

## **Modeling and Parameterization Study of Radiance in a Dynamic Ocean**

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### **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 for the data analysis as 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)
- develop numerical capabilities for free-surface turbulence (FST) and the resultant surface roughness
- develop direct simulations of RT in the presence of SBL processes of wave and turbulence
- 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
- develop inverse modeling for the reconstruction of free-surface properties and objects using measured RT data and direct simulation

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## **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 and FST. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, and the development and transport of FST 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 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 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.

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 message passing interface (MPI) based on domain decomposition.

## **WORK COMPLETED**

During the fiscal year of 2011, substantial progresses have been made including:

- Establishment of an extensive data base of free-surface turbulence with the under-surface temperature and salinity fields. By investigating the free-surface turbulence data base, we obtained substantial new understanding of the physics (Guo & Shen, 2010; Kermani, Khakpour & Shen, 2011; Khakpour, Shen, & Yue, 2011). In collaboration with Prof. Dick Yue's research group at MIT, a large number of RT simulations have been performed using the geometry of the water surface and the underlying distribution of temperature and salinity from the data base to investigate the dependence of the light field on the near-surface turbulence and surface waves (Xu et al. 2011a, b). Research performed includes
  - Investigation of the turbulence transport mechanism near the free surface.
  - Investigation of the effect of the near-surface turbulence on temperature and salinity concentration.
  - Quantification of the turbulence structure of IOPs with empirical models for the dependence of IOPs on temperature and salinity.
  - Development of a hybrid method to combine the Monte Carlo method with numerical ray technique to simulate not only the scattering and absorption processes but also the bending of light during its traveling through turbulent water.
- Investigation of realistic, dynamic wind-wave interaction (Liu et al. 2010), and its effect on the underlying RT.
- Comparison of the numerical results with the field measurement made during the RaDyO SBC experiment in September 2008 and Hawaii experiment in September 2009; incorporation and investigation of data from recent experiments have also started (Xu et al. 2011b). This part of research is conducted in collaboration with Prof. Dick Yue's group at MIT.

## RESULTS

Turbulence transport is important to the variations of scalars (e.g., temperature, salinity, and chlorophyll concentration) near ocean surface, which further affect the variations of inherent optical properties (IOPs). In this study, we have investigated in detail free-surface turbulence and its role on the transport of scalars. A representative result is shown in Figure 1, which is the conditional average of splat events, a characteristic structure of turbulence near the free surface. The result shows that during a splat event, a large amount of kinetic energy associated with horizontal motion is brought directly towards the region right under the free surface from the deep region by vertical motion. The energy associated with vertical motion is brought upwards to the near-surface region, transported by the pressure to the free surface, and then redistributed to the energy associated with horizontal motion by pressure-strain correlation.

Figure 2 shows an example of the scalar transport by the turbulence near a free surface, which is the conditionally averaged result of the flow and scalar fields, with the conditional averaging performed with respect to strong scalar flux events. The high surface flux is accompanied by the large surface divergence (Figure 2b) and the splat radiating motion there (Figure 2a). That is, the large vertical motion associated with the splat event not only brings large amount of turbulence energy to the free surface but also brings scalar to the free surface.

Radiative transfer in the upper ocean is strongly affected by the inhomogeneity in IOPs, especially the absorption and scattering coefficients and refractive indices, which is caused by the fluctuations in

temperature, salinity, and chlorophyll concentration. In FY11, we made substantial progress in the investigation of the role of turbulence on the radiance field near the ocean surface. Our investigation shows that the IOPs strongly depend on the near-surface turbulence and surface waves. A representative result is plotted in Figure 3, which shows the vertical variations of the mean values and standard deviations of IOPs in ocean turbulence. Different conditions of turbulence, surface waves, temperature, salinity, and chlorophyll concentrations are considered.

Figure 4 shows a representative, instantaneous irradiance field with consideration of variations of IOPs due to turbulence flows near ocean surface. The variations of IOPs induce different variations in the patterns of downwelling irradiance field at different depths. Near the ocean surface, the effect of the turbulence on the downwelling irradiance field is relatively small, due to the small distance of light propagation (Figure 4a). At relatively deep region, the variations in the downwelling irradiance are obvious (Figure 4c). The pattern of upwelling irradiance resembles that of the downwelling irradiance (Figure 4b and d).

