Quantifying the Dynamic Ocean Surface Using Underwater Radiometric Measurement

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LONG-TERM GOALS

The primary focuses of this research are to understand the requirements of the inverse modeling of sea-surface processes on the accuracy, resolution, and coverage of underwater unpolarized and polarized light-field measurements, to master the theoretical constraints and computational resources required of the modeling and simulation, and to improve the forward theoretical and simulation prediction capabilities in terms of accuracy and efficiency. We aim to investigate the feasibility and limitations of achieving the inverse problem of modeling the ocean surface using underwater light measurements. Our ultimate goal is to establish an efficacious, robust framework for the unique and efficient solution of the inverse problem in terms of both the statistical characterization and direct phase-resolved prediction of the ocean surface.

OBJECTIVES

The scientific and technical objectives of our research are to:

- Develop numerical capabilities for the large-eddy simulation (LES) of the dynamically-coupled wind-wave-turbulence flows and surface roughness.
- Develop parameterization modeling of key effects of the dynamical ocean surface on the underwater light patterns and statistics
- Develop highly computationally-efficient Monte Carlo radiative transfer (RT) modeling and a semi-analytical model for Green function of 3-D RT equation.
- Develop a computational framework of the inverse problem for ocean waves and upper ocean vortical flows using under water radiance data.
- Use computational tools for the inverse problem to model key flow processes at the sea surface based on underwater light measurement and to quantify the feasibility requirements and limits on applicability of the inverse problem.
**APPROACH**

We develop a suite of comprehensive, efficient, and physical-based numerical tools for the simulations of ocean waves, turbulence, and radiance transfer, and the data assimilation capability of ocean waves. The simulation of ocean waves and turbulence is coupled with the calculation of radiance transfer and the inverse modeling of data assimilation.

For the dynamical evolution of nonlinear ocean waves, we employ a computational tool called simulation of nonlinear ocean waves (SNOW), which is an accurate and efficient tool for the nonlinear wave simulation in a phase-resolved framework. The SNOW simulates nonlinear waves based on Zakharov equation using a pseudo-spectral method. The SNOW is capable to resolve nonlinear wave-wave interactions to any desired perturbation order. We have also included the wave-breaking dissipation model and the wind forcing directly through the coupling with wind simulation to the SNOW. Such simulation will provide detailed spatial and temporal information of broadband waves in realistic ocean environment.

In addition to ocean waves, surface roughness associated with turbulent flow and wind also strongly affects the radiative transfer at ocean surface. In this study, we perform LES to simulate the turbulent flow in the upper ocean under the ocean waves as well as wind above waves. In our LES, three-way interactions among wind, wave, and turbulence are captured. The governing equations for the resolved turbulence eddies are the filtered Navier-Stokes equations. An advanced scale-dependent Lagrangian dynamic model for subgrid-scale (SGS) is used. At the sea surface, a promising model proposed by PI’s group is employed to dynamically address the sea-surface roughness effect without empirical tuning of model coefficient. For surface wave with moderate slope, an accurate simulation with boundary-fitted grid is used. The nonlinear viscous kinematic and dynamic boundary conditions are applied at the free surface. For steep and breaking surface waves and air-water mixed flow, a hybrid multi-fluids simulation is performed on a fixed Eulerian grid. The multi-fluids flow simulation combines the strengths of level-set, volume-of-fluid, and ghost fluid methods. Such turbulent flow simulation will provide modeling of sea-surface roughness.

