Rogue Wave Statistics and Dynamics Using Large-Scale Direct Simulations

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LONG-TERM GOAL

The long-term goal is to study the generation mechanisms and evolution dynamics of rogue waves using large-scale three-dimensional nonlinear phase-resolved wavefield simulations and to establish the foundation for the development of effective tools for prediction of rogue wave occurrences in realistic ocean wave environments.

OBJECTIVES:

The specific scientific and technical objectives are to:

- Obtain representative large-scale rogue wave datasets using direct simulations

- Verify the validity and limitations of existing theories and models for the statistics of large-amplitude wavefields and the occurrence of rogue waves

- Understand the fundamental mechanisms for rogue wave development. Of particular interest is to validate (or invalidate) the hypotheses and assumptions underlying the existing theories, statistics and models/tools for rogue wave prediction

- Elucidate the evolution kinematics and dynamics of rogue wave events

APPROACH

The objectives stated above are achieved in a coordinated effort involving three major activities: (I) Development of a significant number of large-scale computations and datasets for nonlinear evolution of wavefields for different initial wavefield (spectral) parameters and environmental/boundary conditions; (II) Use of direct computations to quantitatively verify and validate existing theories and models for wavefield statistics and the hypotheses on rogue wave formation; and (III) Use of these

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14. ABSTRACT

The long-term goal is to study the generation mechanisms and evolution dynamics of rogue waves using large-scale three-dimensional nonlinear phase-resolved wavefield simulations and to establish the foundation for the development of effective tools for prediction of rogue wave occurrences in realistic ocean wave environments.

15. SUBJECT TERMS

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computations to systematically investigate the stochastic and deterministic mechanisms underlying the occurrence of rogue wave events and to characterize the statistical and physical properties of such events.

For the large-scale computations, we apply the direct phase-resolved **s**imulations of **n**onlinear **o**cean **w**avefields (SNOW). SNOW resolves the phase of a large number of wave modes and accounts for their nonlinear interactions up to an arbitrary high order *M* including broadband non-resonant and resonant interactions up to any specified order. SNOW achieves an exponential convergence and a (near) linear computational effort with respect to the number of wave modes *N* and the interaction order *M*, and has high scalability on high-performance parallel computing platforms (Wu 2004; Wu *et al* 2005). Unlike phase-averaged and model-equation-based approaches, SNOW accounts for physical phase-sensitive effects in a direct way. These include the initial distribution of wave phases in the wavefield specified by wave spectrum, energy dissipation due to wave breaking, and input due to wind forcing.

From the direct simulation, we obtain datasets of wave elevation and kinematics of the complete wavefield during its evolution. By analyzing these datasets, we can determine the statistics of the wavefield, identify rogue wave events, compute the statistics of rogue waves, study the development of rogue waves and groups, and understand details of the rogue wave dynamics.

WORK COMPLETED

- *Generation of realistic ocean wavefield datasets*: Performed a significant number of SNOW computations for large-scale phase-resolved nonlinear wavefield evolution from which we obtained a collection of rogue wave data set for both two- and three-dimensional wavefields with a wide range of spectral parameters.

- *Understanding nonlinear wavefield statistics*: Investigated the characteristics of nonlinear wave statistics under general wave conditions based on the phase-resolved SNOW simulation datasets, and examined the validity of the existing classical theories and model equations with the focus on nonlinear effects.

- *Understanding rogue waves*: Analyzed the characteristics of rogue wave statistics, the mechanisms of rogue wave event development, and the kinematics and dynamics of rogue wave events.

RESULTS

Based on large-scale phase-resolved SNOW simulations which are verified to be in good agreement with available field/laboratory wave data, we find that nonlinear effects in wavefield evolution affect significantly the statistics of ocean surface waves. Specifically, SNOW computations of nonlinear ocean wavefield evolutions show that: (a) surface wave elevation of high sea states exhibits apparent non-Gaussian features with Kurtosis much larger than that by linear theory; (b) Rayleigh distribution generally underestimates the occurrences of large crest height and large crest-trough height; (c) the (nonlinear) effects in (a), (b) are stronger for wavefields with larger effective steepness and/or smaller directional spreading angle; (d) Tayfun distribution (including second-order effects) can give a reliable prediction for wavefields with wide directional spreading; and (e) frequency-dependent angular

spreading with bi-modal spreading for short wave components is generally observed in nonlinear wavefield evolution.

