# Nonlinear Internal Waves - A Wave-Tracking Experiment to Assess Nonlinear Internal Wave Generation, Structure, Evolution and Dissipation over the NJ shelf

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## LONG-TERM GOALS

The thrust of this project is the investigation of non-linear internal waves which appear as waves of depression when propagating on a near-surface interface and as waves of elevation when propagating on a near-bottom interface. We have had the good fortune to observe (by shipboard wave-tracking and from bottom-moorings) both waves of depression and of elevation propagating inshore from the Oregon shelf break into shallow water and have now successfully applied these types of observations to a study of waves over the New Jersey shelf.

The long-term goal of this program is to understand the physics of small-scale oceanic processes including internal waves, hydraulics, turbulence and microstructure that act to perturb the circulation in coastal oceans and, in doing so, affect the propagation of sound and light. Ongoing studies within the **Ocean Mixing Group** at OSU emphasize observations, a continual program of sensor and instrumentation development, and interaction with turbulence modelers.

## OBJECTIVES

Our present objectives are directed toward

- an investigation of the generation, structure, evolution and dissipation of non-linear internal waves that propagate over the New Jersey shelf as part of the Nonlinear Internal Wave / Shallow Water 06 (NLIWI/SW06) experiment. We ultimately seek to determine
    - the characteristics of the shelf/slope/stratification/forcing that lead to the generation of these waves;
    - their evolving structure as they propagate onshore;
    - how the distinctive turbulent wakes (leading to dissipative energy losses) are initiated in the waves;
    - the energy lost to bottom stress from the induced reverse-flow beneath the waves;
    - the energetics of the waves from shelf break to shore;
    - the final fate of the waves – do they lose their energy *before* reaching shallow water? or do they break up into a variety of modes *in* shallow water?

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- completion of analyses of data previously obtained to determine the generation, structure, evolution and dissipation of non-linear internal waves of both depression and elevation over the Oregon shelf. This analysis will support the analysis of results from the New Jersey shelf, and help to generalize our understanding of the physics.

## APPROACH

For NLIWI/SW06, we have combined acoustic flow imaging techniques with shipboard ADCP and microstructure profiling measurements (using Chameleon). This has permitted an observational view of shoreward-propagating internal solitary waves (both near the surface and near the bottom) not previously achieved. These observations have been supplemented by deployment of 4 bottom landers outfitted with upward-looking ADCP (to obtain water column velocity profiles), acoustic Doppler velocimeters (to detect the turbulent component of the velocity signal at 1 m height above the seafloor) and CTD. Three of these landers were also outfitted with high-resolution pressure sensors.

For NLIWI/SW06, we have collaborated with Andone Lavery (WHOI), who deployed a high-frequency broadband acoustic backscattering system intended to obtain a remote measure of the turbulence that we coincidentally sample *in situ* using Chameleon. The resultant data set is extensive and offers a new look at the internal structure of the waves.

## WORK COMPLETED

Experiments were conducted over the Oregon shelf in 2001 and 2003. In 2001, the focus was near-surface internal waves of depression. In 2003, the focus was near-bottom internal waves of elevation. Five papers have been published or submitted. Analysis continues.
The field program for NLIWI/SW06 has just ended at this writing. For this experiment, four bottom landers were deployed (late July – early September 2006). These were outfitted similarly to that described by Moum & Smyth, 2006, Moum etal, 2006a. All were successfully recovered and all have data. As well, a 28 day shipboard experiment was executed to track waves through the extensive SW06 mooring array – including our landers, 62 moorings were deployed, all with at least some measurement to detect NLIWs. This was highly successful, as well, yielding near-continuous wave-tracking by acoustics, radar (all recorded) and over 7500 turbulence profiles through NLIWs.

## RESULTS

1) The quality of the bottom-mounted velocity profile measurements is much higher than can be achieved from shipboard measurement, which is subject to the motion of the sea surface. These measurements allowed a detailed evaluation of the pressure field of NLIWs. This was a necessary precursor to a correct evaluation of NLIW energy transport. The wave pressure field is composed of an external hydrostatic pressure (surface displacement), an internal hydrostatic pressure (isopycnal displacement) and nonhydrostatic pressure (vertical accelerations) (Figure 1; Moum and Smyth, 2006). From this we infer the structure of trains of propagating nonlinear internal waves (both surface-trapped and bottom-trapped; Figure 1). The significant result from this analysis is the determination that the seafloor pressure signal of nonlinear internal waves is detectable. Our recently-recovered seafloor pressure measurements provide experimental verification of this (Figure 2).

