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

Lian Shen
Department of Civil Engineering
Johns Hopkins University
Baltimore, MD 21218
phone: (410) 516-5033 fax: (410) 516-7473 email: LianShen@jhu.edu

Award Number: N00014-06-1-0073

LONG-TERM GOAL

The primary focus of this research is to integrate dynamical processes of wave and turbulence in the upper ocean surface boundary layer (SBL) into a physics-based computational capability for the time-dependent radiative transfer (RT) in the ocean. The combined capability we develop will provide direct forward predictions of the radiance distributions in the upper ocean. We aim to use this capability for understanding the basic features and dependencies of oceanic radiance on the wave environment, to provide guidance and cross-calibration for field measurements, and to validate and benchmark existing and new theories. As an ultimate goal, the proposed direct simulation also provides a framework, in conjunction with sensed radiance data, for the optimal reconstruction of salient features of the ocean surface and the above-water scene.

OBJECTIVES

This project is part of the modeling effort in the Radiance in a Dynamic Ocean (RaDyO) DRI. The scientific and technical objectives of our research are to:

- develop numerical capabilities for the direct simulation of nonlinear capillary-gravity waves (CGW) with the inclusion of wave breaking dissipation, energy input by wind, and surfactant effects
- develop numerical capabilities for free-surface turbulence (FST) and resultant surface roughness
- develop bubble transport simulation in CGW-FST field, with bubble source models using simulations of steep breaking waves and measurement data
- develop direct simulations of RT in the presence of SBL processes of wave, turbulence, and bubbles
- obtain validations and cross-calibrations against field measurements
- use numerical tools of forward prediction to understand and characterize the radiance distribution in terms of the SBL dynamical processes, and to parameterize and model radiance transport and distributions

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE
A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Johns Hopkins University,Department of Civil Engineering,Baltimore,MD,21218

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- develop inverse modeling for the reconstruction of free-surface properties and objects using measured RT data and direct simulation

APPROACH

We develop a simulation approach based on direct physics-based simulations and modeling to solve the problem of ocean RT in a dynamic SBL environment that includes CGW, FST roughness, wave breaking and bubble generation and transport. 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 transfer.

For the nonlinear gravity-capillary wavefield evolution, we employ an efficient phase-resolved computational approach. With this approach, we obtain detailed spatial and temporal information of the wavefield during its nonlinear evolution. This computational tool is based on an efficient high-order spectral (HOS) method that we developed for direct simulations of nonlinear gravity wavefield evolution. HOS is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. Using direct efficient HOS computations and sensed wave data, we can obtain a phase-resolved reconstruction of nonlinear wavefield evolution based on multi-layer optimizations. With this highly efficient approach, we expect to capture realistic ocean gravity and capillary wavefield that has a wide range of length scales.

In addition to CGW, radiative transfer at ocean surface is also affected by surface roughness associated with FST. In this study, for moderate wave amplitudes, the FST field is obtained from simulation of the Navier-Stokes equations on a boundary-fitted grid subject to the fully-nonlinear free-surface boundary conditions. When waves steepen and break, an interface capturing method on fixed Eulerian grids is used, with which the air and water together are treated as a system with varying density, viscosity, and diffusivity. Effects of surfactants can be captured through the Plateau-Marangoni-Gibbs effect for which we perform direct simulation of the surfactant transport in the free-surface flow, which is in turn affected by the surfactant-laden boundary conditions. To capture the interaction between FST and CGW, we will perform FST simulations with realistic wave inputs obtained from the HOS CGW simulations.

