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

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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 **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
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)**	**12**	

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 2008, substantial progresses have been made including:

- To investigate the effect of turbulence on the radiative transfer, we simulated the turbulent transport and diffusion of heat in the upper ocean, investigated the variation of IOPs and refraction index due to sea water temperature change, and elucidated the effect on RT.
- In anticipation of large wave and high wind condition in the Hawaii experiment planned for the end of FY08, we have investigated the radiative transfer under steep and breaking waves. Research performed includes:
  - Development of Monte Carlo simulation tool for RT with steep and overturning water surface for breaking waves, and development of simulation capability for photon multiple air-to-water and water-to-air entries to address plunging breakers and air entrainment.
  - Development of numerical capability for simulation of steep and breaking waves using advanced level-set and volume-of-fluid methods.
  - Simulation of various breaking wave cases including collapse of steep waves, dispersive focusing of wave packet, and wave steepening under wind action.
  - Simulation of RT under steep and breaking waves, and characterization of the underwater radiance field.
- As a potentially important application of underwater RT study for the navy, we investigated radiance field in the ship wake. Research performed includes:
  - As a canonical problem for the near wake, we investigated the surface features behind a surface body and the underwater optical signature.
  - For the far wake, we simulated the Kelvin wake behind a ship and its interaction with the ambient broadband wind-wave, based on which the RT simulation underwater has been performed.
- We have compared our simulation results with measurement and other modeling results in the literature, and have started the incorporation and analysis of data from the recent measurement.
- We investigated the reverse modeling of sea surface geometry based on the underwater light field and wave dynamics. Canonical problems studied include:
  - Reconstruction of the water surface geometry before and after wave breaking based on underwater irradiance distribution.
  - Reconstruction of the surface wave pattern in the ship wake using underwater irradiance distribution.

RESULTS

In previous years of the project, our study focused on relatively mild sea conditions. In anticipation of large waves and high winds in the Hawaii experiment planned for the end of FY08, we recently investigated the radiative transfer under steep and breaking waves. Substantial progress has been made towards the numerical simulation of wind-wave evolution including wave growing, steepening, and breaking. With the sea surface geometry obtained from wave simulation, we performed radiative transfer simulation. Our RT simulation tool is improved to address the complexities of breaking waves, in particular, the steep wave surface and the multiple photon entries of air-to-water and water-to-air that are associated with wave overturning and air pocket and entrainment.

Figure 1 shows a simulation result of wind forced steep water wave. Under wind action, the water surface is featured by dominant progressive wave and small scale surface variation in the transverse direction. The former has steep crests, which cause radiance focusing near the surface; the latter has small transverse curvatures, which cause mild radiance focusing at a deep location. As a result of this different focusing depths, the horizontal distribution of the downwelling irradiance varies from the spanwise structure dominant in shallow regions (Figures 1b and 1c), to streamwise structure dominant in deep regions (Figures 1d and 1e).

Figure 2 shows the simulation result of irradiance field under a breaking wave that initially has a large steepness. The surface complexity induced by the wave breaking apparently affects the surface refraction and underwater transmission of the radiance, which differs from that in the regular Airy or Stokes wave cases. As shown in Figure 2(a), right before the wave breaking, the large convex curvature of the crest generates a wide irradiance focusing region underwater; meanwhile, due to the steep slope on the forward face of the crest, significant amount of irradiance is lost when the light rays penetrate the air-water interface. As a result, a dark zone exists underneath the forward face of the wave. During the wave breaking, air pockets and bubbles are generated, which lead to the total internal reflection of the light ray, upward transfer of the irradiance, and an underwater dark region (Figure 2b). Meanwhile, small scale surface ripples and short waves are generated, which cause shallow irradiance focusing over a wide region of the breaking wave. After wave breaking, the water surface is full of three-dimensional patterns, generating complex three-dimensional downwelling irradiance field under the water surface (Figures 2c and 2d).

