalees with the internal tide energy (middle panel), with a peak near Aug 20 that occurs during neap tides and is a factor of ten greater than that during spring tides. For refgerence, the shelfbreak forcing is shown in the lower panel.

3) NLIW Temporal and Spatial Variability

NLIW energies were highly variable on synoptic timescales (Figure 2) and poorly correlated with the barotropic tide (Figure 3). NLIW variability is instead explained by the variability in the internal tide, which shows a similar temporal structure. This confirms that NLIW intensity is controlled by the strength of the internal tide. A more complete understanding of the mechanisms that set the strength of the internal tide (both spatial and temporal variability) is necessary for prediction of the NLIW generation.

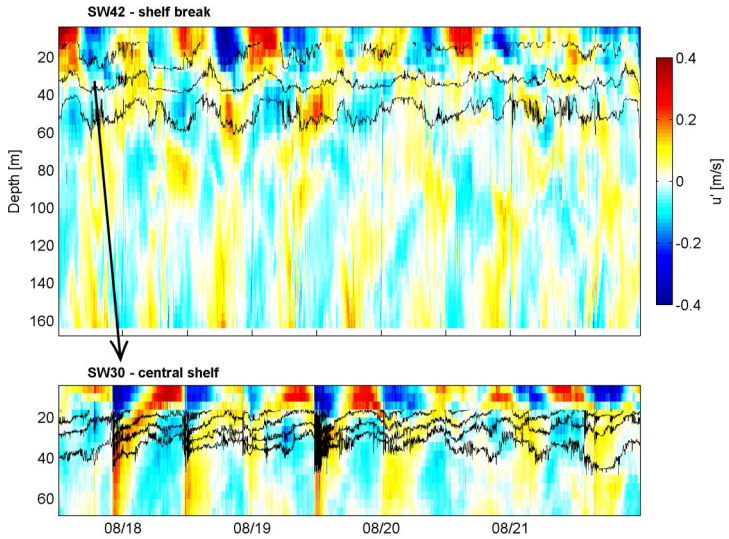

Figure 3: Depth-time plot of velocity (color) and density (contours) at the shelfbreak (top) and 70-m isobath (bottom). NLIWs appear inshore on the leading edge of the steepened internal tide.

Wave arrival times were moderately phase-locked to the barotropic tide only during 8/16-8/23 (red dots in upper panel, figure 3) – a period when NLIW packets arrived on the leading edge of the steepened internal tide (figure 4). But even during this period, there is no one-to-one correspondence between the strength of internal tide pulses at the shelf break (upper panel) and the amplitude of NLIW packets that arrive at the 80-m isobath 7 hours later (Moum and Nash, 2008 – figure 2). Influences from the mesoscale stratification & velocity, deviations in internal tide phasing or direction, and/or interactions with other waves must be responsible for this complexity.

4) Internal Tide Structure & Generation

SW06 shelfbreak moorings reveal strong gradients in the internal tide energy flux, computed following Nash et al (2005). During most time periods, the shelf break is one source of the internal tide (Baines 1982), with energy radiating both onshore towards the shelf and offshore over the slope, roughly along tidal characteristics (Figure 5). However, during the 16-26 Aug period of strong NLIW activity, the internal tide source appears to have shifted offshore to at least the 500-m isobath. The source of this baroclinic energy and the reason for its intensification are not currently known. However, such variability is common of many continental shelves – from the US east and west coasts (Nash et al 2004, Lerczak et al 2003, Nash et al 2007) to the SCS (Duda and Rainville, 2007).

