A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

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LONG-TERM GOALS

The ultimate goal is to develop direct simulation/physics-based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. This direct simulation-based model will include and integrate all of the relevant dynamical processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transport.

OBJECTIVES

To include and integrate relevant dynamical processes in the upper ocean surface boundary layer (SBL) into a physics-based computational prediction and inverse capability for the time-dependent radiative transport:

- Develop direct simulation of upper ocean hydrodynamic processes and forward prediction of radiative transfer

- Obtain understanding, modeling and parameterizations of dependencies of oceanic radiance on the surface wave environment

- Provide guidance for field measurements and obtain cross validations and calibrations with direct simulations and modeling

- Provide a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data

To reach these objectives, we had and would continue to have a close collaboration with Professor Lian Shen of the Johns Hopkins University (JHU) on the modeling of free surface turbulence roughness.

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APPROACH

A simulation approach, based on direct physics-based simulations and modeling, is applied to solve the problem of ocean radiance transport (RT) in a dynamic ocean SBL environment that includes nonlinear capillary-gravity waves (CGW), free-surface turbulence (FST) roughness, wave breaking, and bubble generation and transport. The radiative transport is governed by Snell's law and Fresnel transmission at the water surface, and absorption and multiple scattering in the water underneath. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, the development and transport of FST, and the generation and transport of bubbles are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transport.

Nonlinear CGW: An efficient phase-resolved computational approach based on Euler equations is used to compute spatial and temporal nonlinear evolution of capillary and gravity waves. This computational tool builds on an efficient high-order spectral method that we developed for direct simulations of nonlinear gravity wavefield evolution. Nonlinear gravity-gravity and gravity-capillary wave interactions are accounted for up to an arbitrary order in the wave steepness. The requisite computational cost is almost linearly proportional to the interaction order and the number of wave modes. This approach enables phase-resolved computations of large-scale nonlinear CGW.

FST-Wave Interactions: Navier-Stokes equations based DNS is employed to resolve all eddies in free surface turbulence. LES and LWS are used to compute large eddy and large wave components explicitly, with effects from small-scale motions being represented by subgrid-scale (SGS) models. Fully nonlinear viscous free-surface boundary conditions are imposed. Effects of surfactants are captured through the Plateau-Marangoni-Gibbs effect with surfactant transport directly simulated.

Steep and Breaking Waves: A Navier-Stokes equations solver for fully coupled air-wave interactions with a level-set method for free surface tracking is employed to compute the details of free surface signature and dissipation due to steep and breaking waves.

Bubble Transport in CGW and FST: Direct simulation is developed to compute bubble motion in CGW and FST environment. Both Lagrangian and Eulerian approaches are used to trace bubble trajectories. Bubble motion is subject to forces due to added mass, buoyancy, drag, lift, and fluid stress gradients arising from the continuous-phase acceleration. Bubble source is determined based on experimental measurements and/or existing data.

Radiative Transfer in CGW and FST: Monte Carlo simulation of radiance transfer (RT) (e.g. Walker 1994) is developed with the free surface deformation obtained from direct CGW and FST computations. The effects of absorption and multiple scattering on RT are included. Bubble scattering effects are also considered based on bubble distribution and transport and Mie theory.

WORK COMPLETED

Development of nonlinear CGW simulation capability: Continued the development of a direct simulation capability for nonlinear CGW evolution by extending the high-order spectral method for gravity waves to general broadband nonlinear wavefield interactions involving swell, seas, and capillary waves. Of particular focus was on the inclusion of capillary waves, long-short wave interactions, wave breaking dissipation, surfactant effects, dissipation due to free surface turbulence, and energy input by wind.

Development of Monte Carlo RT simulation: In order to study the influence of dynamical ocean surface on underwater irradiance transfer and distribution, we developed a three-dimensional coupled atmosphere-ocean Monte Carlo radiative transfer simulation capability for both polarized and unpolarized lights. The RT simulation is time independent, but accounts for the effect of complex unsteady three-dimensional ocean surface including CGW and FST roughness. In RT, multiple refractions at ocean surface, total internal reflection, all orders of multiple scattering, and scattering and absorption of both water molecules and marine aerosols are all considered. In order for practical applications, various techniques including the use of biased sampling algorithms and parallelization of the code (with MPI) were employed to speed up the program.