Besides the collapse of steep waves, the dispersive focusing of wave packet can also cause wave breaking. We simulated the latter as well, and performed the same analysis for the radiative transfer as in Figure 2. Representative results are shown in Figure 3, which show essentially the similar features as in Figure 2, indicating the generality of our results for different wave breaking cases.

The radiative transfer in the upper ocean is also affected by turbulence. The turbulent transport and diffusion of heat causes variation in sea water temperature, which in turn affects the absorption and scattering coefficients and refraction index, and thus affects the radiance distribution. As a first step of this study, we consider the heat transfer near the sea surface with the heat treated as a passive scalar and turbulence boundary layer process isolated from the wave effect. Our turbulence scalar transport code is capable of incorporating the surface elasticity effect of surfactants. Figure 4 shows an example of our simulation. From the simulation, we obtain instantaneous, three dimensional description of the temperature field, based on which the spatial variation of IOPs is determined empirically based on previous measurement study. Effect of IOP variation caused by turbulence is clearly shown in the irradiance field plotted in Figure 4.

Radiative transfer in the upper ocean can be affected significantly by processes such as the passage of a surface ship. In this study, we consider as a canonical problem the interaction of ship Kelvin wake with wind-waves of following seas, head seas, and beam seas. We found that the relative magnitude of the ship waves and the wind-waves plays an essential role in the underwater radiance distribution. Figure 5 shows some examples. For the relatively calm sea case, the irradiance field is dominated by the Kelvin wave pattern. When the wind-wave becomes stronger, the underwater radiance signature of the Kelvin wave becomes less obvious. Among the cases with different wind-wave propagation directions, the effect of Kelvin wave on irradiance field is about the same between following seas and head seas, and is weak for the beam seas. This result indicates that to detect the passage of surface ship based on underwater light field, beam sea condition is probably the most difficult.

In FY08, we continued the attempt of reverse modeling of the sea surface geometry based on underwater irradiance field. Our ultimate goal is to develop a reverse modeling framework based on wave dynamics, radiative transfer, and data assimilation. Figure 6 shows a preliminary result for the wave before and after breaking shown in Figure 2. It is found that the depth of the irradiance data the reverse modeling is based on plays an essential role in the sea surface reconstruction. If the irradiance field far away from the sea surface is used, the reverse modeling underestimates the surface slope. On the other hand, if the irradiance field close to the surface is used, the reverse modeling overestimates the surface slope. At the optimum depth, it is found that the large-scale surface features can be recovered. Nevertheless, the breaking wave introduces great complexity to the problem, and we are still in the process of investigating the feasibility of reverse modeling for waves during break.

To investigate the feasibility of detecting the passage of surface ships based on underwater radiance signal, which may have important navy applications, we performed reverse modeling of the sea surface wave pattern for the problem of ship Kelvin wave interacting with wind-waves shown in Figure 5. Figure 7 shows a preliminary result. It is found that as the depth of available radiance data increases, the quality of reverse modeling decreases. Nevertheless, it appears that the ship Kelvin wave is more distinct than the wind-wave in the result of reverse modeling. Such finding is promising, and continued investigation in this direction will be one of the focuses of our next phase of study.

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.