For rogue wave events, we find that (i) nonlinear self-focusing of wave groups play an important role in the formation and development of rogue waves in ocean wavefield evolution; (ii) occurrence of rogue waves is closely correlated to kurtosis of the wavefield, with larger kurtosis associated with rogue waves of higher height; (iii) occurrence of rogue waves (especially of large height) is usually correlated with broadband wave spectra; (iv) occurrence probability of rogue waves is higher as effective steepness of wavefields increases; and (v) NLS model underestimates the occurrence of rogue waves, especially large rogue wave events, as nonlinear broadband wave-wave interaction effects (higher than third/fourth order) are not properly considered.

(I) Long-time nonlinear evolution of a Stokes wave train: To elucidate the effects of nonlinear broadband wave interactions in rogue wave development, we perform fully-nonlinear SNOW computations of long-time evolution of a Stokes wave train. The steepness of the initial wave train is 0.06. Small disturbances at a broad band of wavenumbers around the primary wavenumber are added at the initial time. Figure 1a displays the time variation of maximum crest/trough elevation and maximum wave height in the entire wavefield during the evolution. The time variation of the associated kurtosis of the wavefield is also shown, figure 1b. In the initial period of evolution, modulational instability causes spreading of wave energy from the primary wave to its dominant sidebands. As a result, large waves are developed with wave height approaching $\sim 2.3 H_0$, where H_0 is the wave height of the initial wave train. The corresponding kurtosis of the wavefield reaches a large value of ~ 6.0. For t/T < 4000, the phenomenon of recurrence is observed. For t/T>4000, as broader sidebands are developed, the recurrence is lost, and the wavefield becomes irregular. Importantly, the wave height of developed extreme waves becomes larger and can reach a value of $\sim 4.5 H_0$. The inspection of the wave spectrum of the wavefield reveals that larger rogue waves are always correlated with broadband wave spectra of the wavefield. These results show that nonlinear focusing of wave groups together with nonlinear broadband wave-wave interactions can cause the development of rogue waves. Low order models (such as those based on NLS equation) may not be able to properly predict and describe rogue waves (especially of large height).

(II) Maximum wave height during evolution of nonlinear long-crested wavefields: Understanding of the dependence of maximum wave height on wavefield conditions is of importance to the study of rogue wave occurrence and characteristics. Based on SNOW simulations, we obtain time histories of maximum wave height during nonlinear wavefield evolution. Figure 2 shows sample results on the variation of maximum wave height during nonlinear evolution of long-crested wavefields for three different wave spectra. These are given by JONSWAP spectra with enhance parameter $\gamma=3.3$ but different combinations of effective steepness ε and peak period T_p. The comparison of the results in figure 2 indicates that rogue waves of higher height occur in a wavefield with larger effective steepness and/or larger spectrum bandwidth ($\Delta k/k_p$, where Δk is the width of the spectrum and k_p the peak wavenumber). The occurrence frequency of these rogue waves also increases for larger effective steepness and/or broader wave spectrum.

(III) Rogue wave occurrences in nonlinear short-crested wavefields: In order to understand the occurrence of rogue wave events in three-dimensional wavefields, we compared the numbers of rouge wave events identified in the evolution of nonlinear wavefields for different wave spectra parameters. Figure 3 shows the comparison of the number of rogue wave events detected in the SNOW simulated

