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

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Award Number: N00014-15-1-2294

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 2017. Research performed includes:

- Incorporation of surface tension effect in the two-layer fluid model
- Mechanistic study of the nonlinear resonant interaction among three wave components in the extended two-layer fluids model
- Numerical reproduction of the internal wave-induced signature on surface waves with realistic parameters and high resolution down to capillary wave scales

RESULTS

Surface tension can play a vital role at fluid-fluid interface, particularly affecting the dynamics of small scale motions by imposing an additional pressure difference. In light of the potential impact surface tension may have on the flow motions in the two-layer fluid model, we extend our current numerical code by direct calculation of the pressure difference caused by surface tension at the two interfaces. The theoretical basis of the calculation is the Young-Laplace equation, and the additional pressure term has been fully validated for pure capillary waves. The incorporation of surface tension effect greatly improves our ability to capture the fluid motions down to the capillary wave scales.

We have performed a series of numerical experiment to investigate the dynamics of resonant triads using the updated two-layer model. The surface tension, as expected, can be crucial to the wave system dynamics in certain scenarios, such as micro-gravity environment in space. Figure 1 shows four different classes of triad interaction when the surface tension effect is considerably more significant than gravity. The numerical result lay a solid foundation for the future applications in space science, and is of theoretical significance for enriching our understanding of nonlinear triad interactions in these type of systems.

We have also reproduced the surface signature long observed by remote sensing techniques by setting up simulations with realistic parameters using the updated model. Figure 2 shows the surface signature induced by internal solitary wave in the ocean, which is clearly identified by the surface tension-related pressure. To the best of our knowledge, this is the first time such signature can be captured by directly resolving both the capillary wave and the internal wave motions at realistic conditions. The surface signature is also a qualitative validation of the model, which is now ready for our next stage effort to incorporate simulation data from mesoscale.

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.

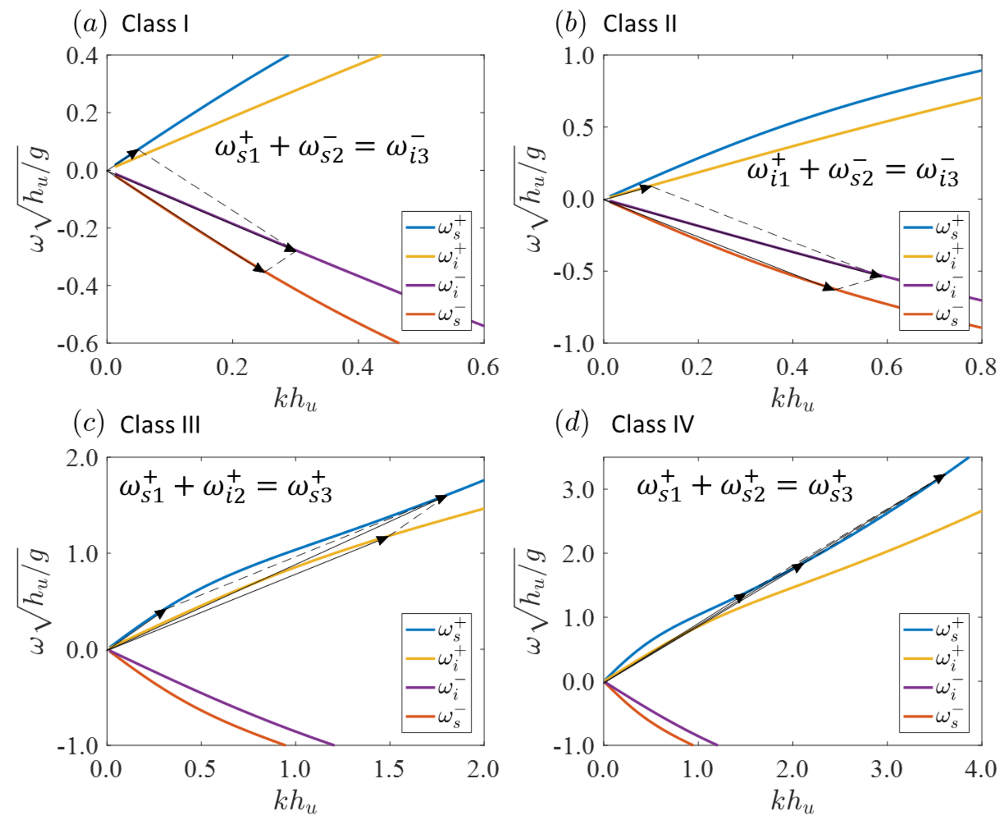

Figure 1. Four classes of triad interaction in the two-layer wave system with surface tension incorporated. Surface modes (resp., interfacial modes) are denoted by subscript 's' (resp., 'i').

