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14. ABSTRACT

The ultimate goal is to understand and quantify wave-breaking dissipation using large-scale phase-resolved simulation of three-dimensional nonlinear wave-field evolution and to develop effective modeling and parameterization of wave-breaking dissipation for phase-averaged wave prediction models. Characterize wave-breaking events in terms of magnitude, time and location of wave energy dissipation, obtain the spatial, temporal distribution and statistical characteristics of wave-breaking dissipation, and quantify the dependence of wave-breaking dissipation on wave spectral parameters.

15. SUBJECT TERMS

Wave Breaking, Wave-breaking dissipation, phase-resolved wave-field simulation, phase-averaged wave prediction

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Quantifying Breaking-Wave Dissipation Using Nonlinear Phase-Resolved Wavefield Simulations

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LONG-TERM GOAL

To understand and quantify wave-breaking dissipation using large-scale phase-resolved simulation of three-dimensional nonlinear wave-field evolution; and to develop effective modeling/parameterization of wave-breaking dissipation and wind forcing for phase-averaged wave prediction models.

OBJECTIVES

The specific scientific and technical objectives are:

- To characterize wave breaking events in terms of magnitude, time and location of wave energy dissipation. Obtain the spatial, temporal distribution and statistical characteristics of wave-breaking dissipation.

- To quantify the dependence of wave-breaking dissipation on wave spectral parameters and investigate the effect of wave-breaking dissipation on wave-spectrum evolution.

- To develop effective modeling/parameterization of wave-breaking dissipation for phase-averaged wave prediction models (such as WAM and SWAN).

- To understand energy balance in an evolving wave field and to develop wind-forcing modeling and parameterization for phase-averaged wave prediction models.

APPROACH

Direct large-scale phase-resolved simulations of three-dimensional nonlinear wave-field evolution are employed to investigate the characteristics and develop effective modeling of breaking-wave dissipation. The computational tool that we use is the so-called SNOW (**s**imulation of **n**onlinear **o**cean **w**aves) which has been developed and continuously improved over the past twenty years at MIT under the support of ONR. In SNOW, key physical mechanisms such as nonlinear broad-band wave-wave interactions and wave-breaking dissipation are modeled in a direct physics-based context. Unlike phase-averaged approaches, SNOW obtains deterministic predictions wherein precise ocean surface and whole-field particle velocities are given. SNOW is developed based on a high-order pseudo-spectral method, which follows the evolution of a large number (N) of wave modes and accounts for their nonlinear interactions up to an arbitrary order (M) in wave steepness. Significantly, SNOW obtains an exponential convergence and requires an approximately linear computational effort with N, M. It is a powerful tool for direct simulations of realistic ocean wave-field evolution.

In SNOW computations, we apply an adaptive algorithm to model the effect of wave breaking using effective low-pass filtering in the spectral domain for relatively small-scale breaking and local smoothing in the physical domain for large-scale breaking. Significantly, this approach does not involve free/adjustable parameters. This wave-breaking model is found to be robust and capable of reliably predicting the energy dissipation in wave breaking events. It is validated by direct comparisons to experimental measurements of various two- and three-dimensional breaking wave events before and after breaking. In large-scale nonlinear wave-field simulations, the wave-breaking model is shown to be effective in obtaining phase-accurate wave fields involving extensive wave breaking. A powerful aspect of this SNOW capability is that the wave-breaking occurrence in space and time does not need to be pre-specified but is obtained from the evolution itself. By tracking the energy loss in the SNOW simulation resulting from application of the breaking treatment, the magnitude as well as the spatial-temporal location of the wave energy loss can be quantified. More details on the implementation and verification of this wave-breaking model/treatment can be found in Yue (2008) and Xiao *et al* (2013).

To study wave-breaking dissipation associated with evolving wave fields, we perform large-scale SNOW simulations of nonlinear wave-field evolution in domains of $O(10^{3\sim4})$ km^2 with evolution time up to O(1) hour. The wave fields with various spectral parameters (such as peak period, band width, propagation direction spreading, and significant wave height) are considered. Each simulation typically uses $N= O(10^{3\sim4})$ wave modes per dimension and nonlinearity order $M = 3\sim4$ to include modulational instability and quartet/quintet resonant wave-wave interactions. From the simulated nonlinear wave fields, we identify various types of wave-breaking events and then characterize/quantify the associated energy dissipation. Based on these results, we develop effective modeling and parameterization of wave-breaking dissipation for phase-averaged wave prediction models.

WORK COMPLETED

- ***Development and verification of robust effective wave-breaking model in SNOW.*** Based on experiments and observations of two-dimensional and three-dimensional wave breaking events, we developed and improved an effective robust phenomenological wave-breaking model and incorporated it into phase-resolved SNOW simulations to account for wave energy dissipation during wave breaking. This modified model could automatically determine the onset of wave breaking, differentiate the wave-breaking type (such as spilling or plunging breaking), and remove an appropriate amount of wave energy associated with the breaking from the wave field. The efficacy of this model was continuously improved by direct comparisons against laboratory measurements for the energy loss and detailed wave kinematics in two-dimensional and three-dimensional breaking events.