Validation of RT simulations: The RT simulations were systematically validated by comparisons to existing experimental data and other model predictions. The comparisons were made for the transmission of photons at the ocean surfaces, radiance distribution at different depth, and the degree of polarization distributions.

Investigation of underwater irradiance characteristics in CGW and FST environments: To understand the correlation between underwater irradiance and ocean surface environments, we performed the Monte Carlo radiative transfer simulations under various surface wave conditions. Based on the simulations, we characterize the basic features of the irradiance and investigate their dependences upon physical wave and IOP parameters.

RESULTS

We systematically validated the developed RT simulation model by making direct comparisons with theories, existing numerical model prediction, and available experimental measurements. The developed RT simulation model is effective and useful for predicting three-dimensional polarized and unpolarized radiative transfer in the atmosphere-ocean system.

Comparison to theory: *Validation of photon interactions with atmosphere-ocean boundaries*
We first compare our simulation to the theoretical solution of Zaneveld *et al*. (2001) for the distribution of irradiance below a simple regular sinusoidal wave. As in Zaneveld *et al*. (2001), for simplicity, the absorption and scattering effects are ignored in the simulation. In the simulation, the wave elevation is given by $\eta(x)=0.12\sin(\pi x)$ m. The comparison is displayed in figure 1, where simulation results with two different discretizations are shown. Clearly, the simulation results agree very well with the theory of Zaneveld *et al*. (2001). This example also indicates the presence of a strong correlation between underwater irradiance pattern and surface wave profile.

Comparison to other model prediction: *Validation of averaged radiance distribution*
Among all the interested quantities in the simulation, the most fundamental one is the radiance distribution. Hence, to validate the present simulation, we compared our Monte Carlo model prediction of radiance distribution with the result of invariant imbedding method (Mobley 1994). In the simulations, we assume a flat ocean surface. Indices of refraction of water and air are 1.34 and 1.0, respectively. All IOP's are independent of water depth. The sun irradiance is normalized to be 1.0 $Wm^{-2}nm^{-1}$. Sun light is incident directly into the ocean surface without diffusions at a zenith angle =60°.

For the optical properties of water, the phase function is taken to be Petzold average particle phase function; and single scattering albedo of water is ω=0.8. In the simulation, the number of photon used is 10^6. Figure 2 shows the comparison between the present model and the invariant imbedding method for radiance distribution at two optical depths. The present solution agrees very well with the prediction by the invariant imbedding model.

Comparison to experimental measurements:

(I) Validation of averaged radiance distribution: For further validation, we make direct comparisons of our model prediction with experiment data of radiance profiles by Adams *et al* (2002). For comparisons, the following conditions are considered in the simulation. The sky model is chosen as so-called SEMI-EMPIRICAL SKY RADIANCE MODEL (Harrison & Coombes 1988). The opaque parameter C=0.1 for clear skies. Absorption coefficient of the ocean a=0.0472 m^{-1}, scattering coefficient of the ocean b=0.1106 m^{-1}, and phase function is Petzold function. The measurement depth is the same as that in experiments: Z= –50 m. The number of photons used is 10^6. The comparison for the radiance distribution is shown in figure 3. The present simulation result compares excellently with the experimental data.

(II) Validation of averaged polarization distribution: Likewise, an important validation on the prediction of polarization pattern is also made. Figure 4 compares our simulation results of the polarization degree pattern with the experimental data of Adams *et al* (2002). We chose the simulation conditions based on the parameters in the experiments: absorption coefficient a=0.0472 m^{-1}, scattering coefficient b=0.1106m^{-1} and Rayleigh scattering matrix is used for Mueller matrix. The incident light is completely unpolarized. Measurement depth Z=–50m. As in the above, the number of photons is 10^6. As shown in figure 4, our simulation gives a basic shape of polarizations matching experimental data very well.

IMPACT/APPLICATIONS

The capability of accurate prediction of the irradiance transfer across ocean surface and in the water may enable the development of a novel approach for accurate measurements of complex ocean boundary layer processes and reliable detection of the presence of structures/objects on or above ocean surface based on sensed underwater irradiance data.

