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

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Award #: N00014-08-1-0991
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LONG-TERM GOALS

I seek 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.

OBJECTIVES

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 like the New Jersey shelf – site of the SW06 experiment. 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 project, I seek to:

- describe the 3D structure, energy and timing of the ~100 NLIW packets that propagated through the SW06 mooring array;
- elucidate the process by which a nearly-linear internal tide steepens and forms NLIWs;
- understand what sets the conversion efficiency between barotropic tide, baroclinic tide, and NLIW packets;
- determine the external factors (seasonal/mesoscale/tidal) that control NLIW energetics and variability in the coastal environment; and
- quantify the sensitivity of indirect measures (SAR imagery, glider dynamics, bottom pressure) to detect NLIW amplitudes/energy/timing.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Structure, Energetics and Variability of the Non-Linear Internal Wave Climate over the New Jersey Shelf**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon State University,College of Oceanic & Atmospheric Sciences,Corvallis,OR,97331-5503**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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

APPROACH

Three water-column moorings and four bottom landers were deployed to capture the full water column variability of density (sound speed), velocity and bottom pressure. Combined with the other SW06 resources, the 3D wave structure, propagation direction, baroclinic energy density and energy flux is determined. Data integration with wave-tracking experiments is used to confirm moored energy/flux estimates. Divergences of energy flux are used to assess generation location and conversion efficiencies, and phasing of baroclinic signals (and their relationship to the barotropic tide) elucidate mechanisms. Model-data comparisons are used to aid interpretation.

WORK COMPLETED

A full census of NLIW timing, structure, propagation direction, and wave energetics at all SW06 ADCP moorings has been completed. This database, CTD-ADCP mooring data (w/ Duda) and ADCP/P-pod bottom lander data (w/ Moum) are available to SW06 collaborators, and were used extensively by Emily Shroyer for her PhD thesis. Results are being widely disseminated (to date, 4 papers have been published, 2 are under review, and 3 will be submitted shortly)

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.
So 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. Subtle changes in the location of shelfbreak fronts, sub-tidal currents and near-inertial variability also set the strength of the internal tide, its nonlinear steepening, and subsequent propagation of NLIWs. Significant progress has been made in the following areas:

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 ($\boldsymbol{F_E} = < \boldsymbol{u_w}\, p_w > + \boldsymbol{u_w}\, E$) have been computed for all waves during the experiment. The nonlinear contribution to the energy flux ($\boldsymbol{u_w}\, E$) is appreciable for most waves (usually >25% of $\boldsymbol{F_E}$); 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 2009e). This result provides a simplified means of estimating NLIW energy and flux, if the result is indeed as universal as it appears to be.

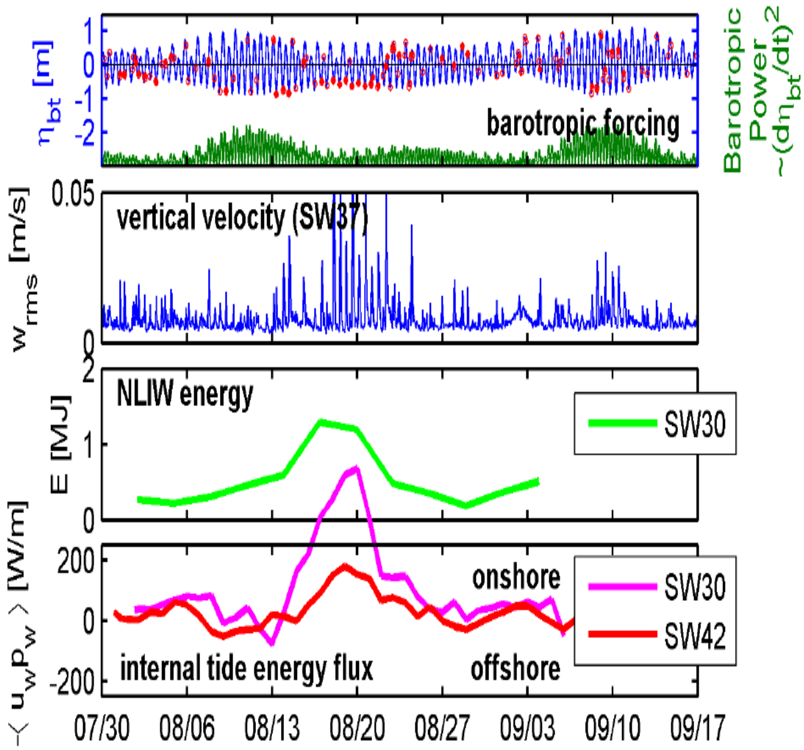

Figure 1: Summary of NLIW temporal variability. Forcing by the barotropic tide (elevation & power; top row) is poorly correlated with NLIW vertical velocity at SW37, the 70-m isobath (2nd row). Red dots in upper panel represent wave arrival times at SW37. The resultant NLIW energy (3rd row) is found to covary with the internal tide energy flux, both inshore and at the shelfbreak (bottom row).

