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.* (2006a)). 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

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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.

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.*, 2006a), while ROMS is a curvilinear- and sigma-coordinate regional simulation tool that solves the primitive equations (Shchepetkin & McWilliams, 2005). 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

Development of a one-way nested tool nesting SUNTANS inside Rutgers ROMS is complete and has been applied to study internal waves on the Australian North West Shelf. The code developed for this tool is being migrated for compatibility with UCLA-ROMS which will implement two-way parallel nesting routines. We have refined our SUNTANS simulations of Monterey Bay and have calculated the tidally-averaged energy flux associated with internal waves and have used the results to aid in the planning of the AESOP field experiments. SUNTANS simulations of internal waves in the South China Sea using 1 km resolution have been performed using 128 processors on the JVN cluster at the ARL Major Shared Resource Center.

RESULTS

We have performed simulations of internal waves on the Australian North West Shelf as a testbed for development of the ROMS-SUNTANS coupled simulation tool. To date, the coupled tool has a one-way static nesting capability, in that ROMS runs separately from SUNTANS and writes output files that are subsequently read in as initial and boundary conditions for SUNTANS simulations. The simulations can be performed with an arbitrary number of processors for both simulation codes, although each code is run individually, or "off-line". The procedure for performing the simulations is depicted in Figure 1, which depicts the complex preprocessing required to map the SUNTANS boundary points to their associated ROMS points for creation of the input data files. Current work is focusing on automating this process so that both ROMS and SUNTANS run concurrently and feed information back and forth to each other via message passing (for parallel programming) rather than via transfer files.

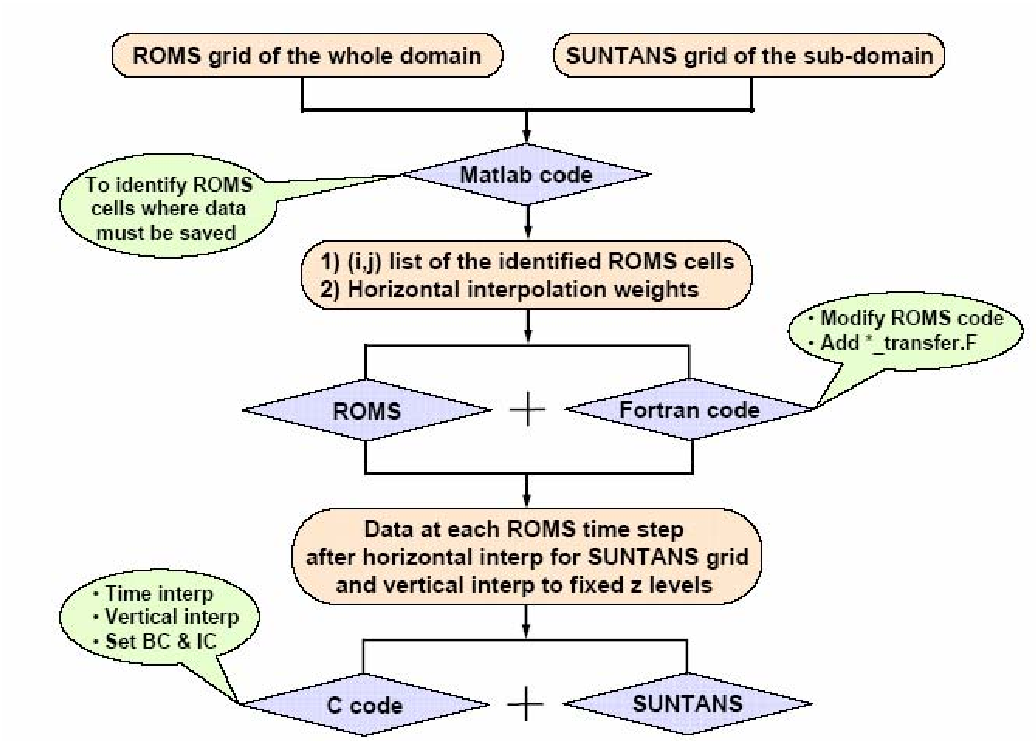

Figure 1. Flowchart depicting the preprocessing procedure for one-way nesting of SUNTANS within ROMS.

Figure 2 depicts the ROMS domain and the associated SUNTANS domain used to simulate nonlinear internal waves on the Australian North West Shelf, while Figure 2 depicts results of internal waves within the SUNTANS domain. As described in Fringer et al. (2006b), these simulations represent multiscale simulations of internal waves with lengthscales of a few kilometers in a domain that is thousands of kilometers in extent, a feat that would be computationally impossible without the nesting tool. While the grid spacing in the ROMS simulation is 2 km and the time step is 2 minutes, the finest grid spacing in the SUNTANS simulation is 200 m and the time step is 20 seconds.