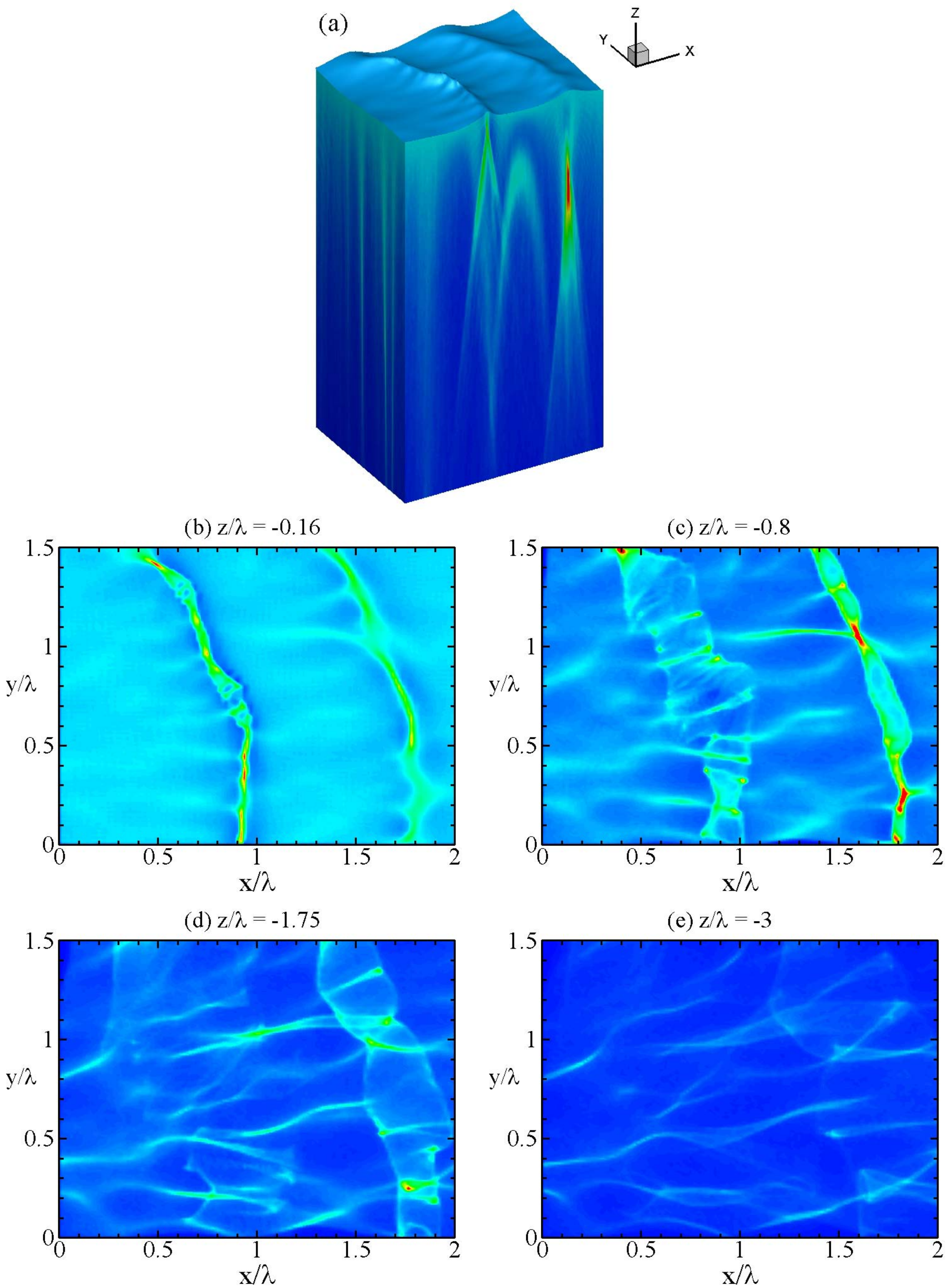

Figure 1. Distribution of downwelling irradiance under steep wind-wave. Plotted are (a) three-dimensional illustration, and (b)-(e) horizontal distributions of downwelling irradiance at different depths (normalized by the wave length of the dominant surface wave).

