

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

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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.*, 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 a detailed analysis of the internal wave field in Monterey Bay in support of AESOP. This formed the Ph.D. dissertation of Steven Jachec, who recently graduated. Recent results from his dissertation are presented below. Simulations of the internal wave field in the South China Sea in support of NLIWI have also been performed. The one-way nesting routines for the ROMS-SUNTANS coupling tool have been transferred from their Rutgers ROMS implementation into the UCLA version of ROMS. Simulations of idealized geometries and simplified cases of Monterey Bay have been performed.

RESULTS

In order to obtain a more detailed picture of internal wave generation and dissipation sites in Monterey Bay (Figure 1), Figure 2 depicts the energy flux divergence. This indicates internal tide generation when the divergence is positive and internal tide dissipation when it is negative. As shown in Figure 2(a), the Sur Platform is among the most prominent generation regions, while MSC acts as a conduit that focuses internal wave energy that is eventually lost to dissipation, as shown in Figure 2(b). While these figures give a depth-averaged picture of the overall internal tidal energetics, our three-dimensional simulations have also provided a detailed picture of the generation and interaction of multiple internal wave beams in three dimensions. As depicted in Figure 3, because of the low internal Froude number and the relatively steep bathymetry (Vlasenko et al. , 2005), internal tidal beams are generated at the Sur Platform in regions where the bathymetry is critical with respect to the M2 tide. While it is clear that beams emanate from the platform itself, there are beams that propagate at an angle to the transect (not shown). These out-of-plane beams are generated by critical topography along the shelf break and propagate westward. Although they do not contribute significantly to the energy flux, these beams, and others that intersect the plane depicted in Figure 3, demonstrate how the internal tidal dynamics at a point result from the complex intersection of multiple internal tidal beams generated at multiple sites throughout the Bay.

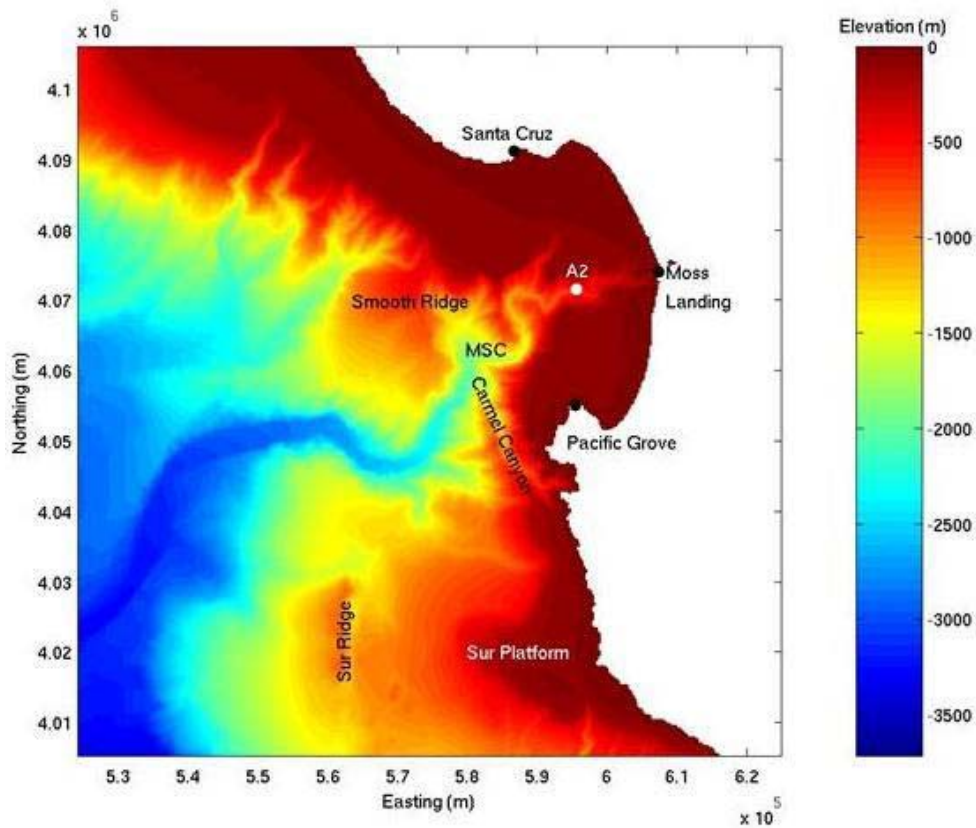


Figure 1: Monterey Bay bathymetry depicting geographical points of interest, including Sur Platform, where most of the internal wave energy in the region is generated.