## **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.

## **PUBLICATIONS**

Guo, X. & Shen, L. (2010), Interaction of a deformable free surface with statistically steady homogeneous turbulence, *Journal of Fluid Mechanics*, **658**, 33-62.

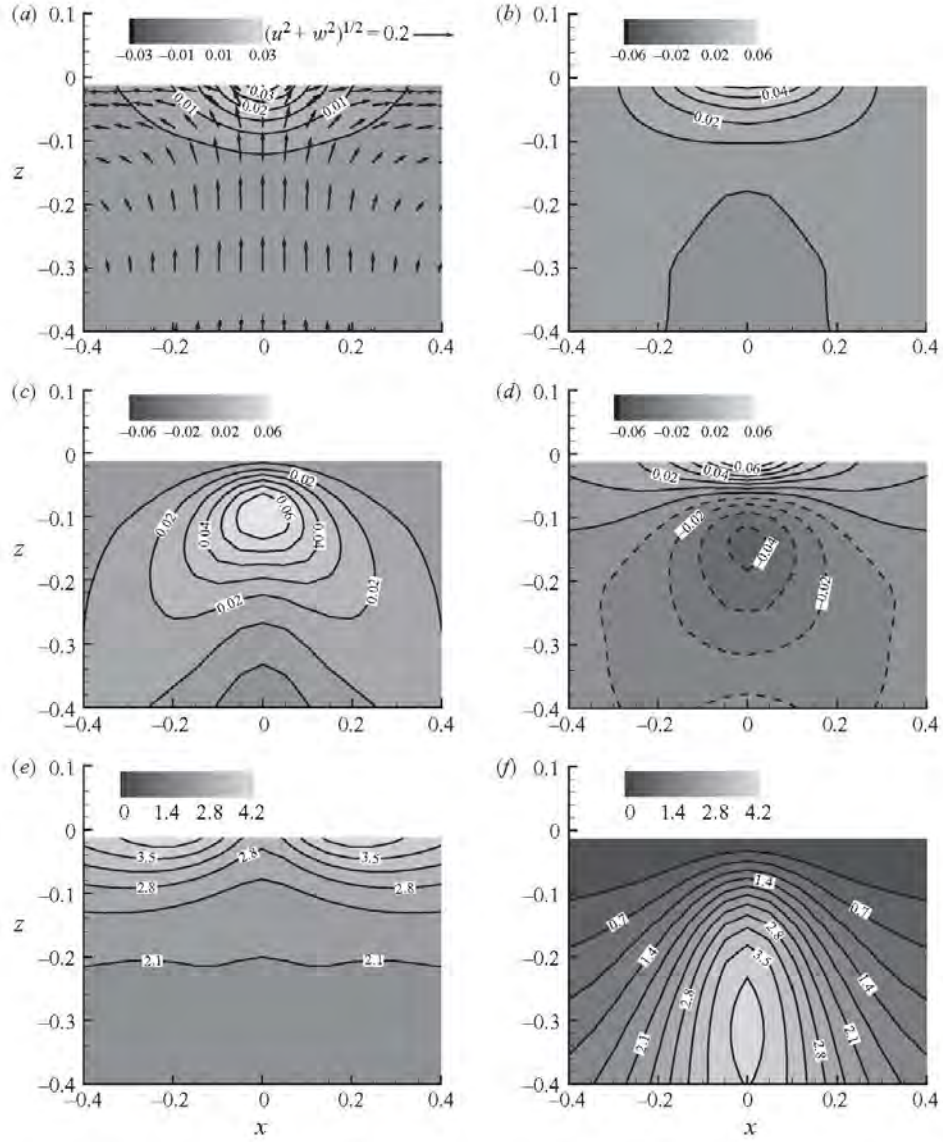
Kermani, A., Khakpour, H. R., Shen, L., & Igusa, T. (2011), Statistics of surface renewal of passive scalars in free-surface turbulence, *Journal of Fluid Mechanics*, **678**, 379-416.

Khakpour, H. R., Shen, L., & Yue, D. K. P. (2011), Transport of passive scalar in turbulent shear flow under a clean or surfactant-contaminated free surface, *Journal of Fluid Mechanics*, **670**, 527-557.

