Dynamic Simulations of Realistic Upper-Ocean Flow Processes to Support Measurement and Data Analysis

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LONG-TERM GOALS

The primary focus of this research is to use computer simulations as a useful research tool to understand the mechanisms of the interactions among Langmuir cells, waves, and currents. This project is intended to be a modeling component of the over Langmuir Cell DRI. Our ultimate goal is to advance our understanding of and establish an efficacious modeling capability for upper ocean boundary layer (OBL) processes to serve for Navy applications.

OBJECTIVES

The scientific and technical objectives of our research in this project include:

- Directly capture the generation and evolution of Langmuir cells in simulations; quantify the statistics of Langmuir turbulence.
- Investigate the onset of wave breaking; quantify wave breaking intensity and model the resultant injection of turbulence to upper-ocean; study wave breaking effect on Langmuir cells.
- Develop physics based wind force modeling for oceanic flows; investigate the impact of spatial and temporal variations of wind-forcing on waves, currents, and Langmuir cells.
- Investigate effects of surface waves on upper OBL and mixed layer; identify and quantify the key turbulence mixing and transport processes in the flow, and model their dependence on environmental conditions.

APPROACH

Our project builds on a suite of advanced computational tools, including: (i) Wave-surface-fitted LES, which can explicitly resolve phase-resolved wave effect in the simulation of near-surface turbulence and thus has the capability of directly capturing the formation and evolution of Langmuir cells without the rigid-lid approximation used in traditional LES; (ii) Phase-resolved wave simulation, which can compute the nonlinear evolution of wave-field; (iii) Multi-fluids simulation of air–water mixed flow, which can compute wave breaking; and (iv) A novel dynamic sea-surface roughness model, which together with coupled wind LES can yield accurate modeling of wind forcing on upper ocean flows dynamically according to environmental conditions. Enabled by these sophisticated simulation tools, we will match the realistic field conditions in the DRI for the direct comparison with field observations.

In this project, we will perform dynamic simulations of upper-ocean flows with many of the constraints in the existing models removed. Specifically, we aim to perform simulations for realistic wind and waves conditions, with the interactions of currents and turbulence with dynamically evolving waves directly captured. As a result, the formation and evolution of Langmuir cells, the injection of momentum and energy from wave breaking to the ocean, the forcing by wind, and the processes of turbulence production, transport, and dissipation in the upper OBL and mixed layer can be elucidated and quantified in a physics-based computational framework for the first time. Such computations will be carried out in close collaboration with the field measurement in the DRI. We will use our simulations as a useful tool to help the validation, assimilation, synthesis, and interpretation of measurement data.

WORK COMPLETED

This project has just started. The funding arrived in the summer of 2014. During the first few months of this project, our research efforts focused on the further making of detailed research plan and the necessary preparations for the study in the coming years. We have also performed a study on Reynolds shear stress in waves, which is an important quantity in the study of upper-ocean turbulence-wave interaction process.

RESULTS

As a result of our planning and preparation efforts in the first few months of this project, we have identified the following major research tasks for the coming years:

1. Use our wave-surface-fitted LES to directly capture the generation and evolution processes of Langmuir cells; improve the quantification of Stokes drift in a realistic wave-field; quantify the statistics of Langmuir turbulence; investigate wave group effect on Langmuir circulation.
2. Use our phase-resolved simulation of wave-field to investigate the onset of wave breaking; use multi-fluids simulation of breakers to quantify wave breaking intensity and model the associated injection of momentum and energy to upper-ocean; investigate wave breaking effect on Langmuir circulation.
3. Use our wind LES together with a novel dynamic sea-surface roughness model to develop physics based wind-forcing modeling for oceanic flows; investigate the impact of spatial and temporal variations of wind forcing on waves, currents, and Langmuir circulation.
4. Use our LES tools at various levels of sophistication, including wave-surface-fitted LES, traditional rigid-lid LES with vortex force, and a new wave-directly-forced LES on regular grid, to investigate upper OBL and mixed layer; identify and quantify the key turbulence mixing and transport processes in the flow, and model their dependence on surface wave, wind, and current conditions; reveal engulfment process at the thermocline; investigate heterogeneity effects including fronts, swells, and wave breaking on Langmuir turbulence in the mixed layer.

The Reynolds shear stress has been playing an important role in the quantification and modeling of wave-turbulence interaction in upper-ocean. As a canonical problem, the interaction of initial homogeneous turbulence with a progressive wave was simulated in our study. Based on the simulation data, we have analyzed the property and dynamics of Reynolds shear stress.

Figure 1 shows the wave effect on turbulence shear stress in the wave Eulerian frame. In the near surface region, turbulence shear stress is positive under the backward slope and negative under the forward slope. This distribution is due to the blockage effect of the free surface. That is, the flow motions in the direction normal to the sloped wave surface are restrained and the near-surface motions are mainly along the surface-tangential direction. As the depth increases, the blockage effect of the free surface is reduced. Comparing the strong wave distortion case (left figure) to the intermediate wave distortion case (right figure), we found that in the strong wave distortion case, turbulence shear stress under the backward slope has smaller magnitude than that under the forward slope, whereas in the intermediate distortion case, the difference is less obvious. As the depth increases, the turbulence shear stress under the backward slope decreases, changes its sign to negative, and becomes negative at all the wave phases in the strong wave distortion case.