The high-resolution mapping of the free-surface deformation from our direct CGW and FST calculations is coupled into the computation of the underwater radiance field. As light enters the water from the air, they are modified in both propagation direction and intensity at the sea surface subject to Snell's law and Fresnel transmission. The propagation of radiance in the sea water is captured by simulation of radiative transport subject to absorption and multiple scattering. In this study we perform direct simulations of RT in a three-dimensional, temporally-evolving, upper-ocean environment with the key SBL processes being directly simulated. We will first focus on a Monte Carlo simulation of photons while other techniques for the direct simulation of radiance will be investigated at a later stage of this project. In order to capture radiative scattering by bubbles which are generated by wave breaking, we first simulate transport of bubbles by tracking Lagrangian trajectories and by computations with an Eulerian multi-phase fluid modeling. Based on the simulated locations and populations of bubbles with various size distributions, scattering of radiance is solved numerically using the radiative scattering result of individual bubbles obtained with the Mie theory.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the CGW, FST, and RT simulations. The suite of codes developed for this research is parallelized using massage passing interface (MPI) based on domain decomposition.

WORK COMPLETED

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

- Development of numerical capability for simulation of the interaction between free surface and strong ocean turbulence using advanced level-set, volume-of-fluid, and ghost fluid methods.
- Establishment of an extensive simulation database for free-surface turbulence, based on which substantial new understanding of the flow physics has been obtained. Using the surface geometry obtained from free-surface turbulence simulation, a large set of RT simulations has been performed to obtain instantaneous, three-dimensional radiance field underwater.
- Investigation of realistic, developing seas subject to wind-wave dynamic two-way coupling, and study of the effect on underwater radiative transfer.
- Comparison of the numerical results with experimental and other modeling results in the literature; incorporation and investigation of data from the recent experiments have also started.
- Development of numerical capability of the data assimilation to reconstruct the surface geometry based on sensed underwater light variation and wave dynamics. Research performed includes:
    - Reconstruction of the initial free surface geometry based on the sensed underwater light information.
    - Development of data assimilation based on the initial free-surface reconstruction for two-dimensional case.
    - Extension of the data assimilation tools developed to three dimensional cases.
    - Investigation of data assimilation for free-surface vortical flow.

RESULTS

Radiative transfer in the upper ocean is strongly dependent on surface geometry, which is affected by the interaction of free surface and ocean turbulence. In this study, we have developed an advanced multi-fluids simulation capability based on level-set, volume-of-fluids, and ghost fluid methods. We have obtained extensive datasets for free-surface turbulence with a wide range of Froude and Weber numbers and the associated surface geometry. The above developments enable us to systematically study the free-surface turbulence and its effect on underwater radiative transfer for a complete physical picture. A representative result is plotted in Figure 1, which shows the water surface geometry and the underwater downwelling irradiance field. Various cases are considered, including small surface elevation, gravity dominated, surface-tension dominated, and strong turbulence.

The radiative transfer in the upper ocean is characterized by free-surface turbulence structures. Figure 2 shows the simulation results of the irradiance field under a breaking surface captured in a case of strong free-surface turbulence. The complex surface geometry induced by the breaking strongly affects the surface refraction and underwater transmission of irradiance. As shown in Figure 2(a), at the initial stage of the breaking, due to the covering of the plunging jet, significant amount of irradiance is lost when the light rays penetrate the air-water interface several times. As a result, a dark zone exists under the plunging jet. Right behind the jet, the large convex curvature of the surface generates an irradiance focusing region. During the breaking, the plunging jet reconnects to the water surface and generates splash-up, and the dark zone disappears (Figures 2b and c).

Figure 3 shows the simulation results of the irradiance field under a splat event for both the small surface elevation and violent surface cases. For the small surface elevation case (Figure 3a), the irradiance focuses at the center of the splat event due to the convex curvature. The dark circle around the splat represents the surface wave generated. For the violent surface case (Figure 3b), the irradiance focuses only at the initial stage. As time goes on, the splat event leads to surface breaking and the surface geometry becomes very complex. A dark zone appears underneath.

Besides the characteristic structures, we also investigated the statistics of the irradiance field. Figure 4 shows the spectra of surface slope and underlying downwelling irradiance for different Froude numbers. It shows that there exists clear dependence of downwelling irradiance on the slope of surface elevation. As the Froude number increases, the effect of the gravity becomes less significant, and the surface tension becomes relatively more important. As a result, the surface slopes at large and small scales increase and decrease, respectively. Consequently, the downwelling irradiance increases at large scales and decreases at small scales.