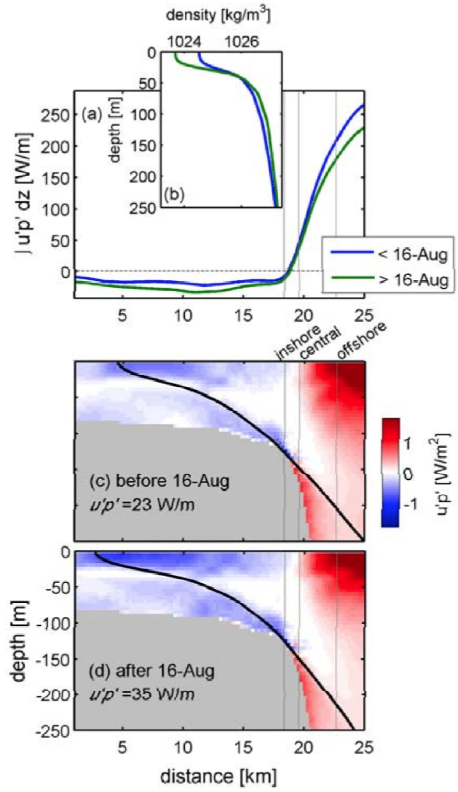

Figure 4: top: depth-integrated energy flux for 2 stratifications representative of spring (blue) and neap (green) conditions. Bottom plots show that differences in energy flux distributions for these two periods. Differences are relatively small compared to those observed.

To assess the role of mesoscale changes in stratification on NLIW occurence, numerical simulations of internal tide generation were performed by Sam Kelly using MITgcm (figure 4). These show that shelfbreak-generated waves predominantly radiate their energy offshore, with less than 20% propagating on-shelf. Moreover, changes in stratification similar to those observed yield changes in energetics by less than 50%, so are unable to account for the large differences in NLIW energy flux observed during the spring vs. neap periods.

5) Separation of local and remote sources through coherent/incoherent analyses.

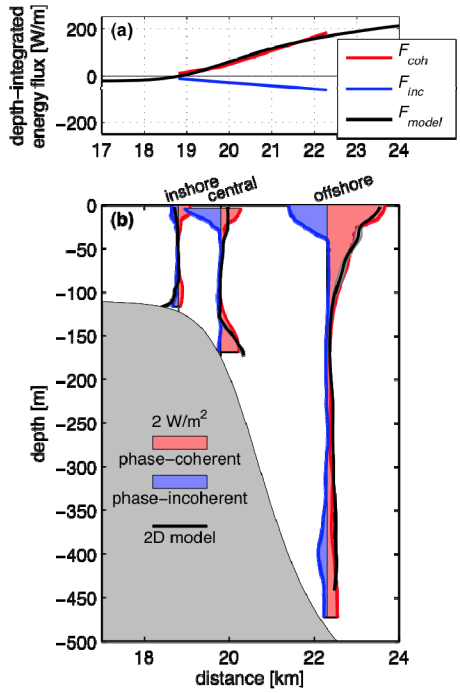

Figure 5: Energy flux across the shelf break for phase-locked (red), phase-incoherent (blue) and modeled energy fluxes. Top shows depth integrals and bottom shows vertical structure. Phase-locked signals diverge across the shelfbreak and are consistent with MITgcm modeled fluxes. Phase-incoherent signals are directed onshore and converge across the shelf break.

To decompose the wavefield into its contributions from locally-generated waves vs. those with remote sources that are shoaling on the slope, velocities and pressures were separated into their coherent and incoherent parts. Energy fluxes were computed from the resultant quantities, as shown in figure 5. This decomposition illustrates that phase-locked motions produce internal tides that radiate away from the shelfbreak, track the spring-neap cycle, and are consistent with modeled energy fluxes. In contrast, the incoherent signals are associated with onshore energy flux, are somewhat random in their temporal evolution, but produced peak energy fluxes that coincided with the peak period of NLIW activity, as illustrated in figure 6. This would appear to explain the conundrum that NLIWs observed during SW06 were strongest during neap tides (figures 1, 2, 6).

