Large Amplitude Breaking Internal Solitary Waves: Their Origin and Dynamics

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LONG-TERM GOALS

To determine the mechanisms of generation, propagation, dissipation, mixing and decay of large amplitude internal waves formed by tidal flow past topography.

OBJECTIVES

Our objectives are to use both acoustic remote sensing and *in situ* profile observations of large amplitude internal waves, together with highly resolved numerical simulation, so as to develop a predictive understanding of their behavior, with application to their generation by flow past topography, their contribution to mass and momentum transport, mixing, modulation of near surface bubble clouds and related properties. A further objective is to use the numerical simulation to test hypotheses related to observed convective overturning and shear instability induced by the waves under different conditions of stratification and shear and to estimate the mixing and dissipation resulting from these processes.

APPROACH

Our approach includes the analysis of internal wave measurements acquired on a series of cruises to the Oregon shelf and Knight Inlet, in which detailed observations of internal waves were acquired. This analysis includes both the interpretation of sequential ship runs across the internal waves, especially in the generation region, and slow traverses which are most appropriate for resolving small scale instability and overturning. The primary observations consist of rapid CTD profiling, ADCP measurements and high resolution acoustic backscatter imaging. Photography from fixed wing (Oregon shelf) and rotary wing (Knight Inlet) aircraft provide supporting data. The observations were acquired on the Oregon Shelf in a collaboration with J. Moum (OSU), L. Armi (SIO) and S. Vagle (IOS); The observations in Knight Inlet were acquired with S. Vagle, P Cummins (IOS) and L. Armi (SIO).

Model calculations are carried out with either the incompressible Euler or Navier-Stokes equations under the Boussinesq approximation (c.f. Lamb, 1994, Cummins 1995) with background stratification and current matching the observations. Additional comparisons are carried out with available laboratory model observations. There are two motivations in this modeling effort. In the collaboration with Patrick Cummins the goal is to understand the generation of large amplitude nonlinear waves through detailed comparison with observations. In the collaboration with Lamb the goal is to reproduce the observed fine structure, breaking of the internal waves and small scale shear instability, with a high resolution two-dimensional numerical model. If the model can reproduce these features it

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will provide a tool for examining related aspects such as mixing and energy dissipation. Additional collaborative efforts exist with J Grue (U. Oslo) in which the results of analytical modeling are compared with the generation of shear instability and breaking.

WORK COMPLETED

Data from two cruises have been analyzed. For the study of large amplitude internal wave generation we have used results from sequential density and velocity sections over the Knight Inlet sill in which the flow is strongly forced (Armi & Farmer, 2002), that is, the tidal current is great enough to displace the flow control to a point downstream of the sill crest. In this case the subcritical response over the sill has an upstream expression in the form of a wave of depression. Nonlinear steepening of the leading edge of this wave leads to dispersion and the formation of an internal undular bore (see Figure 1). This bore is almost arrested by the accelerating flow, but eventually advances upstream away from the sill (Farmer & Armi, 1999a, b). The full sequence of events leading to wave generation has now been successfully modeled (Figure 2, 3) and published by Cummins, Vagle, Armi & Farmer (2003).

