Surface Wave Processes on the Shelf and Beach

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LONG-TERM GOAL

There is a growing need for surface wave information on the continental shelf and beach to estimate sea state, and to provide input for models of currents, sediment transport, radar backscatter and aerosol generation. While surface wave spectra in the open ocean evolve slowly over distances of O(100-1000 km), wave properties on the continental shelf and beach are highly variable (typical length scales of 0.1-10 km) owing to a variety of topographic effects (e.g., shoaling, refraction, scattering) and strongly enhanced nonlinear interactions and dissipation. The long-term goal of this research is to develop a better understanding of the physical processes that affect the generation, propagation and dissipation of surface waves in shallow coastal waters, and improve the accuracy of models that predict the transformation of wave properties across the shelf and beach.

OBJECTIVES

- predict accurately the nonlinear shoaling transformation of ocean surfaces on beaches including the excitation of infragravity motions
- evaluate models for wave dissipation by bottom friction
- determine the scattering effects of resonant wave-wave and wave-bottom interactions on the evolution of wind sea and swell spectra on the continental shelf
- improve the representation of source terms in operational wave prediction models
- determine the effects of wave nonlinearity and directional spreading on sea surface statistics
- determine the importance of wave reflection and trapping by steep submarine topography

APPROACH

A combination of theory, analytical and numerical models, and field experiments is used to investigate the physical processes that affect surface wave properties on the continental shelf and beach. The transformation of wave spectra across the continental shelf is predicted with models based on a spectral energy balance that include the effects of refraction, scattering by resonant wave-wave and wave-bottom interactions, and bottom friction. On beaches near-resonant triad interactions transfer energy to harmonic components and infragravity waves. A new model is under development, based on the Boussinesq equations and a heuristic parameterization of surf zone dissipation, that predicts the evolution of a random wave field over a gently sloping beach. Whereas wind waves and swell are mostly dissipated in the surf zone, infragravity waves reflect from the beach and radiate seaward across the shelf. A spectral WKB approximation is used to describe the refraction and topographic trapping of infragravity waves.

Extensive field data are used to verify predictions of topographic and nonlinear effects, and to estimate the energy losses owing to bottom friction and wave breaking. The data sets include measurements from arrays of pressure sensors, current meters, and directional buoys deployed in a series of experiments (DUCK94, SandyDuck, SHOWEX) on a wide shelf with a relatively straight beach along the North Carolina coast (Figure 1). A new experiment (NCEX) is planned on the southern California coast to study wave transformation over a steep, irregular shelf. Analysis techniques applied to the measurements include various inverse methods to extract directional and wavenumber properties from array cross-spectra, bispectral and trispectral analysis to detect nonlinear coupling, as well as standard statistical methods to determine empirical relationships between observed variables.

WORK COMPLETED

A stochastic model for wave shoaling evolution on a gently sloping beach was developed based on a third-order statistical closure of Boussinesq equations (Herbers and Burton, 1997). Model predictions of the nonlinear transformation of frequency and directional wave spectra are in good agreement with field data collected during DUCK94 and SandyDuck. An extension of the model through the surf zone using a heuristic parameterization of surf zone dissipation was completed and is currently being evaluated with field data.

The role of nonlinear triad interactions in the spectral energy balance of breaking waves was examined using direct estimates of the advection and nonlinear source terms obtained from measured wave spectra and bispectra. The main result of this analysis is a surprisingly close balance between energy losses in the energetic part of the spectrum and nonlinear energy transfers to higher frequencies. These observations show that the spectral evolution in the surf zone is strongly controlled by nonlinear triad interactions whereas dissipation appears to be confined to the high-frequency tail of the spectrum.

The effect of wave breaking on the directional properties of shoaling waves was investigated with measurements from cross-shore arrays of bi-directional current meters deployed by R. T. Guza and S. Elgar on barred and planar beaches. On both beaches the observed directional spreading of wave energy increases sharply in the surf zone. The observed dramatic directional broadening may have important implications for wave-driven longshore currents and sediment transport.