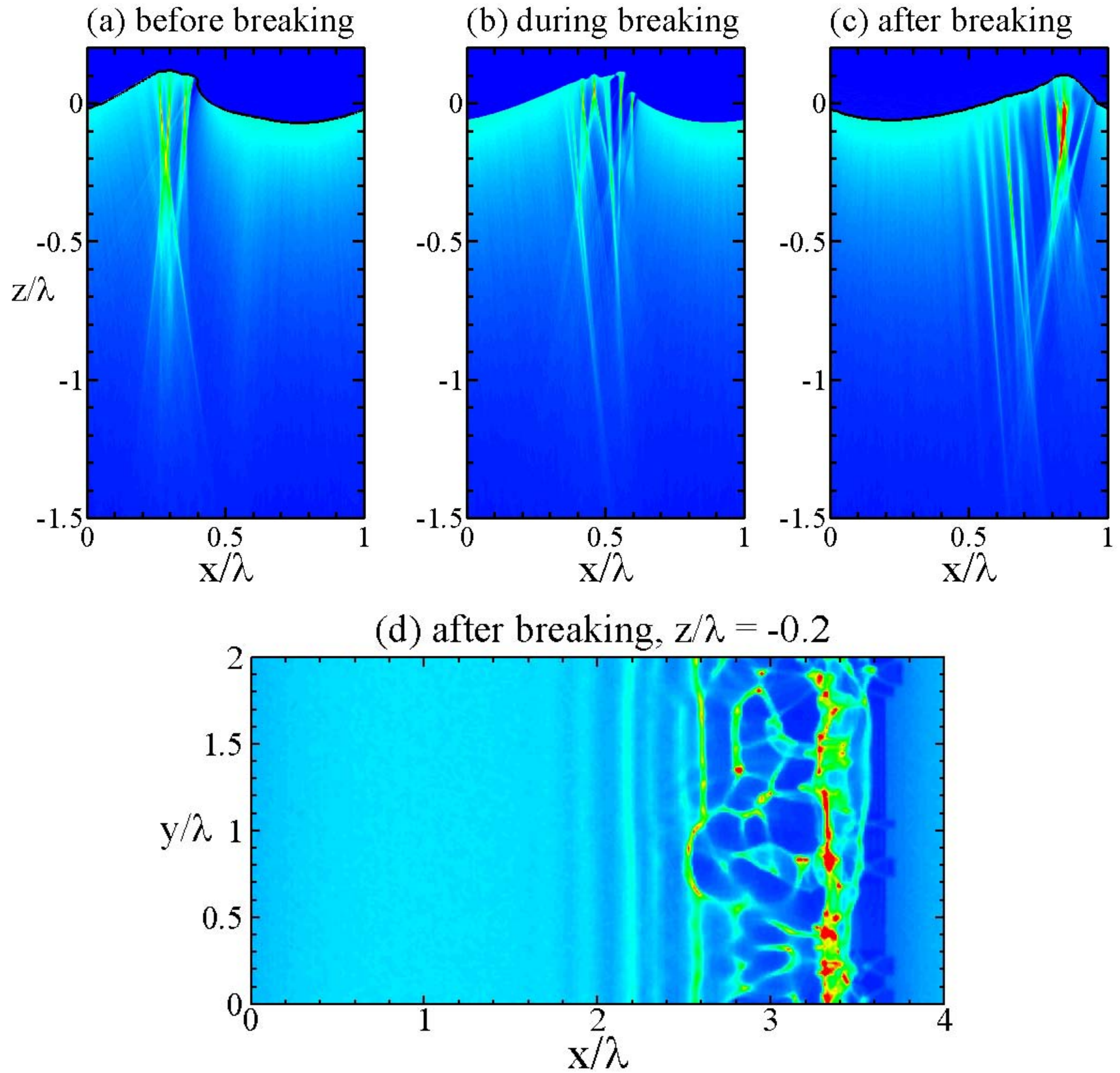

Figure 2. Irradiance field under breaking wave generated by collapse of a steep wave. Plots (a)-(c) show the vertical distribution of downwelling irradiance before, during, and after wave breaking, respectively. Plot (d) shows the horizontal distribution of downwelling irradiance after wave breaking at depth z/ λ = -0.2 (normalized by the wave length of the dominant surface wave).