In order to obtain realistic wavefield under the action of wind, which is not always in the wave propagation direction in practice, it is useful to simulate the wind-wave interaction with an oblique angle between the wave and wind. Figure 5 shows a result of such simulation. The time signal of irradiance at an underwater location is also shown. The appearance of intense flashes with short duration agrees with field observation.

In FY10, we made substantial progress in the development of a reverse modeling framework based on wave dynamics, radiative transfer, and data assimilation. We developed the numerical capability of data assimilation based on the sensed underwater irradiance information, and further extended the modeling capability from two dimensional to three dimensional. Figure 6 shows a typical result of surface reconstruction. It is shown that with data assimilation using wave model and radiative transfer simulation, the reconstruction of the surface can be significantly improved. In general, the surface can be reconstructed reasonably well with even a small number of sensors. On the other hand, the surface is sensitive to the sampling frequency. For the dominant wave component, the quality of the surface reconstruction is relatively less sensitive to the sampling frequency. For short waves, high frequency is needed. Nevertheless, data assimilation of ocean surfaces at large scales is complex, and we are still in the process of investigating the feasibility of reverse modeling for large scale surface features.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of time-dependent oceanic radiance distribution in relation to dynamic SBL processes. Our work is intended as part of an overall coordinated effort involving experimentalists and modelers. The simulation capabilities developed in our research will provide experimentalists with a powerful tool to validate the observation data. The simulation tool is expected to provide some guidance for field measurement planning. The simulation can also provide whole-field (spatial and temporal) data that helps the interpretation of sparse observation datasets. From simulation, some physical quantities that are difficult to measure can be obtained. What is also significant is that the simulation can be used as a useful tool to isolate physical processes that are coherent in the natural environment. With such analysis, improved understanding, modeling and parameterizations of dependencies of oceanic radiance on SBL environment will be obtained. Our ultimate goal is to use the forward modeling capabilities resulted from this project as a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of oceanic radiative transfer in relation to dynamic surface boundary layer processes.

RELATED PROJECTS

This project is part of the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) DRI (http://www.opl.ucsb.edu/radyo) . Our study is performed jointly with Professor Dick K.P. Yue's group at MIT and is in close collaboration with other investigators in this DRI.

