Development of a Highly Efficient and Accurate Wind-Wave Simulation Framework for Operational Data Assimilation

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LONG-TERM GOAL

This research aims at developing a highly efficient yet accurate computation framework for simulation and prediction of wave and wind coupled motions with wave phases being resolved, which will lead to an advanced data assimilation tool to provide more comprehensive environmental input for naval applications. Our ultimate goal is to pave the way for developing an operational tool for the Navy to use for ocean-wave-atmosphere battlespace sensing and prediction with high resolution.

OBJECTIVES

The scientific and technical objectives of this research are to:

(1) use the detailed physics revealed in coupled wind-wave simulations to obtain a fundamental understanding of wave surface layer processes, based on which physics-based advanced wave-layer models can be developed;

(2) adopt a highly accurate immersed boundary method to perform turbulence-wave simulation on fixed Cartesian grid to achieve superior computation efficiency; and

(3) use the developments in (1) and (2) to pave the way for the development of a computation framework for data assimilation with a focus on the reconstruction of wavefield and the retrieval of coherent flow structures from field measurements.

APPROACH

This research builds on the combined simulation of wind-wave interaction achieved in a fully dynamical, two-way coupled context. In the simulation, evolution of wavefield is simulated with an efficacious high-order spectral (HOS) method that captures all of the dynamically important nonlinear wave interaction processes. Large-eddy simulation (LES) is performed for the marine atmospheric boundary layer (MABL) in a direct, physical context with wave phases of the broadband wavefield being resolved. In LES, fully resolving the boundary layer at the air-sea interface is prohibitively expensive. We use a wall-layer model to represent the momentum exchange between the outer layer and the small but dynamically important eddies in the inner layer. The extensive, high resolution data

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obtained from the coupled LES-HOS simulation provide a unique opportunity to develop, assess, and calibrate wave-layer models.

In this study, we will adopt the immersed boundary method (IBM) approach for turbulence simulation near surface waves, with the constraints of the moving water surface represented by a body force through a discrete force method, which can capture the boundary precisely. We use large-scale high-performance computation on massively parallel computers. Our coupled LES-HOS code is parallelized using massage passing interface (MPI) based on domain decomposition. With the developments of wave-layer model and IBM method for turbulence-wave interaction, the computational cost will be reduced significantly. The simulation capabilities developed in this study will be used for data assimilation with a focus on the retrieval of coherent flow structures and the reconstruction of wavefield based on measurements. The simulation results obtained in this study will be compared with and validated against field measurement data.

WORK COMPLETED

During the fiscal year of 2010, substantial progresses have been made in this project, including:

- Development of wave-dependent dynamic wall-layer model and surface roughness parameterization.
- Establishment of a coupled wind-wave computational framework with the implementation of wall-layer model.
- Elucidation of the vertical variation of wind energy spectrum above water waves.
- Elucidation of the wind oblique angle effect on the wind pressure distribution and the wave growth rate.
- Elucidation of the dependence of vortical structures on the wind oblique angle.

RESULTS

The details of the structure of wind turbulence boundary layer and their dependence on wind-wave interaction are important for the development of advanced wall-layer models over waves. Based on our simulation data, we have investigated the characteristics of wind velocity spectrum and its variation with the height. Figure 1 shows the spectra for all of the three wind velocity components at the height of z^+=4.7 and 146.3 above the mean surface level for wind over water waves with ak=0.25 and c/u*=14. In the figure, *kx* and *ky* are the wavenumbers (normalized by 2/*Lx*, where *Lx* is the streamwise domain size) in the streamwise and spanwise directions, respectively. For large height (z^+=146.3), the velocity spectra are similar to those in turbulence boundary layer over a flat surface. However, near the wave surface (z^+=4.7), there exists a peak in the spectrum of the vertical velocity component at the wavenumber corresponding to the water wave. This result indicates the strong disturbance of the wave on the turbulence field in the near-surface region, and is consistent with the observations from previous studies (e.g., De Angelis *et al.* 1996).