We have developed three-dimensional forward unpolarized and polarized Monte Carlo (MC) models to simulate the light propagation in the inhomogeneous upper ocean subject to Snell’s law, Fresnel transmission, scattering, and absorption. The instantaneous surface geometry is obtained in the SNOW and ocean turbulent flow simulation. When photons travel in sea, they are affected by the light absorption and scattering effects in water. In the unpolarized MC simulation, the photon traveling distance, scattered polar angle, and azimuthal angle are determined stochastically. Finally, radiance is quantified through the statistics of the photons. To consider the polarized light process, we have also developed numerical tools to simulate the vector RT equation. In the polarized RT simulation, photon traveling path length, source function, and scattering angle is chosen based on several biased sampling techniques to reduce the variance of the results and account for the Mie scattering. Our code is validated by comparing with previous modeling and measurement. The effect of turbulence on the variation of inherent optical properties (IOPs) is also considered. We have developed an extended MC simulation capability with inhomogeneous RT equation with empirical formulations for the dependence of absorption coefficient, scattering coefficient, refractive index, and phase function on a variety of physical quantities such as temperature, salinity, and chlorophyll concentration which are provided by our ocean turbulent flow simulation.
For the inverse modeling, we have developed an efficacious optimization scheme to reconstruct the sea surface based on the RT, wave, and turbulence simulations. We have also developed a framework of data assimilation of surface motion through the adjoint model of 4DVAR. The inverse modeling will play an important role in this project.

To meet the computational challenges of the research in this project, the simulation tools for wave, turbulence, RT, and inverse modeling are developed in the framework of large-scale high-performance computation on parallel computers. The developed codes are parallelized using message passing interface (MPI) based on domain decomposition.

WORK COMPLETED

During the fiscal year of 2014, substantial progresses have been made. Research performed includes:

- Investigation of the dynamical interaction between wave and ocean turbulence in terms of Reynolds stress, vortex dynamics, and the energy transfer between wave and turbulence in both the Eulerian and Lagrangian frames of surface wave.
- Development and improvement of numerical capability for large-scale wind-wave interaction.
- RT simulation using the dynamical surface geometry obtained from large-eddy simulation of ocean turbulence and surface wave motion.
- Investigation of inverse modeling for the reconstruction of wind-sea surface based on underwater irradiance field.
- Investigation of realistic ocean wave-field subject to wind forcing and nonlinear wave-wave interaction, and their effects on underwater irradiance field.

RESULTS

Underwater turbulence is an important factor affecting the motion and geometry of ocean surfaces. When surface waves propagate over a turbulent ocean zone, turbulence dissipates and scatters surface waves and generates new small-scale surface waves. On the other hand, surface waves also distort the underwater turbulence and affect the transport of scalar quantities (e.g., temperature, salinity, and chlorophyll concentration). To understand the radiative transfer underwater, there is a critical need for the study of the dynamical interaction between waves and ocean turbulence.

We have performed quadrant analysis to understand the effect of waves on the variation of turbulence shear stress underneath. Figure 1 shows the joint probability density function for the streamwise and vertical turbulence velocity components under the backward and forward slopes in the strong wave distortion case (left figure) and the intermediate wave distortion case (right figure). In the strong wave distortion case, under the forward slope, the turbulence motions are mainly in quadrant 2 and 4. Under the backward slope, although the motions are mainly in quadrant 1 and 3, motions in quadrant 2 and 4 are also important. The contribution of motion in quadrant 2 and 4 to the shear stress is about minus 55% each, more than twice of that in the intermediate wave case. Due to this offsetting effect of the motions in quadrant 2 and 4, the positive shear stress is reduced under the backward slope in the strong wave distortion case, resulting in larger difference from the negative shear stress under the forward
slope and thus larger magnitude of shear stress in Lagrangian frame in the strong wave distortion case than in the intermediate wave distortion case as a net effect.

To future understand the underlying physics of the relatively strong motions in quadrant 2 and 4 under the backward slope in the strong wave distortion case, we have also studied the turbulence motions there in details. Figure 2 shows the condition averaging analysis based on strong quadrant events. Figure 2(a) shows that there exist two triangle-shaped vortical structures, which are the superposition of tilted streamwise and vertical vortices (figure 2b). As shown in figures 2(c) and (d), the tilted vortices induce turbulence downward motion (quadrant 4) and upward motion (quadrant 2), which lead to the variation of turbulence shear stress.