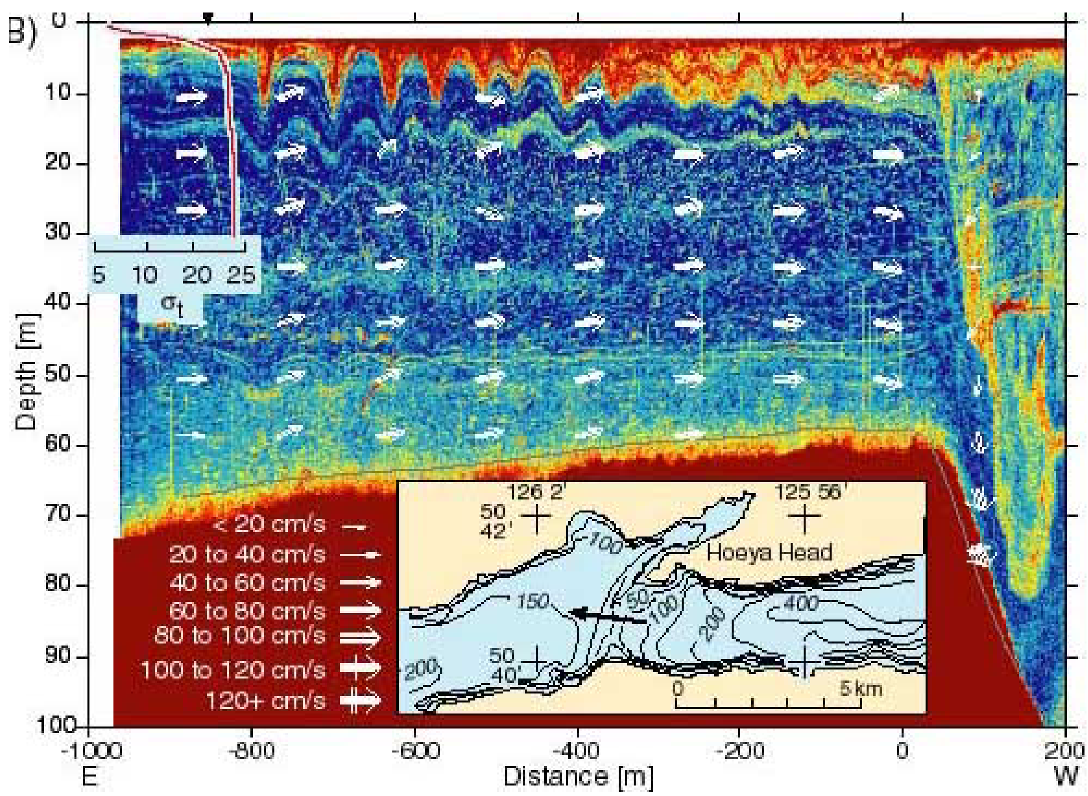

Figure 1: Representative observations of upstream generated nonlinear internal waves. The tidal flow is from left to right and the waves ride at the leading edge of a wave of depression that slowly advances upstream.

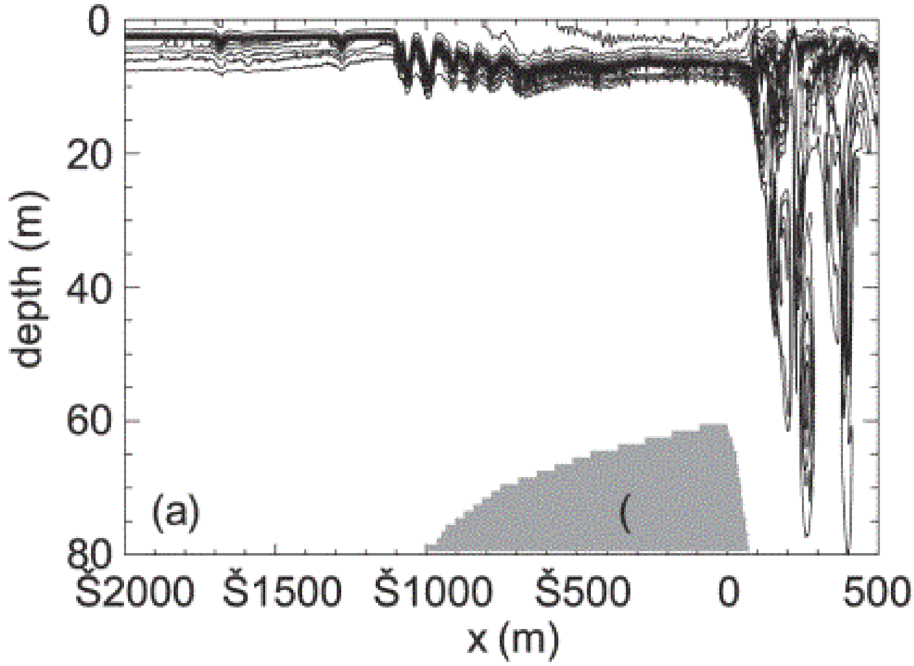

Figure 2: Model simulation of the features illustrated in Figure 1, showing generation of internal waves upstream of topography. Flow is from left to right. As the tidal current increases from rest, a subcritical response generates a subcritical wave of depression that propagates upstream. The leading edge steepens and evolves into a sequence of nonlinear internal waves. (Adapted from Cummins et al., 2003.)