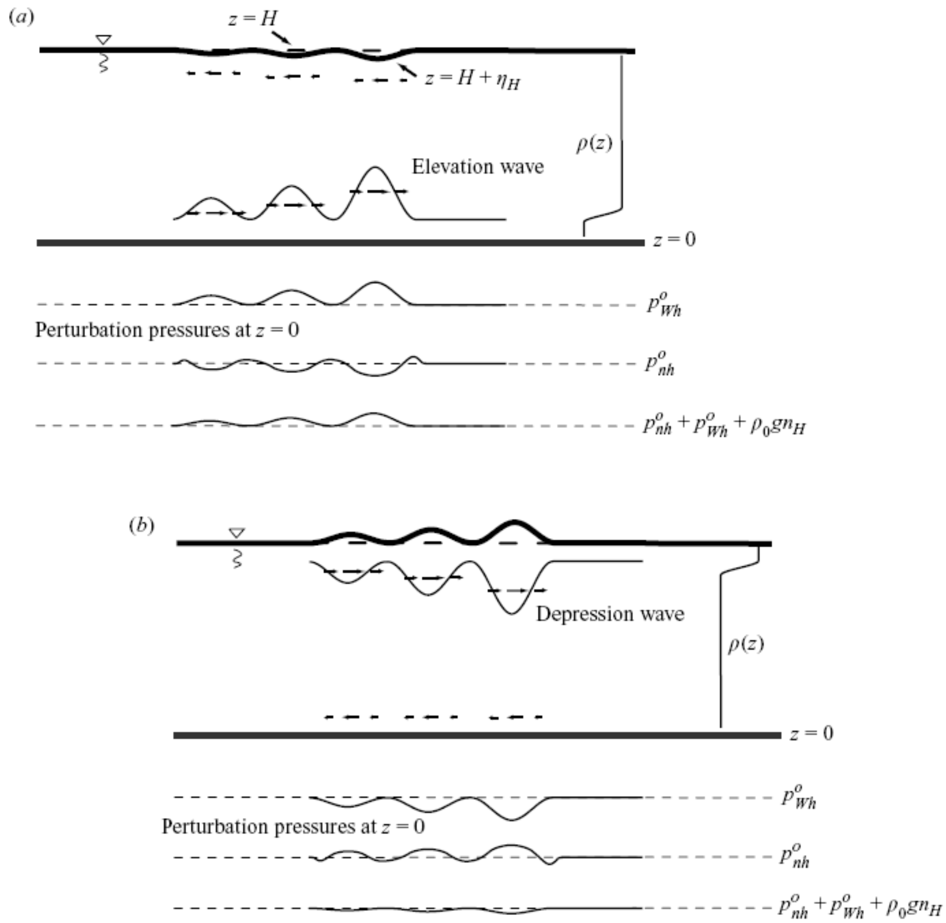


***Figure 1 – (a) Schematic showing surface displacement (exaggerated) and internal (hydrostatic and nonhydrostatic) pressure in a train of three waves of elevation propagating to the right as deduced from detailed velocity and density measurements. The arrows represent relative speeds across the wave fronts and induced speeds near the surface. (b) analogous structure inferred for a train of three depression waves. Moum & Smyth (2006).***

2) Using the bottom-mounted velocity measurements for guidance, we have been able to determine several fundamental aspects of the means by which energy is transported by NLIWs (Moum etal, 2006a). These are as follows:

- there exists a near equipartition between kinetic and available potential energy;
- the energy flux is simply related to the total wave energy by the wave speed, *c*, that is *fE=cE*;
- the pressure-velocity energy flux includes important contributions from both the nonhydrostatic pressure and the displacement of the free surface;
- nonlinear advection of energy contributes significantly to the energy transport, and is approximately twice the pressure-velocity energy flux.