nonlinear wavefields. These wavefields are initially given by JONSWAP spectra with cosine-square angular spreading. They have the same peak enhancement parameter ($\gamma = 3.3$) but different significant wave height (H_s), peak period (T_p), directional spreading width (Θ). The simulated wavefield size is $128\lambda_p \times 128\lambda_p$ (~30km × 30km). The rogue wave events shown in figure 3 are identified by applying large wave detection criterion at 4 sample instants ($t/T_p = 60, 70, 80,$ and 90). For comparison, the prediction by linear Rayleigh theory is also shown. From the comparisons, it can be seen that linear (Rayleigh) theory under-predicts the frequency of rogue wave (with $H/H_s \geq 2.2, 2.3, 2.4$) occurrences compared to those identified in nonlinear wavefields. Such underestimation by Rayleigh theory is more severe for the wavefields with larger effective wave steepness and/or smaller directional spreading. One notes that for the evolution duration considered here, modulational instability plays a dominant role in the formation of rogue waves. The characterization of rogue wave statistics observed here is strongly correlated with modulational instability effects. As the evolution continues, rogue wave occurrence statistics might vary when the effects of higher-order broadband wave interactions become important.

IMPACT/APPLICATIONS

Proper understanding and prediction of rogue wave events in realistic ocean environments is of critical importance to the design of surface ships and safety of naval operations and ocean explorations. The outcome of this research will establish the necessary foundation for the development of effective rogue wave prediction tools.

