Modeling Wind Wave Evolution from Deep to Shallow Water

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LONG-TERM GOALS

Ocean waves are an important aspect of upper ocean dynamics, in particular on the shallow continental shelves and in coastal areas. The long-term objective of this work is to advance modeling capability in such shallow areas by improving model representations of nonlinear effects and dissipation.

OBJECTIVES

The specific objectives of the present work are 1) to develop and implement an efficient, scalable approximation for the nonlinear quadruplet source term, 2) to develop and implement a generalized nonlinear source term that is accurate in water of arbitrary depth, 3) to develop and implement an improved nonlinear closure for triad nonlinear interactions in shallow water, and 4) improve representations of dissipation by wave breaking and wave-bottom interactions.

APPROACH

Modern, third-generation (3G) wave models are based on the action balance (or radiative transfer) equation, which is a geometrical optics description of the evolution of wave energy (or action) through a slowly varying medium and time. In Lagrangian form (for convenience) this balance equation can be written as

$$\frac{dN(\mathbf{k})}{dt} = S_{in}(\mathbf{k}) + S_{ds}(\mathbf{k}) + S_{sc}(\mathbf{k}) + S_{nl}(\mathbf{k}) \qquad (1)$$

where $N(\mathbf{k})$ is the wave action at wavenumber vector $\mathbf{k}$ and t is time. The forcing terms on the right-hand side are known as source terms and account for the input of energy by the wind (S_{in}), spectral redistribution of energy through scattering by seafloor topography (S_{sc}) or through nonlinear wave-wave interactions (S_{nl}) , and dissipation of wave energy (S_{ds}) through e.g. breaking or bottom friction.

In this study we will develop and improve the source terms for nonlinear interactions S_{nl} and energy dissipation S_{ds}, to account for effects of finite depth and shallow water, and to ensure a consistent and smooth model representation of wave evolution from deep to shallow water.

Nonlinearity

We will develop an efficient method for the evaluation of the nonlinear source term, allowing for greater efficiency and accuracy in operational use. To allow modeling of wave propagation from deep to shallow water, we will modify the nonlinear source term to account for changes in relative water depth [Janssen *et al.* 2006], and develop an improved closure approximation for nearshore wave propagation.

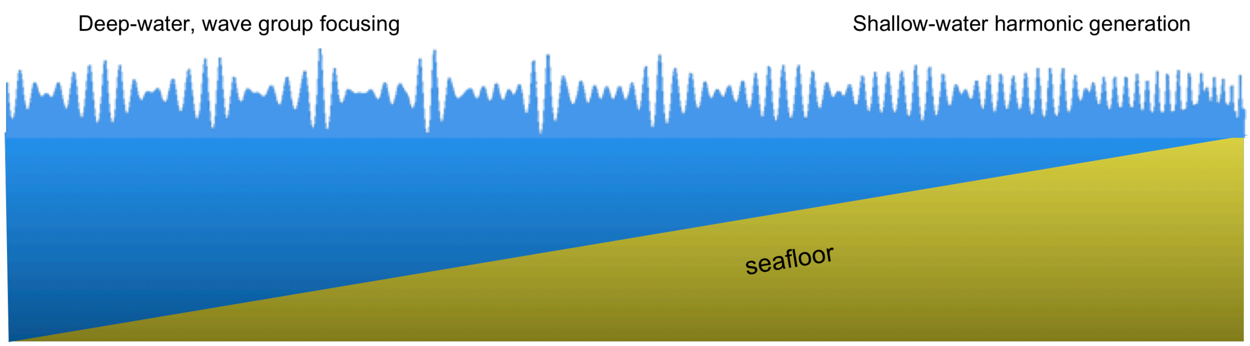

Figure 1. Illustration of changes in nonlinear regimes as ocean waves travel across the shelf into shallow water.

Dissipation

We will develop and test improvements to wave dissipation parameterizations through detailed comparisons against laboratory and field observations.

