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14. ABSTRACT Fundamental research was performed in support of the development of a new generation of wave prediction capability, which is called SNOW (simulation of nonlinear ocean wavefield), for the evolution of large-scale realistic ocean surface and internal wavefields using direct phase-resolved simulations. Large-scale phase-resolved SNOW simulations of nonlinear wavefield evolutions are obtained and used to quantify and understand nonlinear ocean wave statistics and rogue wave kinematics/dynamics and to evaluate the validity and effectiveness of the existing phase-averaged wave prediction tools.					
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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** (simulation of **n**onlinear **o**cean **w**avefield), for the evolution of large-scale realistic ocean wavefields using direct phase-resolved simulations. Unlike the existing 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:

- Develop and improve physics-based phenomenological modeling for wind forcing input and wave breaking dissipation.
- Speed up the computational algorithms 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 wave spectral characteristics or hybrid (multiple-point and/or whole-field) wave measurements. Investigate and understand uniqueness and compatibility issues of such input to phase-resolved reconstruction and forecasting of directional broadband wavefields.
- 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 fluid stratification, variable current, and changing bathymetry.

APPROACH

SNOW employs direct physics-based phase-resolved simulations for predicting the nonlinear evolution of large-scale 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 are 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 area wave measurements into the simulation, 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 wave data or specified wave spectra. 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 the initial condition, SNOW simulation would provide a (short-time) 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 $O(10^{4\sim5}) \text{ km}^2$ 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 $O(10^{3\sim4})$ processors under the DoD challenge project: “Large-Scale Deterministic Predictions of Nonlinear Ocean Wavefields”.

WORK COMPLETED

We focused 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. In addition, we continued to make direct comparisons of the SNOW simulations with wave-basin/field measurements and phase-averaged model predictions, and to apply SNOW computations to investigate the nonlinear wave statistics and the occurrence and characteristics of rogue waves. Specifically, the major work completed includes:

- ***Extension of SNOW for broadband nonlinear wave-wave interactions.*** We modified the HOS algorithm to effectively account for nonlinear long-short wave interactions. The algorithm has been integrated into SNOW to enable the simulation of general broadband

wavefield evolution including long-wave interactions. This allows for improved understanding of the characteristics of short wave motions which are of importance to proper interpretation of remotely sensed ocean surface data.

- **Modeling of wind forcing input:** We continued the development, validation, and calibration of the phenomenological wind input modeling in phase-resolved wavefield simulations by direct comparisons with ONR HiRes 2010 field measurements.
- **Development of an efficient algorithm for steep waves:** We developed and applied a highly efficient computational algorithm, so-called pre-corrected FFT method (PFFT), for fully-nonlinear simulation of very steep waves (Yan & Liu 2011a, b). With PFFT, the requisite computational effort in solving the fully-nonlinear boundary value problem is reduced from $O(N^{2\sim 3})$ to $O(N \ln N)$, similar to that in HOS. Integration of this algorithm into SNOW extended the capability of SNOW to fully-nonlinear simulations of extreme wave dynamics and high sea states with the high computational efficiency retained.
- **Speedup and applications of SNOW simulations:** We continued to improve the computational speed, scalability and robustness of the SNOW code on HPC platforms for the simulation of large-scale nonlinear ocean wavefield evolution. We applied large-scale SNOW computations to study nonlinear wave statistics and occurrence and characteristics of extreme wave events in open seas (Liu, Xiao & Yue 2013).
- **Evaluation and assessment of phase-averaged wave prediction models.** We performed direct comparisons of SNOW simulations with phase-averaged model predictions and laboratory experimental measurements on nonlinear evolution of three-dimensional ocean wavefields. Based on the comparisons, we assessed the validity and limitations of the available phase-averaged wave prediction models, and identified the areas for further improvements (Xiao *et al* 2013).
- **Development, validation, and improvement of the algorithms for radar inversion data:** We developed and validated an effective novel algorithm in reconstruction of sea surface maps from both non-coherent and coherent radar measurements. The algorithms were tested and validated by using various radar wave measurements including ONR HiRes 2010 field wave measurements.
- **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. 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 2010, 2011). Moreover, we applied the SNOW computations to understand the basic features of nonlinear wavefield evolution in littoral regions (Xiao, Liu & Yue 2011a, b).