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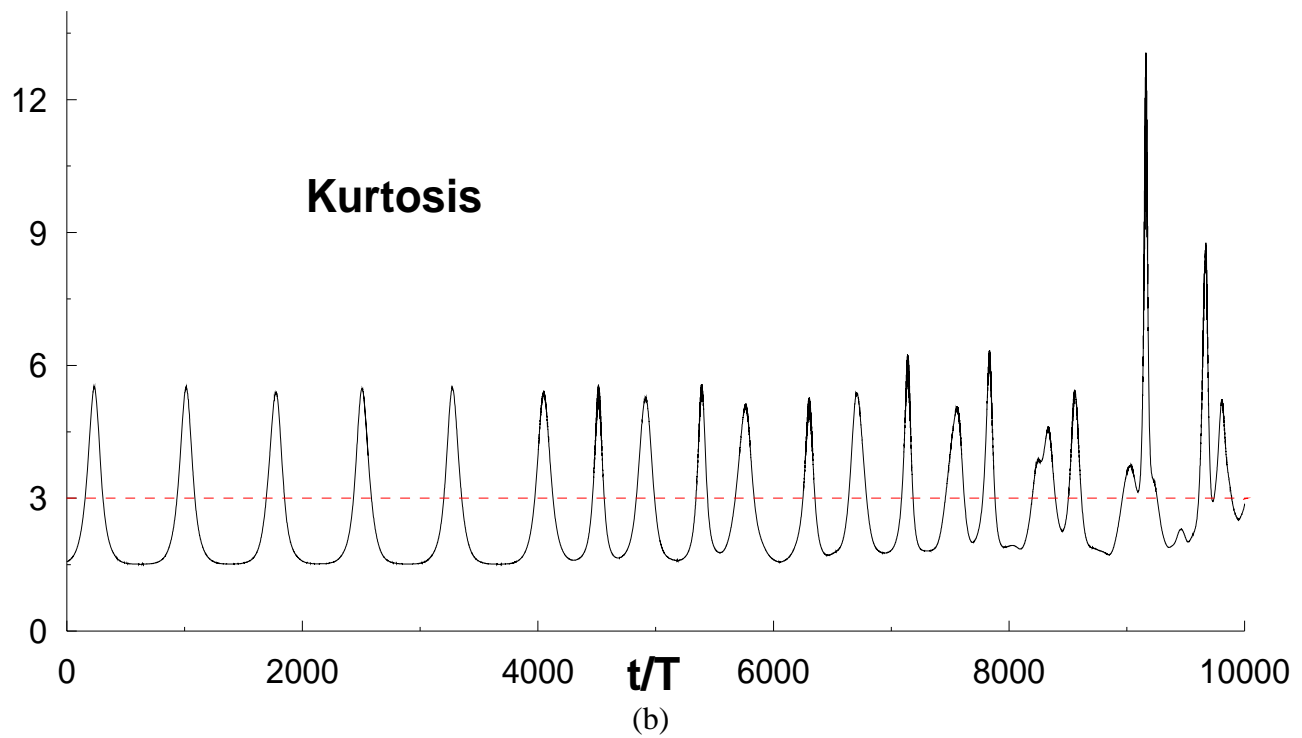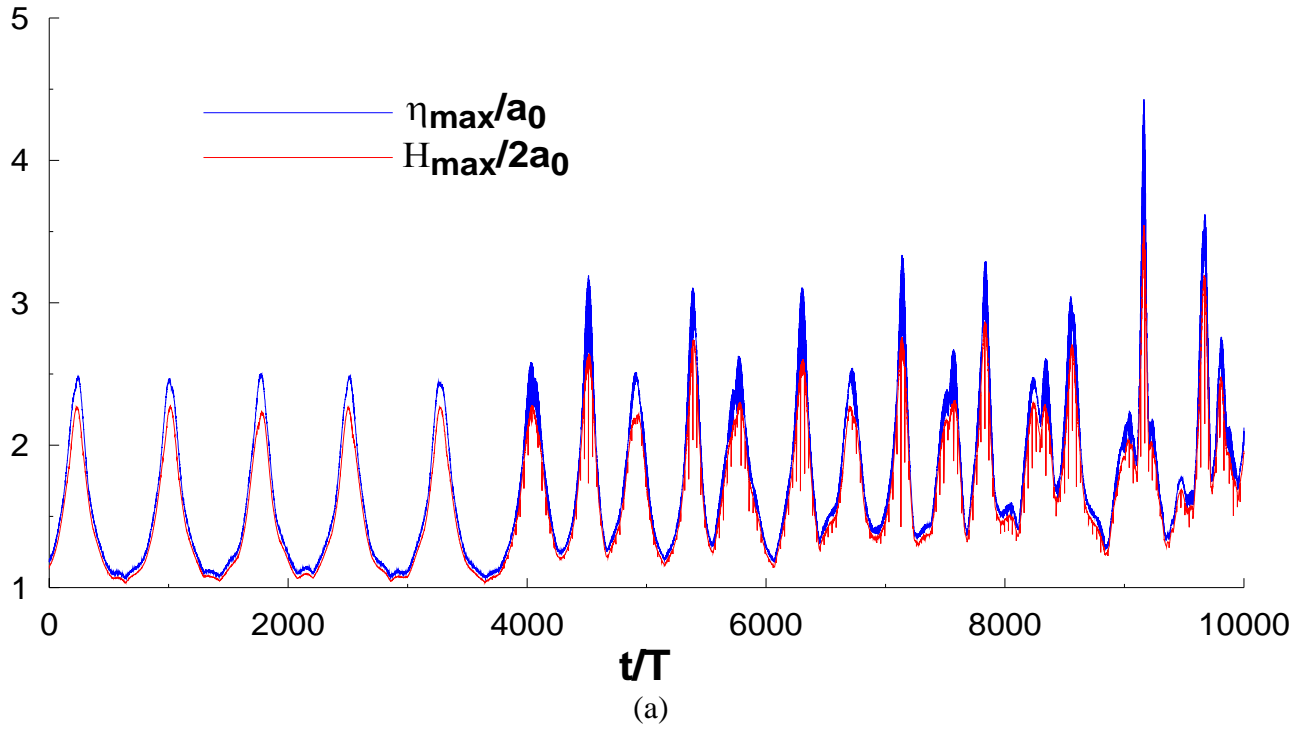
Figure 1: Time variation of (a) maximum crest/trough height (normalized by the initial wave amplitude a_0) (blue line) and maximum wave height (normalized by the initial wave height $2a_0$) (rede line); and (b) kurtosis of the wavefield (black line) in the nonlinear evolution of a Stokes wave train.