In open oceans, the wind direction is not always aligned with the wave propagation direction. For example, in the case of swell propagating into a local wind sea, the local wind and short waves may be in the same direction, but the wind usually has an oblique angle with respect to the swell (see e.g., Donelan *et al.* 1997). It is therefore necessary to understand the effect of wind oblique angle on wind-wave interaction. Previous studies (e.g., Masternbroek 1996; Li *et al.* 2000; Meirink *et al.* 2003) have shown the potential impact of wind oblique angle on wind-wave interaction. Figure 2 shows phase-averaged pressure distribution for different oblique angles. Here, for all of the cases, the mean wind velocity component in the wave propagation direction remains constant, while different cross-wave components are added to the mean wind. As shown in figures 2(a-c), the air pressure distributions are similar for the cases of 0, 30, and 45 degrees of oblique angle. The 60 degrees case (figure 2d), however, shows apparent reduction of air pressure compared with the other three cases. As a result of the pressure variation, the wave growth rate parameter varies with wind oblique angle. Figure 3 shows that, when the wind oblique angle increases from 0 to 45 degrees, the growth rate parameter varies a little, with the value for the 30 degrees case being slightly larger. However, as the wind oblique angle further increases to 60 degrees, the growth rate parameter apparently decreases to about 60% of the value for the 0 degree case. Therefore, for such a large oblique angle, the wind-wave momentum transfer is strongly dependent on the wind direction in an apparently nonlinear way.

In addition to the air pressure distribution, the near-surface vortical structures are also strongly affected by the wind oblique angle. Figure 4(a) shows that, for the 0 degree case, the vortical structures are mainly located near the wave surface. The vortices are characterized by the quasi-streamwise vortices along the wave propagation direction. As the wind oblique angle increases (figures 4b,c), the vortices tend to be along the mean wind direction. Meanwhile, the vertical extent of the vortices increases, as indicated by the change of vortex contour color from green to red. Furthermore, for the case of large oblique angle, the hairpin vortices become more profound, while the quasi-streamwise vortices become less dominant.

IMPACT/APPLICATION

This project addresses the basic physics of wave surface layer, which will lead to better understanding of turbulence-wave interaction dynamics. It is expected to improve simulation efficiency significantly, which will lead to a powerful computational capability for direct comparison between measurement and modeling and for data fusion in field experiments.

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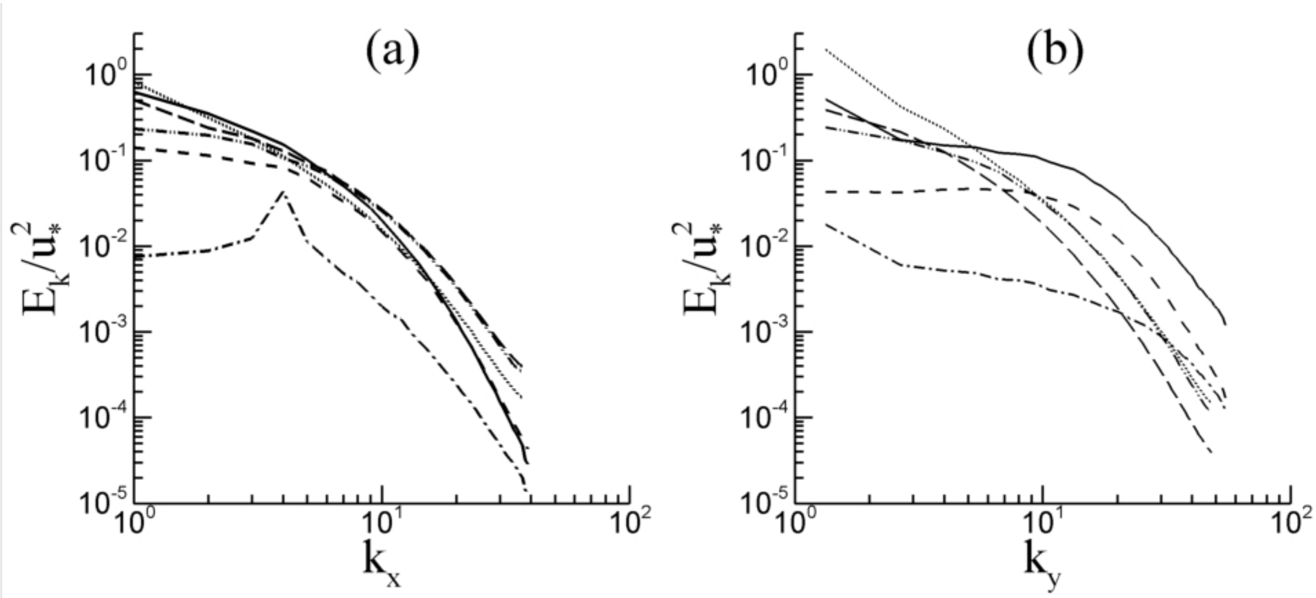

