Multiscale Deterministic Wave Modeling with Wind Input and Wave Breaking Dissipation

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LONG-TERM GOAL

The primary focus of this research is to use large-eddy simulation (LES) and large-wave simulation (LWS) to obtain improved physical understanding of wind-wave-ocean interactions, based on which we aim to develop effective models of wind input and whitecapping dissipation for phase-resolving, nonlinear wave-field simulation at large scales. Our ultimate goal is to establish a numerical capability for predicting deterministically large-scale nonlinear wave-field in real marine environments with the presence of significant wind and wave breaking effects.

OBJECTIVES

The scientific and technical objectives of this research are to:

- develop advanced LES and LWS numerical capabilities for wind-wave-ocean interactions with physics-based subgrid-scale (SGS) models; use high-performance LES/LWS as a powerful research tool to obtain an improved understanding of the flow structure in the atmosphere-ocean wave boundary layer

- develop effective models for wind input and the associated whitecapping dissipation in a direct phase-resolving context, which can be readily incorporated into the deterministic numerical tool of the Simulation of Nonlinear Ocean Wave-field (SNOW)

- understand effects of multi-scale physics and environmental uncertainties upon wave deterministic propagation, and to effectively model these effects; validate the direct modeling and simulation approach, and perform direct comparison with existing theories and field measurements

APPROACH

We use a systematic, multiscale approach to investigate and to model effects of wind input and whitecapping dissipation on wave-field evolution. This includes: (1) use LES and LWS to obtain improved physical understanding of wind-wave-ocean interactions at small scales (O(1~10) significant gravity wave lengths); (2) based on the LES/LWS results, develop advanced wind input and whitecapping models in a direct physical context in terms of surface pressure distribution and flow field filtering, respectively; and (3) incorporate the models into SNOW simulation to investigate local

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effects of wind forcing and whitecapping on large-scale wave-field evolution. Because the physics are being investigated and modeled in a direct, phase-resolving context, we expect models developed in this study are more likely to succeed than traditional phase-averaged parameterizations.

The numerical study of wind-ocean-wave interactions are at two fronts: viscous flow simulation for turbulence-wave interactions at small scales, and potential flow based wave simulation at large scales. For viscous air-wave-water simulations, we use the approach of large-eddy simulation based on filtered Navier-Stokes equations, in which large turbulence eddies are computed explicitly with effects of small eddies being represented by SGS models. A similar LWS approach is used for wave-turbulence interactions, with large wave components being simulated directly and small wave effects modeled.

One of the major issues with simulating coupled air-wave-water turbulent flows is the presence of a deformable, time-evolving free surface, which makes the air and water computational domains irregular. The location and geometry of the free surface are unknown beforehand, and they are part of the solution to be solved for. To overcome this difficulty, we have developed a suite of complementary computational methods, which include a boundary interface tracking method based on boundary-fitted grids for moderate wave slope and an Eulerian interface capturing method based on a level set approach for steep/breaking waves.

The wind input and whitecapping models developed from LES/LWS study will be incorporated to potential flow wave computation using SNOW developed at MIT. The SNOW uses a high-order spectral (HOS) method, which is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. The wind input to the wave-field is modeled by surface distribution of pressure, while wave breaking dissipation is represented by advanced filtering treatment in physical and spectral spaces.

The multiscale modeling of ocean wave-fields will be one of the foci of this research. At local scales, we apply LES and LWS, with which the large eddies and waves are resolved explicitly and structures smaller than the computational grid are modeled. The wind input and models developed based on local-scale LES/LWS are then implemented in SNOW for large-scale simulations. In SNOW, the nonlinear wave interactions, the wind input, and the whitecapping dissipation are all represented in a direct physical context. This approach provides a powerful tool and a unique opportunity to investigate the effects of local processes on large-scale wave-field evolution in a physical-based, deterministic way.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the turbulence and wave simulations. Massage passing interface (MPI) based on domain decomposition is used for parallelization.

