Fundamental Research to Support Direct Phase-Resolved Simulation of Nonlinear Ocean Wavefield Evolution

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LONG-TERM GOAL

The long-term goal is to develop a new generation of wave prediction capability, which is called **SNOW** (**s**imulation of **n**onlinear **o**cean **w**avefield), for the evolution of large-scale nonlinear ocean wavefields using direct phase-resolved simulations. Unlike the phase-averaged approaches, SNOW models the key physical mechanisms such as nonlinear wave-wave, wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation in a direct physics-based context.

OBJECTIVES

The specific scientific and technical objectives are to:

- Continue to develop and improve physics-based phenomenological modeling for wind forcing input and wave breaking dissipation

- Continue to speed up the computational algorithm underlying SNOW simulations on massively-parallel high-performance computing (HPC) platforms

- Extend current capabilities to handle high sea states and very steep local waves while maintaining near linear SNOW operational count

- Extend SNOW simulations to allow more general initial/boundary conditions based on spectral characteristics or hybrid (point and/or whole field) wave measurements. Investigate and understand uniqueness and compatibility issues of such input to phase-resolved reconstruction of directional broadband wavefields.

Report Documentation Page

1. REPORT DATE **30 SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE **Fundamental Research to Support Direct Phase-Resolved Simulation of Nonlinear Ocean Wavefield Evolution**		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) **Massachusetts Institute of Technology,Center for Ocean Engineering,Department of Mechanical Engineering,Cambridge,MA,02139**		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 **Same as Report (SAR)**	18. NUMBER OF PAGES **5**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

- Characterize and quantify the effects of noise, uncertainty, incompleteness, and incompatibility in hybrid wave data on phase-resolved wavefield reconstruction and prediction

- Perform direct validation and quantitative cross-calibration of SNOW simulations with phase-averaged wave model predictions and field/laboratory measurements

- Extend SNOW to general finite water depth by including effects of changing bathymetry, variable current and fluid stratification

APPROACH

SNOW employs direct physics-based phase-resolved simulations for predicting the evolution of large-scale nonlinear ocean wavefields. SNOW is fundamentally different from the existing phase-averaged models in that, under SNOW, key physical mechanisms such as wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation are modeled, evaluated and calibrated in a direct physics-based context. In SNOW, detailed phase-resolved information about the wavefield is obtained, from which the statistical wave properties can also be derived.

SNOW is based on an extremely efficient high-order spectral (HOS) approach for direct computation of nonlinear ocean wavefield evolution. HOS is a pseudo-spectral-based method that employs Zakharov equation and mode-coupling idea and accounts for nonlinear wave-wave, wave-current, and wave-bottom interactions to an arbitrary high order (M) in wave/bottom steepness. This method obtains exponential convergence and (approximately) linear computational effort with respect to M and the number of spectral wave/bottom modes (N). SNOW is an ideal tool for phase-resolved prediction of realistic ocean wavefield evolution.

By incorporating point and/or whole field wave measurements into the simulations, SNOW provides a capability of reconstructing and forecasting nonlinear evolution of phase-resolved ocean wavefields. The objective of wave reconstruction is to obtain detailed specifications (including phase) of a nonlinear wavefield, which matches given (directly or remotely sensed) sensed wave data or specified wave spectrum. Nonlinear wave reconstruction is achieved based on the use of optimizations with multiple-level (theoretical and computational) modeling of nonlinear wave dynamics. Using the reconstructed wavefield as initial conditions, SNOW simulation would provide a deterministic forecasting of the phase-resolved wavefield evolution (Wu 2004; yue 2008).

SNOW computations can now be routinely performed for nonlinear ocean wavefields in an domain of $O(10^{4\sim5})$ km^2 with an evolution time of $O(1)$ hours. Such large-scale SNOW simulations are normally performed on advanced high-performance computing platforms using up to $O(10^3)$ processors (Xiao, Liu & Yue 2011) under the DoD challenge project: "Large-Scale Deterministic Predictions of Nonlinear Ocean Wavefields".

WORK COMPLETED

Over the past year, we continued our research in support of extension of SNOW to the general situations including the presence of non periodic boundary conditions, broadband wave spectrum, steep waves, two-layer fluids, and finite water depth. We continued to improve the algorithm for the reconstruction of sea surface maps from (non-coherent) marine radar measurements. In addition, we continued to make direct comparisons of the SNOW simulations with wave-basin/field measurements

and to apply SNOW computations to investigate the occurrence statistics and characteristics of rogue waves. Specifically, the work completed includes:

- ***Development and improvement of the algorithm for radar inversion data***: We further improved the accuracy and efficiency of the algorithm in reconstruction sea surface maps from marine radar measurements. The algorithm was tested and validated by using various marine radar wave measurements including the ONR HiRes 2010 measurements.

- ***Extension of SNOW for broadband nonlinear wave-wave interactions.*** We extended the HOS algorithm to effectively account for nonlinear long-short wave interactions. The algorithm is integrated into SNOW for the simulation of broadband wavefield evolution including long-wave interactions.