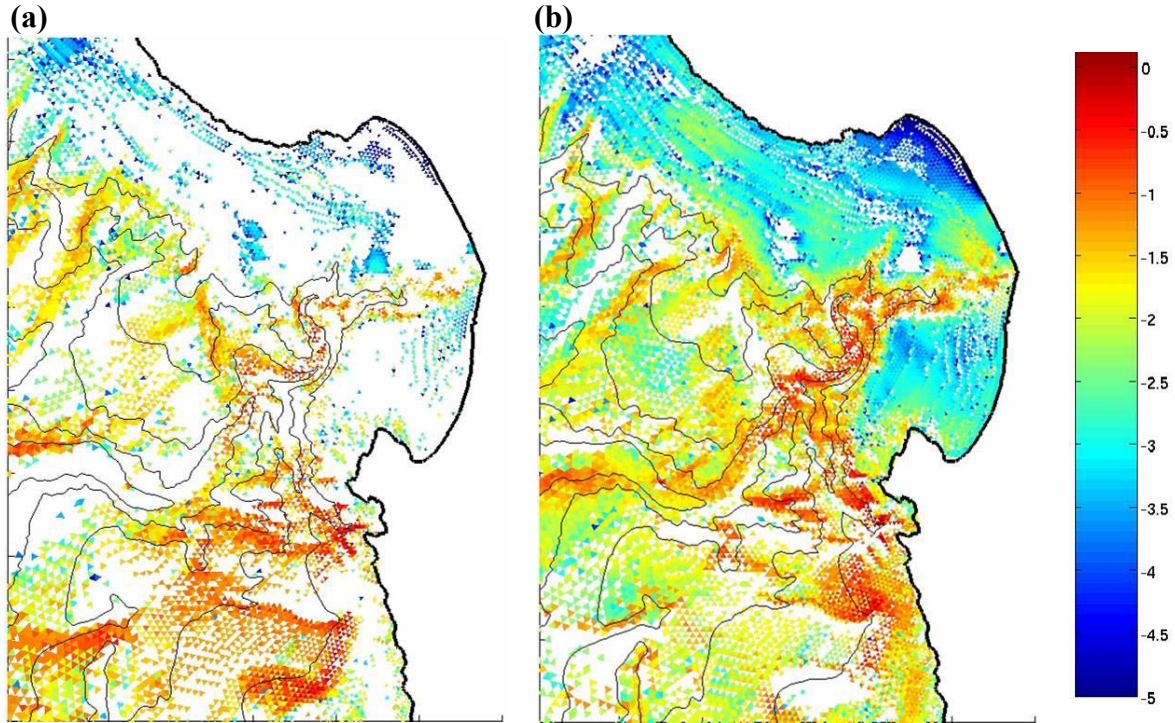


Figure 2: Internal wave energy flux generation (a) and dissipation (b) in units of $\log_{10}(W m^{-2})$ in Monterey Bay, showing how the Sur Platform is the primary generation region for internal tides while MSC acts as a conduit that dissipates internal tidal energy.