3) *NLIW Temporal and Spatial Variability*

NLIW amplitudes during SW06 showed strong along-shelf variability, with factor-of-ten differences over just 15 km separation. Moreover, NLIW energies were highly variable on synoptic timescales and poorly correlated with the barotropic tide (Figure 1). NLIW variability is instead explained by the variability in the internal tide, which shows a similar temporal structure. This confirms that

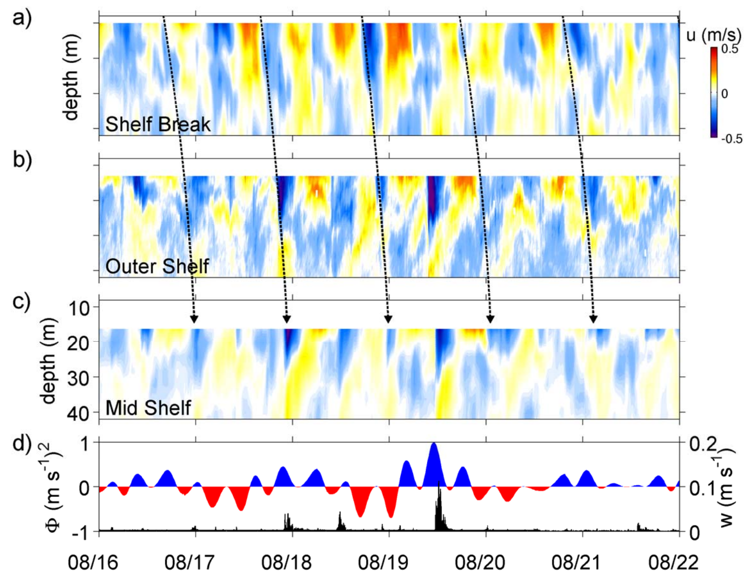

Figure 2: Depth-time plot of velocity at (a) shelfbreak, (b) outer shelf, and (c) mid shelf, showing NLIW steepening at the leading edge of the tide. Occurrence of large NLIWs correspond to periods when near-inertial and semidiurnal motions constructively interfere at the midshelf, as quantified through an interaction parameter Φ that varies on the 1.5 day beat period between f and M2 (from Shroyer et al, 2009d).

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.

Wave arrival times were moderately phase-locked to the barotropic tide only during 8/16-8/23 – a period when NLIW packets arrived on the leading edge of the steepened internal tide (figure 2). But even during this period, there is no one-to-one correspondence between the strength of internal tide pulses at the shelf break (a) and the amplitude of NLIW packets that arrive at the 80-m isobath 7 hours later (c). We show that the beating between the semidiurnal tide and near-inertial waves accounts for the 1.5-day modulation in mid shelf NLIW energies (Shroyer et al, 2009d) and explains why large pulses at the shelfbreak lead to small pulses on the shelf, and vise versa.

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. While the precise source of this baroclinic energy and the reason for its intensification is not currently known, 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).