WORK COMPLETED

Since this YIP project started in June of 2006, encouraging progresses have been made, which include:

- Further development of high-performance numerical capabilities for the direct simulation of interaction of turbulence with dynamically evolving waves; optimum parallelization of codes on various massively-memory-distributed computation platforms has been achieved.

- Preliminary simulations of ocean turbulence-wave interaction and wind-wave interaction; promising results of the statistical, structural, and dynamic features of the atmosphere ocean wave boundary layer start to emerge through systematic analysis of dataset of on-going simulations.

- Quantification of wind-induced pressure at water surface, in terms of wave-phase averaged mean and fluctuating pressure distributions for various wave ages and various wave propagating directions; such information will establish a physical basis for the wind input models to be developed in this project.

RESULTS

During the first four months of this project, promising results have been obtained. One of the major developments during this period is the further improvement and the final completion of a highly-accurate simulation code, which is capable of simulating turbulent flows interacting with water waves. Of significant importance, the waves can dynamically evolve so that true coupling of wind and ocean with waves can be realized. The wavefield is three dimensional and contains multiple components. As a result, realistic sea conditions can be simulated. To test our numerical capability, we have validated our simulation results by comparing with wave theories and results in literatures on flows with wavy surfaces. The robustness of the code is also tested by simulation of wave-current interaction (Figure 1) and wind-wave interaction (Figure 2). Finally, the code is parallelized on massively memory-distributed computing platforms. Our test shows that the parallelization has been optimized in terms of speed-up, scalability, load balancing, and memory allocation.

Preliminary simulations have been performed for winds over complex wavefields. Using SNOW simulation of a three-dimensional, time-evolving developing sea that initially satisfies the JONSWAP spectrum, we obtain a phase-resolved multiscale wavefield as an input for turbulence simulation. Figure 3 shows a representative result of an instantaneous flow field. The success of such simulation shows the robustness of our turbulence simulation capabilities. For our next stage of study, we will perform a systematic investigation for various sea conditions including different wave ages and wind directions in order to develop improved wind input models.

Knowledge on the atmospheric pressure distribution over waves is of paramount importance to the success of wind input modeling. Based on the preliminary simulation results on wind-wave interaction, we have performed initial analysis on the pressure statistics under difference sea conditions. Figure 4 shows a result of winds over swells for different wind speeds. Mean pressure is obtained through phase averaging with respect to the dominant wave component. As expected, the pressure magnitude increases with the wind speed. The phase distribution, which is important for the modeling of wind pumping for waves, moves downwards as the wind speed increases except for very large wind speed (young sea). Also shown in Figure 4 is a case when waves propagate against the wind, where opposite distribution of pressure is obtained. Due to the turbulence in the wind field, it is also important to examine the fluctuation of pressure. Figure 5 shows the vertical profiles of pressure fluctuation obtained from simulation of winds over irregular multiscale wavefield. The pressure fluctuation increases rapidly as wind increases. Figure 5 also shows that when the wind is oblique to the waves, the pressure fluctuation magnitude increases monotonically towards the water surface, while for cases where wind and waves are aligned the maximum is obtained at some distance above the mean sea level. To explain this and other features discovered from the simulation data, further analysis is underway.

IMPACT/APPLICATION

This project aims at basic scientific understanding of the air-sea-wave interaction physics and numerical capability development for ocean wave-field prediction pertinent to Navy applications. It addresses a critical need of the Navy to bridge the gap between the modeling of small-scale air-sea-wave interaction physics and the prediction of ocean waves at regional scales. The proposed research will provide the Navy with a new powerful tool to predict deterministically nonlinear, large wavefield with finely-resolved temporal and spatial detail. The new phase-resolved, deterministic tool is fundamentally distinct from existing phase-averaged, statistical wave modeling tools such as WAM and SWAN, with the potential of being able to make more accurate prediction because of its direct, physics-based approach. Furthermore, the results of this work will also be useful for the comparison and calibration of field measurements and for obtaining physical insights to improve existing phase-averaged wave prediction models.