WORK COMPLETED

The completed work in this project thus far includes:

- Analysis of dissipation in one-dimensional nonlinear shoaling waves (laboratory data set by Boers, 1996) using bispectral analysis.
- Development and preliminary testing of nonlinear shallow-water wave model using a new closure approximation.
- Development and preliminary testing of a new scaling for the breaking parameter γ.
- Completed review of formulations for nonlinear four-wave interactions in shallow water.

RESULTS

Dissipation in nonlinear shoaling waves

Through bispectral analysis of laboratory observations (reported in Boers 1996) we have analyzed the dissipation spectrum in breaking waves. Our findings confirm that in the very nearshore the dissipation is approximately weighted as f^2 (frequency-squared) and the dissipation spectrum approaches a white-noise signature [e.g. Kaihatu et al. 2007]. Further, we find that the weighting of dissipation varies across the flume (figure 2) and for varying incident wave conditions. This dependency is being further investigated.

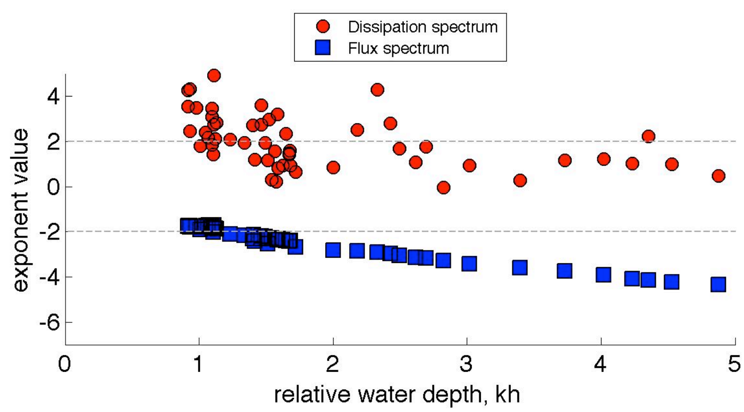

Figure 2. Frequency exponent values from regression analysis for dissipation spectrum and flux spectrum tail as a function of relative water depth.

A nonlinear model for shallow-water wave propagation

Using the results from the dissipation analysis, and implementing an empirical closure approximation, a research model is developed to test the principles and ideas underlying our approach. Model results are in good agreement with flume observations of spectra and higher-order bulk statistics such as skewness and asymmetry (figure 3). These preliminary results show the potential of our modeling approach. A more rigorous modeling effort, borrowing ideas from turbulence renormalized perturbation [e.g. McComb, 1990] theory but using the same basic principles, is presently under development.

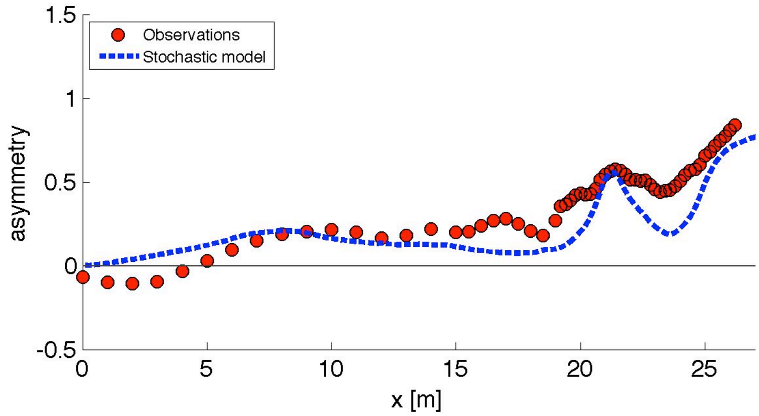

Figure 3. Evolution of asymmetry, a third-order bulk statistics, for Boers experiment 1C (Boers 1996).

Development of a new scaling of breaking parameter γ

The newly developed scaling of the breaking parameter γ, referred to here as n-kd scaling, is implemented, calibrated and tested against field and laboratory observations. Comparisons between model predictions and laboratory observations for both the traditional fixed-value γ and the new n-kd scaling (calibrated with field and laboratory observations) show improved model performance (figure 4). Further testing of the new scaling is presently ongoing [Holthuijsen & Salmon, 2010].