- ***Investigation of stratified fluid and bottom topography effects upon wavefield evolution***: We extended and applied SNOW simulations to littoral zones including stratified fluid, shoaling, and bottom topography effects (Yan & Liu 2011a, 2011b). We investigated the high-order resonant interactions of three-dimensional surface waves and interfacial waves due to a moving underwater object, which helps understand the characteristic wave patterns of submerged objects/obstacle in estuarine water (Alam, Liu & Yue 2011). Moreover, we applied the SNOW computations to understand the basic features of nonlinear wavefield evolution in littoral regions (Xiao, Liu & Yue 2011a)

- ***Speedup and applications of SNOW simulations***: We constantly improved the computational speed, scalability and robustness of the SNOW code on HPC platforms for the simulation of large-scale nonlinear ocean wavefield evolutions (Xiao, Liu & Yue 2011b). We applied large-scale SNOW computations to understand the generation mechanisms and statistical features of rogue waves in open seas in the presence of both winds and swell.

RESULTS

Some key results on the study of rogue waves are presented here. We applied large-scale SNOW computations of nonlinear three-dimensional wavefield evolution to investigate the generation mechanism and characteristics of rogue waves in deep seas. Nonlinear wave-wave interactions, in particular that associated with modulational instability, play a significant role in the generation of rogue waves. The classical linear theory largely underestimates the occurrence of rogue wave events. The occurrence of rogue waves is closely correlated with the kurtosis of the wavefield. The larger the kurtosis of the wavefield is, the higher the occurrence probability of rogue waves is.

The spectral spreading angle of the wavefield critically affects the basic characteristics of rogue waves, particularly the morphology of the rogue wave. For small spreading angles, rogue waves behave like "wall of water" as observed in the field. As spreading angle increases, rogue waves appear in the forms of "three sisters" or "pyramidal waves". Figure 1 illustrates typical characteristic shapes of rogues waves, obtained from SNOW simulations, at different spreading angles.

The occurrence of rogue waves is also significantly affected by the cross-sea conditions. In general, the occurrence probability of rogue waves is increased by the coupling interaction of the cross seas. This effect is more apparent for larger amplitude rogue waves. Figure 2 shows the exceeding probability of wave crest for different angles of the main propagation directions of cross seas. The cross sea consists of a wind sea and a swell. Both wind sea and swell are given by JONSWAP wave

spectrum. The wind-sea (swell) has a significant wave height of 1.2 m (1.6 m) and a peak period of 4 s (6 s). For comparison, the result in the presence of wind sea only is also shown. The results in figure 2 clearly indicate that the rogue wave occurrence is enhanced by the presence of cross seas except when the propagation directions of the wind sea and swell are perpendicular.

IMPACT/APPLICATIONS

This work paves the way toward the development of a new generation of wave prediction tool using direct phase-resolved simulations. It augments the phase-averaged models in the near term and may serve as an alternative for wave-field prediction in the foreseeable future.

RELATED PROJECTS

This project is related to the project entitled "High-Resolution Measurement-Based Phase-Resolved" (N00014-08-1-0610). The present project focuses on the development of advanced algorithms and physics-based modeling for the prediction of large-scale ocean wavefield evolution while the related project focuses on the practical application of the wave reconstruction and prediction capability to realistic ocean environments.