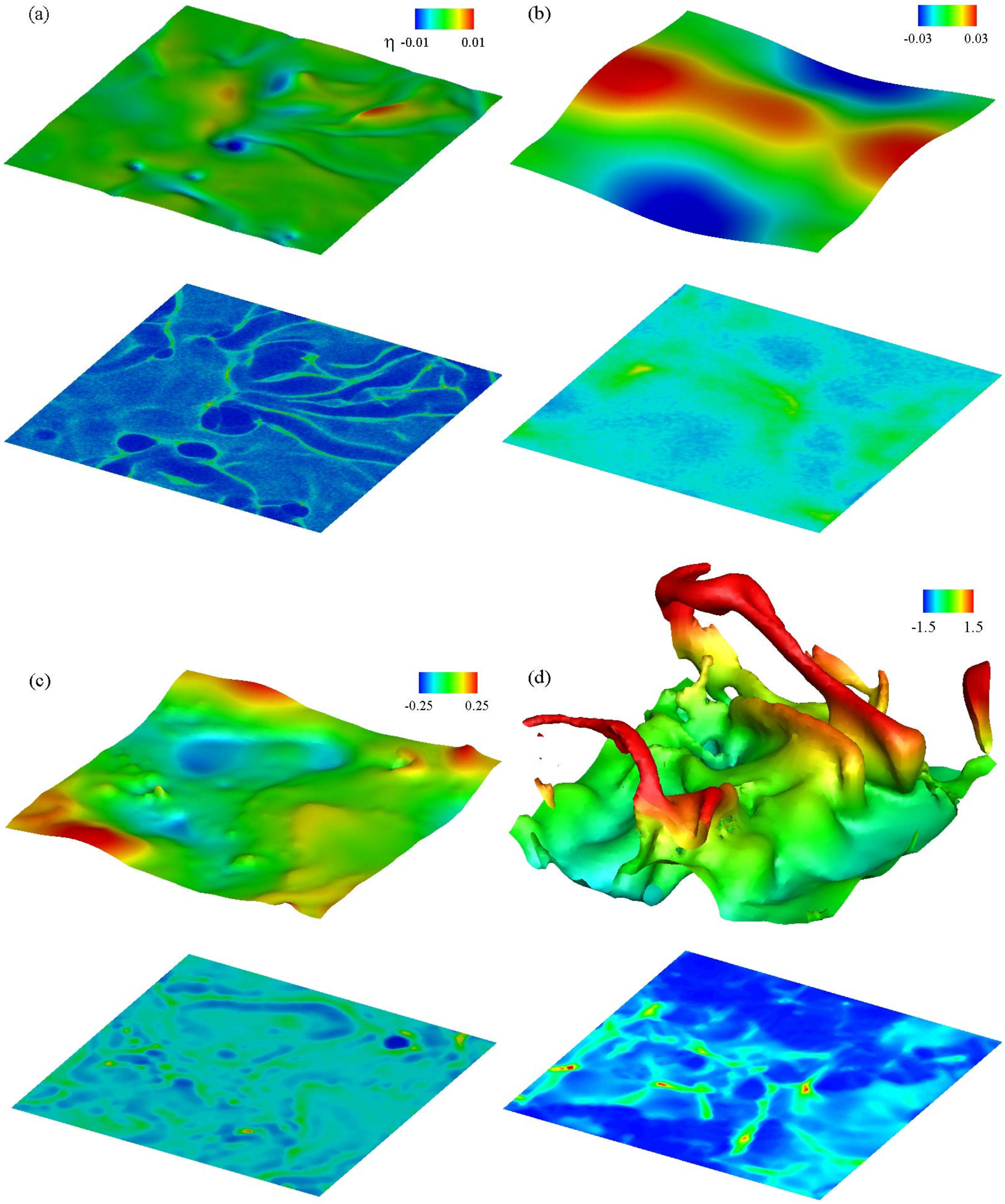

Figure 1. Underwater irradiance field in free-surface turbulence for cases of: (a) small surface elevation, (b) surface-tension dominated, (c) gravity dominated, and (d) strong turbulence. Plotted are surfaces with contours of surface elevation and horizontal distribution of downwelling irradiance field at a representative depth.

