ROMS and SUNTANS Continued Development and Support of AESOP and NLIWI

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LONG-TERM GOALS

Our long-term goal is to develop a parallel ocean simulation tool that is capable of simulating processes on a wide range of scales by coupling two vastly different codes, namely the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams (2005)), and the Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator (SUNTANS, Fringer *et al.* (2006)). The tool will adaptively nest SUNTANS, an unstructured-grid, coastal-scale code, into ROMS, a curvilinear grid, regional-scale code, in regions where the motions are small-scale and so nonhydrostatic. The nested tool will be applied to study highly nonlinear internal waves in the South China Sea in order to develop an improved understanding of mechanisms that govern their generation, propagation, and dissipation.

OBJECTIVES

In support of the long term goal of applying a two-way nested simulation tool to study internal waves in the South China Sea, our objectives are three-fold. The first is to study internal waves in Monterey Bay in support of the AESOP DRI (Assessing the Effects of Submesoscale Ocean Parameterizations), and the second is to study fundamental internal wave processes in the South China Sea in support of the NLIWI DRI (Nonlinear Internal Waves Initiative). The third objective is to develop a two-way coupled SUNTANS-ROMS simulation tool that can be applied to an arbitrary domain of interest. Because recent work employing separate SUNTANS and ROMS simulations has focused on the California coastal current and internal waves in the Monterey Bay region, the west coast was the obvious choice as the study site for the development of the coupled tool, although the ultimate goal is to apply it to the South China Sea.

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14. ABSTRACT
Our long-term goal is to develop a parallel ocean simulation tool that is capable of simulating processes on a wide range of scales by coupling two vastly different codes, namely the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams (2005)), and the Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator (SUNTANS, Fringer et al. (2006)). The tool will adaptively nest SUNTANS, an unstructured-grid, coastal-scale code, into ROMS, a curvilinear grid, regional-scale code, in regions where the motions are small-scale and so nonhydrostatic. The nested tool will be applied to study highly nonlinear internal waves in the South China Sea in order to develop an improved understanding of mechanisms that govern their generation, propagation, and dissipation.

15. SUBJECT TERMS

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APPROACH

The nested simulation tool is a joint effort between Stanford and UCLA to implement a coupled cross scale system comprised of the Regional Oceanic Model System (ROMS) and the local scale code SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator). SUNTANS is an unstructured-grid, z-level, parallel coastal ocean simulation tool that solves the Navier-Stokes equations under the Boussinesq approximation with a large-eddy simulation of the resolved motions (Fringer *et al.*, 2006), while ROMS is a curvilinear- and sigma-coordinate regional simulation tool (Shchepetkin & McWilliams, 2005) that now has a nonhydrostatic module (Kanarska et al., 2006). We are developing a novel dual adaptive scheme to simulate scales that range from meters to hundreds of kilometers by coupling the multi-physics and multi-scale simulation tools ROMS and SUNTANS. ROMS will be statically nested within itself, and adaptive SUNTANS grids will be nested within ROMS and refined based on traditional tolerance criteria (i.e. vorticity and density gradients) as well as the nonhydrostatic pressure, which is a good measure of short-wavelength behavior that requires high resolution if it is to be computed accurately.

Although the long-term goal is to simulate internal waves in the South China Sea, we are developing the nested tool using simulations of the California Coastal Current by nesting SUNTANS grids in the vicinity of Monterey Bay inside ROMS simulations of the entire U. S. west coast. These simulations focus on the regional currents as well as internal waves in Monterey Bay, in support of the AESOP DRI. In addition to developing the ROMS-SUNTANS tool in this domain, we are testing turbulence models that incorporate the large-eddy simulation framework. These will be used to test the effects of submesoscale parameterizations on currents and internal waves in Monterey Bay. The high-resolution simulations of Monterey Bay will be used to compute the internal wave energy flux and energy flux divergence in order to aid in deciding on an appropriate study site for the field component of the AESOP DRI.

While the nested simulation tool is under development for the U.S. west coast in conjunction with simulations of internal waves in Monterey Bay in support of the AESOP DRI, our work also supports the NLIWI DRI by performing simulations in the South China Sea using SUNTANS to study the generation and propagation of internal solitary waves. We are also employing a laboratory-scale LES code to study how internal waves interact with a shelf break. The ultimate goal will be to nest these SUNTANS simulations inside ROMS using the ROMS-SUNTANS nested simulation tool.