Figure 2 shows the result of turbulence shear stress in the wave Lagrangian frame. The magnitude of turbulence shear stress is small near the free surface and increases towards the deep region. This variation indicates that there is a net effect of wave on turbulence leading to a net energy transfer from wave to turbulence. The comparison between the strong wave distortion case and the intermediate wave distortion case shows that the stronger wave distortion, the larger the net effect of wave on turbulence.

IMPACT/APPLICATIONS

Many of our simulation results will be the first of their kinds. Using LES tools at different levels of sophistication ranging from our wave-surface-fitted LES, a new wave-directly-forced LES on regular grid, and conventional LES with vortex force and rigid-lid approximation, our goal is to directly test the Craik–Leibovich theory and seek extension and reformulation of existing theories by considering heterogeneity factors such as wave breaking and wave groupness. Together with experimentalists in the DRI, we aim to advance our understanding and modeling capability of Langmuir cells, waves, currents, and upper OBL processes that can serve for Navy applications.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure, and will provide guidance, cross-calibrations, and validations for experiments. As the ultimate application, through the research in this project we will develop an advanced computation framework for the modeling, analysis, and prediction of the upper-ocean interacting processes of Langmuir cells, waves, currents.

RELATED PROJECTS

This project will be performed in collaboration with other investigators in the Langmuir Cell DRI.

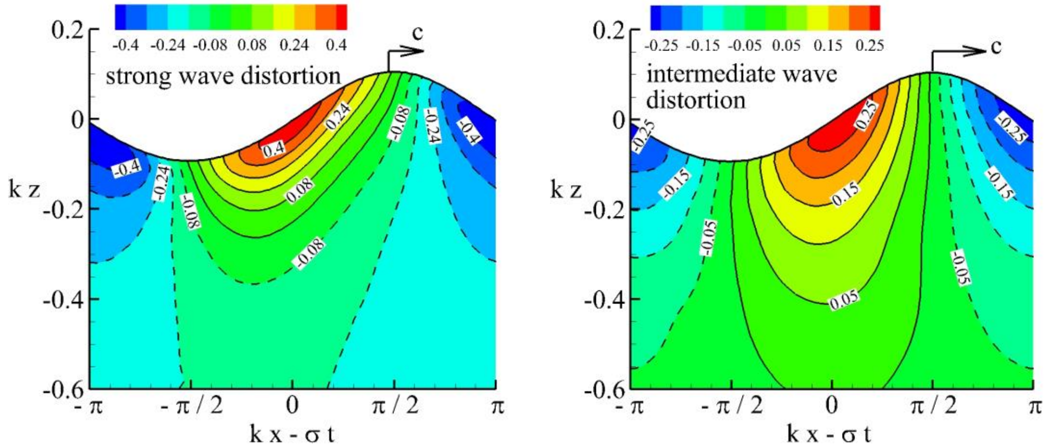

Figure 1. Contours of the normalized turbulence shear stress for the strong wave distortion case (left) and the intermediate wave distortion case (right) in the wave Eulerian frame. The arrows at the wave crest denote the wave propagation direction.

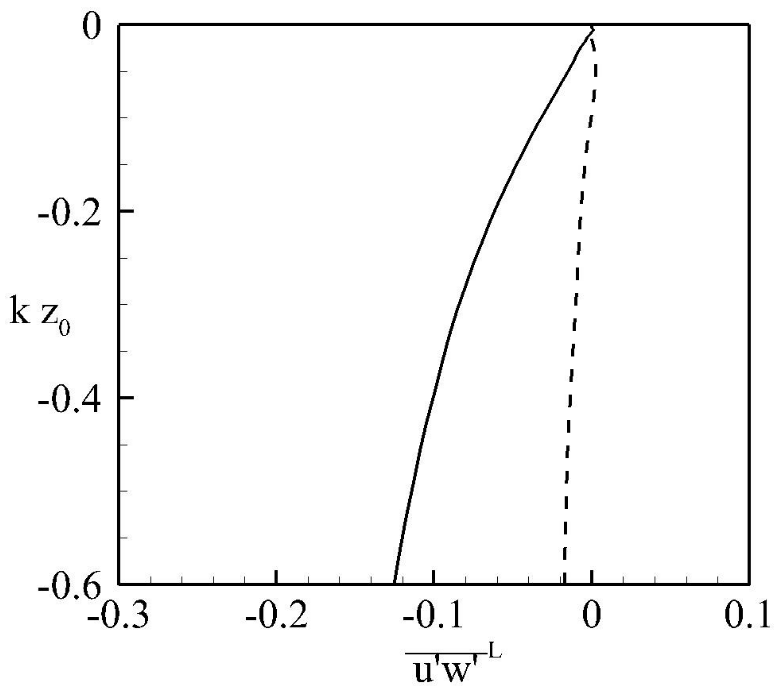

Figure 2. Vertical profiles of turbulence shear stress in Lagrangian frame for the strong wave distortion case (line) and the intermediate wave distortion case (dash).