A Multiscale Nested Modeling Framework to Simulate the Interaction of Surface Gravity Waves with Nonlinear Internal Gravity Waves

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LONG-TERM GOALS

Our long-term goal is to develop a multiscale nested modeling framework that simulates, with the finest resolution being sub-meter scale, surface mixed layer processes arising from the combined action of tides, winds, and mesoscale currents. We focus on studying surface gravity wave evolution and spectrum in the presence of surface currents caused by strongly nonlinear internal solitary waves. We aim at understanding the impact of tidal, seasonal, and mesoscale variability of the internal wave field and how it influences the surface waves.

OBJECTIVES

This project aims at using a novel multiscale nested modeling framework to simulate, with the finest resolution being sub-meter scale while using inputs from 1000 km scale, surface mixed layer processes with an emphasis on the interaction of surface and internal waves. As a model problem of mixed-layer dynamics involving numerous physical processes acting over a wide range of spatio-temporal scales, we will focus on the interaction of surface and internal gravity waves in the South China Sea. We will seek answers to the following questions:

1) How does the wind-wave field evolve in the presence of surface currents driven by internal solitary waves?
2) How does the surface gravity wave field above internal solitary waves modify the mixing and dissipation in the mixed layer?
3) What specific parameters related to internal solitary waves enhance or limit their impact on the surface gravity wave spectrum? How does this affect the detectability of internal solitary waves in SAR imagery?
4) How does the variability of internal solitary wave currents impact the surface gravity wave spectra?

APPROACH

This project builds on a suite of novel and well established simulation tools developed by PI Shen and collaborators. At the finest scale, a large-eddy simulation (LES) code that simulates turbulence-wave interactions on a wave-surface-fitted grid and a nonlinear wave-field simulation code will be employed. The LES code will be driven by currents from a high-resolution, nonhydrostatic, isopycnal-coordinate model by collaborator Dr. Oliver Fringer at Stanford University that will simulate internal solitary wave evolution. Initial and boundary conditions for the latter will be obtained from collaborator Dr. Dong Ko at Naval Research Lab using the East Asian Seas Nowcast/Forecast System (EASNFS), which computes the generation of internal tides and includes assimilated seasonal and mesoscale variability. Ultimately, EASNFS is also nested within Global NCOM. As a result, while this project focuses on small-scale problems with domain size of 1 km and resolutions down to 1 m for turbulence eddies and 10 cm for waves, the fine-scale features are simulated through nesting of four models over spatial scales ranging from 1000 km down to 10 cm.

The LES code simulates turbulence near the sea surface on a wave-surface-fitted grid together with a phase-resolving wave-field simulation code. In the method, the grid evolves dynamically with the wave motion with the kinematic and dynamic sea-surface boundary conditions directly implemented. The LES uses advanced subgrid-scale (SGS) models, including a Lagrangian-averaged scale-dependent dynamic model for the SGS stress and a wave-kinematics-dependent dynamic model for the SGS sea-surface roughness in wind-and-wave interaction. As a result, turbulent eddies in the upper ocean and the sea surface deformation and roughness can be accurately captured in the simulations, with a grid resolution as fine as 1 m in a 1 km domain. Using the wave-field simulation code forced by LES, the resolution of surface gravity waves can be further increased to 10 cm wavelength.

The ocean wave field will be simulated using a novel wave-phase-resolving approach. Conventional wave prediction tools, called the third generation wave models including WAM, SWAN, WAVEWATCH, etc., are all based on formulations with the wave phases averaged. The three major processes in the wave dynamics, namely nonlinear wave interaction, wind input, and wave breaking dissipation, all depend heavily on the modeling of these processes. The existing empirical parameterizations are not suitable for many realistic, complex sea conditions, for which there exist inherent, fundamental difficulties for the traditional phase-averaging approach to further improve. Our wave-phase-resolving method, on the other hand, is a pseudo-spectral method based on the Zakharov formulation of velocity potential and coupling of different wave modes. It accounts for nonlinear wave interactions up to any desired order M in wave steepness. This method is extremely efficient computationally, requiring a computational cost almost linearly proportional to M and the number of wave modes N. The method achieves an exponential convergence of the solution with respect to both M and N. As a result, nonlinear wave interactions can be captured directly in the simulation. Recently, PI Shen's research group has further included wave breaking dissipation model and wind forcing model. As such, all of the essential processes in ocean wave-field dynamics are captured directly in a physical, wave-phase-resolving framework in our simulation.