RELATED PROJECTS

This work compliments a number of on-going ONR projects. In particular, it is closely related to the development of Simulation of Nonlinear Ocean Wave-field (SNOW) by Professor Dick Yue's research group at MIT. The wind input and wave breaking dissipation modeling in this project is to be incorporated into SNOW, and together we will improve the SNOW capability for it to become a next generation of wave model capable of predicting nonlinear wave evolution subject to winds and whitecapping. Such numerical tools will be useful for high-resolution wave-field study.

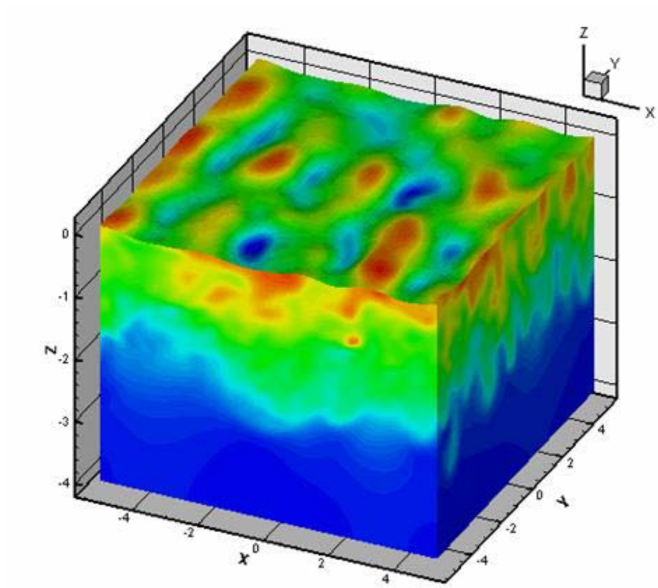

Figure 1. Interaction of waves with turbulence generated by an ocean current. The wave propagates in the x-direction. The current is in the same direction with the mean velocity decays with depth. The waves dynamically evolve under the action of turbulence-wave interaction. At the surface, contours of wave profiles are plotted. In the bulk flow below, magnitude of x-direction velocity component is represented by color contours.