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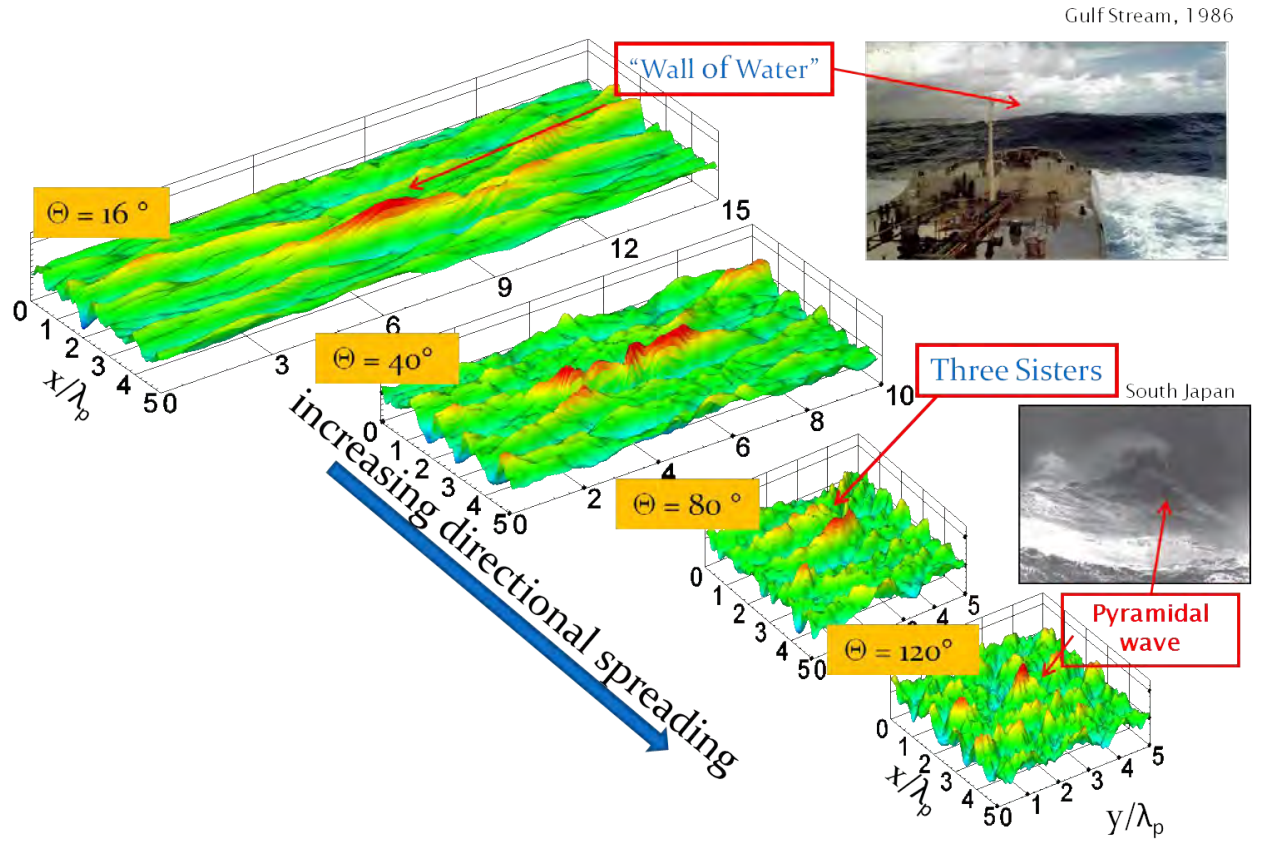
Figure 1. Characteristic rogue waves in wavefields of different spectral spreading angles, obtained from large-scale phase-resolved SNOW computations.
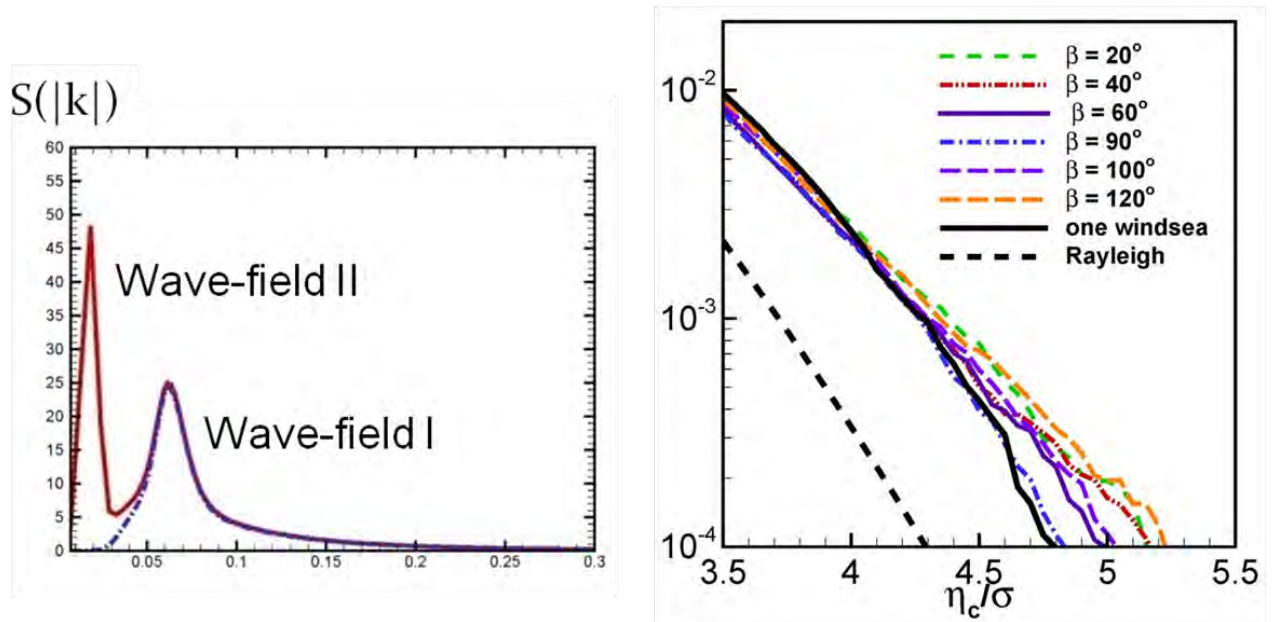

Figure 2. Wavenumber spectra of two cross seas (left panel) and exceeding probability of the wave crest for different angles (of β) of main propagation directions of two cross seas. "One windsea" indicates the presence of one wavefield only.