WORK COMPLETED

Substantial progresses have been made in the fiscal year of 2016. Research performed includes:

- Incorporation of wavelet transform in data analysis for the mechanistic study of nonlinear wave interactions
- Investigation of the nonlinear resonant interaction among three wave components in two-layer fluids model
- Incorporation of the buoyancy effect in the LES code based on the Boussinesq approximation

- Simulation of the surface-internal solitary wave interaction with realistic parameters using the LES code
- Initial analysis of the internal signature on surface waves and reconstruction of the SAR image based on the numerical data

RESULTS

Two different wave motions exist in a two-layer flow due to stratification, namely, barotropic (surface) mode and baroclinic (interface) mode. The former mode features a zero phase difference in the surface waves and internal waves, while the latter mode features a 180° phase difference. Nonlinear resonant interactions occur when two surface-mode waves that satisfy the resonant condition are present in the flow. As a consequence, a third interface mode wave would start to grow in this dynamic system, and the amplitudes of these three components keep increasing and decreasing alternately. Using our simulation results, Figure 1 shows this process by plotting the normalized wave amplitudes as a function of time. Note that while the energy flux among the three components is nonzero, the total energy is conserved in the system. The initial amplitude growth of the interface mode is consistent with the theoretical prediction. Despite the simplicity of the problem setup, it provides a solid validation of our two-layer fluid model and shows that the model can fully capture the nonlinear effect.

We have recently completed the development of our high-fidelity LES code for underwater turbulence study with the undulating wave boundary fully incorporated and buoyancy effectively modeled using the Boussinesq approximation. We apply this advanced tool to a case study of surface-internal wave interaction with realistic parameters, e.g., continuous density variations less than 0.6% in the stratified flow, and a physical domain size of O(1) km. Figure 2 shows the rough and smooth zone in the surface wave field caused by the near-surface current due to the internal solitary wave. Also plotted in the figure is the vertical density distribution, from which the internal wave profile can be identified. The numerical result is consistent with both field experiments and the two-layer model result. The success of LES in the surface-internal wave interaction study establishes a solid foundation for the coupling with large-scale models provided by our collaborators in the next step of research.

We have also completed a preliminary investigation on the surface roughness variation with wavelet transform applied to non-periodic signal analysis. Figure 3 shows the wavelet decomposition of the surface wave field. The spatial variation of the magnitude of different wavelet components is consistent with the analysis based on the velocity distribution induced by ISW, and the smooth/rough zones are also found spanning from the trailing edge to the leading edge. The wavelet analysis has the potential to become an important tool for quantitative explanation of the internal/surface wave interaction processes.

In an attempt to associate our numerical result with SAR images for direct comparison, we reconstruct the normalized radar cross-section by extracting the near-surface current from the surface wave data. The result is shown in Figure 4, and a clear correlation between the cross-section signature and the internal wave is observed. Note that due to the definition adopted here, in the figure the lighter colors corresponds to the rough region of converged surface waves and the darker colors corresponds to the smooth region of diverged surface waves.

IMPACT/APPLICATIONS

This project addresses an essential component in the operational requirements of the Navy, the accurate predictions of motions and transport in oceans. Improved modeling capabilities of processes acting over many scales and understanding of interactions between surface waves and internal gravity waves improves predictive capability critical to naval operations in deep waters. This project also addresses a critical need for the analysis of field data for the Navy. We will use our simulations to study the measurement data collected in South China Sea from the extensive field studies by ONR in recent years. The simulation-based analysis will be invaluable for the interpretation of field data.

TRANSITIONS

The proposed work will lead to highly resolved simulations of internal solitary wave evolution in three dimensions in realistic ocean settings. These simulations will lead to accurate wave-phase- and turbulence resolving simulations of surface waves and knowledge of how they evolve in the presence of three-dimensional spatio-temporally variable surface currents. As a potential outcome of this project, the remote sensing capability of the Navy will likely be improved. These results are likely to shed lights on how satellite SAR images are related to the dynamics of internal and surface waves.

RELATED PROJECTS

This project is part of the NOPP program “Seamless Forecasting from the Deep Ocean to the Coast.” Our work is performed in close collaboration with Dr. Oliver Fringer at Stanford University and Dr. Dong Do at Naval Research Laboratory.