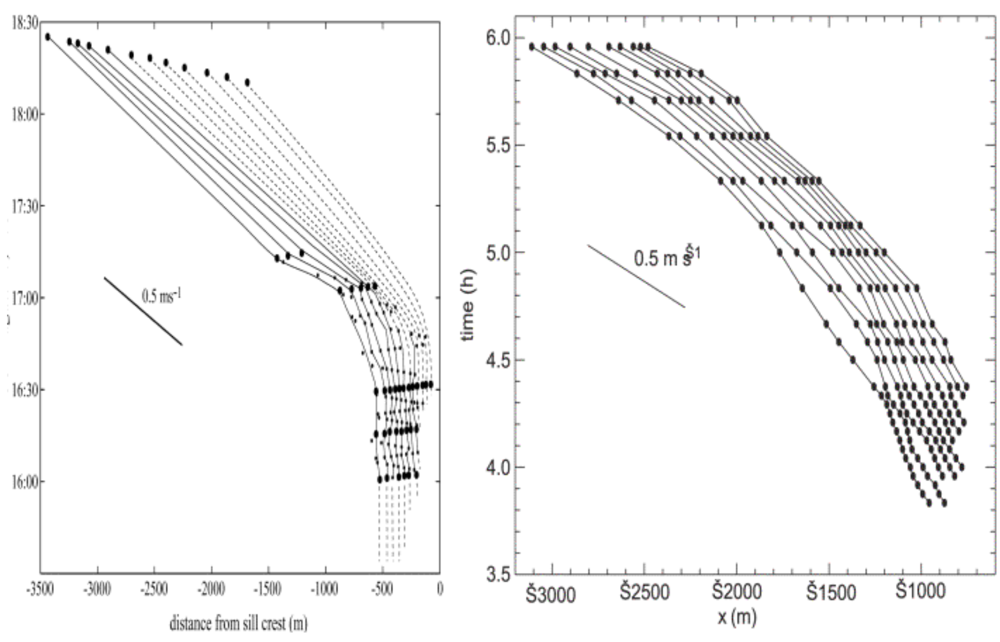

Figure 3: Left, Observed locations of internal waves. Right, Modeled locations. The waves ar initially arrested due to the accelerating tidal current. (Adapted from Cummins et al., 2003).

A preliminary analysis of our measurements of large amplitude internal waves (see Figure 4) on the Oregon Shelf explored the generation of small scale shear instability in terms of solutions to the Taylor-Goldstein equation. The results have been published (Moum, Farmer, Smyth, Armi & Vagle,