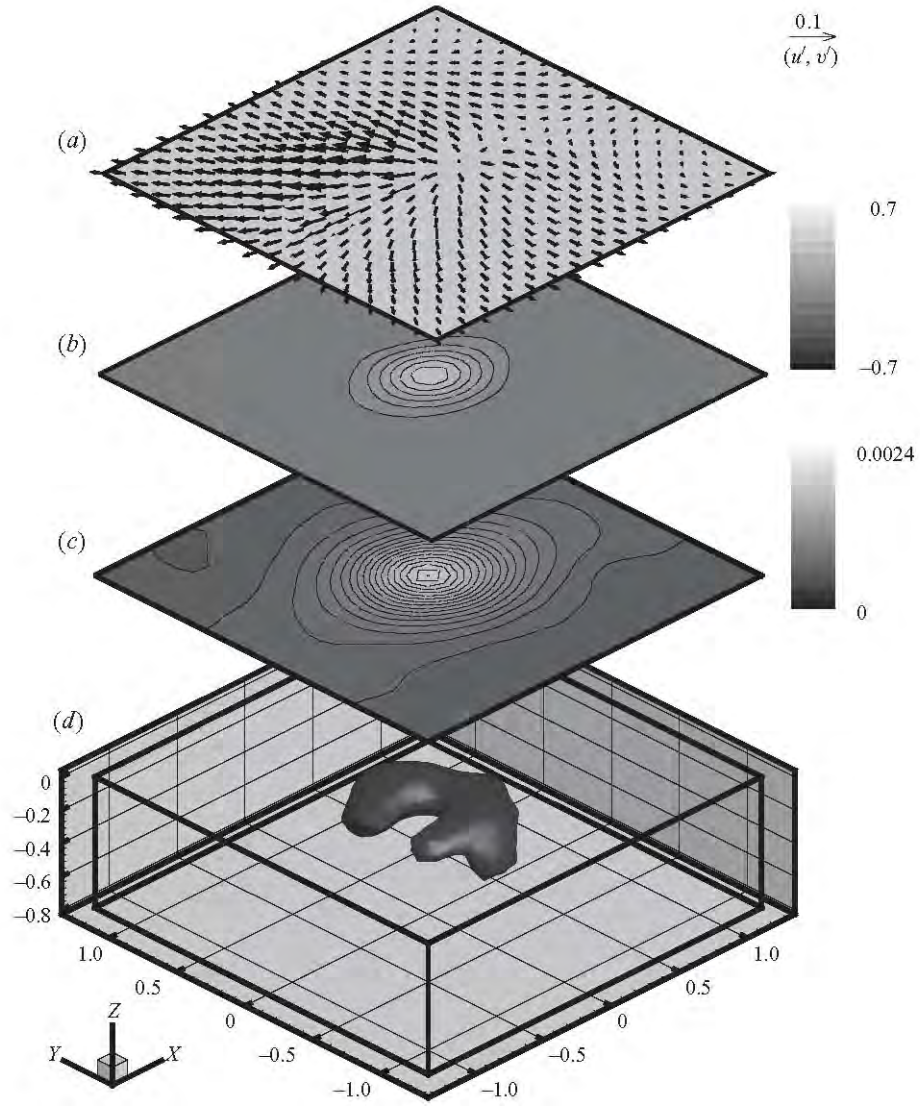
Liu, Y., Yang, D., Guo, X., & Shen, L. (2010), Numerical study of pressure forcing of wind on dynamically evolving water waves, *Physics of Fluids*, 041704.

Xu, Z., Guo, X., Shen, L., & Yue, D. K. P. (2011a), Radiative transfer in ocean turbulence and its effect on underwater light field, *Journal of Geophysical Research – Oceans* (submitted).

Xu, Z., Yue, D. K. P., Shen, L., & Voss, K. J. (2011b), Patterns and Statistics of In-Water Polarization under Conditions of Linear and Nonlinear Ocean Surface Waves, *Journal of Geophysical Research – Oceans* (in press).