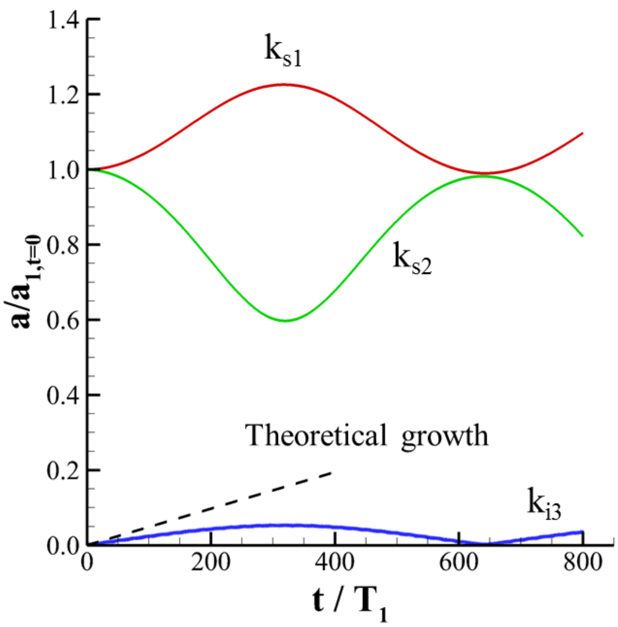

Figure 1. Wave amplitude evolution in the nonlinear triad interaction. Two surface-mode components and one interface-mode component are plotted. The amplitudes and the time are normalized by the initial amplitude and the period of k_{s1}, respectively. The initial theoretical growth of the amplitude of k_{i3} is also plotted.

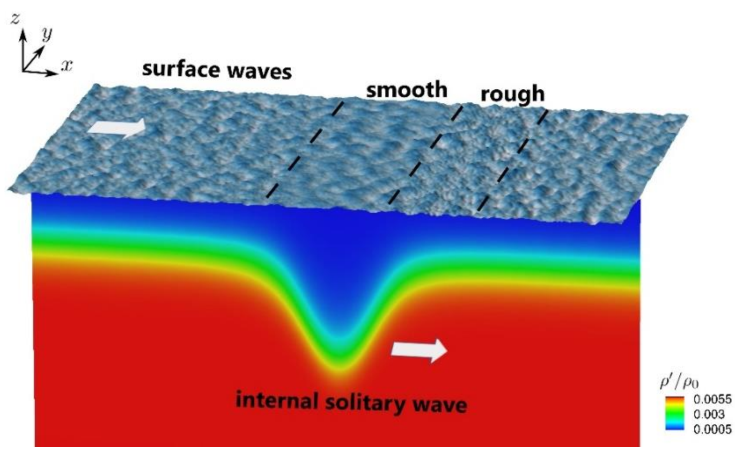

Figure 2. Surface elevation of a JONSWAP wave field and the wave profile of an internal solitary wave. The density distribution on a vertical plane is also plotted. Above the internal wave, the smooth and rough zones at the sea surface are dynamically captured in the simulation.