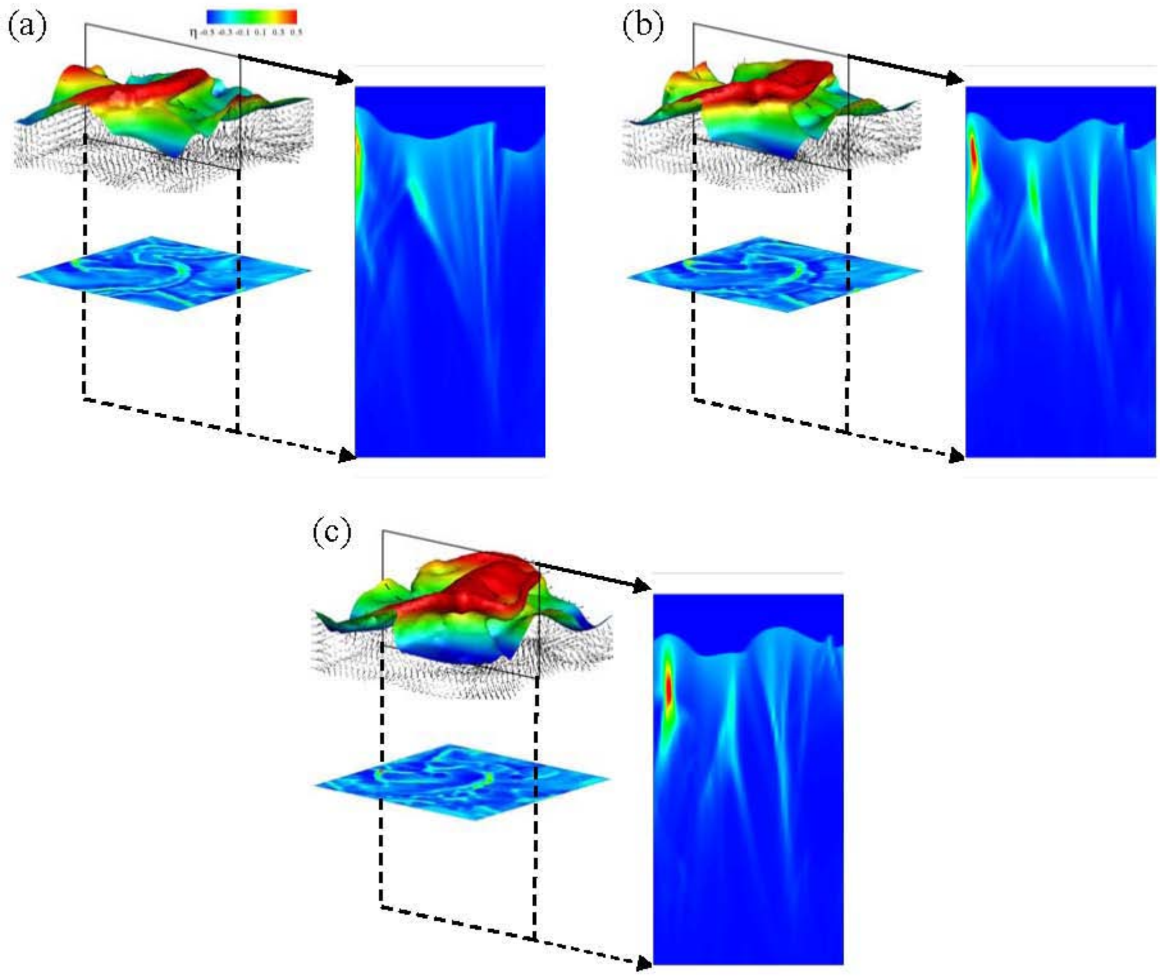

Figure 2. Irradiance field under breaking surface captured in free-surface turbulence simulation. The breaking surface with contours of surface elevation, horizontal distribution of downwelling irradiance field underwater, and vertical distribution of downwelling irradiance field across the breaking surface are shown (a) before, (b) during, and (c) after the breaking.