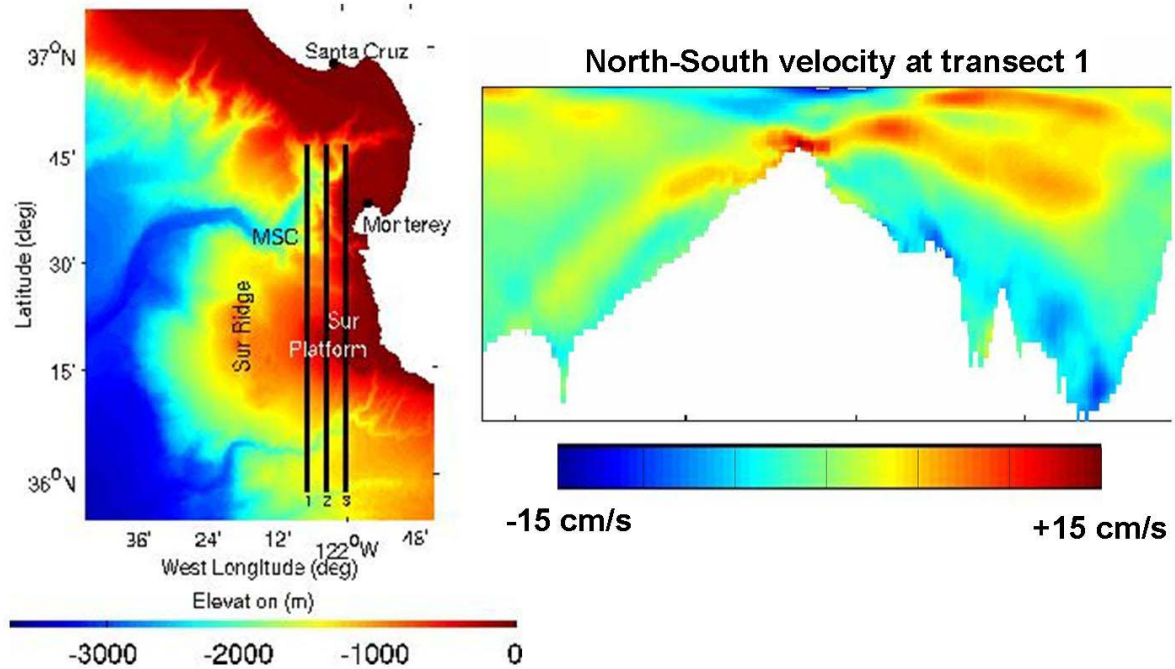


Figure 3: North-south velocity contours along a transect that intersects the Sur Platform, showing the generation of internal tidal beams.

Three-dimensional, nonhydrostatic SUNTANS simulations of the generation, propagation, and eventual dissipation of nonlinear internal waves in the South China Sea domain shown in Figure 4 have been performed using the grid depicted in Figure 5. This grid has a nominal resolution of roughly 2 km in the South China Sea basin, with 500 m resolution in the Luzon Strait region and the Dongsha Plateau. The simulations contain roughly 12 million grid cells and consume roughly 20,000 cpu hours using 64 processors on the parallel computers at the ARL MSRC in order to simulate a complete fortnightly tidal cycle. Results compare well with field data as depicted in Figure 6, which compares temperature contours of observations at mooring B1 (as shown in Figure 4) to the predictions. While arrival times and nonlinear events are predicted well, the amplitude of the peaks in the wave packets are underpredicted. This is to be expected because of the relatively coarse resolution in the basin (2 km) that is being used to simulate nonlinear waves with wavelengths of $O(10 \text{ km})$. We plan on refining the grid in the basin in order to improve the simulated amplitudes in the wave packets.

Figure 7 depicts a planview of the temperature field at a depth of 65 m, and shows how our simulations capture the generation of the nonlinear waves and their subsequent evolution into nonlinear wave packets that interact with the continental shelf. Figure 8 depicts the surface signatures associated with these nonlinear internal waves, at four different snapshots separated by two M2 tidal cycles in time. By tracing the wave fronts back to a hypothetical generation point, the wavetrains that propagate into the basin appear to emerge from a point near the western ridge in the Luzon Strait (depicted by the red dot in Figure 8). This indicates that the waves may be generated as a result of the interaction of internal tidal beams with the thermocline, rather than due to the lee-wave generation mechanism of Maxworthy (1979) at the eastern ridge.