WORK COMPLETED

We have performed two-dimensional idealized simulations to understand the generation of internal tides at a ridge in the South China Sea, and we have also performed three-dimensional simulations of internal waves in the South China Sea using extremely high resolution on 512 processors as part of a DOD challenge allocation. High-resolution grids with cells as small as 25 m have been generated to begin studying nonlinear internal wave activity in Monterey Bay. Simulations of shear instabilities in solitary-like internal waves have been performed using an adaptive mesh refinement code developed by Barad et al. (2008).

RESULTS

For small-amplitude barotropic tidal currents, linear theory indicates that internal tidal beams are generated over bathymetry when the slope of the internal wave beams matches that of the bathymetry (Baines, 1982). Following Vlasenko et al. (2005) this critical-slope mechanism is dominant when the ratio of the barotropic tidal excursion to the topographic length scale is small, and this ratio is given by $\alpha=u_0/\omega L$, where u_0 is the maximum barotropic tidal current amplitude, ω is the frequency of the tidal current, and L is the topographic length scale. Defining the sill Froude number, Fr, as the ratio of the maximum barotropic tidal current to the first-mode internal wave speed over the sill, c_1, such that $Fr=u_0/c_1$, the tidal excursion parameter is given by $\alpha=Fr\,(kL)^{-1}$. Here, k is the wavenumber of the internal tide, such that kL is the ratio of the topographic length scale to the wavelength of the first-mode internal tide. The Froude number determines the nonlinearity of the generation character, so that for a fixed frequency and topography, kL is constant, implying that nonlinear effects associated with increasing α can be studied by increasing Fr instead. In Zhang et al. (2008) we performed simulations over the idealized topography shown in Figure 1, and varied u_0 to study the influence of the Froude number (and hence α) on the generation physics. Those results are summarized here.

In general, over symmetric sill geometries, the results in Zhang et al. (2008) show that internal waves radiate away symmetrically (i.e. on both sides of the sill) in the form of internal tides, and the peaks in the westward-propagating internal tidal signals are formed during peak eastward tidal currents at the sill, similar to the findings of Ramp et al. (2004). Larger sill Froude numbers lead to stronger-amplitude internal tides, which eventually lead to the formation of nonlinear internal wave trains. The distance from the sill at which these trains form decreases with increasing Froude number, as shown in Figures 2(a) and (b), which show that weakly nonlinear waves form more than two internal tidal wavelengths from the sill when Fr=0.21 (Figure 2a), while strong waves form within one wavelength from the sill when Fr=1.07 (Figure 2b). This relationship has important implications for remote sensing of internal waves generated by sills, since SAR signatures of internal waves in the SCS only appear some distance from the sills at which they are generated (Jackson and Apel, 2002).

Zhang et al. (2008) show that the arrival time of peaks in the internal waves a distance from the sill (at the vertical dashed lines in Figures 2a and b) decreases with increasing Froude number, which is consistent with the nonlinear effect of increasing internal wave speed with increasing amplitude. However, when the Froude number at the sill becomes supercritical, the apparent arrival time increases (i.e. a longer travel time) because of the introduction of a hydraulic control at the sill. For subcritical Fr, peaks in the eastward-propagating internal wave signatures always coincide with peak westward tidal currents over the sill. When the flow becomes supercritical, the internal waves are effectively trapped at the sill until the flow becomes subcritical, at which point the internal waves are "released." In the limit of infinitely strong tidal flow such that the ebb tidal flow is always supercritical, the peaks in the internal waves coincide with slack tides after ebb. Otherwise, the apparent generation time coincides with the phase in the tide in which the flow over the sill becomes subcritical. This behavior is depicted in Figure 3, which shows the phase lag between the peak ebb tide over the sill and the time at which the internal tides begin propagating to the east.

While the simulations of Zhang et al. (2008) are designed to understand the large-scale generation physics and do not resolve instabilities that may result within the solitary-like internal gravity waves as they propagate, we have conducted simulations using an adaptive mesh refinement code (Barad et al., 2008) to simulate shear instabilities in solitary-like internal gravity waves (Barad and Fringer, 2008).