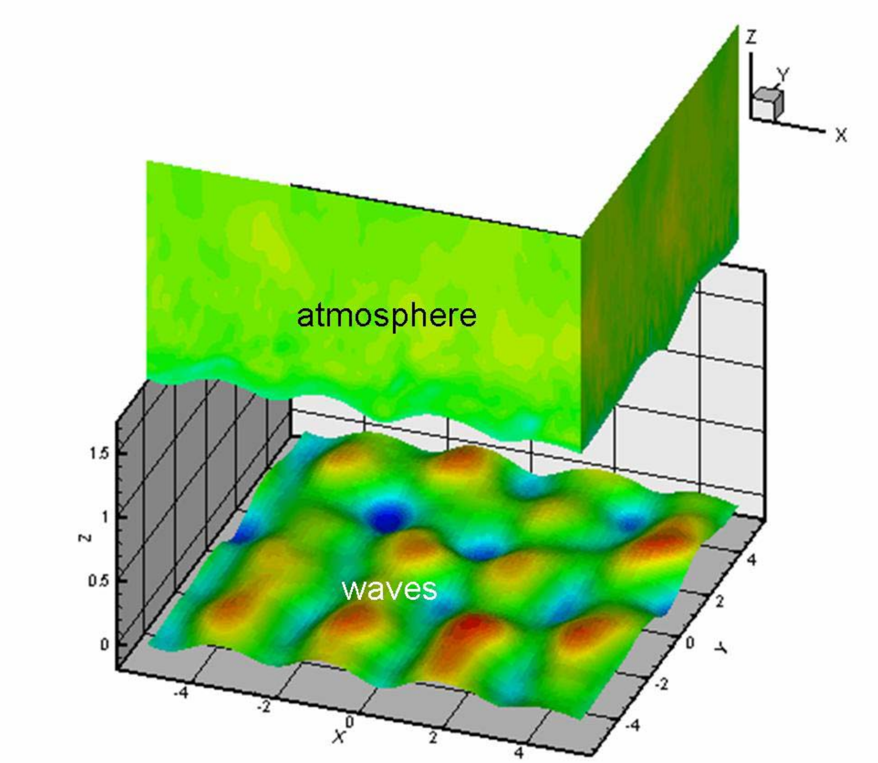

Figure 2. Influence of an irregular time-evolving swell on atmosphere. Wind velocity and wave profiles are represented by color contours.

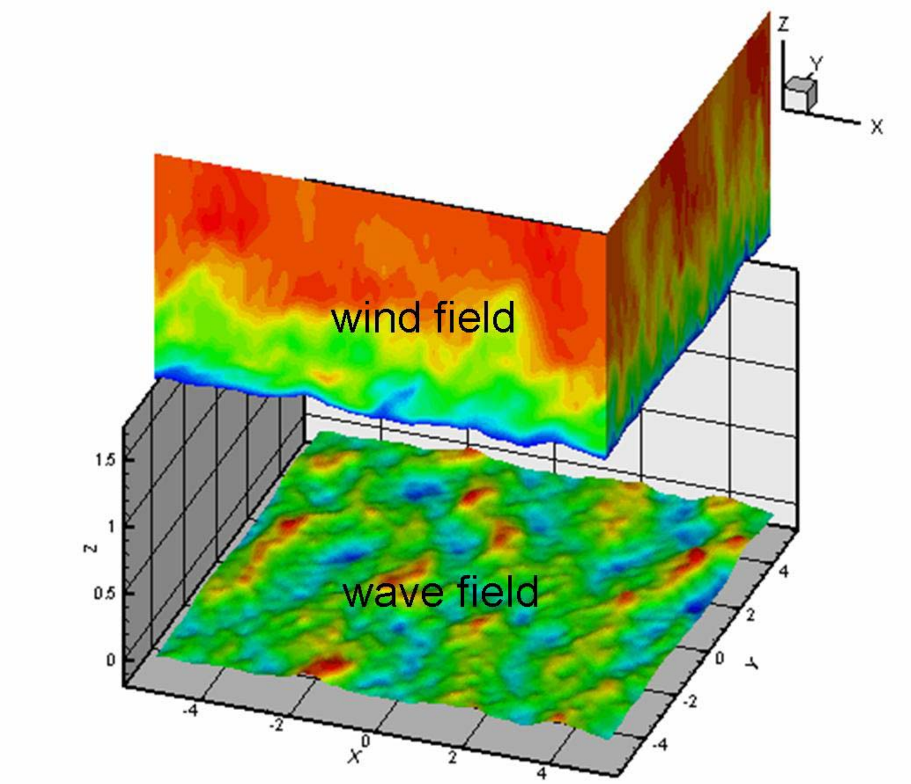

Figure 3. Simulation of wind over wavefield. The waves are obtained from SNOW simulation of three-dimensional, time-evolving, nonlinear wave system initially satisfies the JONSWAP spectrum. Wind velocity and wave profiles are represented by color contours.