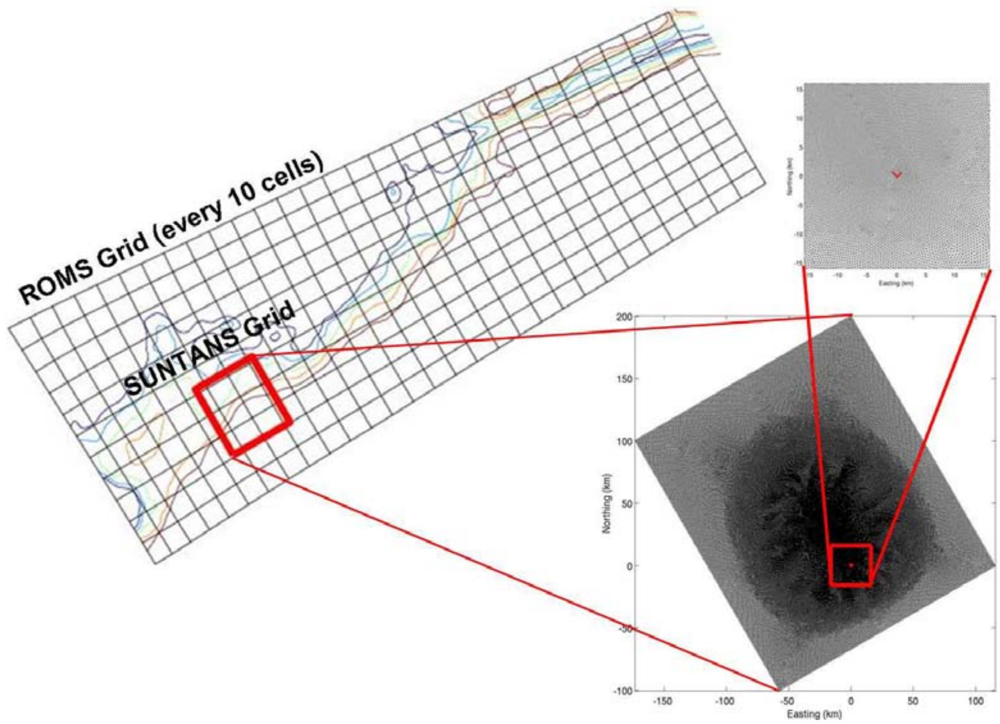

Figure 2: Depiction of the SUNTANS grid nested within the ROMS grid, showing how a resolution of 200 m is achieved within the SUNTANS grid while the extent of the entire ROMS domain is roughly 2500 km.