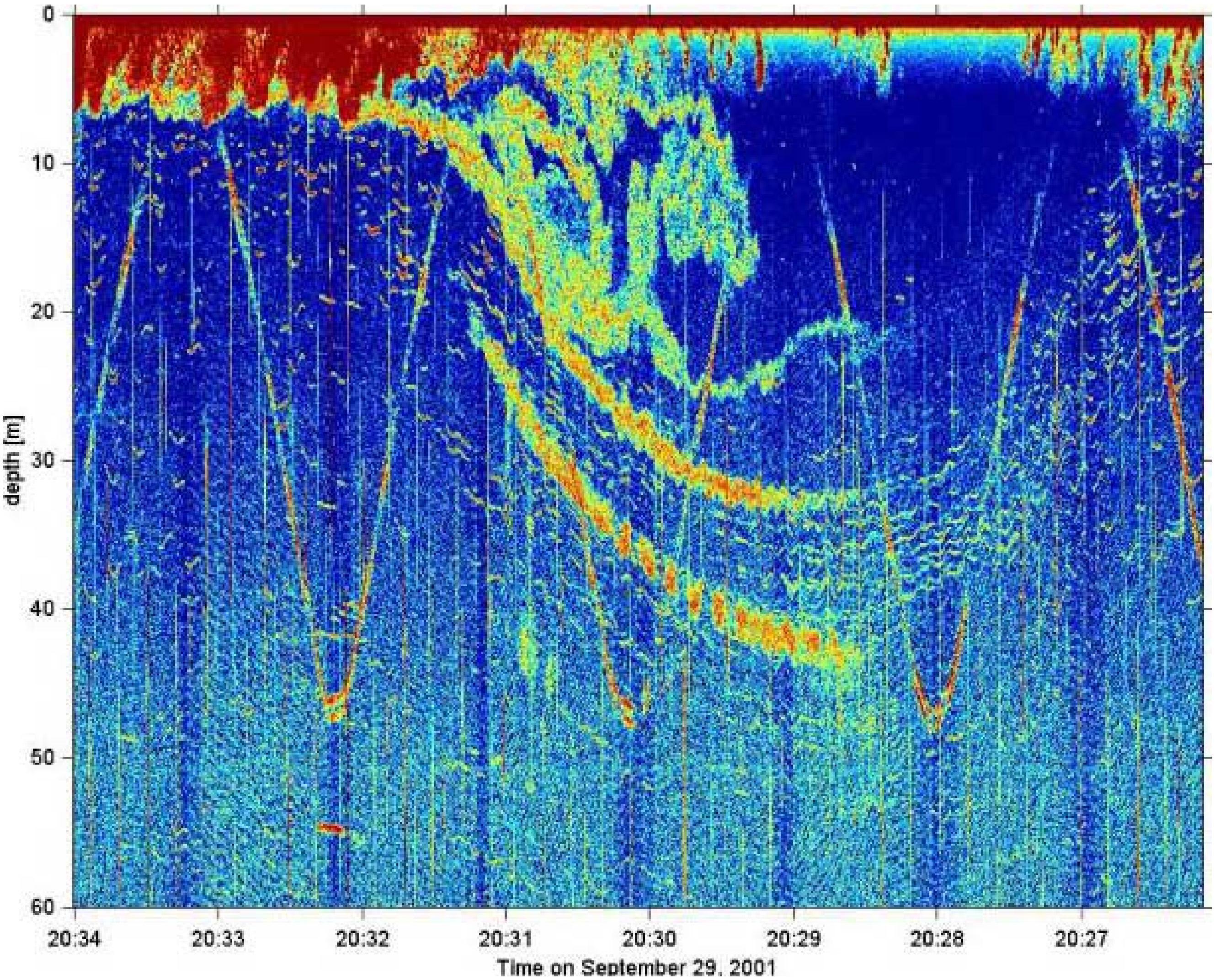

Figure 4: Acoustic image of breaking internal wave observed over the Oregon Shelf. The acoustic backscatter is enhanced along unstable shear lines and reveals a large scale convective overturn on the left side of the wave trough. The wave is tyravelling from left to right. Smaller scale instabilities occur in advance of the over turn. Enhanced backscatter along isopycnals at greater depth (30m and 40m) is attributed to small scale shear instability and enhanced soundspeed microstructure.