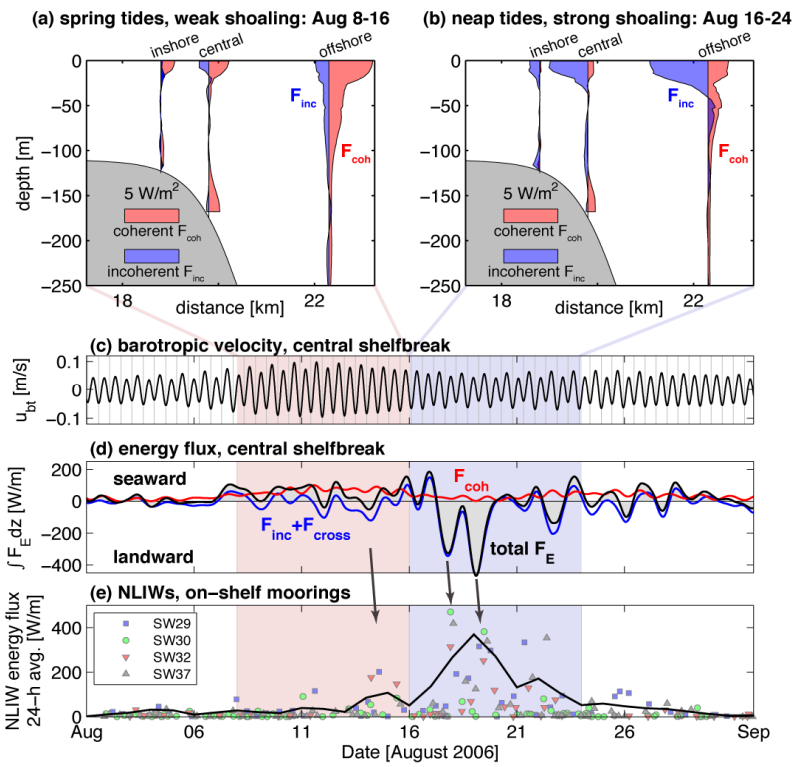

Figure 6: Coherent (red) and incoherent (blue) energy fluxes, divided between the two time periods of spring and neap local forcing. During spring forcing (a), there is strong energy flux divergence at the shelfbreak, but most of the energy radiates offshore. During neap tides (b), local generation is weak, but strong sources of onshore, incoherent energy exist, presumably the result of shoaling of remote tides. For reference we show the barotropic tides (c), baroclinic energy flux (d) and their relationship to NLIWs (e), which shows that NLIW occurrence corresponds to the period of strong internal tides at the shelfbreak.

MENTORSHIP & COLLABORATION

In addition to the above analyses, this award supported Nash in mentoring doctorial candidate Emily Shroyer (now Ph.D., graduated Sept 2009 and currently a WHOI postdoctoral scholar; co-advised w/ J. Moum. Data, analyses, and contributions to five papers coauthored with E. Shroyer and J. Moum were supported by this grant. In a addition, PhD candidate Sam Kelly has been supported by this award, and has produced two papers partially supported by this award.

IMPACT/APPLICATION

These analyses provide the physical understanding of mechanisms so NLIW occurrence, energetics, and propagation characteristics can be predicted. This will lead to a general understanding of processes to aid NLIW prediction elsewhere.

RELATED PROJECTS

These observations and analysis are part of a coordinated effort to define the structure, energetics and timing of the signals that emerge from the interaction of the stratification with the shelf break for other

DRI participants. In addition, a combination of long and short-term programs on the New Jersey shelf (initiated by personnel at Rutgers University, the CoOP-sponsored LATTE program, LEAR and AWACS) includes additional moorings, gliders, and surface velocity from long-range (100 nm) CODAR coverage. These projects are highly synergistic and will be used to study a wide variety of physical, biological and acoustic properties of the region.

Despite dramatic differences in NLIW climate at the SCS and NJ shelf sites, there are important common threads in these two NLIWI DRI projects. Most significant, NLIWs seem to first appear at the internal tide surface reflection at both SCS and SW06 sites (albeit with dramatically different signal strengths). Differences in NLIW regularity and three dimensionality at each site may arise solely from the contrasting complexities in the internal tide: SW06→ complicated, SCS→simple. If this is indeed the case, accurate prediction of the linear, internal tide may be sufficient to predict NLIW energy levels. A common connection between the two NLIWI experiments may be the importance of mesoscale/seasonal changes to NLIW generation and variability. We expect to elucidate these connections through participation in the Internal Waves in Straits Experiment (IWISE).

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Nash, J.D.(2009) Why is NLIW variability on Continental Shelves so complex? ONR Progress review (Chicago, June 2009)

Nash, Kelly, Martini, Alford, Kunze Internal waves and turbulence over a rough and near-critical continental slope (DNVA-RSE Norway-Scotland Internal Waves Symposium, Oslo, Norway, October 2008)

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