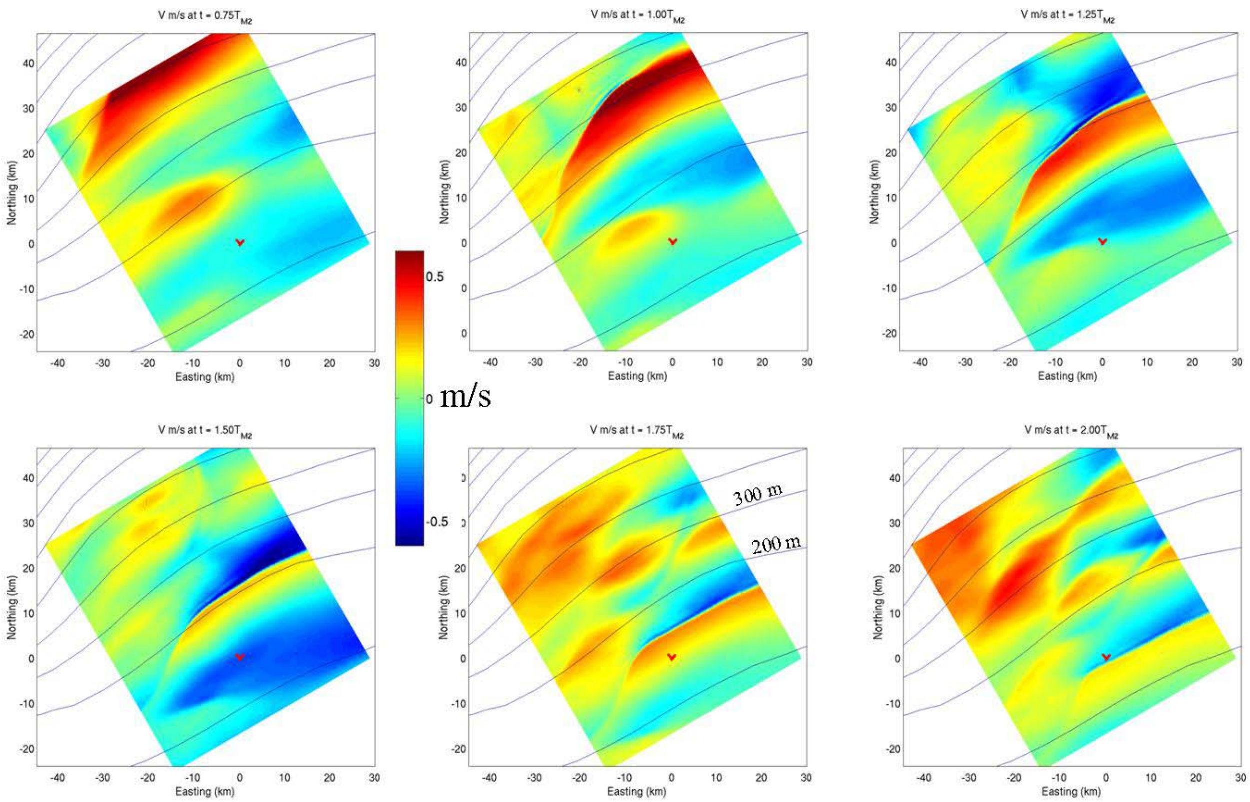

Figure 3: Depiction of the north-south surface velocity field superimposed over depth contours (plotted every 100 m) showing the evolution of highly nonliner internal wave fronts as they propagate southward onto the Australian North West Shelf.

The ROMS-SUNTANS coupled tool will be tested in its two-way nested form in Monterey Bay. Using the domain shown in Figure 4, we have been focusing on high-resolution internal wave studies using SUNTANS as part of our involvement with the AESOP DRI. Through grid studies we have learned that the magnitude of the internal wave-induced velocity field is highly sensitive to the grid resolution (Jachec et al., 2006a). Increasing the grid resolution from 3 km to 300 m leads to an increase in the magnitude of the simulated currents by an order of magnitude because fine resolution is required in order to capture the complex features of the bathymetry that are tightly coupled to internal wave generation. While higher resolution leads to the appropriate magnitude of the velocity field, finely tuned tidally-forced boundary conditions are also paramount to achieving results that match field data. Results of the energy flux calculated using high grid resolution and boundary conditions that are tuned to closely match internal wave field data at station A2 (from Petruncio et al., 1998) in Figure 4 indicate that most of the internal wave energy generation in Monterey Bay occurs to the south over Sur Platform (Jachec et al., 2006b), and as seen in Figure 5, this energy propagates northward into the Monterey Bay Submarine Canyon (MSC in Figure 4).

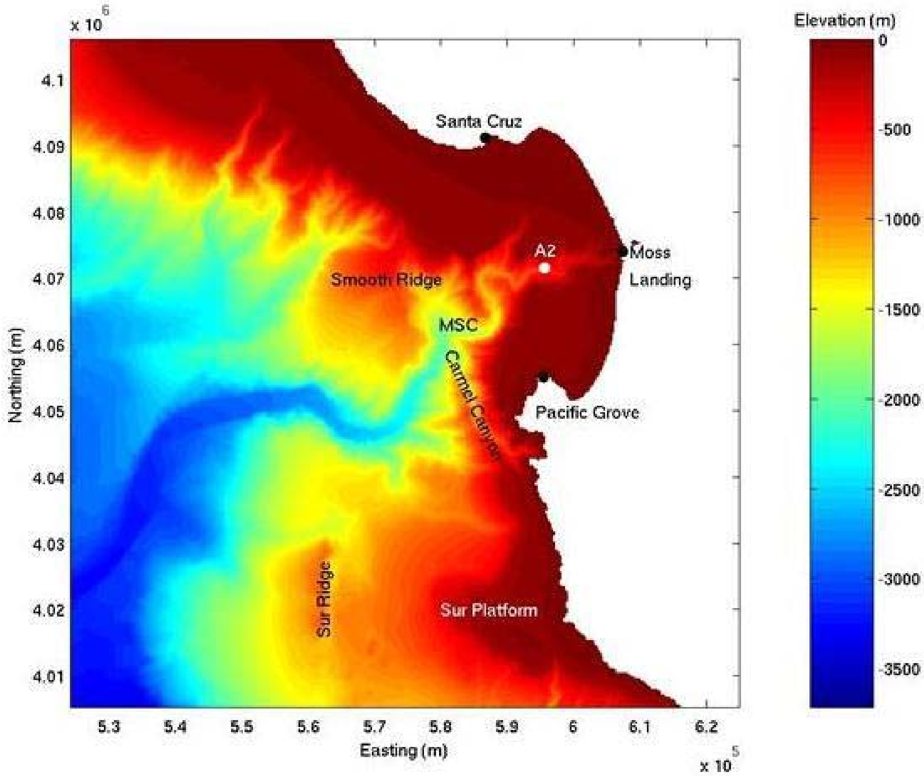

Figure 4: Monterey Bay bathymetry depicting geographical points of interest, including Sur Platform, where most of the internal wave energy in the region is generated.