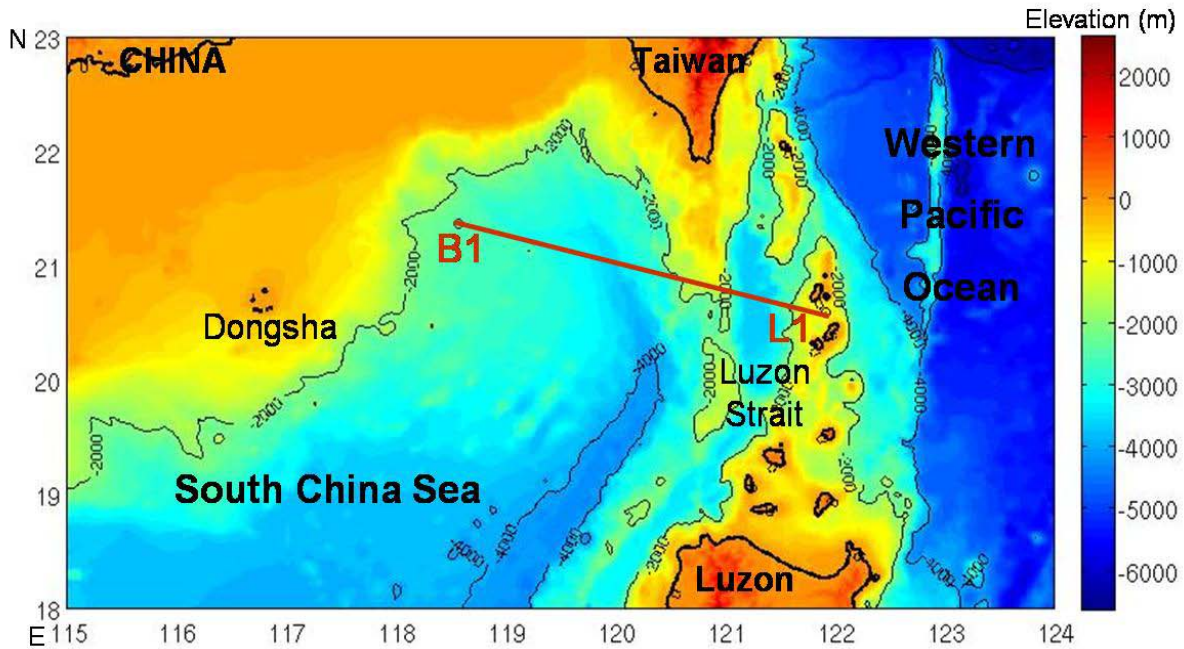


Figure 4: Bathymetry of the simulation domain (in m) used to compute generation, propagation, and interaction of internal waves with the shelf in the South China Sea. L1 and B1 are the locations of the moorings of S. Ramp, NPS.

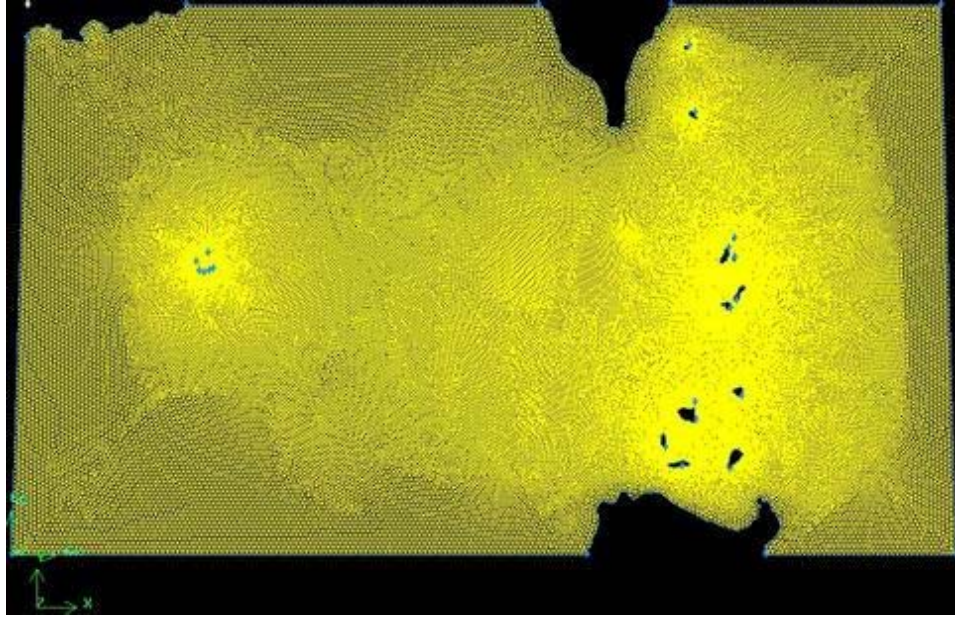


Figure 5: *Unstructured grid with 12 million grid cells (roughly 229^3) used for the simulation of internal waves in the domain depicted in Figure 4.*