- ***Generation of phase-resolved nonlinear ocean wave fields***. We performed large-scale SNOW simulations on modern HPC platforms to obtain three-dimensional phase-resolved time-evolving nonlinear wave fields in a domain of ~10km x 10km for various wave spectra for the study of wave-breaking dissipation.

- ***Characterization of wave-breaking events in phase-resolved wave-field evolution***. In the simulated phase-resolved wave fields, we identified the location and time of occurrence of wave-breaking events and quantified the associated energy dissipation.

- ***Quantification of statistics of wave-breaking dissipation***. Based on the datasets of wave breaking events we collected, we obtained the spatial, temporal distribution and statistical characterization of wave-breaking dissipation. The correlation between occurrence of wave-breaking events and local wave kinematics (such as free-surface elevation, wave steepness, and particle velocity) was also studied.

- ***Investigation of freely decaying weak turbulence of capillary waves***. We extended the SNOW capability to the simulation of gravity-capillary wave dynamics. We applied the capability to investigate the dissipation characteristics of wave breaking through the development of weak turbulence in the high wavenumber region of the gravity-capillary wave field (Pan & Yue 2015).

RESULTS

(1) Efficacy of the phenomenological wave-breaking model in phase-resolved SNOW simulations

We further modified and improved the phenomenological wave-breaking model for effectively and reliably accounting for the effect of wave breaking in SNOW simulations of three-dimensional phase-resolved nonlinear wave-field evolution. In this model, the onset of wave breaking during wave-field evolution is automatically detected based on the spectral saturation level of the wave field; and the wave-breaking strength (related to the type of wave breaking) is estimated based on the wave energy distribution in the wave spectrum. With these, appropriate parameters values are determined in the use of filtering in the spectral domain to account for the wave breaking effect. The efficacy of this model was verified by examining the energy loss and wave kinematics variation in various two- and three-dimensional wave breaking events and comparing these results from SNOW simulations with laboratory measurements. Figure 1 shows a sample comparison between the results in SNOW simulations and laboratory measurements of Rapp and Melville (1990) on the energy loss during two-dimensional wave-breaking events occurred in nonlinear wave group evolution with various wave steepnesses and central frequencies. Excellent agreement between the simulation result and experimental data confirms the efficacy of the new wave-breaking model in SNOW simulations of phase-resolved nonlinear wave-field evolution.

To characterize wave-breaking events in phase-resolved wave-field evolution, we used JONSWAP spectra (with different wave parameters) to generate initial synthetic three-dimensional wave-fields and then simulated their nonlinear time/space evolution with the implementation of newly improved wave-breaking model. From the simulated phase-resolved wave-breaking dissipation field, we identified the spatial location and time of occurrence and strength of wave breaking events. We further quantified wave-breaking kinematics in terms of wave-breaking front length and breaking speed. Figure 2 shows the simulated distribution of wave-breaking front length as a function of breaking speed for different JONSWAP spectra. The results by SNOW simulations agree well with the theoretical power law form derived by Phillips (1985).

(2) Decaying capillary wave turbulence under broad-scale dissipation

We applied direct SNOW simulations to investigate the wave-breaking dissipation characteristics of gravity-capillary wave-fields (Pan & Yue 2014; 2015). By introducing a small amount of wave dissipation, measured by viscosity magnitude γ_0, our results replicated those from experiments of a power-law spectrum with exponential modal decay, as well as monochromatic decrease of the cut-off wavenumber k_c and variation of the spectral slope α during the decay. Based on our simulations, we were able to describe the time-dependent power-law spectrum within the inertial range $[k_b, k_c(t)]$ in an explicit general form:

$$I_\eta(k,t) = I^0 k^{\alpha^0 - A(t-t^0)} e^{-B(t-t^0)}, \qquad (1)$$

where I_0 and α_0 are respectively the spectral amplitude and slope of the spectrum at $t = t_0$, k_b is the (almost) constant wavenumber above which the power-law spectrum is established, and $k_c(t)$ is the spectral location where the spectrum departs from the power law. Here the coefficients A and B are functions of the dissipation magnitude γ_0 only. Equation (1) was shown to fit our numerical data obtained over the ranges of dissipation magnitude, spectral amplitude (nonlinearity) and evolution time that can be obtained by our simulation. In particular, we showed that α at a given time t is uniquely related to the spectral magnitude (nonlinearity), but independent of γ_0. This result is plotted in figure 3.