Figure 1. One-dimensional energy spectra above the wave surface for the intermediate wave case (c/u*=14). At z+=4.7: —, Euu; – – –, Evv; and –·–, Eww. At z+=146.3: · · · ·, Euu; — —, Evv; and –· ·–, Eww. (a) Streamwise direction. (b) Spanwise direction. Here, Euu, Evv, and Eww are the energy spectra for velocity components u, v, and w, respectively.

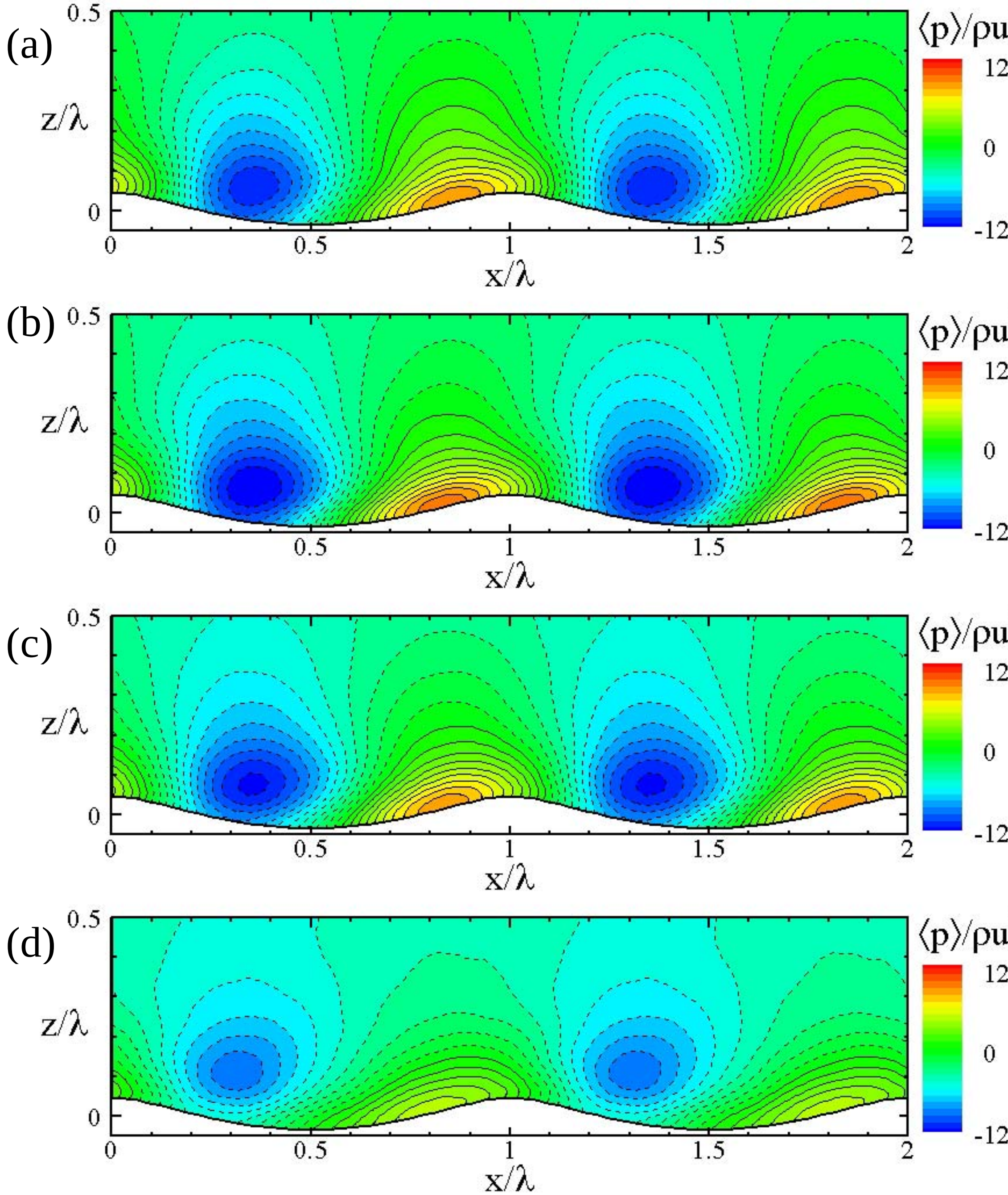

Figure 2. Phase-averaged contours of pressure for turbulence over Stokes waves with steepness ak=0.25 and wave age c/u*=5. In all cases, the streamwise component of the mean wind velocity remains the same, while a spanwise component in the +y-direction