Figure 4 shows a progressively zoomed-in view of a simulation of a train of solitary-like internal gravity waves that have evolved from an initial Gaussian of depression on the left side of the domain. This simulation is highly multiscale and would not be possible without adaptive mesh refinement, since the size of the billows is O(1 m) while the size of the domain is O(10 km). Although the canonical value for the Richardson number (Ri) of 1/4 is a necessary condition for instability of stratified shear flows, these results indicate that a sufficient condition for instability is Ri=0.1, since the results indicate that internal waves can propagate in the absence of billows for Ri well below 1/4. As shown in Figure 4, billows form at the trough of the leading wave where the shear is the strongest (and hence Ri is the lowest), and these billows are left behind as the wave propagates to the right. Although the incipient instability that leads to the billows is two-dimensional, a three-dimensional secondary instability forms that leads to substantial dissipation and mixing, as shown in Figure 5.

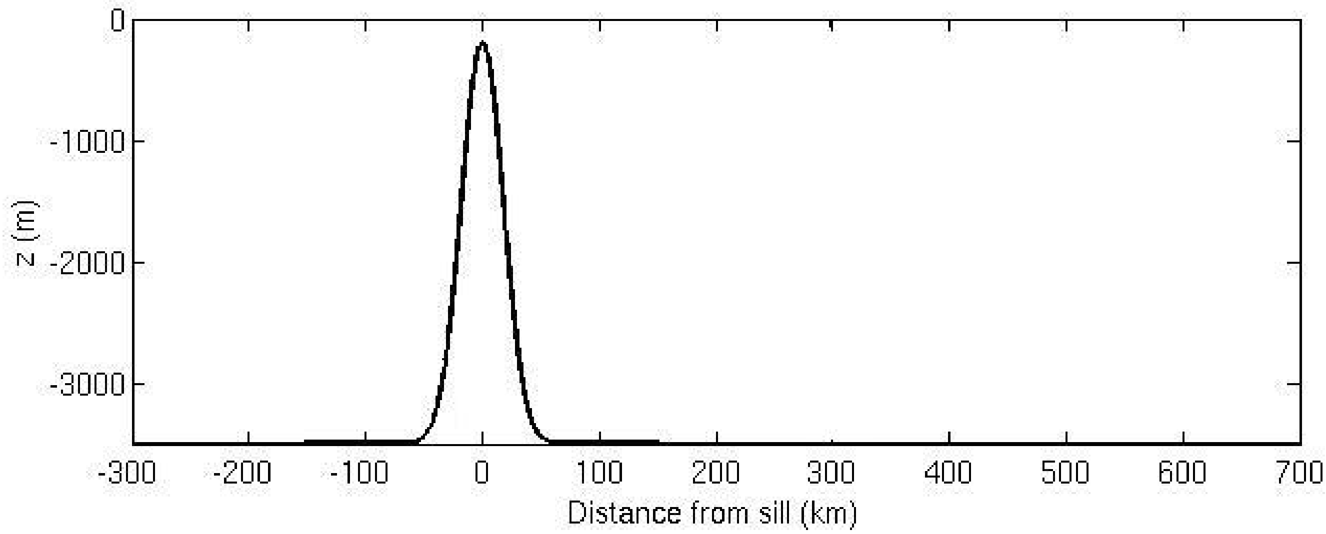

Figure 1: Two-dimensional idealized sill used in simulations to understand generation of nonlinear internal tides.