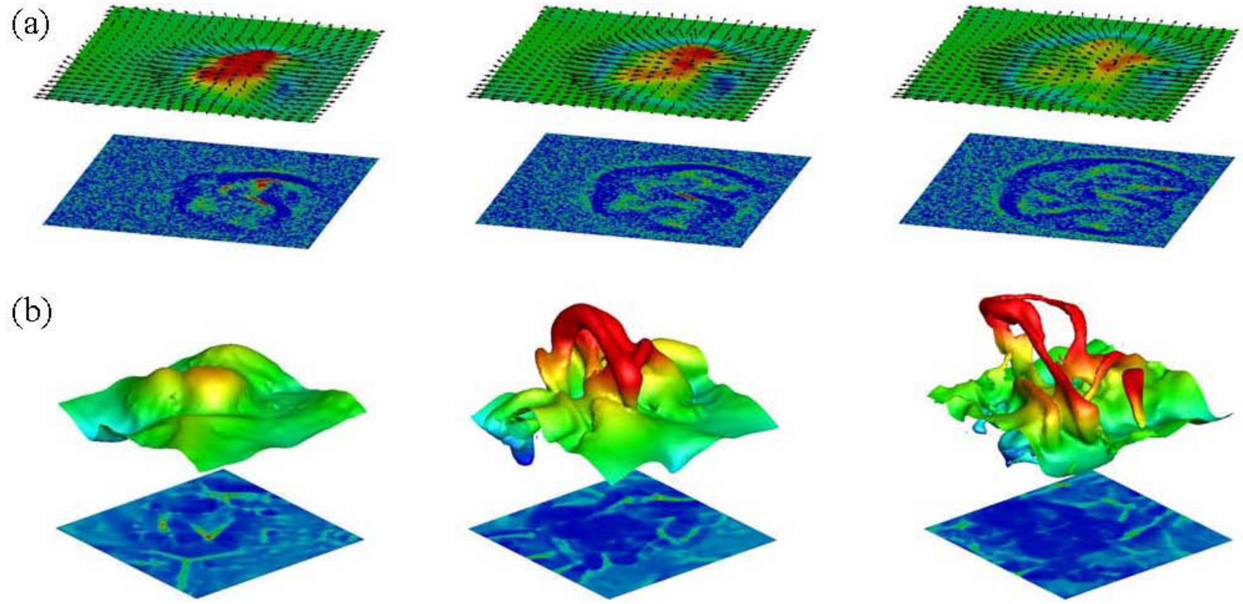

Figure 3. Irradiance field under surface splat event for: (a) a small surface elevation case and (b) a violent surface case. Plotted are surface with contours of surface elevation and horizontal distributions of downwelling irradiance at a represented depth.

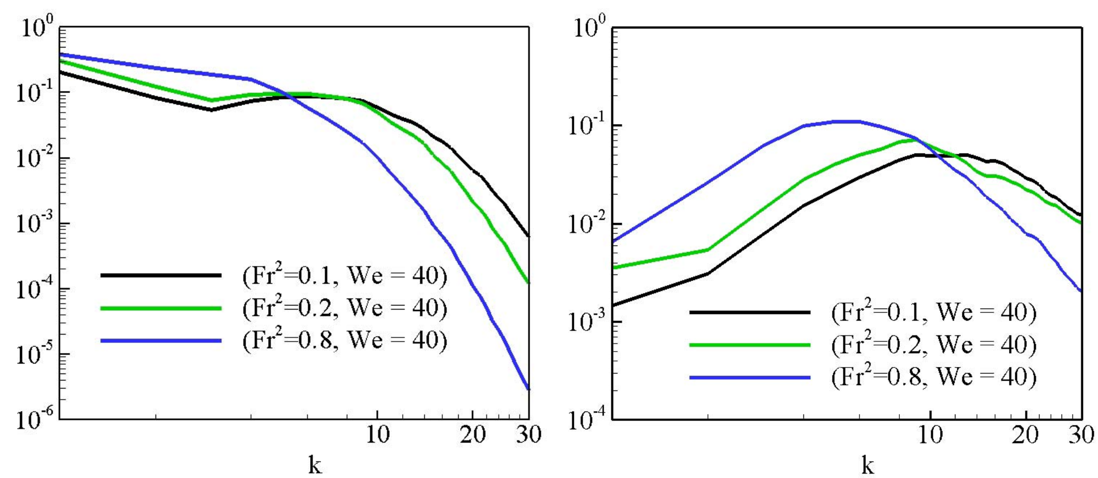

Figure 4. Left: spectra of surface slope for different cases of free-surface turbulence. Right: spectra of downwelling irradiance underwater. The spectra are normalized by the root-mean-square values of the corresponding variables.