Wind-wave interaction is another important factor on the motion and geometry of ocean surfaces. We have investigated wind-wave interaction, its corresponding irradiance field underneath, and the reconstruction of sea surface based on the irradiance field. Figure 3 shows an example of instantaneous wave surface, downwelling irradiance field at representative depths, and the corresponding reconstructed surface using inverse modeling. Before the wave breaks (figure 3a), the surface and irradiance field are mainly two dimensional. The irradiance focuses under the wave crest. As the depth increases, only the wave crest has signatures in the irradiance field. The reconstructed sea surface is very similar to the real surface, when the irradiance field at the depth of the order of the wavelength is used. As the depth increases, the reconstructed surface still captures the surface variation at large scales. At the early stage of wave breaking (figures 3b and 3c), the surface and irradiance field become three dimensional. In front of the irradiance focus under the wave crest, a dark zone is shown due to the multiple penetrations of the light rays across the breaking wave plunging jet. Although the reconstructed surface shows a regular wave due to its limitation on breaking surface, the reconstructed surface still captures the three-dimensional surface features and the steep and mild slopes of the wave forward and backward slopes, respectively. After the wave breaking (figure 3d), the surface and irradiance field become three-dimensional and lose the two dimensional signature of the initial wave. The reconstructed surface captures the relatively large scale features. The above investigation shows that to reconstruct the small features of the sea surface, irradiance data at the depth at the order of the feature scales is needed.

In addition to the local wind-wave interaction simulation, we have also investigated the irradiance field under large-scale realistic ocean wind-waves. Figures 4 shows an example of JONSWAP ocean waves with representative wind speed and fetch values. In general, the irradiance field focuses at certain depth due to the energy concentration in the wave spectrum. The comparison of the irradiance field among cases with different wind speed and fetch shows that the focus depth of the irradiance field is more sensitive to the wind speed. As the wind speed increases, the irradiance focus depth moves towards to the ocean surface. In the deep region, the signature of irradiance focus becomes less obvious.

**IMPACT/APPLICATIONS**

This study aims to obtain a deep understanding of the feasibility and limitations of reverse modeling and to develop the modeling tools to characterize the ocean surface using underwater radiance measurements. The simulation and modeling tools developed in our research will fundamentally improve the capability of ocean surface reconstruction and the understanding of the correlation between the surface motion and the underwater radiance field. The result of our analysis and modeling
is also expected to provide guidance for experimental observation. In our study, various wind-wave conditions are considered, including severe flow conditions, e.g., strong wind blowing over breaking waves, highly mixed air and water, etc. Many of the above processes are difficult to measure directly. With the establishment of the simulation database of underwater radiance field under various wind and wave conditions, our study will help to interpret sparse observation datasets. The ultimate application of this project is to provide a framework for the development of underwater-radiance-based surface reconstruction tools for navy operations.

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. This project will also establish a framework and a physical basis to characterize the ocean surface using underwater radiance measurements.

RELATED PROJECTS

This project is performed in collaboration with Professor Dick K.P. Yue’s group at MIT who is funded separately.
Figure 1. Joint probability density function for streamwise and vertical turbulence motion of strong wave distortion case (left) and intermediate wave distortion case (right), (a) under the backward slope, and (b) under the forward slope. The contributions from different quadrants to the total Reynolds shear stress are listed in the plots.
Figure 2. Averaged flow field conditioned upon strong turbulence motions in quadrant 4 under wave backward slope. In (a), vortical structures are shown, and the corresponding free surface is sketched on top which is lifted up for better visualization. In (b), the side view with contours of turbulence shear stress and velocity vectors on the streamwise and vertical cross-section is plotted. The tilted streamwise and vertical vortical structures are sketched, with the white arrows denoting vorticity vectors. In (c, d), the front view with velocity vectors and contours of streamwise and vertical vorticity on the spanwise and vertical cross-section is plotted.
Figure 3. Irradiance field under wind-forced breaking waves captured in the wind-wave simulation, and reconstructed surface based on underwater irradiance field. The breaking surface profiles and horizontal distribution of downwelling irradiance field at representative depths (left) and reconstructed surface based on the irradiance field are shown (a) before, (b) at the early stage of, (c) during, and (d) after wave breaking.
Figure 4. Irradiance field under ocean waves with JONSWAP spectra for various wind speed and fetch.