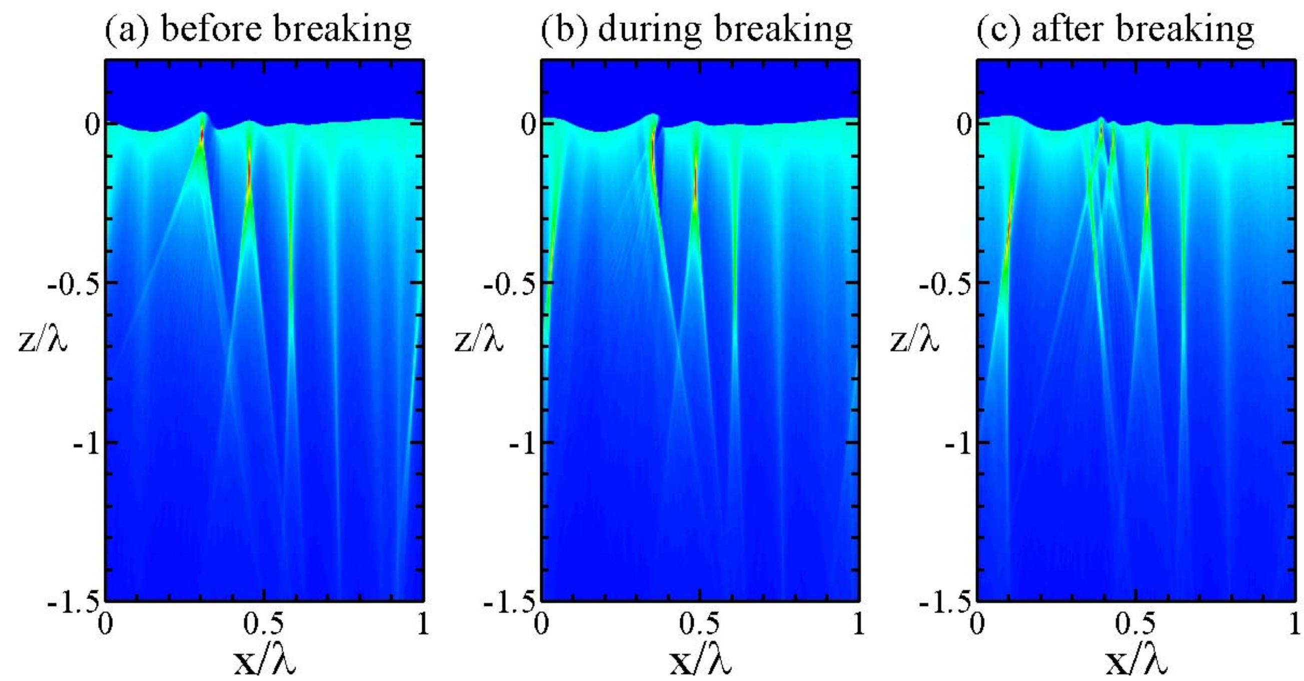

Figure 3. Irradiance field under breaking wave generated by dispersive focusing of surface waves. Plotted are distributions of downwelling irradiance on a vertical plane crossing the breaking crest (a) before, (b) during, and (c) after wave breaking. Here λ is the wave length of the dominant surface wave.