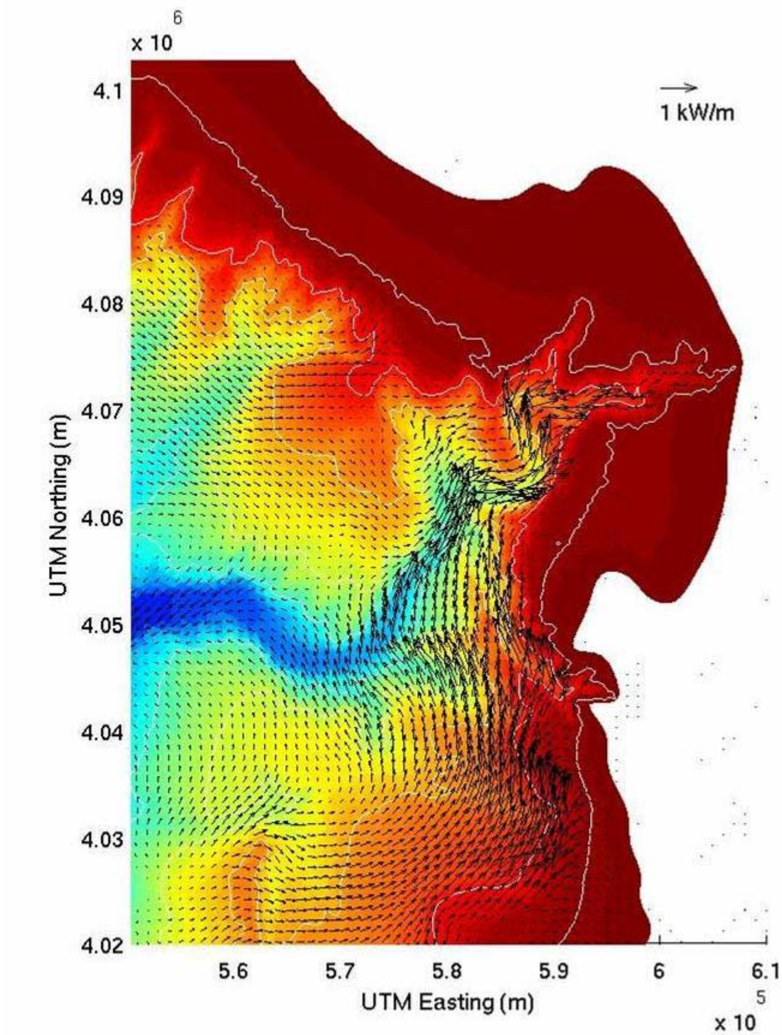

Figure 5:Internal wave energy flux vectors in Monterey Bay, showing how a significant amount of energy is generated to the south of the Bay over Sur Platform, and this energy propagates northward into the Monterey Bay Submarine Canyon, where it is ultimately dissipated.

As part of our ongoing effort to understand the three-dimensional distribution of internal wave energy in Monterey Bay, we have computed the three-dimensional energy flux divergence to gain an understanding of the horizontal and vertical structure of internal tide sources and sinks in Monterey Bay. Using the positive energy flux divergence as a surrogate for internal wave generation (while negative energy flux divergence implies an internal wave energy sink), Figure 6 depicts three-dimensional isosurfaces of internal tidal energy generation (in W/m3) between Sur Platform and Monterey Bay. The magenta isosurface (0.003 W/m3) indicates that energy flux divergence over the Sur Platform is not confined to the bottom. This implies that internal wave energy generated at the bed due to the interaction of the barotropic tides with topography propagates upwards and transfers its energy into the pycnocline, and this is manifested by a positive internal wave energy flux divergence high in the water column.

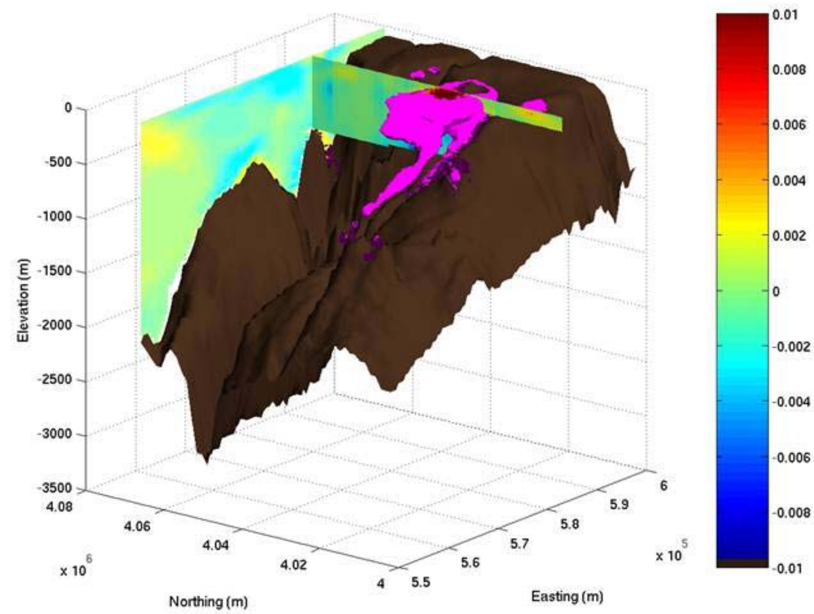

Figure 6: Three-dimensional picture of the complex distribution of internal wave energy flux divergence in Monterey Bay. The isosurface indicates a value of 0.003 W m-3 while the colorbar indicates the values in the contour plots in the two transects.