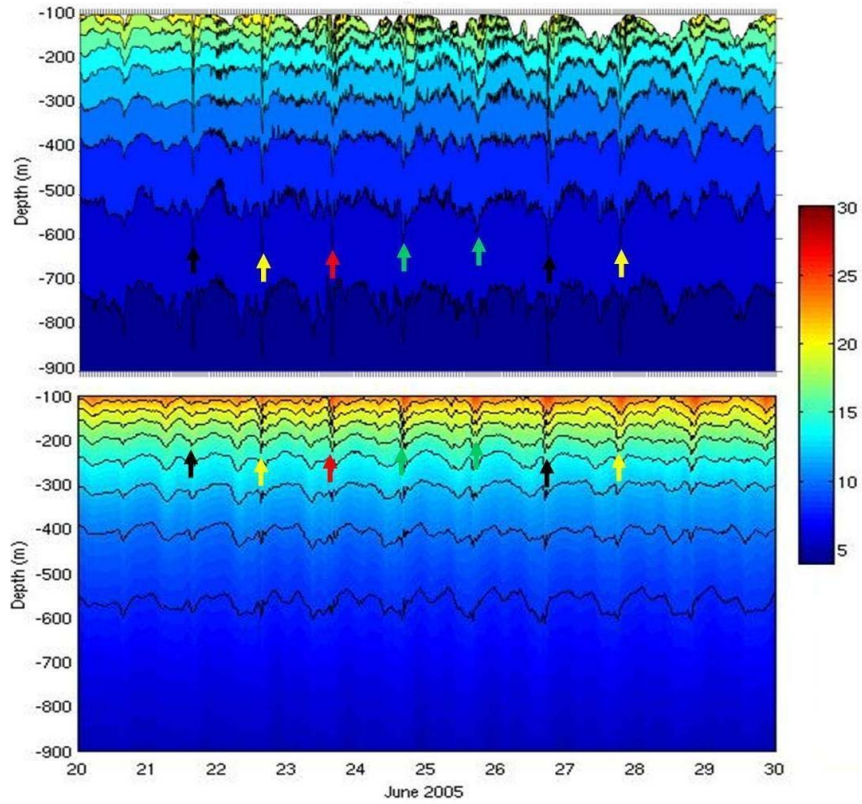


Figure 6: *Comparison of observations (top) of temperature contours (in $^{\circ}\text{C}$) to the simulation results (bottom) at mooring B1. Mooring data courtesy of S. Ramp, NPS. Colored arrows highlight nonlinear wave events with amplitudes in excess of 100 m.*