The bad news is that the transport of energy by NLIWs is complex and not easily evaluated in detail without highly-resolved measurements of velocity and density. The good news is that it can be simply approximated as $cE$.

3) From wave-tracking measurements on the Oregon coast, we have been able to assess a rough long-propagation range energy balance, $dE/dt=-\rho\varepsilon$ (Moum etal, 2006b). This differs from the solibore model of Henyey and Hoering (1997) in which the potential energy across the wave balances $-\rho\varepsilon$. However, there exists some evidence of a transition from solibore-like state to solitary-wave-like state.

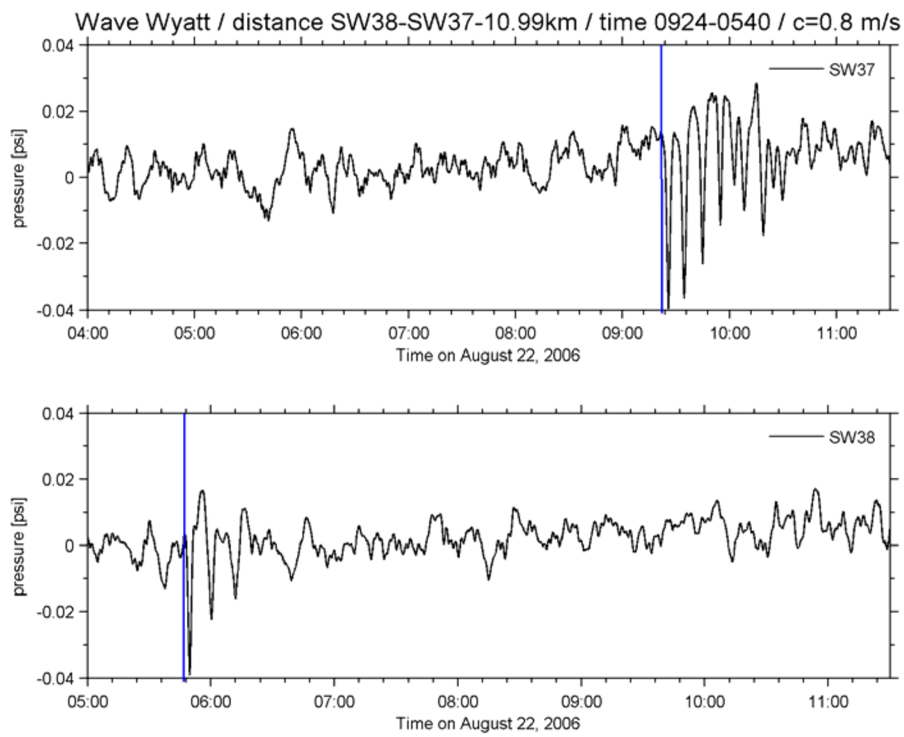


***Figure 2 – Seafloor pressure measurements at 2 locations on the NJ shelf in summer 2006 (NLIWI/SW06). These clearly show the bottom pressure due to a passing train of nonlinear internal waves that we also tracked with shipboard measurements. The wave speed determined by differencing the time between the 2 locations matches our tracking measurement. The sign of the pressure perturbation indicates that the pressure in these waves of depression is dominated by the internal hydrostatic pressure (due to the depression of isopycnals). This measurement represents direct experimental verification of the prediction by Moum & Smyth (2006).***

4) NLIWI/SW06 was a resounding success. All lander data was recovered, and 28 days of shipboard profiling allowed us to follow 26 NLIW trains across the shelf and through the acoustic mooring array through a full spring-neap+ cycle. This will allow a detailed examination of the wave's evolution across a weakly-sloping shelf. It has also offered some new perspectives of the structure of NLIWs. One example is unambiguous evidence of transformation from depression to elevation waves (Figure 3). Another is the existence of intrusive NLIWs, that is, waves which elevate isopycnals above a density interface and depress isopycnals below (Figure 4). These are two examples from a plethora that have been reported to some extent in at-sea daily reports from R/V Oceanus on the SW06 website.