Calculations of the internal wave energy flux have also been the focus of our simulations of internal waves in the South China Sea as part of our involvement in the NLIWI DRI. As depicted in Figure 7, the domain for these simulations is much larger than the Monterey Bay domain (by a factor of 5 north-south and 3 east-west) although the internal wave features of interest have roughly the same wavelength. For this reason the South China Sea is the target for production-scale two-way coupled simulations using the ROMS-SUNTANS simulation tool that we are developing. While this is the ultimate goal, we are also performing large-scale parallel simulations of this domain using SUNTANS and the grid depicted in Figure 8. Due to the large problem size, tidal simulations over a fortnight on this grid consume roughly 10,000 processor hours using 128-processor parallel calculations at the ARL Major Shared Resource Center. High-resolution simulations allow calculations of large-scale features while computing details of the flowfield in specific areas of interest. Figure 9 depicts the internal wave energy flux in the vicinity of the Luzon Strait as computed in a smaller domain than that shown in Figure 8 using 2 km resolution near the Luzon Strait. As these simulations were designed to understand the distribution of internal wave energy flux in the vicinity of the Luzon Strait region, absorbing boundary conditions were used along the boundaries to prevent internal wave energy from reflecting back into the domain. To aid in the placement of instrumention, these high-resolution simulations provide a detailed picture of the velocity field around the Batan Islands, as depicted in Figure 10. While significant internal wave energy is generated over most of the ridges at the Luzon Strait, these islands are hypothesized to contain a sill over which a great deal of the highly nonlinear internal wave features in the South China Sea originate.

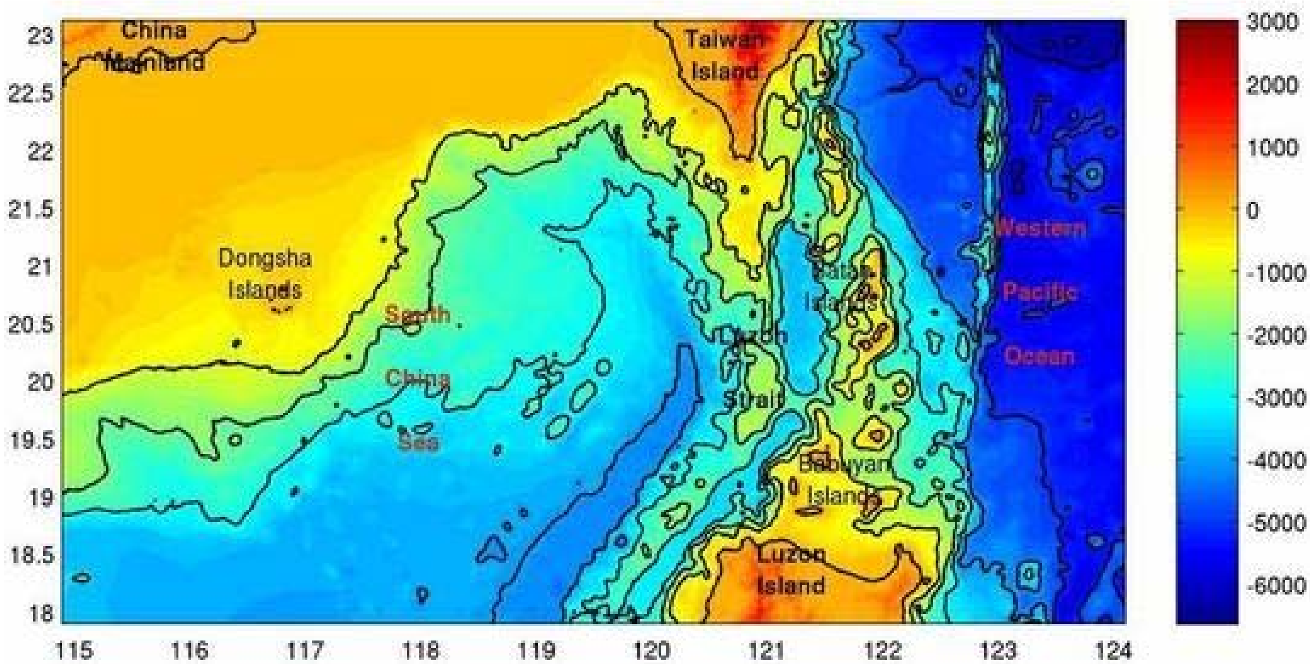

Figure 7: Bathymetry of the simulation domain used to compute generation, propagation, and interaction of internal waves with the shelf in the South China Sea.