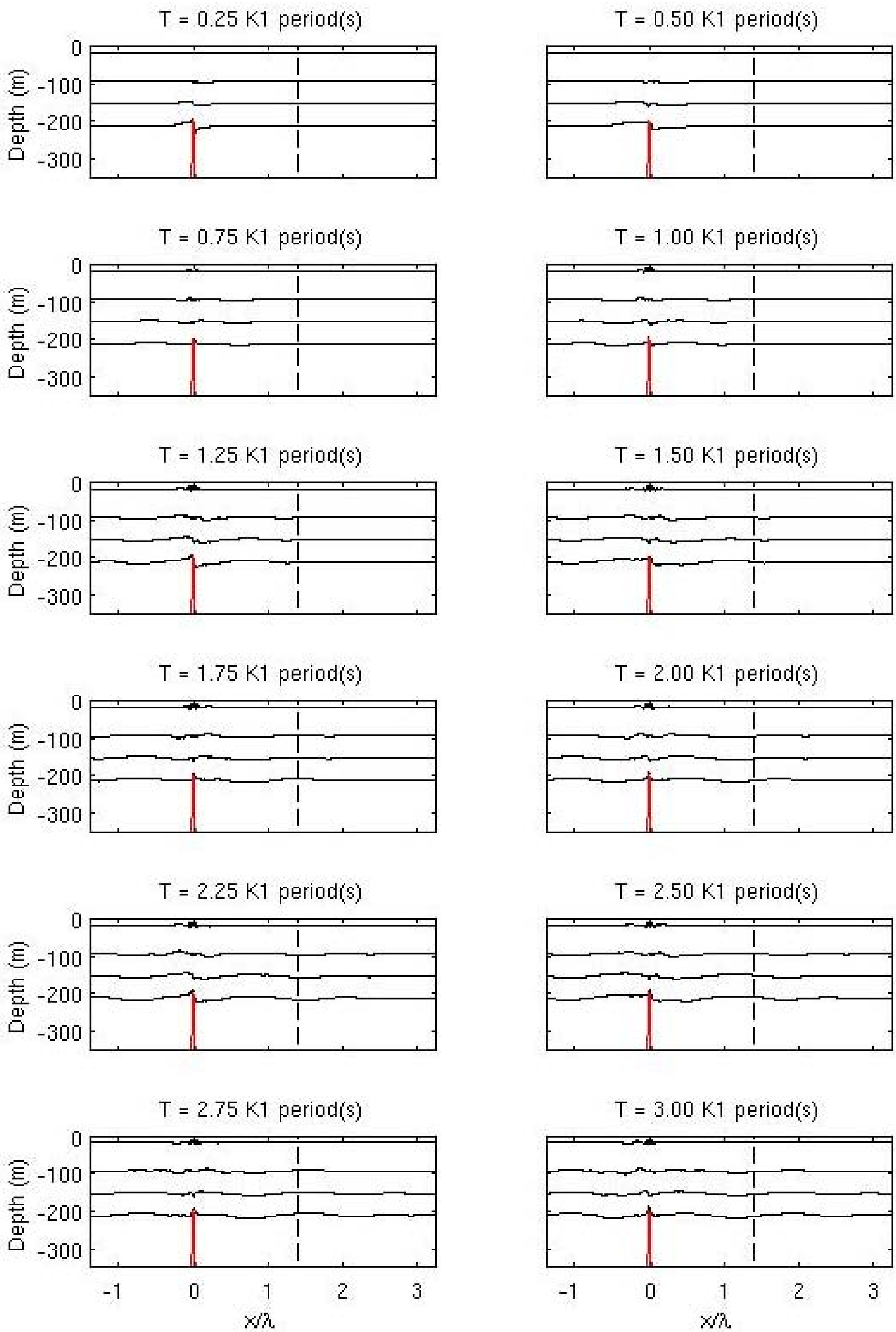

Figure 2a: Generation of internal tides and nonlinear internal waves over a two-dimensional sill when the maximum Froude number over the sill is 0.21.