RESULTS

SNOW is a powerful alternative for ocean wave prediction. SNOW has been applied to understand the generation mechanisms and occurrence statistics of rogue waves (Xiao *et al* 2013) and interaction mechanisms of surface/internal waves with bottom variations (Alam, Liu & Yue 2010, 2011), quantify nonlinear ocean wave statistics (Xiao, Liu & Yue 2011a,b), evaluate the validity of phase-averaged

wave models (Xiao et al 2013), and develop effective modeling of breaking-wave dissipations (Pan & Yue 2013). Two representative results are given below.

(1) Assessment of the Validity of Model Equations in Predicting Nonlinear Wavefield Evolution

The model equations are commonly used in understanding nonlinear wave dynamics and predicting nonlinear wavefield evolution owing to the high efficiency in computation. The model equations are typically developed based on the assumptions of narrow bandwidths of wavenumber and propagation direction of the wave components in the wavefield. It is of scientific interest and practical importance to understand and evaluate the applicability of these models in predicting nonlinear wavefield evolution. We applied the direct phase-resolved SNOW computations, which do not have limits in bandwidths of wavenumber and propagation direction, to obtain the spectrum evolution of nonlinear wavefields and then compared the result to those by the model equations.

We considered a narrow-band Gaussian-shaped spectrum with initial wave steepness $\varepsilon = 0.1$ and spectral bandwidth $\delta = 0.1$. Figure 1 shows the time evolution of the wave spectrum and compares the results obtained by the modified nonlinear schrödinger equation (MNLS) (Dysthe 1979), the slightly broadband modified nonlinear schrödinger equation (BMNLS) (Trulsen & Dysthe 1996), and the direct SNOW computation. Unlike the SNOW results, the MNLS and BMNLS results show that the wave energy continues to spread to the transverse direction as the evolution time increases. In particular, the spreading of energy to the transverse direction predicted by MNLS is much stronger than that by BMNLS. Since BMNLS includes higher order bandwidth effects than MNLS, the observed over-spreading of wave energy to the transverse direction is due to incomplete consideration of the bandwidth effect in MNLS and BMNLS. Thus, MNLS and BMNLS are not effective in the prediction of long time nonlinear evolution of directional ocean wavefields (Xiao *et al* 2013).

(2) Evaluation of Energy Flux in Turbulence of Capillary Waves

We applied direct phase-resolved SNOW simulations to investigate the energy flux in turbulence of capillary waves. We considered the inertial range spectrum of capillary wave turbulence. Recent experimental measurements (Falcon *et al.* 2007) reported a linear scaling of surface elevation spectrum $\langle |\eta_k|^2 \rangle$ with energy flux P . This is in apparent disagreement with weak turbulence theory (WTT) which predicts $\langle |\eta_k|^2 \rangle \sim P^{1/2}$ (Zakharov and Filonenko 1967). We conducted a direct numerical investigation of the problem by using SNOW (with a modification for capillarity wave dynamics). By considering a range of P spanning two orders of magnitude, we showed that the square-root and linear scalings are realized at relatively low and high values of P (associated with low and high nonlinearity of the wave system) respectively, thus resolving the controversy.

In figure 2, we plotted the (normalized) energy of the inertial range E_i (as a reflection of magnitude of $\langle |\eta_k|^2 \rangle$) with respect to the energy flux P evaluated in the numerical simulation. For small values of P , our results confirm the dependence $\langle |\eta_k|^2 \rangle \sim P^{1/2}$ predicted by WTT. For large values of P , we found a linear scaling relation $\langle |\eta_k|^2 \rangle \sim P$, consistent with the experimental findings. Therefore, the results from WTT and the experimental measurements are not in disagreement but are in fact complementary and are realized at different levels of nonlinearity for this problem (Pan & Yue 2013).

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). This project focuses on the development of advanced algorithms and physics-based modeling for phase-resolved prediction of ocean wavefield evolution while the related project focuses on the practical application of the wave prediction capability to realistic ocean environments.