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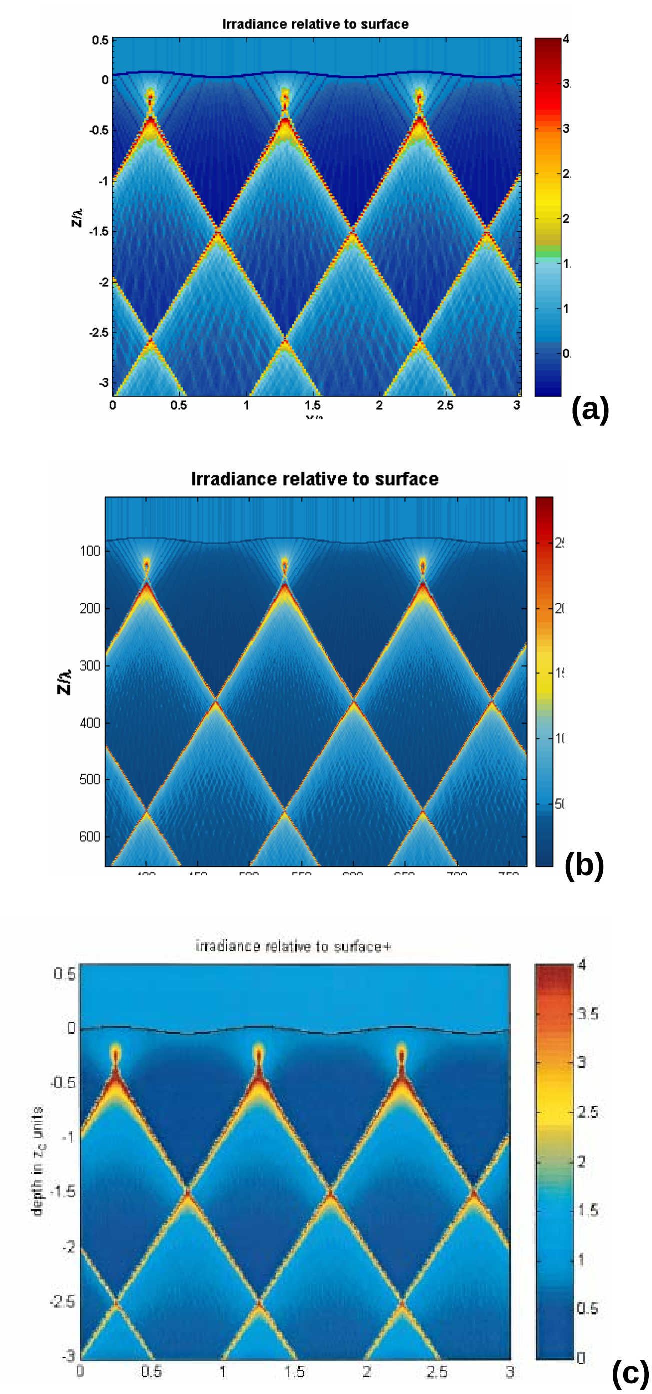

Figure 1: Comparison of irradiance distribution below a airy wave between the present simulations using 512 (a) and 1024 (b) grid points in the horizontal direction and the theoretical prediction of Zaneveld e al. (2001) (c).