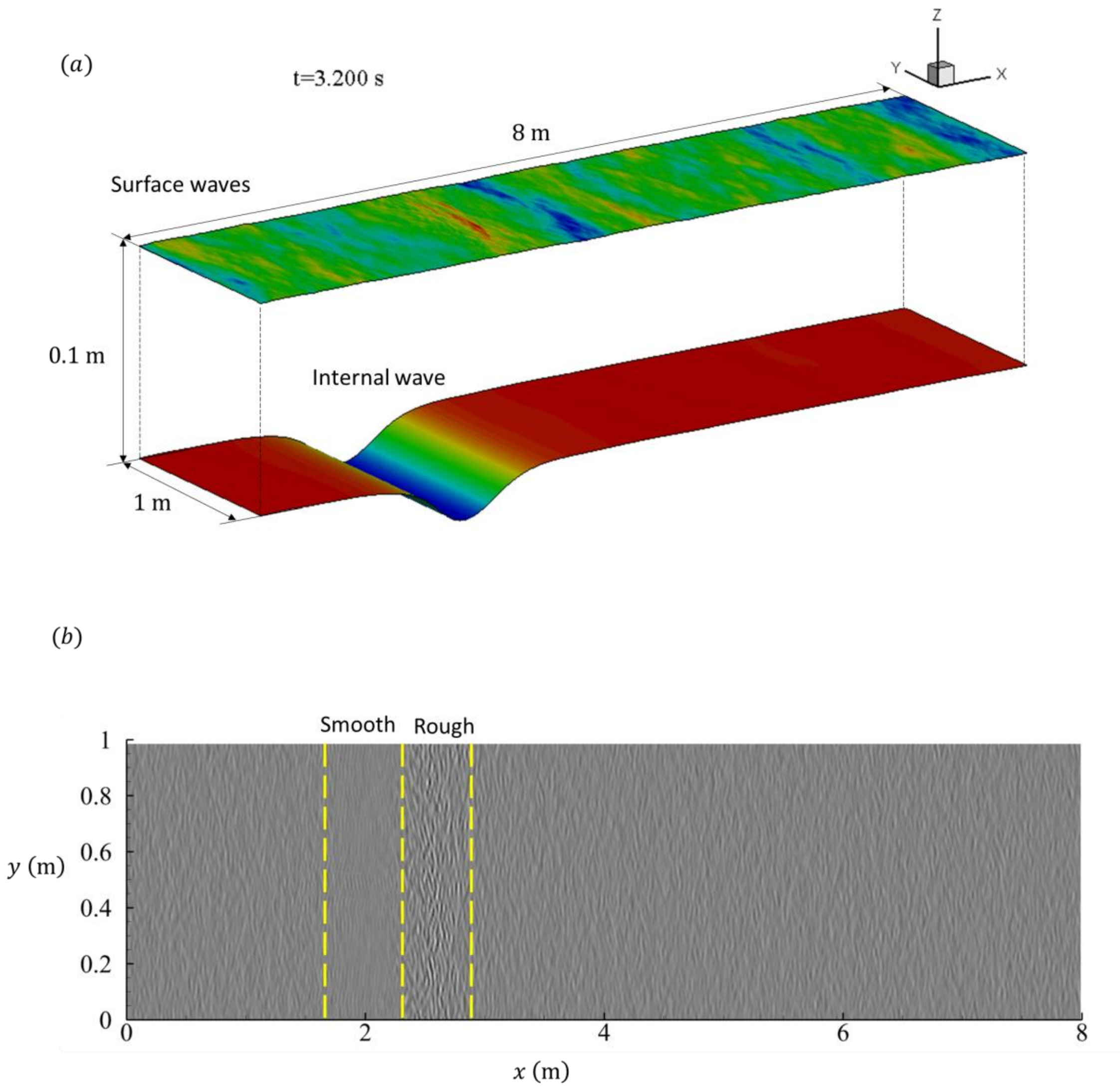

Figure 2. Surface signature induced by internal solitary wave. In (a), the instantaneous surface wave field and the internal wave are plotted. In (b), the surface signature, i.e., the smooth and rough region identified using the surface tension-related pressure, is plotted.