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STUDENTS GRADUATED

2 PhD and 1 Master students (2 females)

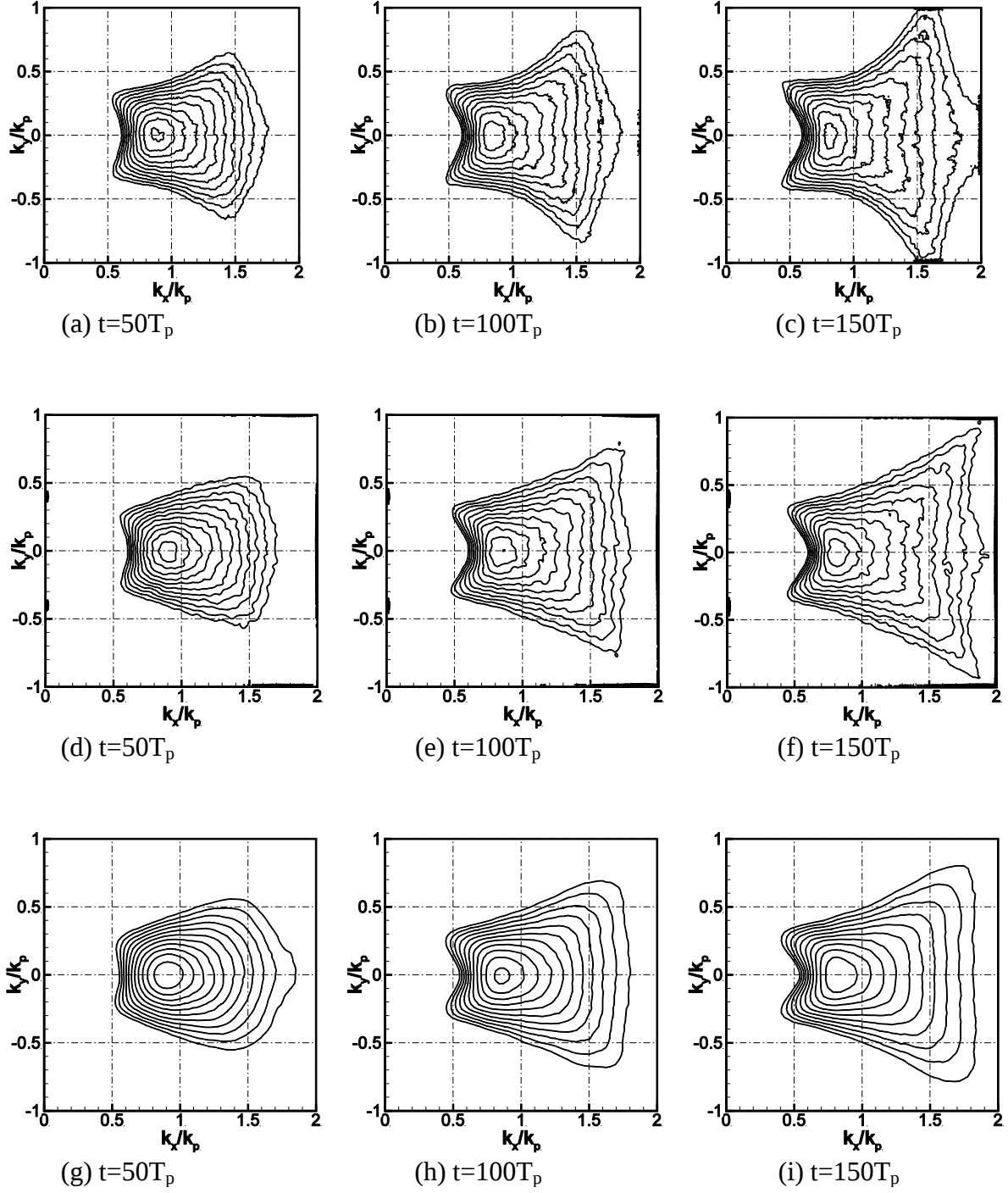


Figure 1: Time evolution of a narrow-band Gaussian-shape spectrum with initial steepness $\varepsilon = 0.1$ and spectral bandwidth $\delta = 0:1$. The results are obtained by model equations, MNLS ((a), (b), (c)) and BMNLS ((d), (e), (f)), and direct SNOW computations ((g), (h), (i)). The contour value is logarithmic ranging from 1×10^{-6} to 1×10^{-4} .