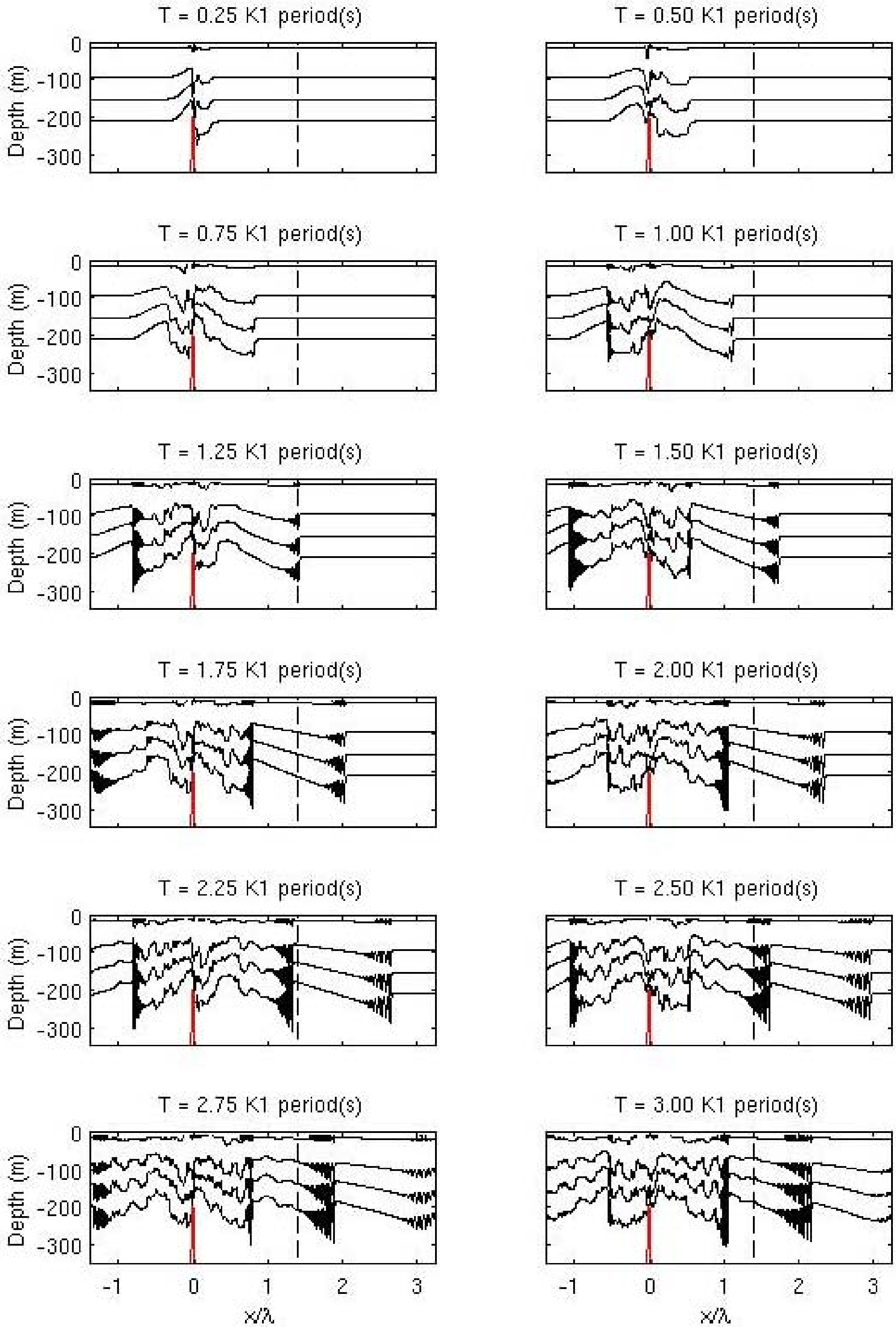

Figure 2b: Generation of internal tides and nonlinear internal waves over a two-dimensional sill when the maximum Froude number over the sill is 1.07.

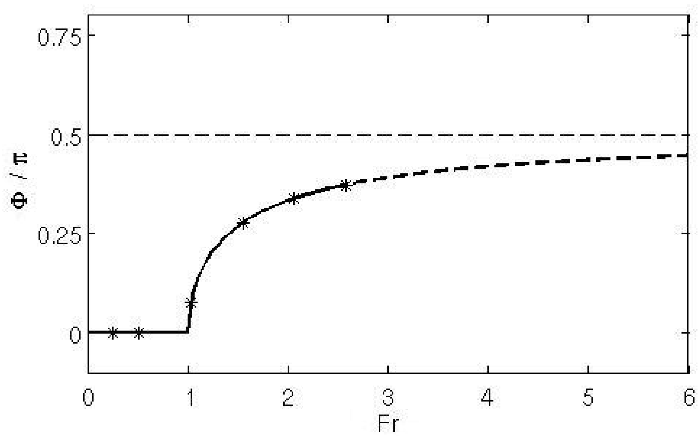

Figure 3: Phase lag Φ between the release time of the internal tides and peak ebb currents over the sill. For Fr<1, Φ=0, such that the waves always emerge at peak ebb, while for Fr>1 the phase lag approaches π/2, or slack after ebb.