IMPACT/APPLICATIONS

Phase-resolved computations of nonlinear wave-field evolution enable understanding and accurate prediction of detailed processes of wave breaking and the associated energy dissipation, which provides the basis for developing effective modeling of wave-breaking dissipation that is of critical importance for the practical (phase-averaged) wave prediction tools (such WAM and SWAN).

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STUDENTS GRADUATED

1 PhD student

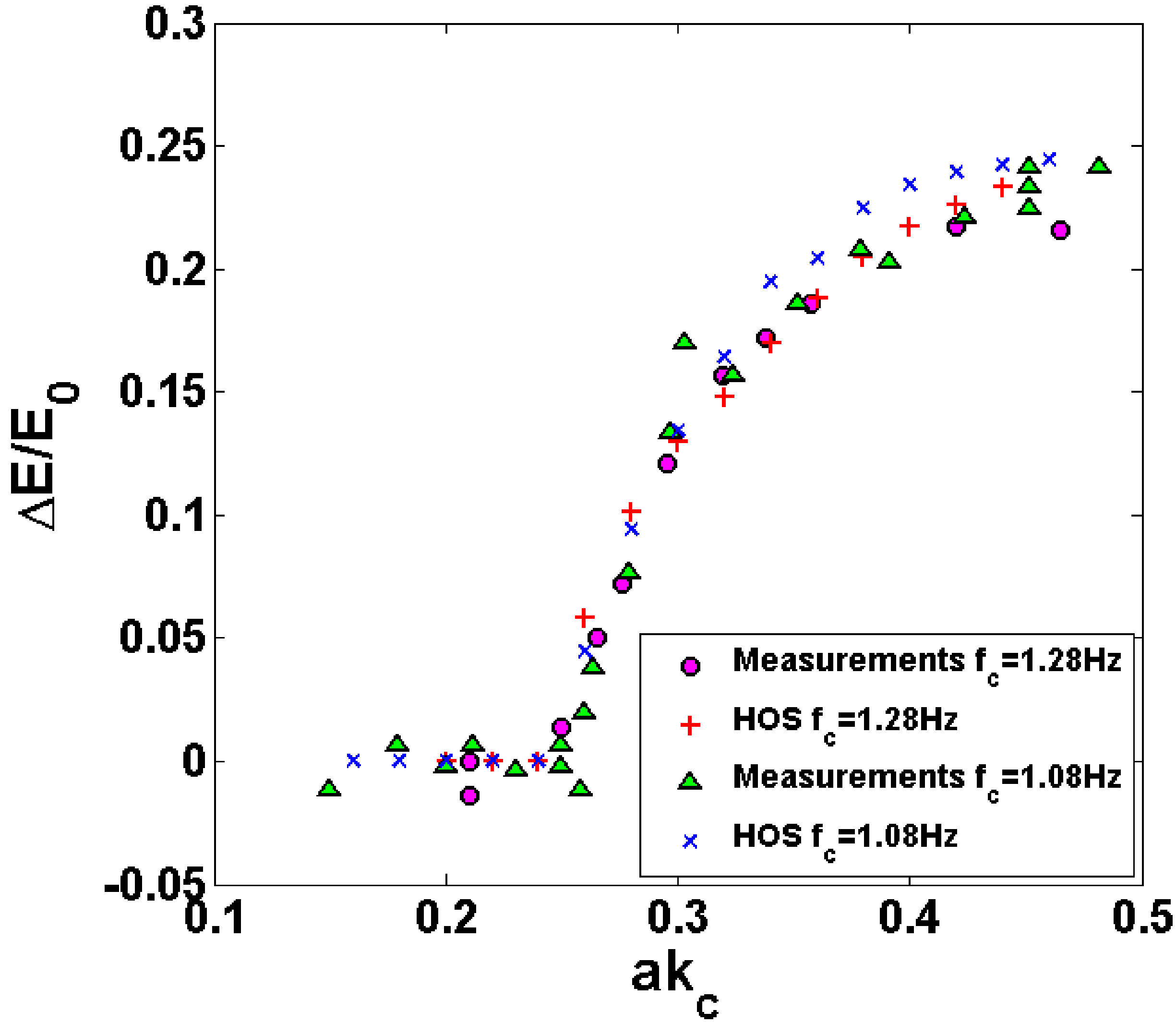

Figure 1. Comparison of energy loss in wave breaking between direct SNOW simulations (denoted as HOS in the figure) and laboratory experimental measurements of Rapp and Melville (1990). The results are for two-dimensional wave-breaking events developed during nonlinear wave group evolution that are initiated with different wave spectra. The wave spectra considered have a wide range of wave steepness and two different central frequencies: f_c=1.08Hz, and f_c=1.28Hz.

