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 massage passing interface (MPI) based on domain decomposition.

WORK COMPLETED

During the fiscal year of 2015, substantial progresses have been made. Research performed includes:

− Development and improvement of numerical capability for multi-phase flows. Investigation of the dynamical interaction between wind and waves, with a focus on energy transfer.
− Development and improvement of numerical capability for large-scale wind-wave interaction, with the incorporation of the effects of atmospheric stability. Investigation of the scalar transport process in neutral, convective, and unstable atmospheric conditions.
− RT simulation using the dynamical surface geometry obtained from the simulation of surface wave motion.
− Investigation of the correlation between the upwelling irradiance field and the surface wave motion.

RESULTS

Wave reconstruction based on data assimilation has been of great research interest in ocean modeling and wave forecast. As a nonlinear wave field evolves, it influences both the upwelling and downwelling irradiance field. The process is dominated by the focusing and defocusing effects of the wave surfaces on light beams, similar to those of lens in geometrical optics. To improve the robustness and accuracy of wave field reconstruction and forecasting technique, it is important to investigate the mechanism governing the dependence of irradiance field on the wave motions.

We have designed a numerical experiment for the modeling of the upwelling irradiance field in air. The experiment corresponds to the setup in some laboratories with upward-facing light sources. As shown in figure 1 (a), the physical processes include light propagation, scattering, absorption, partial reflection, refraction, and total internal reflection, the last of which is absent in downwelling irradiance because the refraction index of air is smaller than that of water. Figure 1(b) shows a simulation result of the irradiance distribution in air, which is modulated by the wave field through the surface geometry. The result shows the energy attenuation with height above the ocean surface due to the light absorption in air. Another phenomenon that can be observed in the upwelling irradiance field is the existence of focusing and defocusing regions, which suggests that detecting upwelling irradiance can be a useful tool for wave field reconstruction.

Based on the data acquired from the numerical experiment, we are able to obtain a more complete picture of the upwelling irradiance distribution in the air. Figure 2 shows the contours of the upwelling irradiance at different heights above the wave surface. Near the sea surface, e.g., on the horizontal
plane $z/z_0=0.25$, the upwelling irradiance has a nearly uniform distribution. As the height increases, e.g., on the plane $z/z_0=1.25$, the focusing and defocusing effects of the nonlinear wave field become more significant. From both figure 1 and 2, it is evident that the swell and JONSWAP wave field have different effects on the irradiance. The swell has the similar effect on the incident beams as optical lens, due to its weak nonlinearity, and focuses (resp., defocuses) light near crests (resp., troughs). The JONSWAP wave field, on the other hand, greatly increases the randomness of the direction in which the light propagates, because of its broadband energy spectrum. When the height is further increased, e.g., on the plane $z/z_0=3.25$, the radiance intensity attenuates radically as the energy is absorbed by the air.

Our simulation results suggest that there exists strong correlation between the upwelling irradiance distribution and flow structure. Such a correlation has been found in the downwelling irradiance field. On one hand, this correlation indicates that the effect of total internal reflection on upwelling irradiance in the air is small so that it has similar properties as downwelling irradiance in the water. But on the other hand, it enables us to develop an alternative approach for the inverse modeling of the surface wave field. Consequently, the upwelling irradiance field can be used as a means of wave field reconstruction with the same method as the downwelling irradiance field. This alternative approach is useful because upwelling irradiance has advantages over downwelling irradiance field in terms of light source in some experiment study, and can serve as an important supplement to the wave reconstruction technique.

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 interprete 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. (a) Sketch of physical processes in the radiative transfer of collimated light, including reflection, refraction, and scattering; (b) the irradiance distribution in the wind field. Also shown in (b) is the direction of wave propagation. The nonlinear wave field includes a JONSWAP wave field and a swell.
Figure 2. Contours of the upwelling irradiance at different height above the wave surface.