is added to the mean wind velocity. As a result, the total mean wind velocity is oblique to the wave propagation direction (+x-direction) with the oblique angle equals: (a) 0 degree; (b) 30 degrees, (c) 45 degrees, and (d) 60 degrees. The dashed contour lines represent negative values.

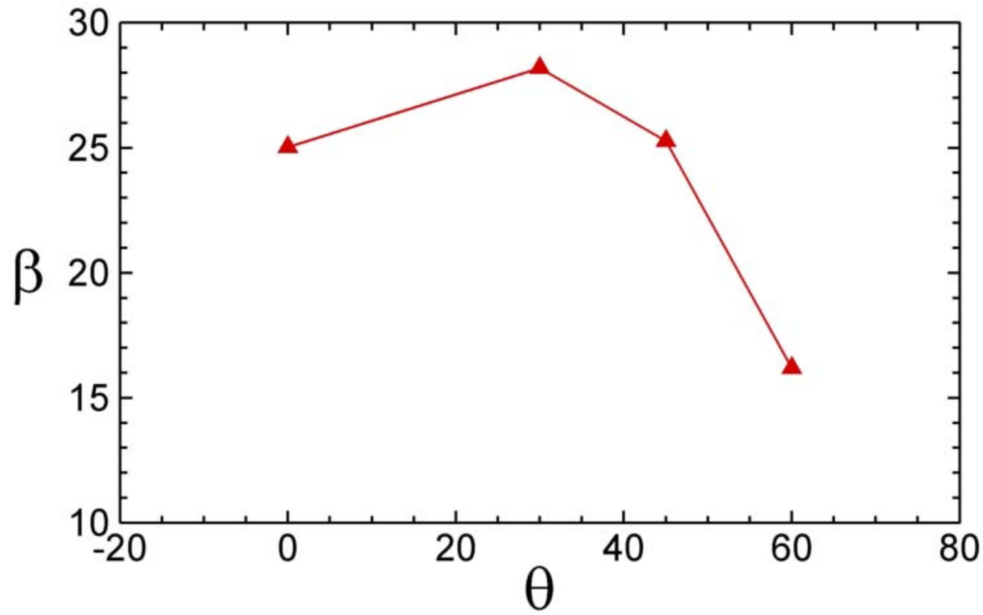

Figure 3. Dependence of wave growth rate parameter β on the wind oblique angle. For all of the cases, the mean wind velocity component aligning with the wave propagation direction (+x-direction) remains the same. The obliquity between wind and wave is caused by adding a spanwise mean wind velocity in the +y-direction.