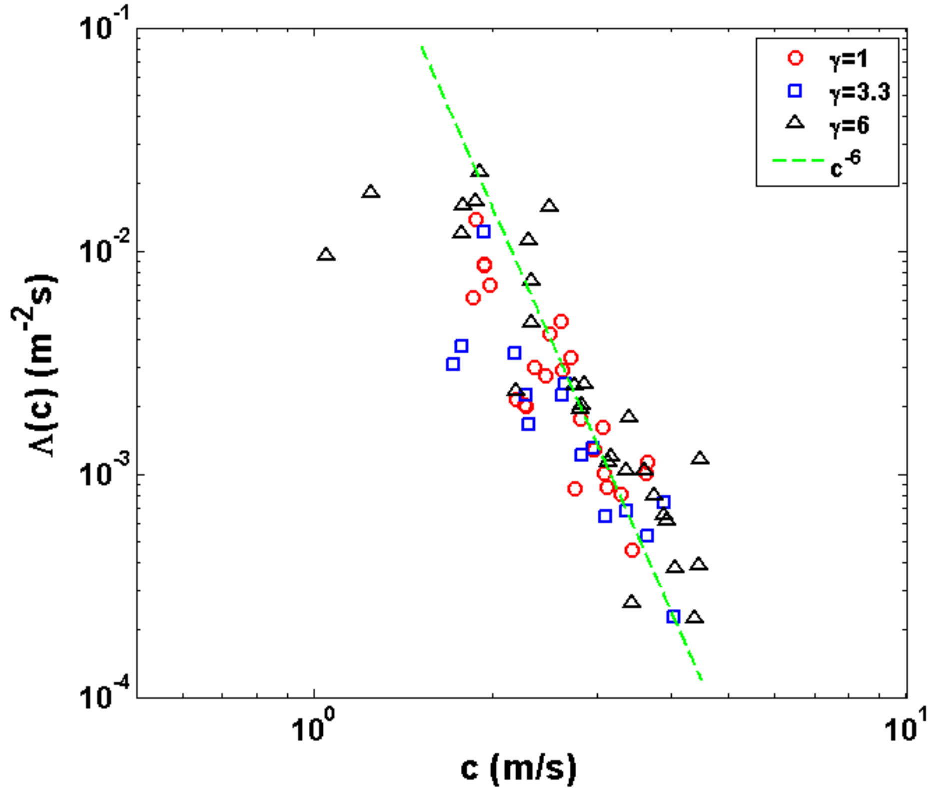

Figure 2. Simulated distribution of wave-breaking front length $\Lambda(c)$ as a function of breaking speed c, compared with theoretical power law form c^{-6}, for different JONSWAP spectra with peak enhancement factor $\gamma = 1$ (∘), $\gamma = 3.3$(□), $\gamma = 6$(Δ).

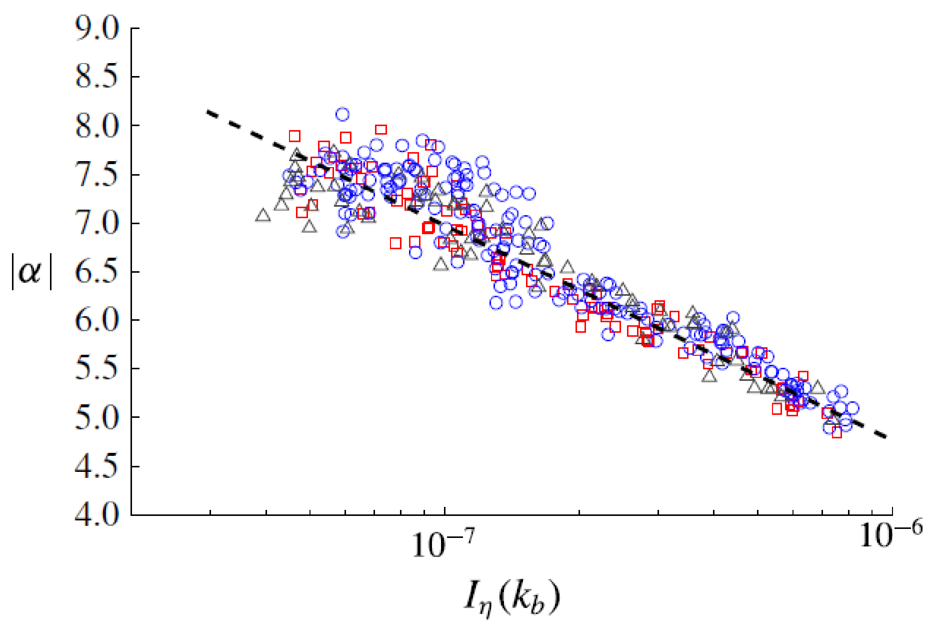

Figure 3. Spectral slope $|\alpha|$ as a function of $I_\eta(k_b)$ for three different values of $\gamma_0 = 0.8 \times 10^{-5}$ (∘), 1.6×10^{-5} (□) and 2.4×10^{-5} (Δ).