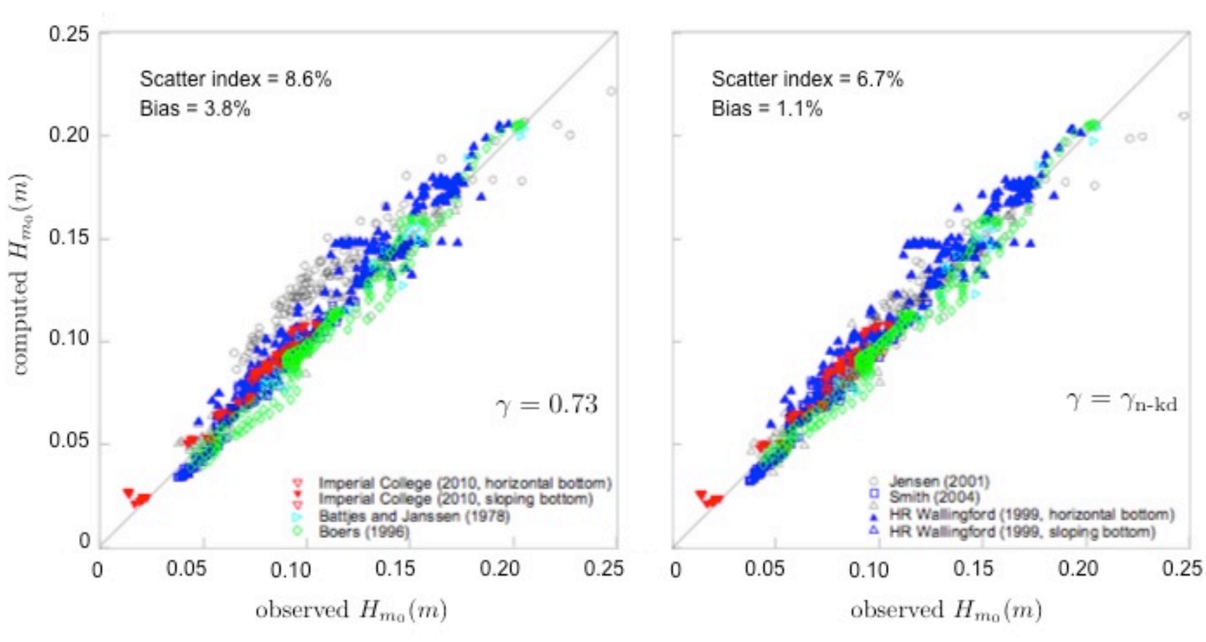

Figure 4 Scatter plots for predicted and observed significant wave height for a number of laboratory studies. Left panel: breaker index default fixed value $\gamma = 0.73$. Right panel: new $n - kd$ scaling for γ .

IMPACT/APPLICATIONS

Economic Development

The improvements to coastal wave prediction models as developed in this project, will contribute to various industries operating on the continental shelf and the coastal zone, such as fisheries, and shipping and offshore industry. Further, the availability of better wave prediction models will benefit coastal and ocean engineering companies e.g. in the design and operation of offshore and coastal structures, and the development of coastal management strategies.

Quality of life

The improvements to coastal wave prediction models as developed in this project, will improve modeling capability of coastal circulation and transport processes, which will benefit coastal recreation (more reliable knowledge of wave heights, rip currents etc), coastal management, and help mitigate pollution hazards for humans (recreation) and coastal ecosystems.

TRANSITIONS

Economic Development

The developments in this project will be made available as open source software and as modules to widely used operational wave models. These models are used by NOAA and other agencies involved in coastal development and management, and by many coastal and ocean engineering companies.

Quality of life

The software developed within this project will be disseminated in open source models used by local and federal agencies and companies involved in coastal recreation (surf prediction, rip currents, pollution), coastal management, and mitigation of coastal hazards.

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