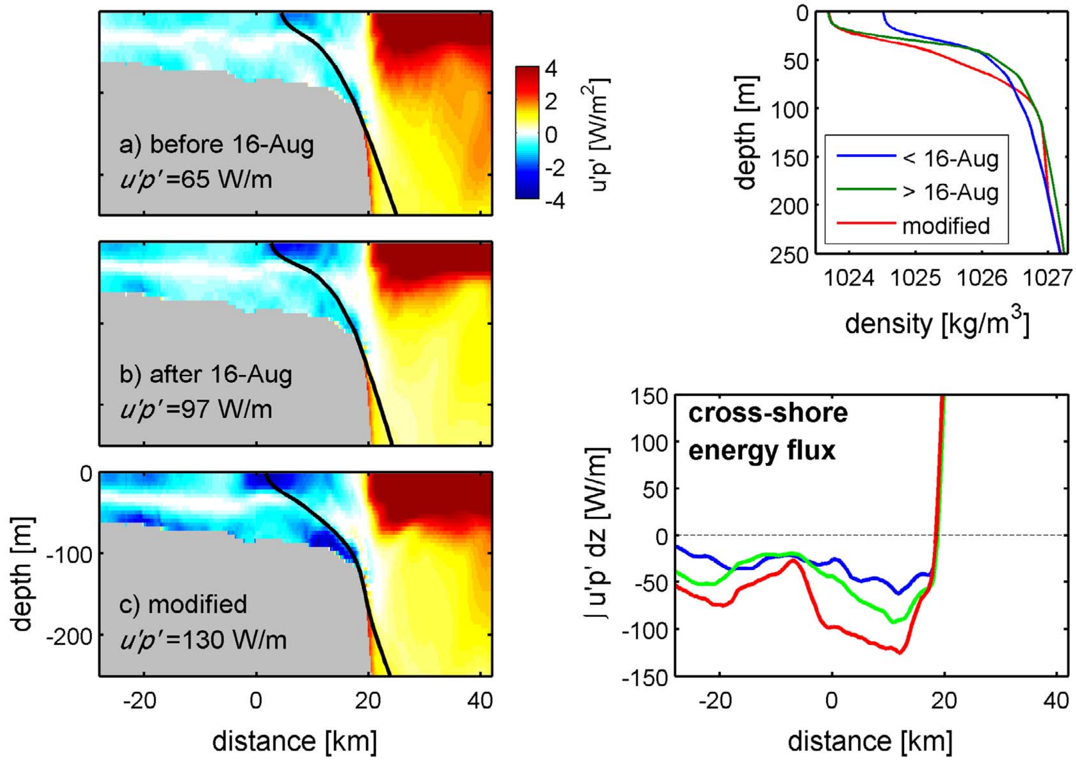

Figure 3: Energy flux profiles near the shelfbreak during periods of weak (left) and strong (right) NLIW activity. A 5 W/m² onshore internal tide occurs at all stations during strong NLIW activity.

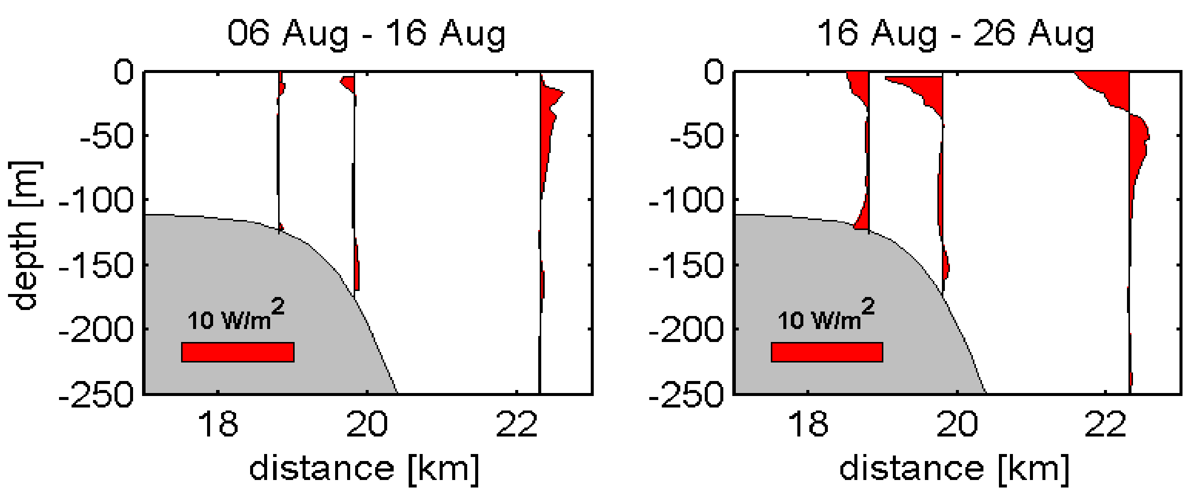

Figure 4: Internal tide conversion from MITgcm numerical simulations. More than factor-of-two differences in generation can be attributed to the effect of shelfbreak stratification.

5) *Stratification and its Influence on NLIW/ Internal Tide conversion:*

Numerical simulation of wave generation using NJ topography and realistic stratification during Aug 2006 have been performed by Sam Kelly (currently funded through this grant). These simulations show that internal tide generation on the NJ shelf is strongly dependent on not only the magnitude of stratification, but also its vertical distribution relative to topographic steepness, as expected through Baines (1982). Significant increases in the strength of the resultant wavefield, and its propensity for NLIW steepening occur for NJ stratifications similar to that during Aug 2006 neap barotropic tides.