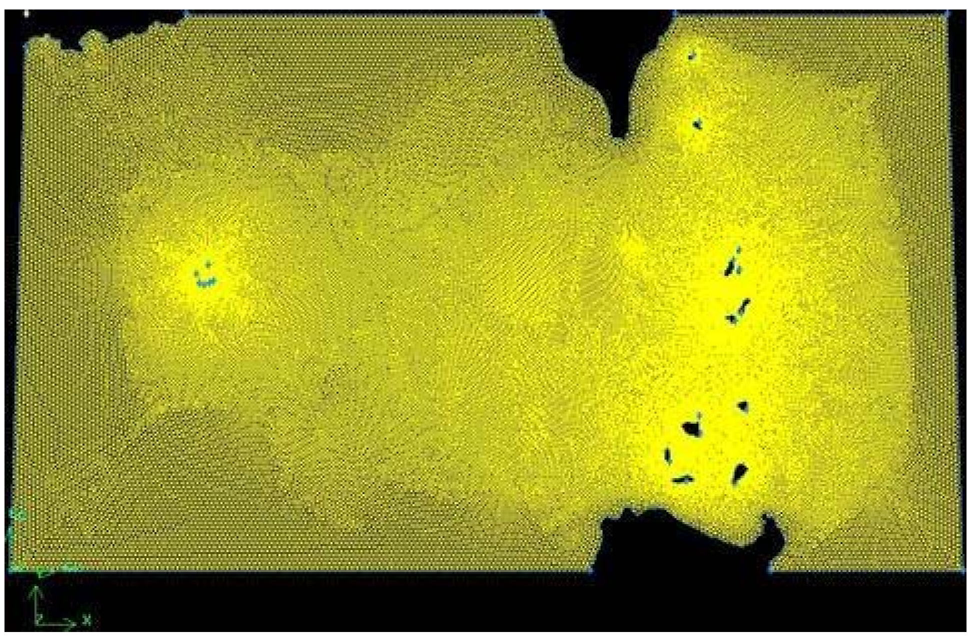

Figure 8: Unstructured grid with 12 million grid cells (roughly 2293) used for the simulation of internal waves in the domain depicted in Figure 7.

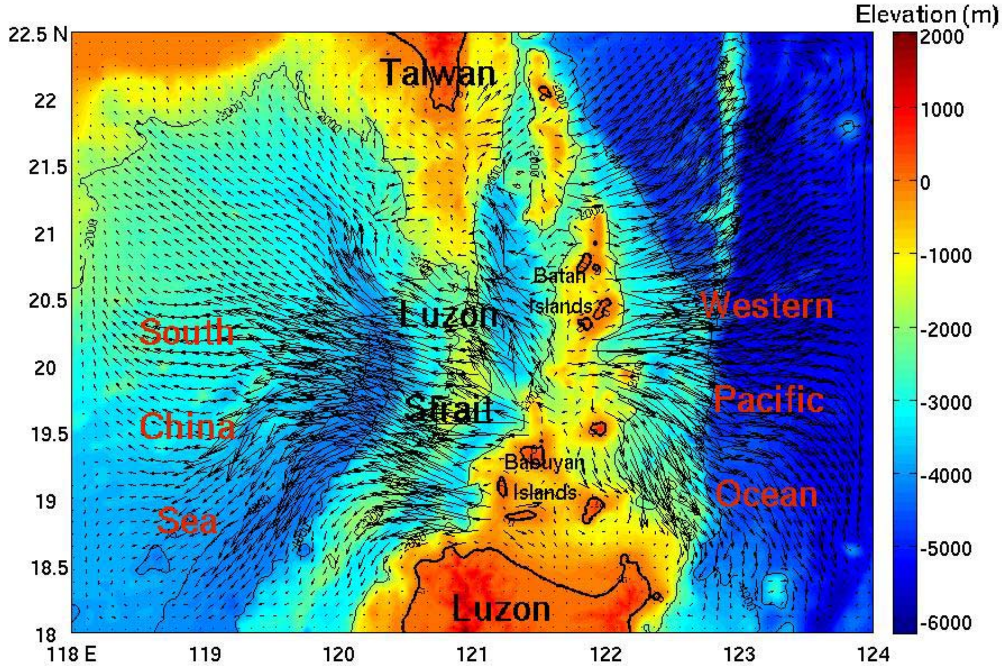

Figure 9: Internal wave energy flux (the largest is 10 kW/m) produced by the interaction of the M2 barotropic tides with the bathymetry in the Luzon Strait. The energy flux vectors are interpolated onto a coarse Cartesian grid from the fine unstructured grid for clarity.