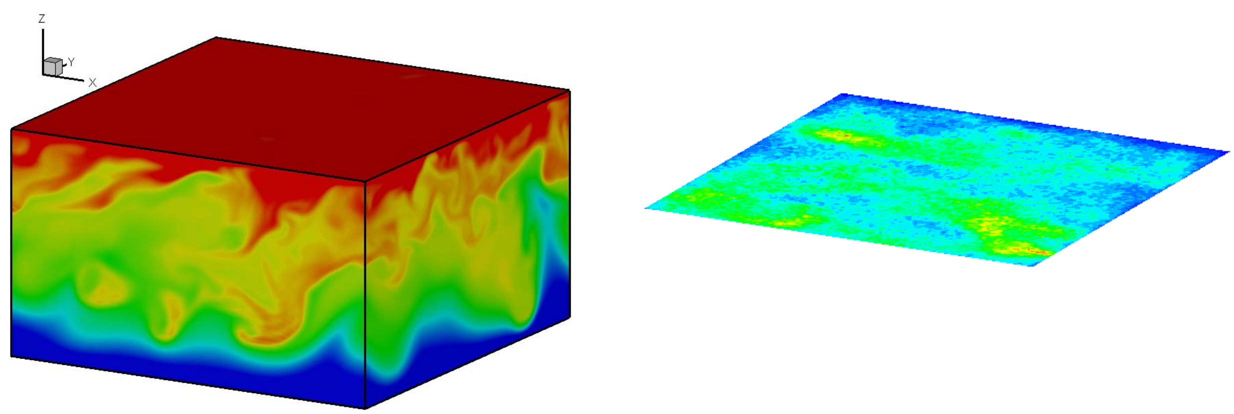

Figure 4. Left: near surface distribution of temperature in turbulence. Right: underwater downwelling irradiance horizontal variation.