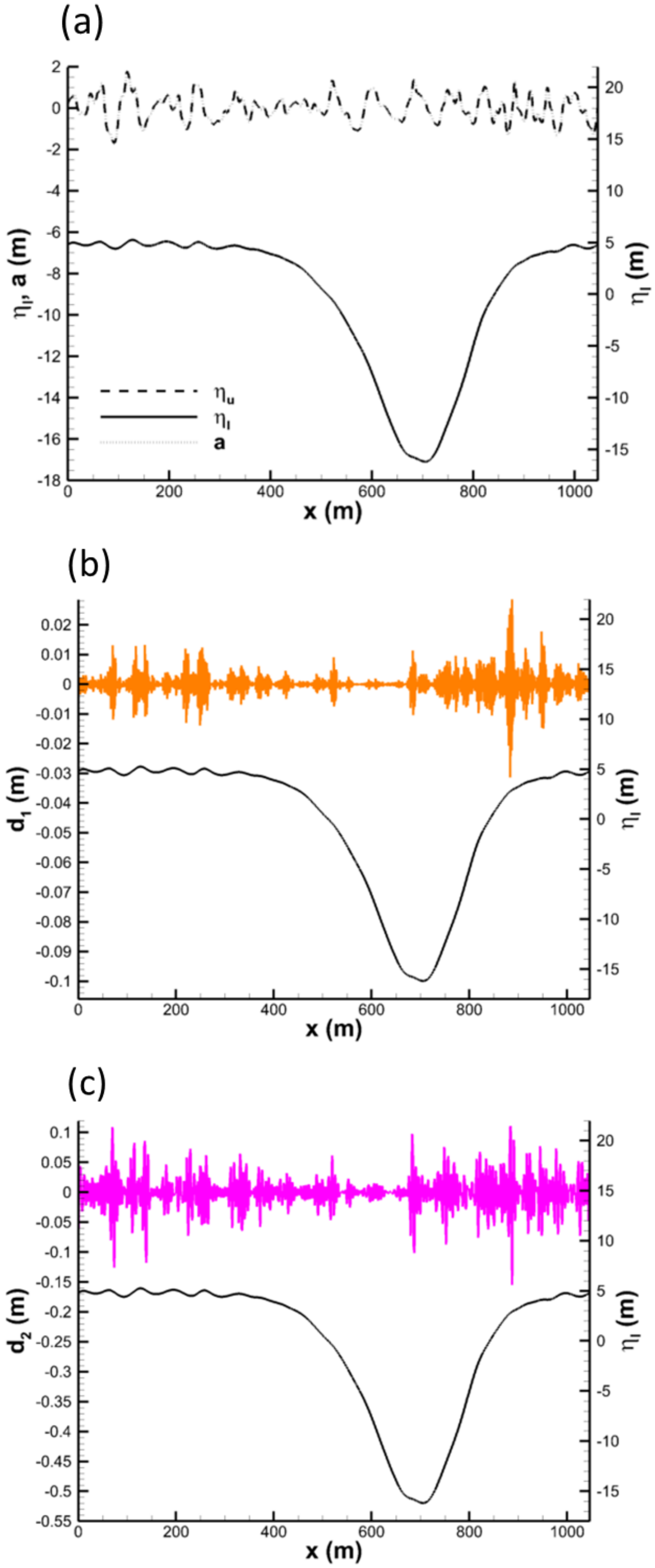

Figure 3. Wavelet analysis of the surface wave field above an internal solitary wave. In (a), the raw signal, i.e., the surface elevation, the internal wave profile, and the base component are plotted. In (b) and (c), the wavelets d_1 and d_2 are plotted.

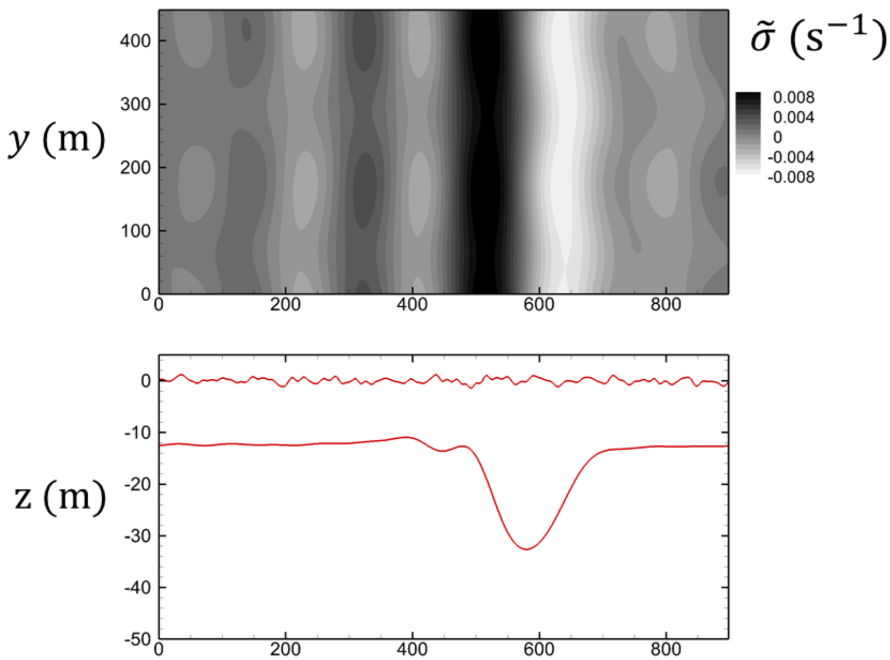

Figure 4. Normalized radar cross section of the reconstructed SAR image based on the numerical data. The internal wave profile is also plotted.