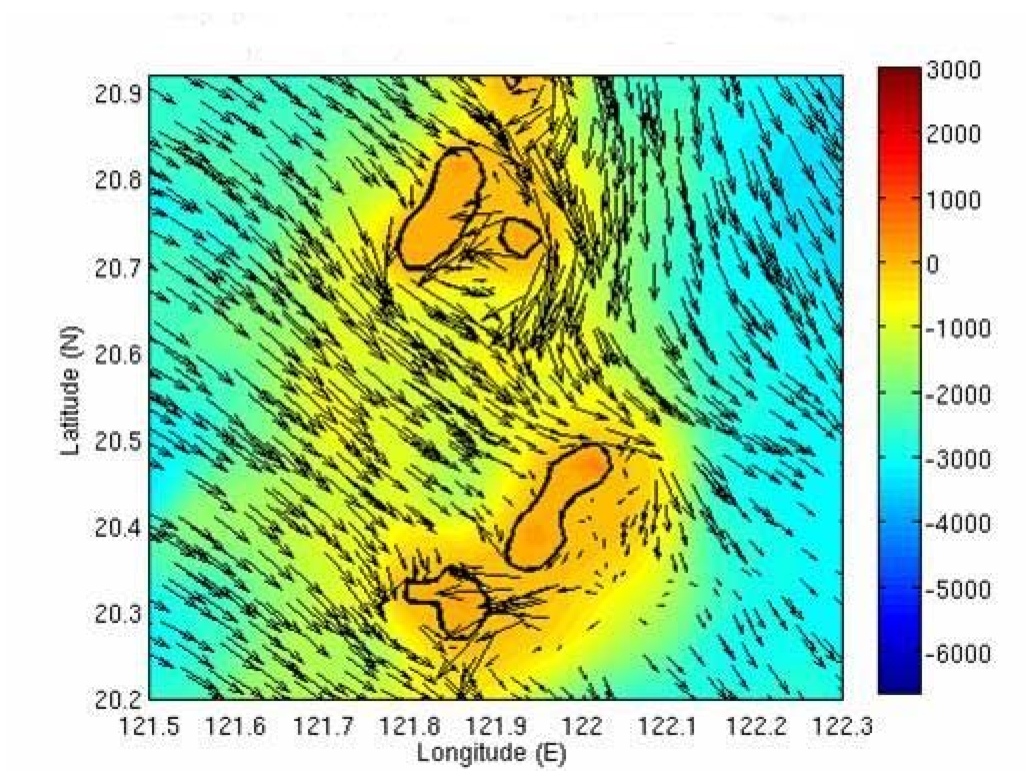

Figure 10: Surface velocity vectors at high tide in the vicinity of the Batan Islands. Color contours indicate the depth and every third vector is plotted for clarity.

To study fundamental physics of how internal waves interact with bathymetry, both in Monterey Bay and in the South China Sea, we have performed direction numerical simulations (DNS) with a nonhydrostatic, rigid-lid code, in order to understand how internal wave energy is partitioned upon interacting with a shelf break, as depicted in Figure 11. As presented in Venayagamoorthy and Fringer (2005, 2006), we have found that the interaction process is a strong function of the Froude number of the incident wave and the slope angle. In fact, there is an optimum Froude number that maximizes the relative internal wave energy that is transmitted onto the shelf, as depicted in Figure 12. Although these simulations were performed for laboratory-scale waves, the results can be applied to analyze the bulk energetics of the interaction of a highly nonlinear field-scale internal wave with a shelf break.