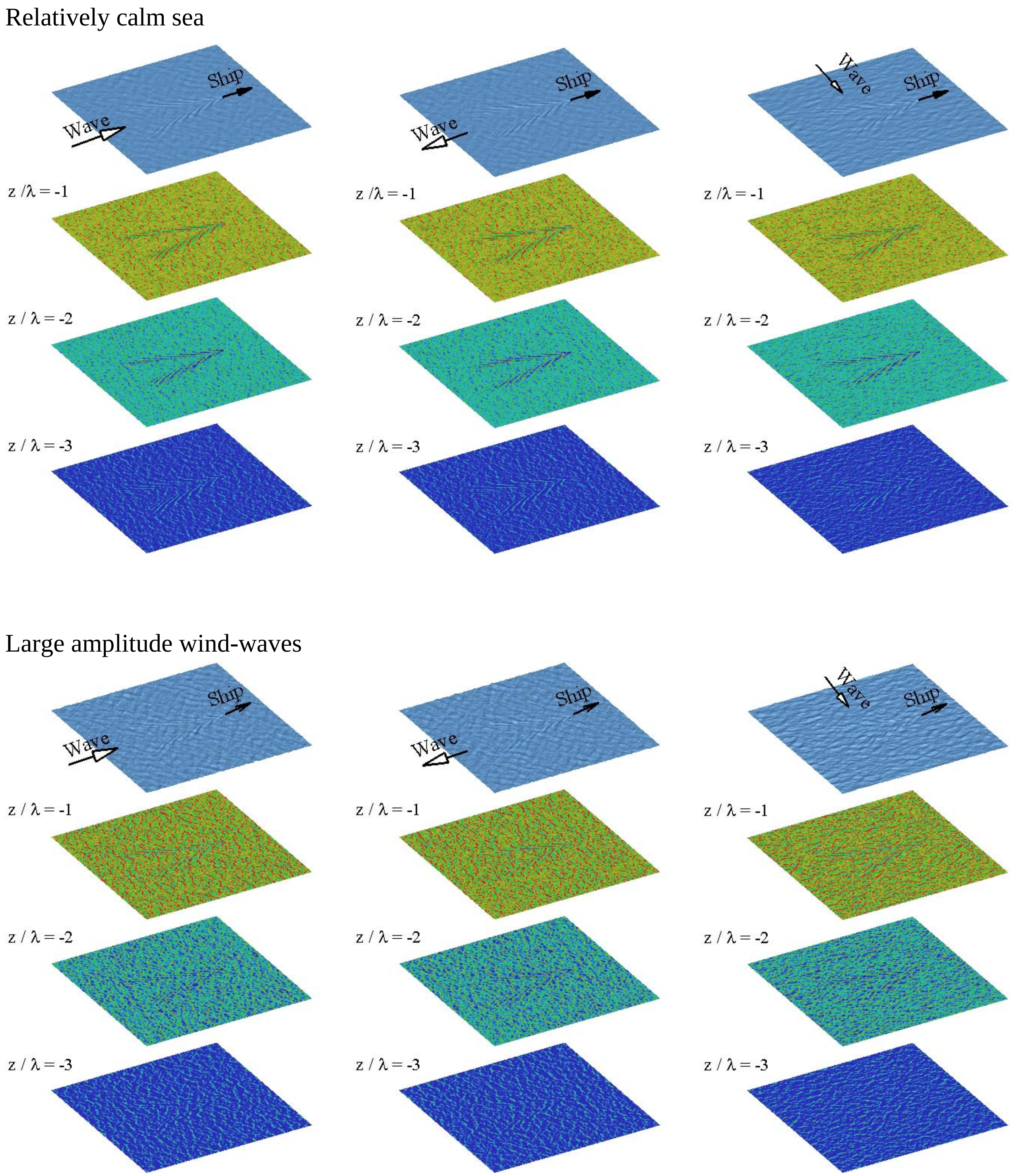

Figure 5. Waveform at the sea surface and the underwater irradiance distribution. At the sea surface, the V-shaped Kelvin wake behind a surface ship interacts with wind-waves of following seas, head seas, and beam seas. Two scenarios, one with a relatively calm sea and one with waves of relatively large amplitude, are considered. The underwater downwelling irradiance at various depths (normalized by the wave length of the dominant surface wave) is shown.