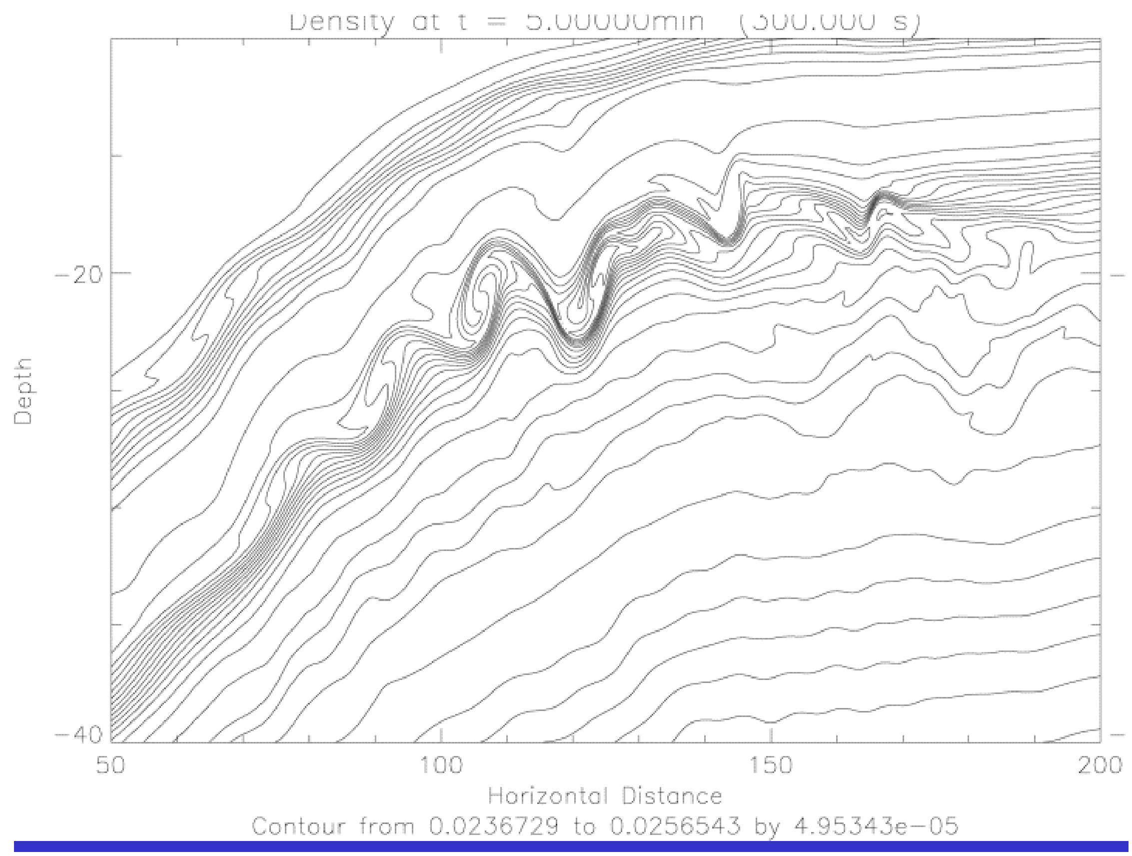

Figure 5: Small scale shear instability predicted by numerical model for representative density and shear structure of Oregon Shelf. The instability evolves towards the trailing edge of the wave.

2003). A numerical simulation has been implemented with K. Lamb, using upstream density and shear profiles. While these simulations remain at an early stage of development, the results (Figure 5) illustrate the way in which shear instabilities induced by deformation of the streamlines and isopycnals as the wave passes lead to the formation of small scale instabilities.

RESULTS

This work has demonstrated a mechanism for the generation of large amplitude internal waves upstream of a topographic feature. Subcritical flow over a sill leads to an upstream wave of depression, the leading edge of which is subject to nonlinear steepening, resulting in the formation of a nonlinear train of waves. A second result of this work has been the demonstration of the formation and roll up of small scale shear instabilities induced by wave deformation of streamlines and isopycnals, similar to those observed over the Oregon Shelf.

IMPACT/APPLICATIONS

Large amplitude internal waves are almost ubiquitous in the coastal ocean and have significant influence on mixing, sediment suspension, etc., as well as presenting hazards to coastal engineering and some defense applications. The present work has led to the elucidation and modeling of a wave generation mechanism expected to be common wherever there is strong near surface stratification, shallow topography and strong tidal currents and therefore provides a basis for internal wave prediction for environments having similar stratification and topography.

RELATED PROJECTS

River Influences on Shelf Environments http://mixing.coas.oregonstate.edu/
Shoaling solitary waves http://www.moisie.math.uwaterloo.ca/~kglamb/kglamb.html
Computational methods for stratified flows involving internal waves
http://www.math.ntnu.no/~bryn/stratos/

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PUBLICATIONS

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HONORS/AWARDS/PRIZES

David Farmer, Graduate School of Oceanography, University of Rhode Island, was elected Fellow of the American Geophysical Union.