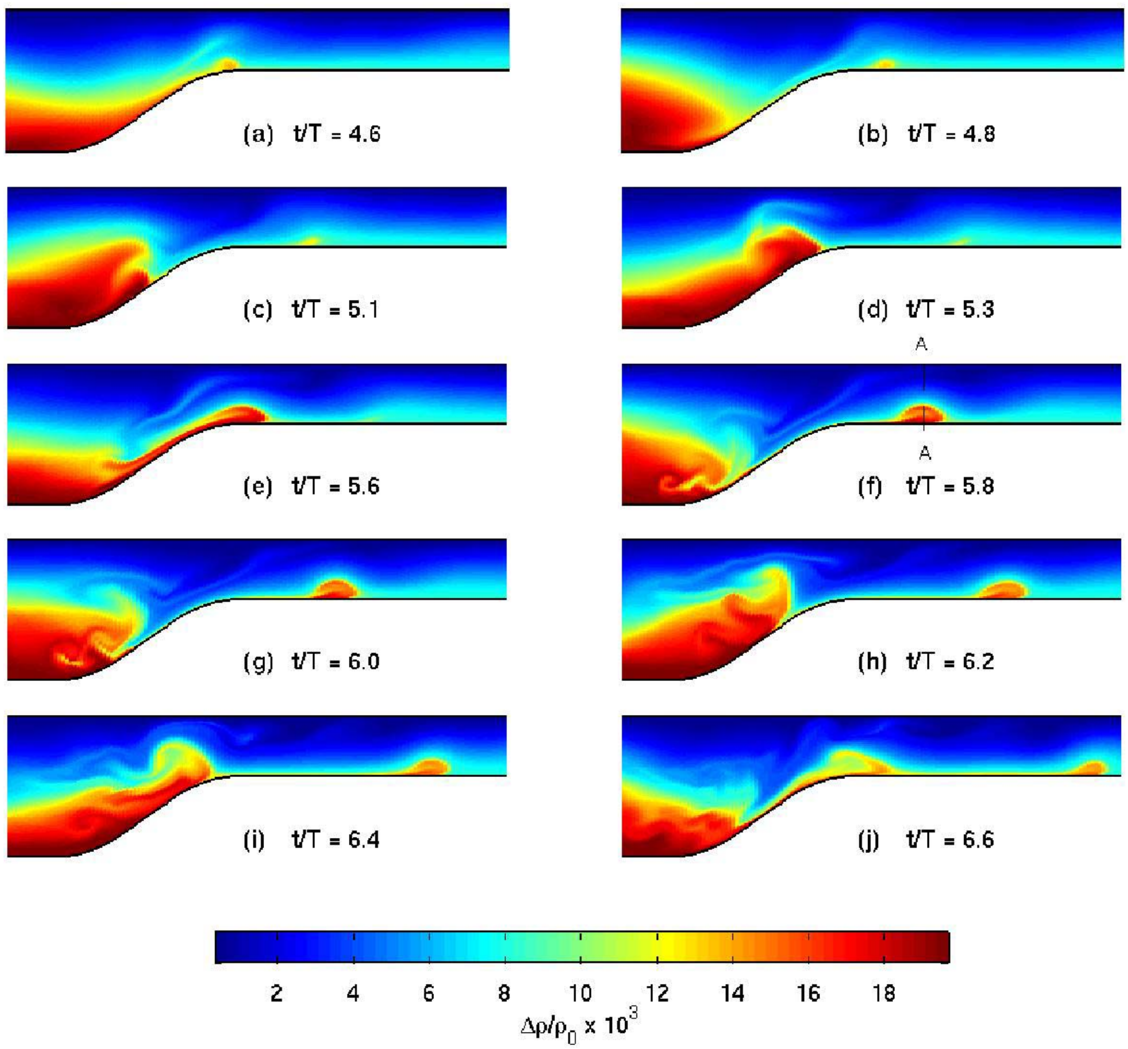

Figure 11: Interaction of a first-mode internal wave with an idealized shelf break. The time is normalized by the internal wave period T.

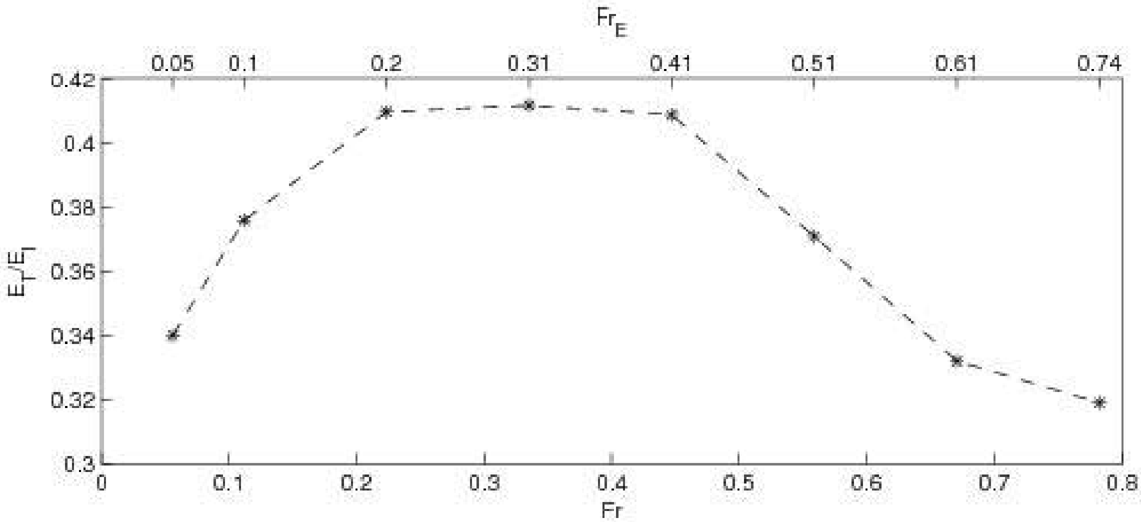

Figure 12: Ratio of transmitted to reflected energy for an internal wave incident on a shelf break as a function of the Froude number (Fr=u/c, where c is the internal wave phase speed and u is the maximum internal wave-induced velocity) of the incoming wave, showing how the transmitted energy peaks around Fr=0.3. The upper axis label represents FrE, the ratio of the internal wave excursion lengthscale to the topographic lengthscale.

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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