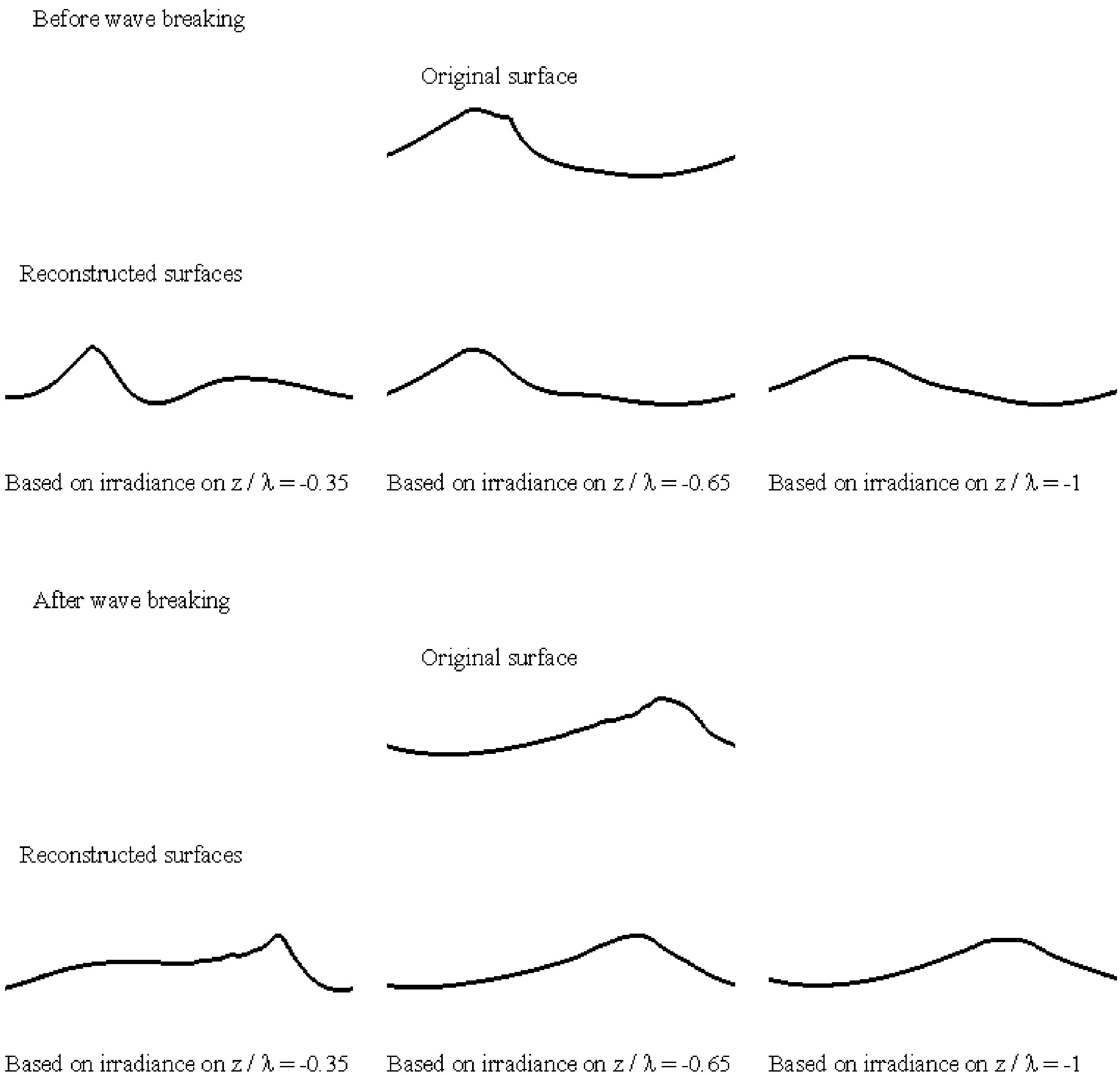

Figure 6. Reconstruction of water surface elevation profiles before and after wave breaking, based on underwater irradiance field. Comparison of the original surface with constructed surfaces using radiance data at various depths (normalized by the wave length of the surface wave) is shown.

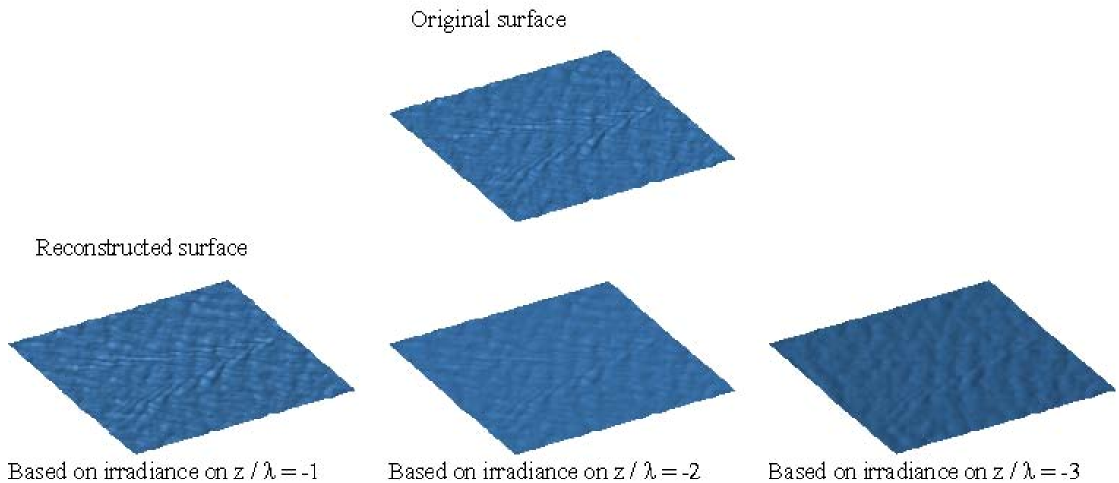

Figure 7. Reconstruction of the waveform at sea based on underwater irradiance field for the case of ship Kelvin wave interacting with wind-waves of following seas. Comparison of the original surface with constructed surfaces using radiance data at various depths (normalized by the wave length of the dominant surface wave) is shown.