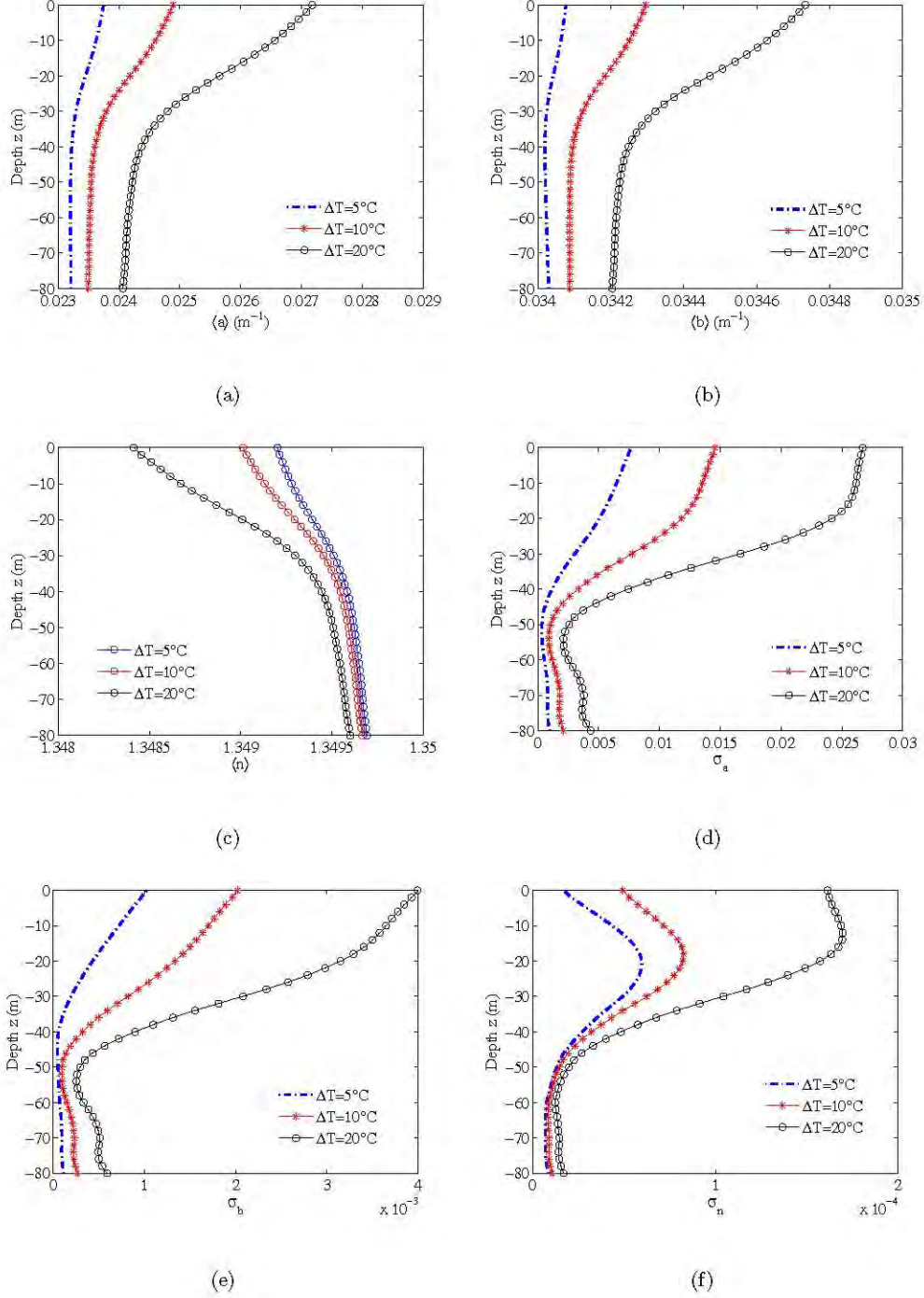


**Figure 1. Conditionally averaged result of splats. On the vertical cross-section passing the splat center, contours of (a) pressure-strain correlation, (b) turbulent transport of energy associated with horizontal motion, (c) turbulent transport of energy associated with vertical motion, (d) pressure transport, (e) kinetic energy associated with horizontal motion, (f) kinetic energy associated with vertical motion.**