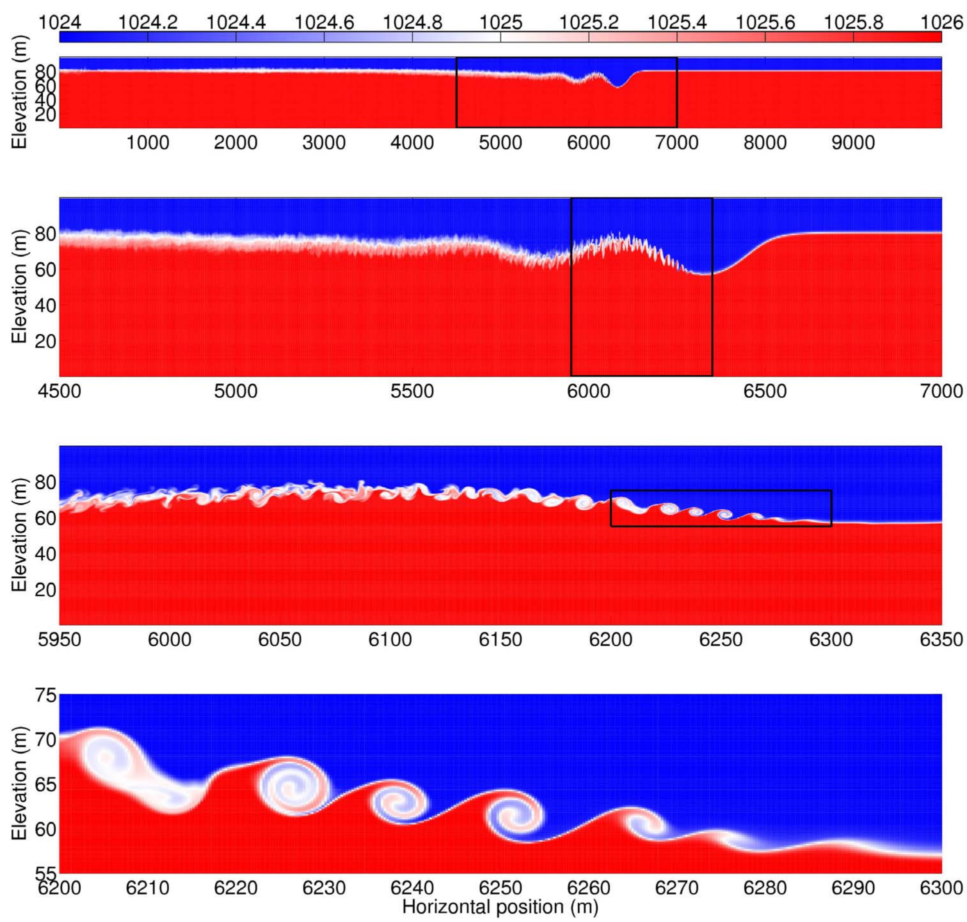

Figure 4: Simulation of a shear instability in the leading wave of a train of solitary-like internal gravity waves of depression using adaptive mesh refinement. Contours are of density in units of kg m^{-3}, while each plot is a zoomed-in view of the previous plot.

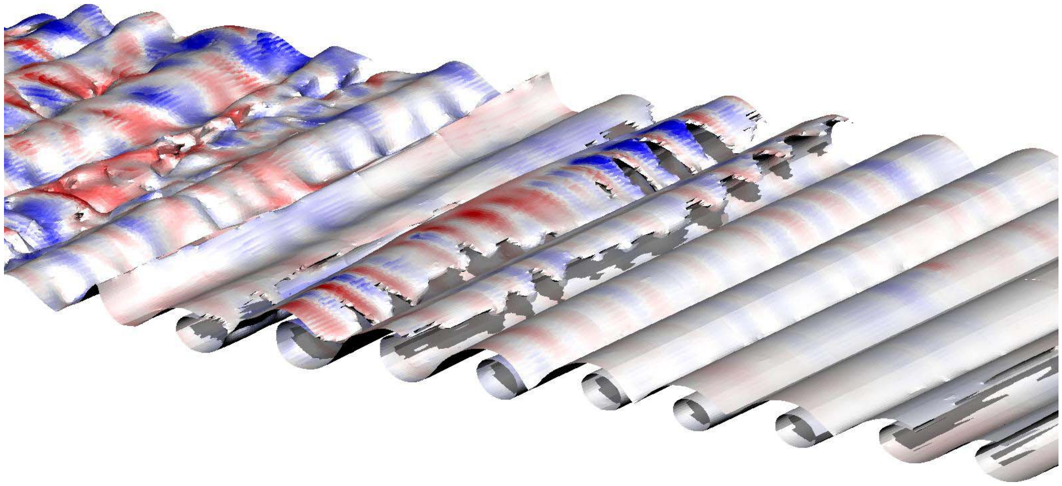

Figure 5: Isosurfaces of the mean density in the pycnocline of a breaking solitary-like internal gravity wave. Red indicates positive, while blue indicates negative lateral velocity.

RELATED PROJECTS

We are collaborating with Prof. Greg Ivey of the School of Environmental Systems Engineering at the University of Western Australia to understand the nonlinear evolution of internal waves on the Australian North West Shelf. This project involves one-way nesting of SUNTANS within the Rutgers version of ROMS and is being supported by Chevron Energy Technology Co. and Woodside Oil.

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HONORS/AWARDS/PRIZES

Oliver B. Fringer, ONR Young Investigator Award, 2008.