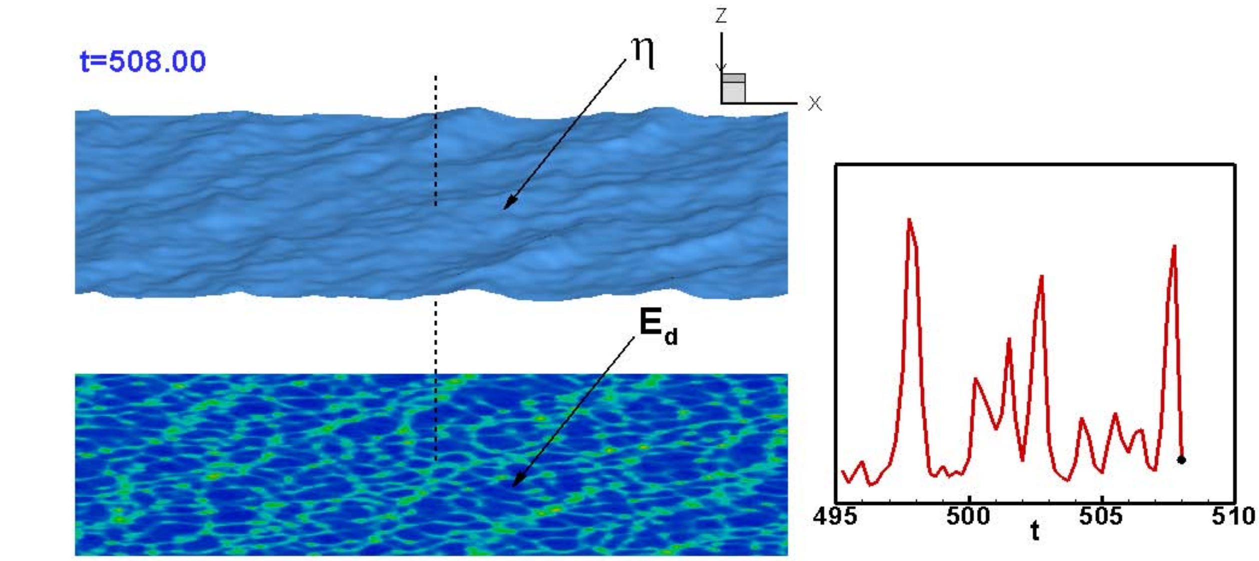

Figure 5. Left: instantaneous water surface obtained from wind-wave simulation and horizontal distribution of underwater irradiance obtained from RT simulation. Right: time history of irradiance at the point marked in the left figure.

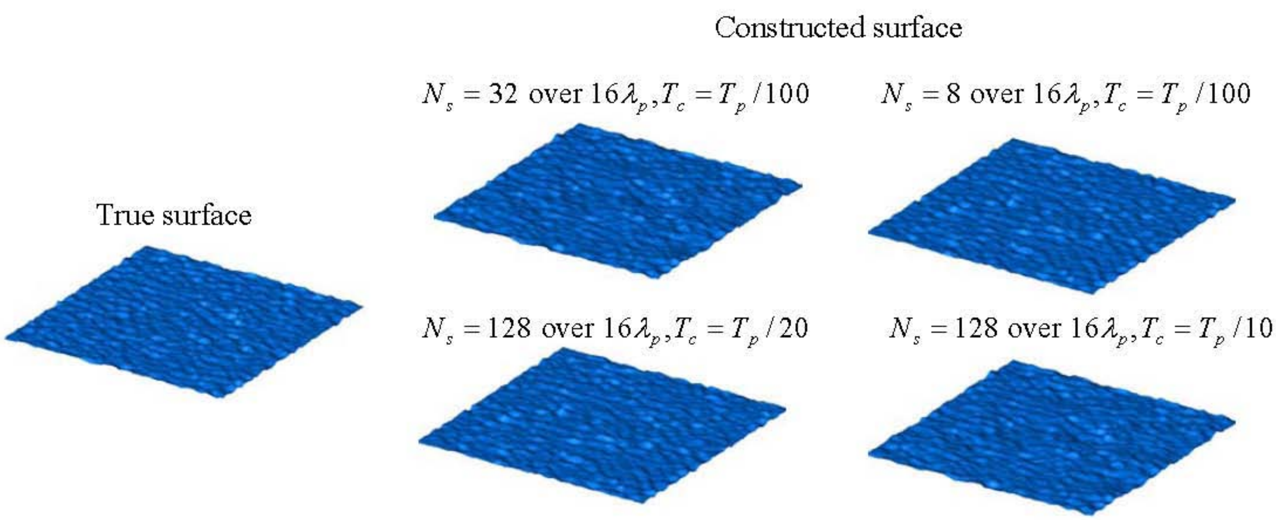

Figure 6. Reconstruction of the waves at sea based on underwater radiance field. Shown is the comparison of the original surface with reconstructed surfaces using radiance data with various sensor numbers N_s and sampling frequencies T_c. Here, λ_p and T_p are respectively the wave length and frequency of the dominant surface wave.