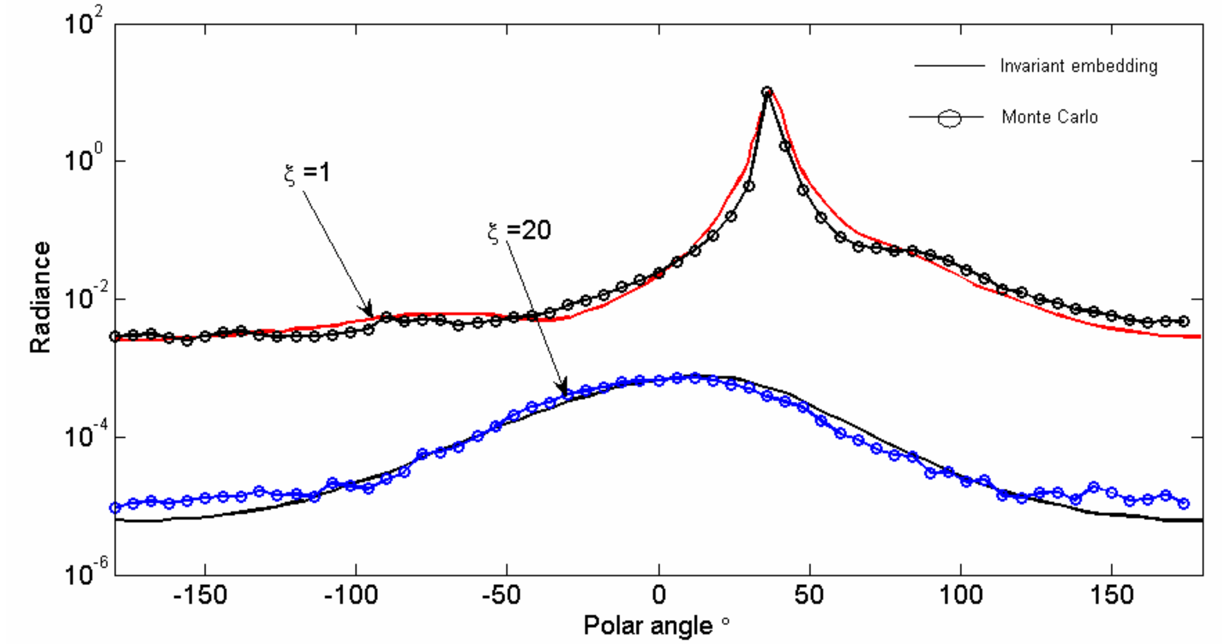

Figure 2: Comparison of radiance distribution at two optical depths, 1 and 20, between the present Monte Carlo model (o) and the Invariant embedding model (—).

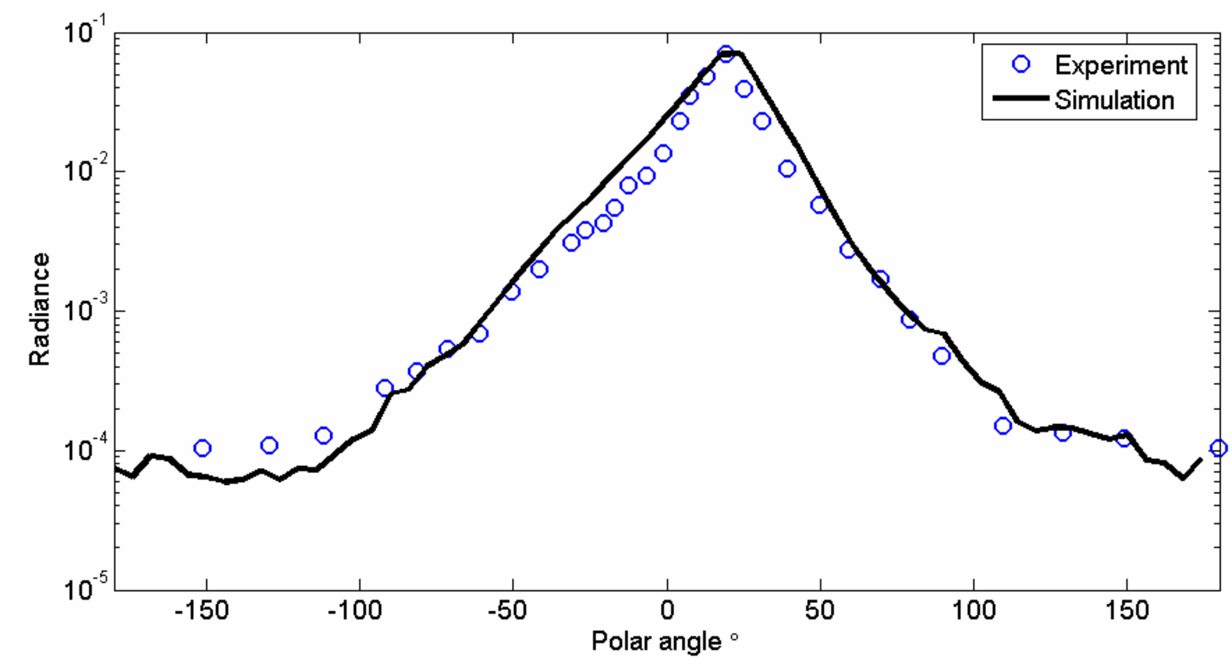

Figure 3: Comparison of radiance distribution at the water depth of 50m between present Monte Carlo model prediction (—) and experimental measurements of Adams et al (2002) (o).