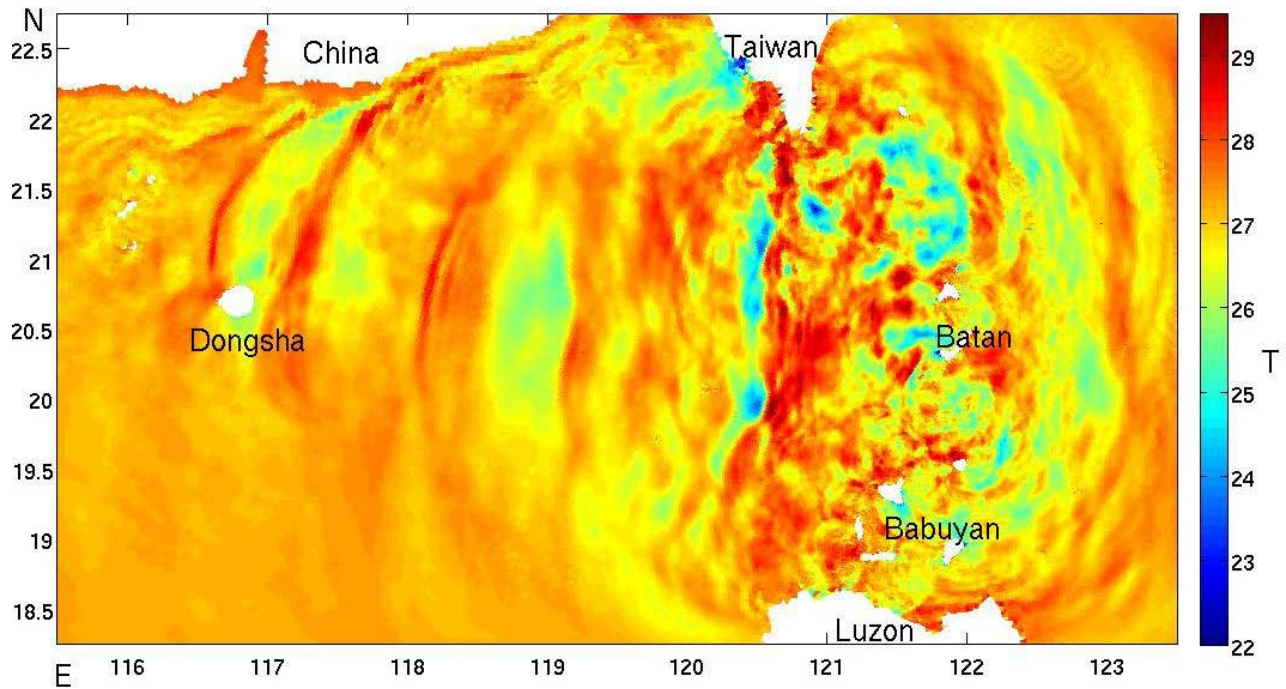


Figure 7: Temperature contours at a depth of 65 m, showing the formation of nonlinear wave trains that propagate across the South China Sea and eventually dissipate on the continental shelf.

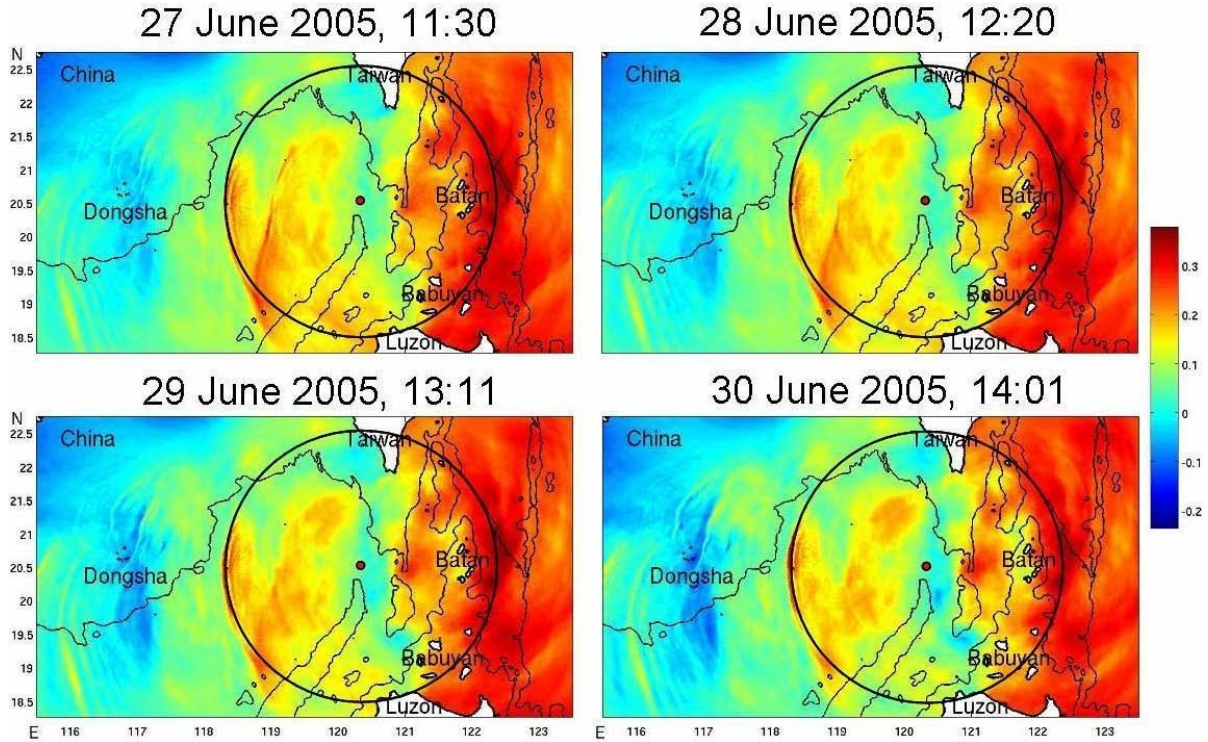


Figure 8: Surface expressions of internal waves in the South China Sea (in m) 2 M2 periods after one another. The red dot indicates the internal wave source inferred from the wave fronts.

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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