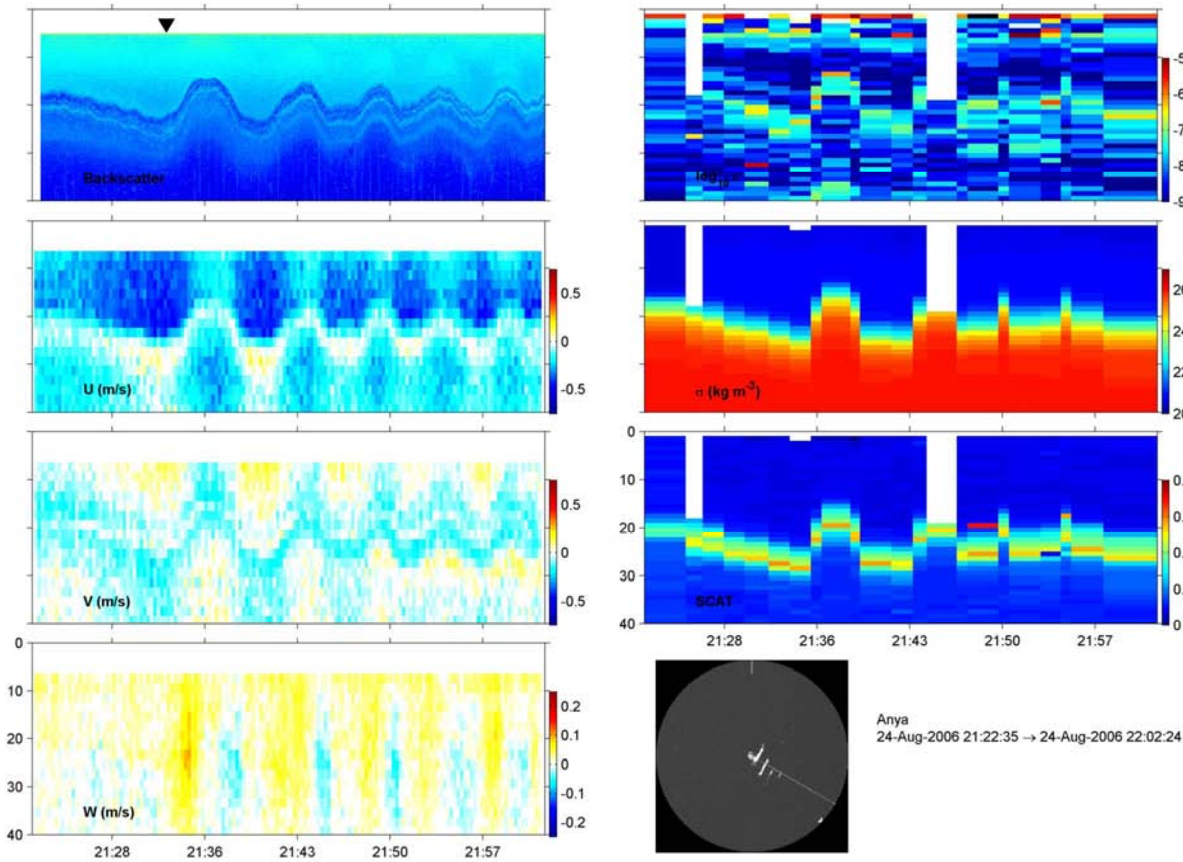


*Figure 3 – Elevation nonlinear internal waves on the NJ shelf. Sequence of acoustic backscatter, velocity, density and turbulence profiling through a nonlinear internal wave train that has been tracked for approximatley 50 km as it propagated onshore over the NJ shelf during NLIWI/SW06. A radar image made at the time of the inverted triangle is shown at lower RH corner. This particular wave originated as a wave of depression. At this stage, the water depth has shallowed to about twice the depth of the dominant pycnocline and the leading wave appears to be a wave of elevation. Note that the 1st vertical velocity pulse is UP, where previously it had been DOWN.*