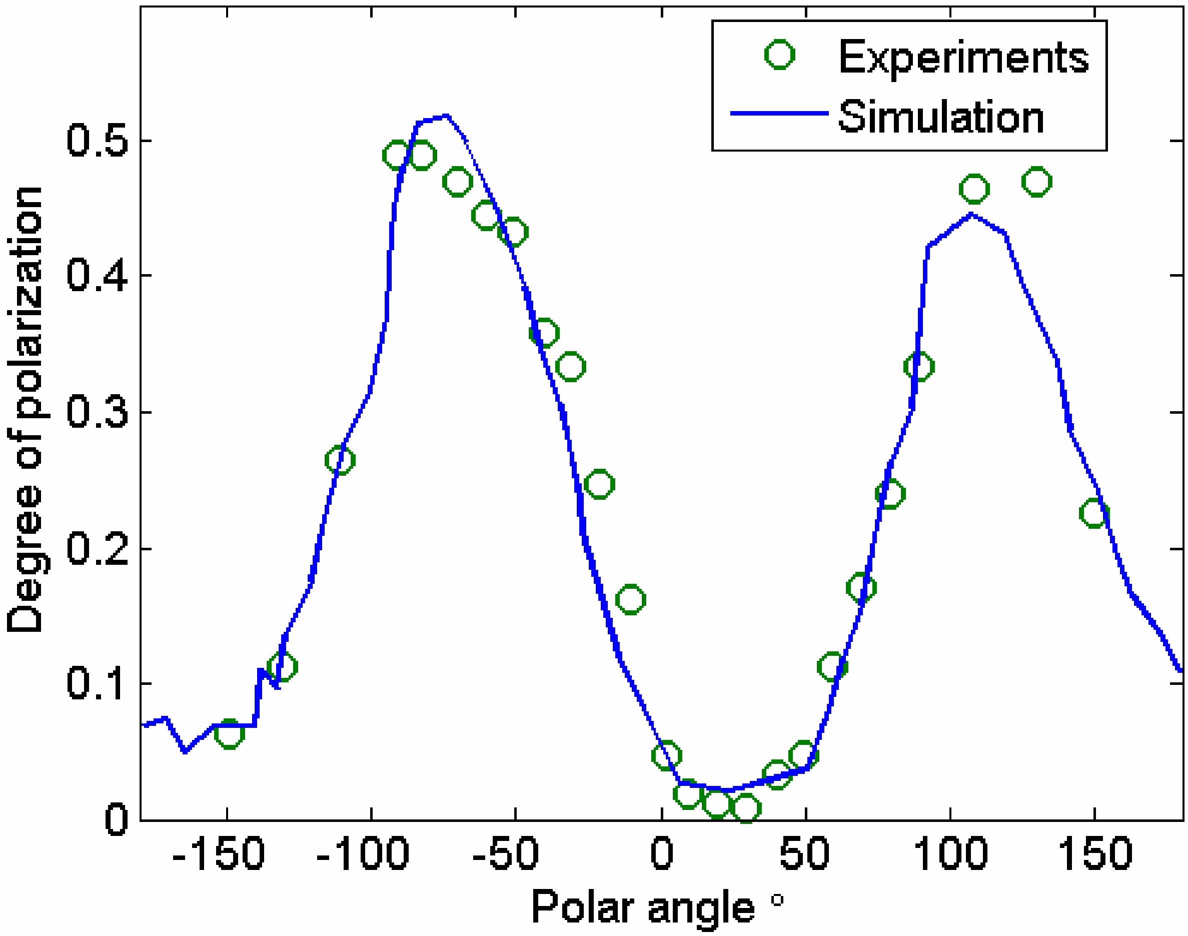

Figure 4: Comparison of degree of polarization distribution at the water depth of 50m between present Monte Carlo model prediction (—) and experimental measurements of Adams (2002) (o).