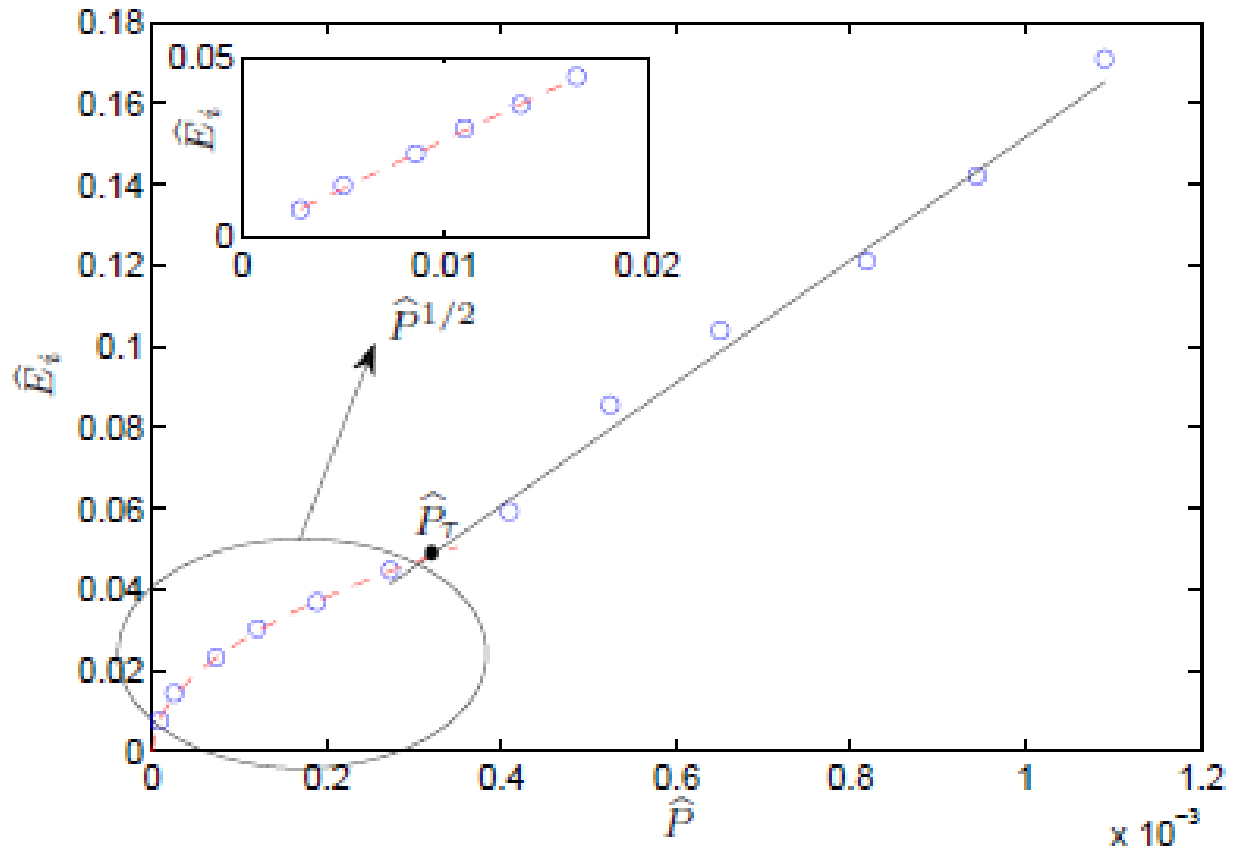


Figure 2: Energy of the inertial range E_i ($\circ$) with respect to the energy flux P in the series of SNOW simulations, with square-root (---) and linear (—) fittings for small and large values of P . Inset: Values ($\circ$) and fitting (---) of E_i with respect to $P^{1/2}$ for lower values of P .