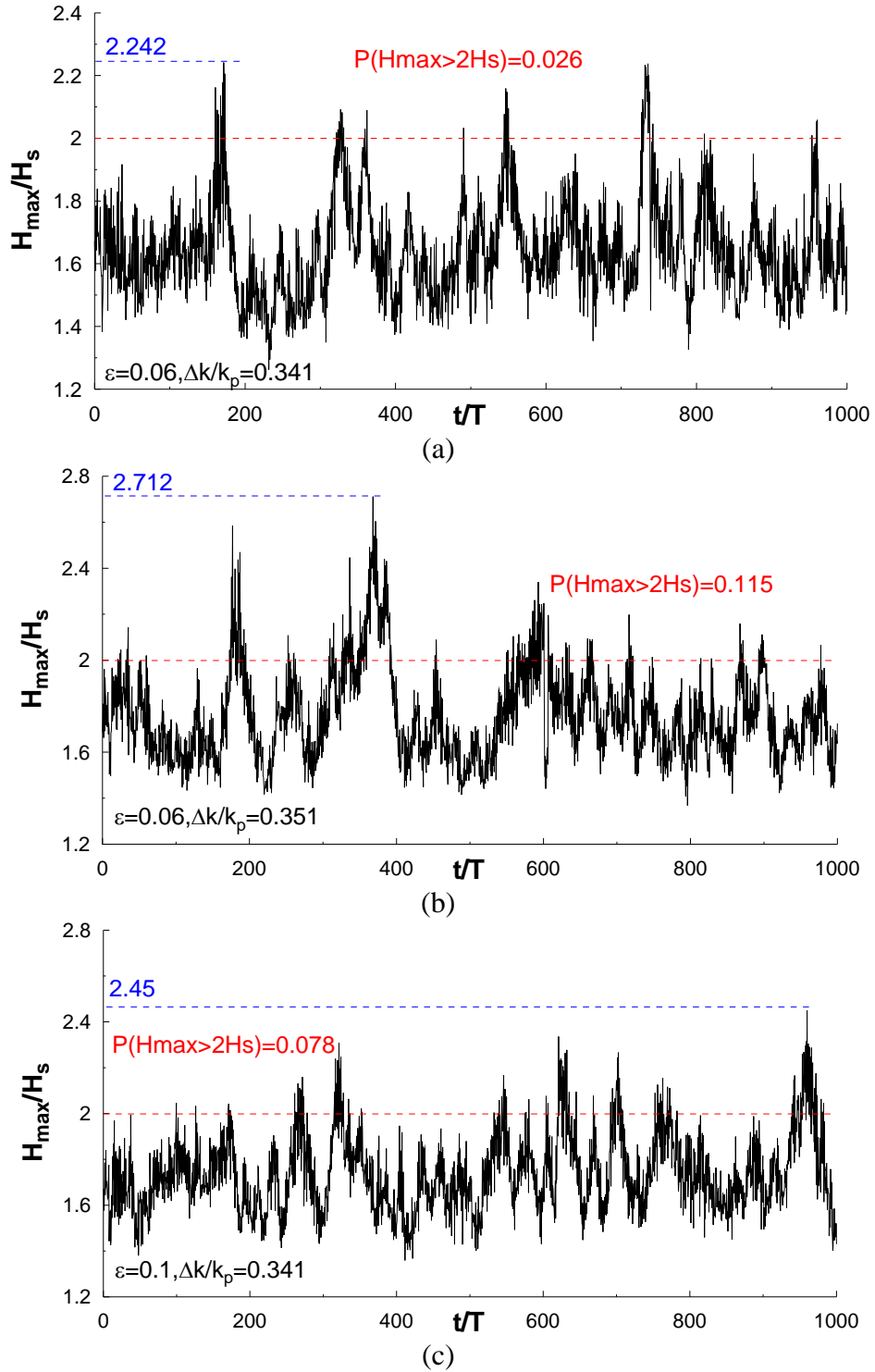
Figure 2. Time variation of maxim wave height (normalized by significant wave height Hs) in nonlinear evolution of wavefields given by JONSWAP wave spectra with (a) enhance parameter γ=3.3, effective steepness ∈ = 0.06, and peak period Tp=9.5s; (b) γ=3.3, ∈ = 0.06, and Tp=8.8s; and (c) γ=3.3, ∈ = 0.10, and Tp=9.5s.
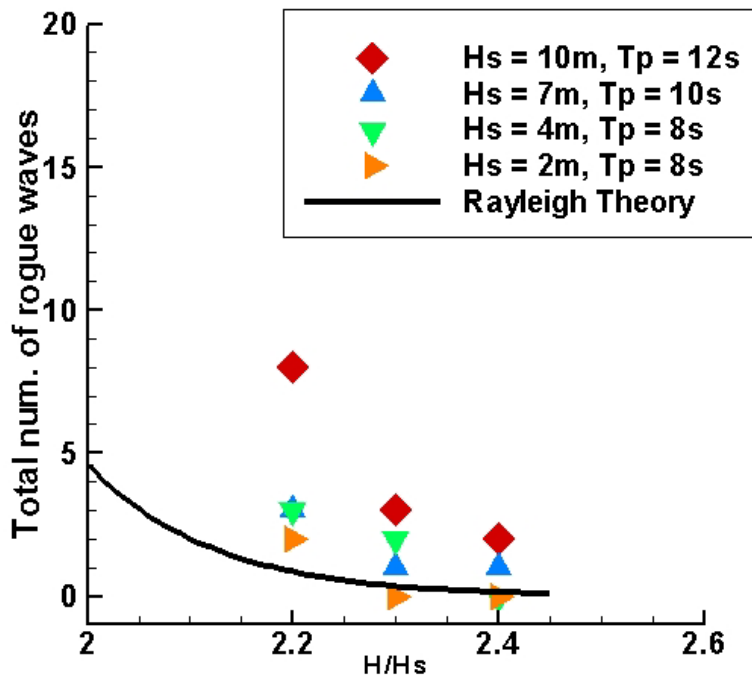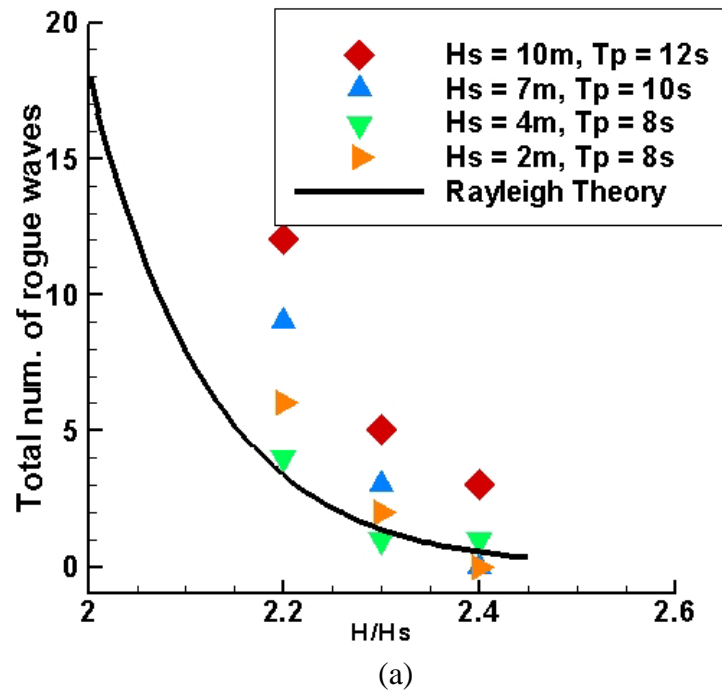
Figure 3: Numbers of rogue wave events detected at four sample instants from SNOW simulated nonlinear wavefields of four different wave spectra with significant wave height (Hs) and peak period (Tp) marked in the figures. The spreading angle of the wavefield is: (a) $\Theta = 80^o$ and (b) $\Theta = 40^o$. For comparison, the prediction by Rayleigh distribution (black line) is also shown.