6) *Generation theory and modeling*

Barotropic to baroclinic conversion rates have been diagnosed using numerical simulations of wave generation. These are compared to theoretical generation models (i.e., Baines 1982 and Nycander 2005), as shown in figure 5. Spatially-integrated conversion rates are found to be well-represented by Nycander's Green's function formulation; however, variability due to small-scale roughness is not captured by either Nycander or Baines' formulations, and may be responsible for the complex 3 dimensionality we observe in the observed wavefields.

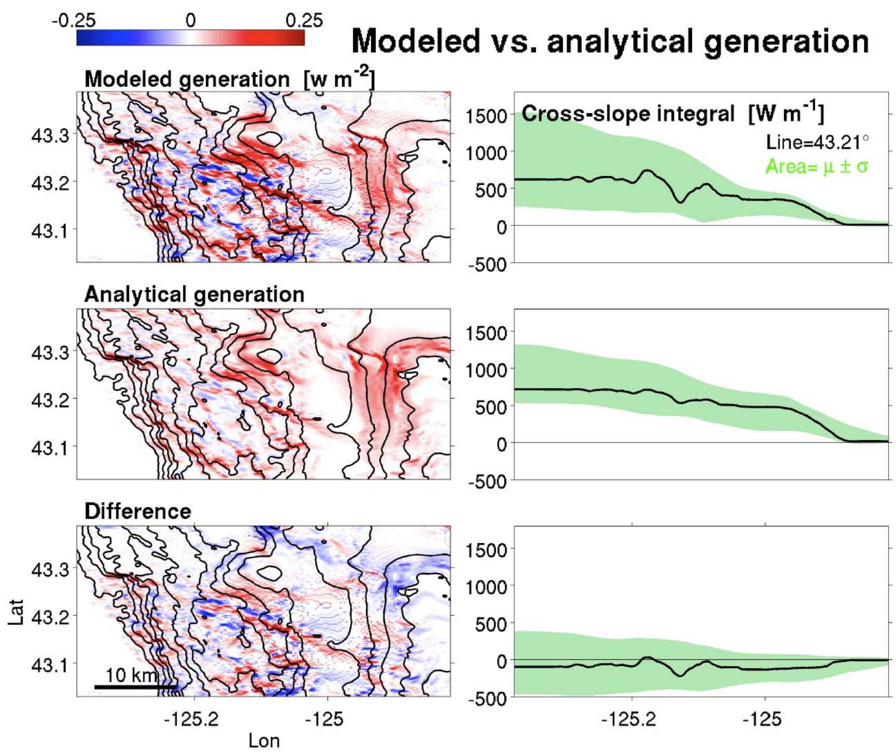

Figure 5: Left: spatial patterns of barotropic to baroclinic conversion, as assessed from the divergence of the baroclinic energy flux (top). This is compared to Nycander's (2005) analytical formation (middle). The difference (bottom) is mostly associated with high-k generation, so averages to zero in cross-slope integrals (right).

7) The lifecycle of NLIWs from generation through decay:
Using our census of NLIW events and energetics, the conversion efficiencies from the quasi-linear internal tide to NLIWs through their decay have been assessed. Shroyer et al. (2009e) provide a complete description of the NLIW life-cycle, and show that turbulent dissipation balances the observed wave decay. Moreover, the heat flux associated with this dissipation (Shroyer et al 2009c) accounts for 50% of the time average on the New Jersey shelf, highlighting the importance of NLIW-induced mixing in diffusing the shelfbreak stratification and providing nutrients to the euphotic zone.

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. Papers in press, under review, or soon to be submitted by Shroyer, Moum and Nash (see PUBLICATIONS section) are titled:

- Observations of polarity reversal in shoaling nonlinear waves
- Mode-2 waves on the continental shelf: Ephemeral components of the nonlinear internal wave field
- Vertical Heat Flux and Lateral Particle Transport in Nonlinear Internal Waves
- Nonlinear Internal Waves over New Jersey's continental shelf
- Energy transformation and dissipation in the evolving NLIW field over New Jersey continental shelf
- Mesoscale influences on the generation of the internal tide and nonlinear internal waves over New Jersey’s continental shelf.

In a addition, PhD candidate Sam Kelly is currently being supported by this award, and has two papers under review or soon to be submitted.

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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TALKS presented with the support of this award

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)

Nash, Shroyer, Kelly & Moum: (2008) Tidal(?) Generation of NLIWs on a Continental Shelf (AGU 2008 Fall Meeting)

Nash, Moum, Shroyer, Duda, Irish & Lynch (2008) Variability of NonLinear Internal Waves on the Continental Shelf (AGU Ocean Sciences 2008, Orlando FL)

Shroyer, Moum & Nash (2008) Shoaling Nonlinear Internal Waves (AGU Ocean Sciences 2008, Orlando FL)

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