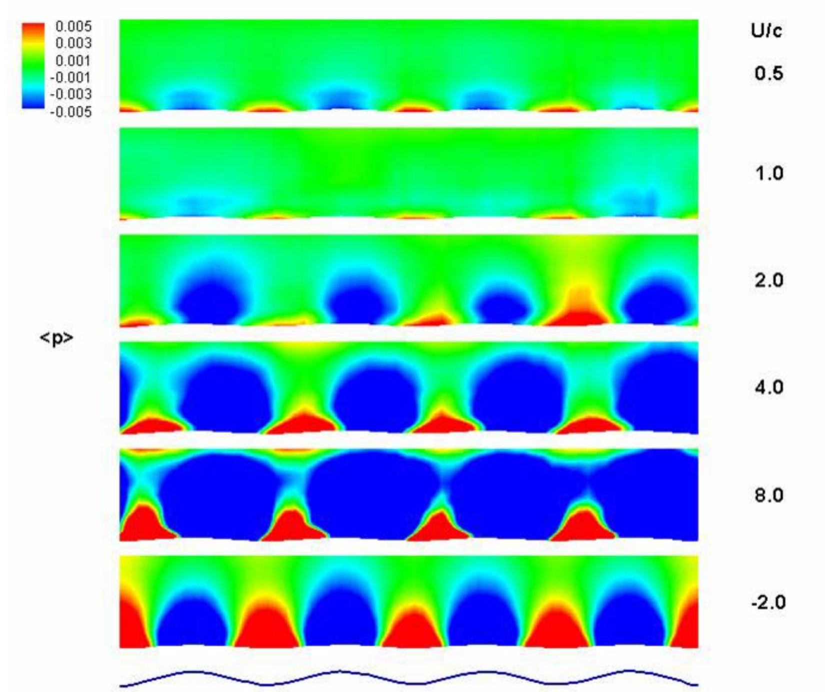

Figure 4. Spatial distribution of pressure in the wind over water waves for various wave ages. The wave propagates from left to right. The mean pressure is obtained by conditional averaging with respect to wave phases.

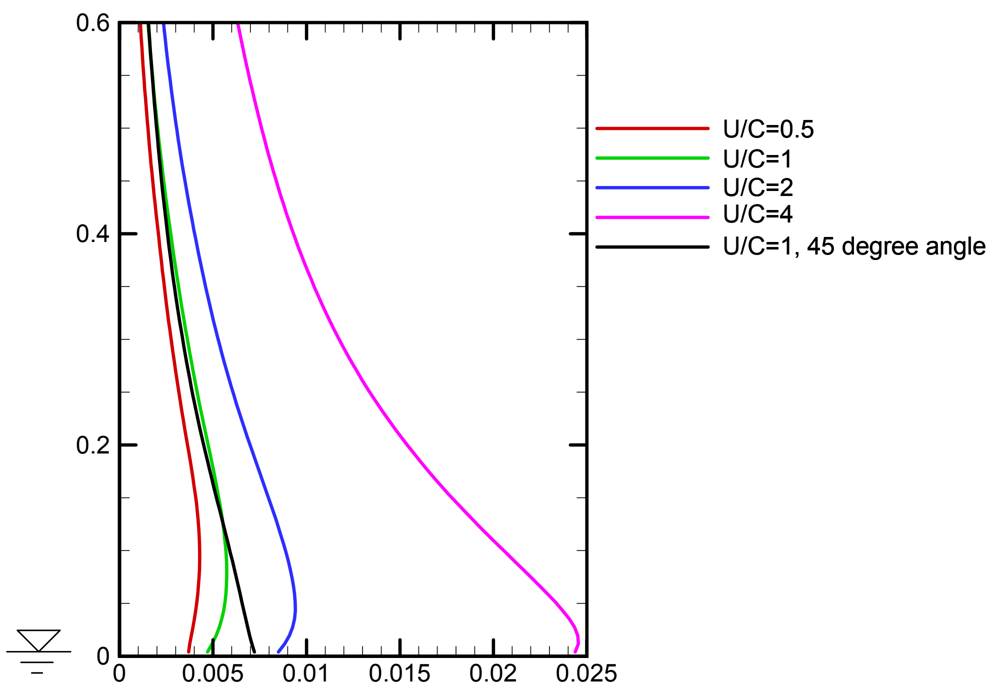

Figure 5. Profiles of pressure fluctuation magnitude over three-dimensional, time-evolving wavefield under different wind conditions. The wavefield is obtained from nonlinear SNOW simulation of multiscale, three-dimensional, time-evolving surface waves.