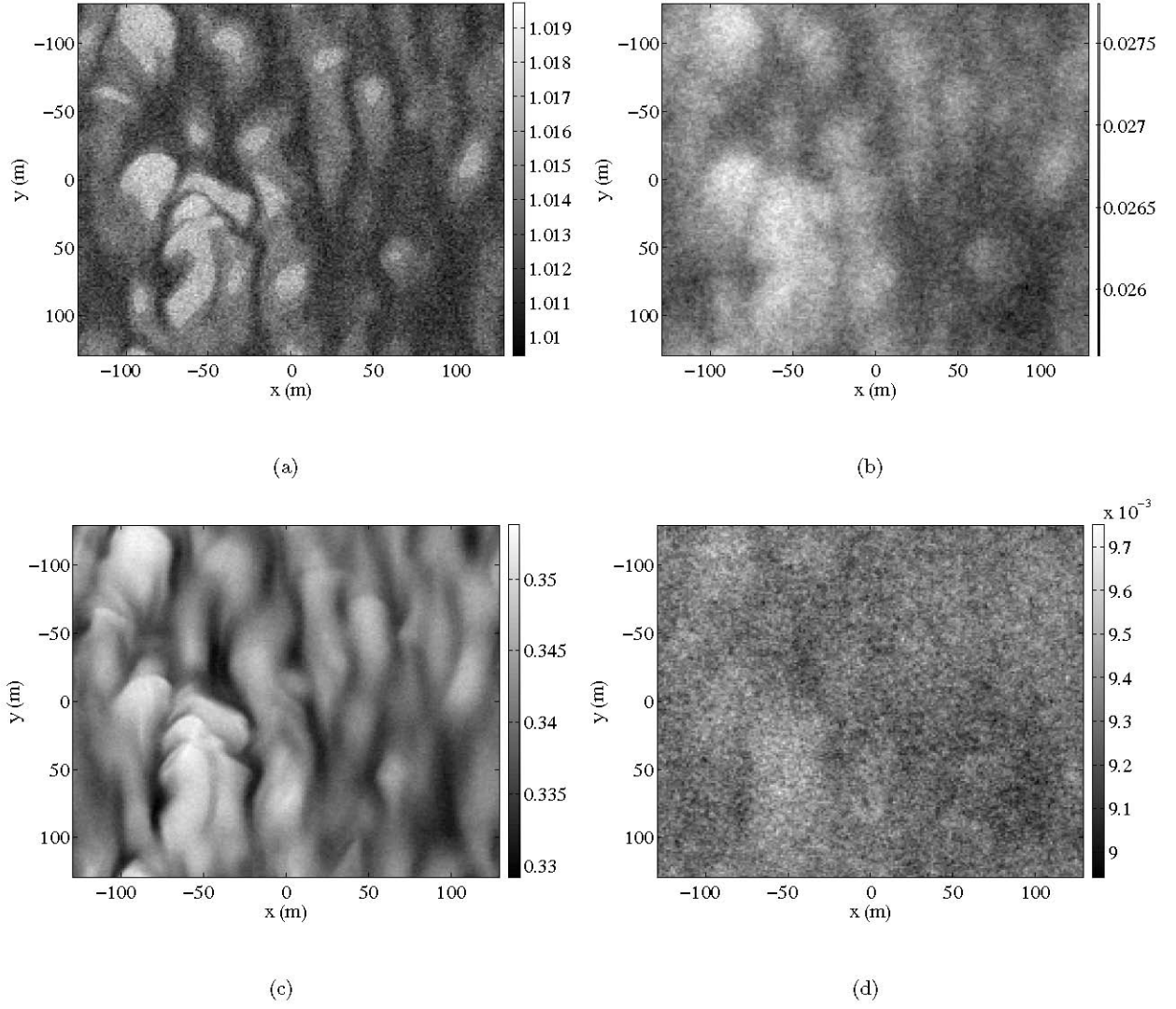


**Figure 2. Conditionally averaged result of flow and scalar fields, with the conditional averaging performed with respect to strong scalar flux events. The following are plotted: (a) vectors of fluctuating velocity at the surface, (b) contours of surface divergence at the surface, (c) contours of scalar flux at the surface, and (d) coherent vortex structure.**





**Figure 3. Vertical variation of mean values and normalized standard deviations of IOPs in ocean turbulence. (a) Mean value of absorption coefficient  $\langle a \rangle$ ; (b) mean value of scattering coefficient  $\langle b \rangle$ ; (c) mean value of refractive index  $\langle n \rangle$ ; (d) normalized standard deviation of absorption coefficient  $\sigma_a$ ; (e) normalized standard deviation of scattering coefficient  $\sigma_b$ ; and (f) normalized standard deviation of refractive index  $\sigma_n$ .**



**Figure 4. Instantaneous irradiance field below an ocean surface with turbulence underneath.**  
**(a) Downwelling irradiance  $E_d$  at  $z = -1$  m; (b) upwelling irradiance  $E_u$  at  $z = -1$  m; (c)**  
**downwelling irradiance  $E_d$  at  $z = -50$  m; and (d) upwelling irradiance  $E_u$  at  $z = -50$  m.**