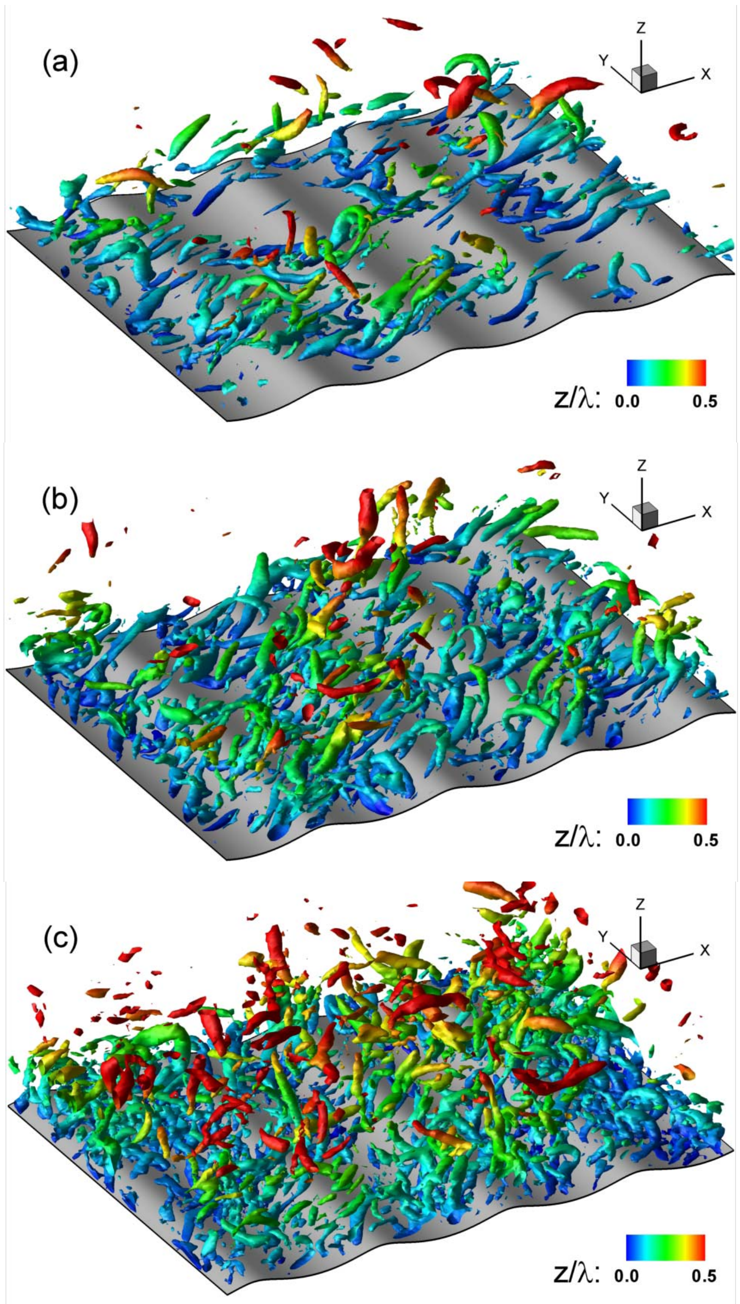

Figure 4. Snapshot of near-surface coherent vortical structures in instantaneous turbulence field over water waves with steepness ak=0.25 and wave age c/u*=5. The vortical structures are represented by the isosurface of λ_2=-1. Here, λ_2 is the second largest eigenvalue of the tensor $S^2+\Omega^2$, where S and Ω are respectively the symmetric and antisymmetric parts of the velocity gradient tensor. In all of the cases, the streamwise component of the mean wind velocity remains the same, while a spanwise component in the +y-direction is added to the mean wind velocity. As a result, the total mean wind velocity is oblique to the wave propagation direction (+x-direction) with the oblique angle equals: (a) 0 degree; (b) 30 degrees, and (c) 60 degrees. The contours indicate the height above the mean surface level normalized by the wavelength λ.