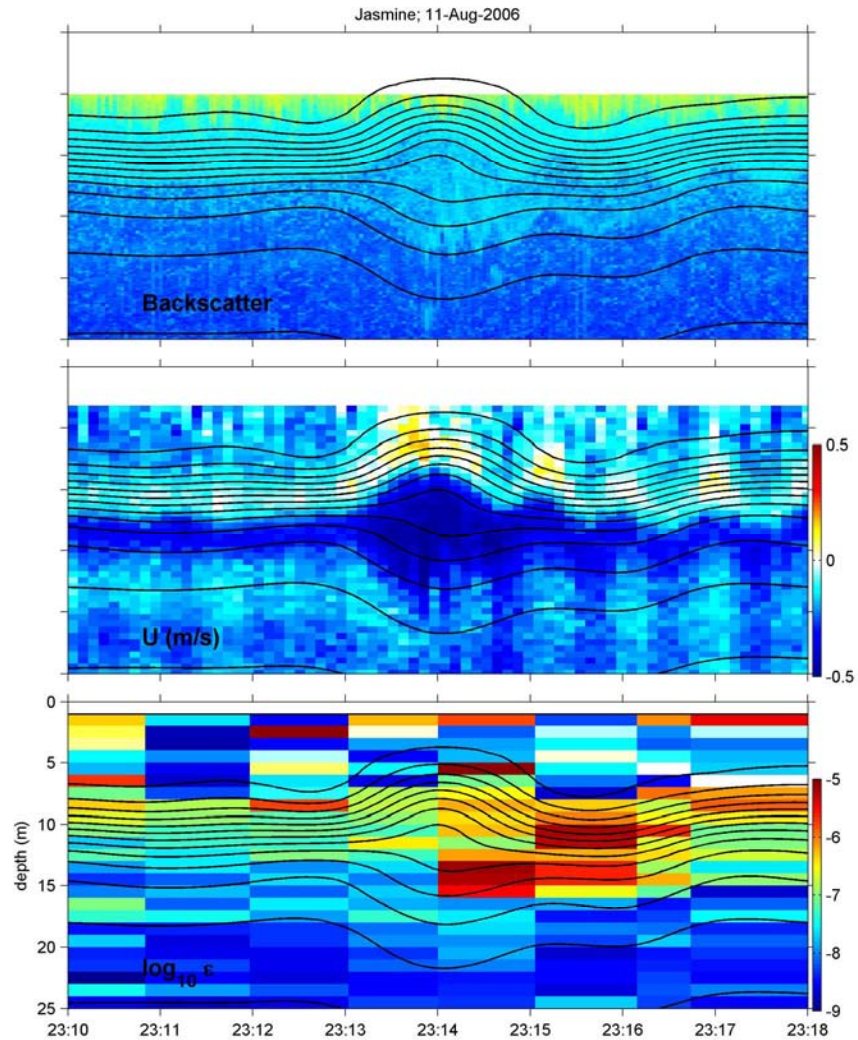


***Figure 4 – Intrusive nonlinear internal waves on the NJ shelf. This example shows acoustic backscatter, velocity in the wave propagation direction and turbulence dissipation, with isopycnals plotted on the image plots. The wave displaces isopycnals above 12m vertically upward and below 12m vertically downward. The wave's lee is highly turbulent.***

## IMPACT/APPLICATION

Experimental verification of the existence, sign and magnitude of the bottom pressure signature of NLIWs indicates what we understand the physical structure of the wave pressure signal. This permits extension of the measurement to practical applications such as simple wave detection and more scientific applications such as inexpensive multi-component wave antennae.

Our explanation of the nonlinear internal wave pressure signal also gives us confidence in our assessment of wave energy transport. This differs significantly from the way that energy is transported in linear internal waves. The dominant terms are the pressure-velocity flux with a pressure form that is fundamentally different from that of a linear internal wave, and a nonlinear advection term that does not exist for linear internal waves. Our determination that $fE=cE$ simplifies matters.

## RELATED PROJECTS

The SW06 experiment involves collaboration with a large range of PIs, including physical oceanographers and acousticians. The examination of nonlinear internal waves includes collaborations with David Farmer (URI), Larry Armi (SIO), Jody Klymak (SIO), Jonathan Nash (OSU) and Bill Smyth (OSU). Continued analysis of various aspects of differential diffusion begun with the support of ONR for our observations of this phenomenon in the ocean continues in collaboration with Bill Smyth (OSU) and Jonathan Nash (OSU). A close collaboration with Andone Lavery (WHOI) and Dezhang Chu (WHOI) on analysis of broadband acoustic turbulence data from SW06 is ongoing.

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