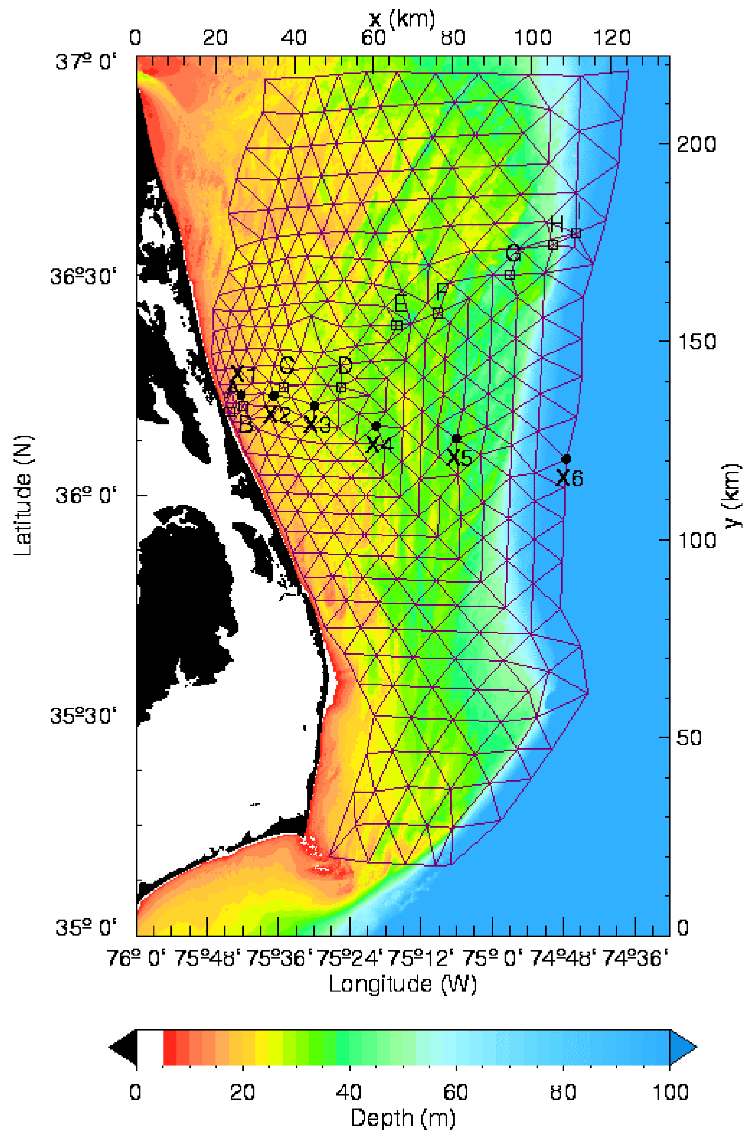

FIGURE 1. Implementation of the non-stationary spectral wave model CREST on the North Carolina shelf. Source terms in the energy balance are evaluated at the nodes of the triangular mesh. Advection terms are evaluated using a full ray method that resolves sub-grid-scale refraction. Labels A-I indicate a transect of bottom pressure sensors deployed during DUCK94. Labels X1-X6 denote a transect of surface-following directional buoys deployed during SHOWEX. A coherent array of bottom pressure sensors was co-located with buoy X2 on the inner shelf.

The nonlinear dispersion of random surface gravity waves in shallow water was investigated with boussinesq theory and field data. A theoretical dispersion relation for a root-mean-square average wavenumber as a function of frequency, the local water depth, and local wave statistics was derived for directionally spread waves propagating over a gently sloping beach. Wavenumbers estimated from array measurements collected during SandyDuck deviate by as much as 20-30% from the linear dispersion relation, and are in excellent agreement with the nonlinear Boussinesq theory predictions.

A cross-shelf transect of six Datawell Directional Waverider buoys and a high-resolution coherent array of five bottom pressure sensors (Figure 1) were deployed on the North Carolina continental shelf during September-December 2000 as part of the SHOWEX Experiment (in collaboration with W. C. O'Reilly). Unique observations of the evolution of frequency-directional wave spectra across the shelf were collected for a wide range of conditions including energetic seas during the passage of Hurricanes Floyd and Irene, and long period swells from Hurricanes Gert and Jose. Supporting measurements of seabed characteristics (collected in collaboration with T. Drake and J. McNinch) include sediment samples, side-scan sonar surveys of wave-induced sand ripples, and high-resolution surveys of small-scale bathymetry. The combined data sets will be used to examine the effects of wave-bottom interaction processes on the evolution of wave spectra across the shelf.

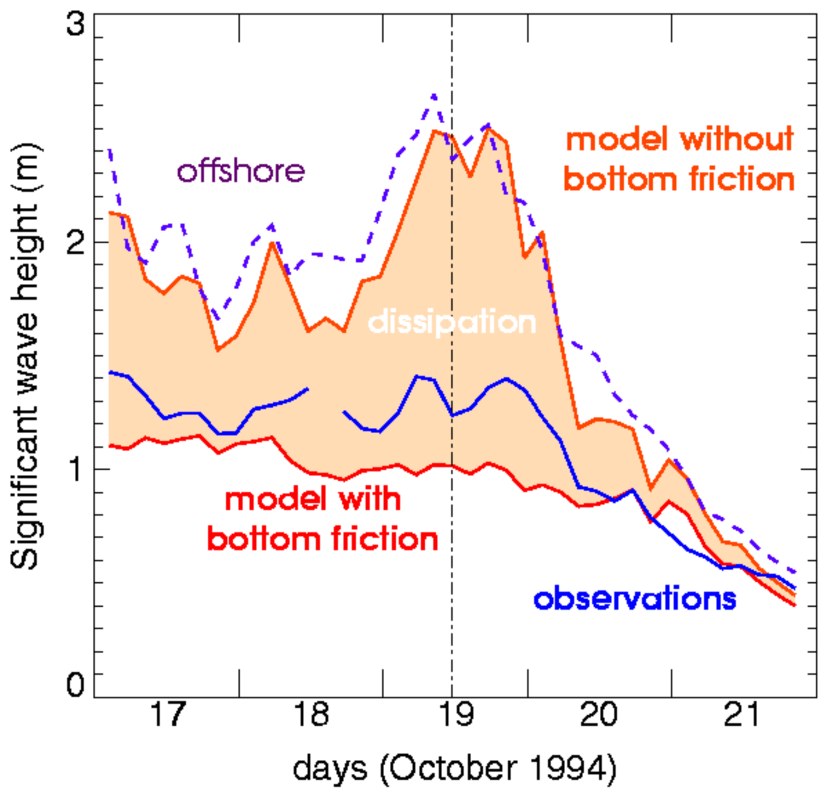

FIGURE 2. Hindcast of swell on the inner shelf (site B, Figure 1). Observed wave heights (solid blue curve) are generally much smaller than the offshore wave height (dashed blue curve), and are in good agreement with model predictions that include bottom friction (lower red curve). The difference between wave heights predicted by model runs with and without bottom friction (shaded) illustrates the strong dependence of bed roughness on wave conditions, consistent with variations in observed swell decay.

RESULTS

Graduate student Fabrice Ardhuin developed a nonstationary model for spectral wave evolution across a continental shelf based on a hybrid Eulerian-Lagrangian numerical scheme. The advection terms in the energy balance equation are computed using a full (Lagrangian) ray method whereas source terms are evaluated on a fixed Eulerian grid and interpolated onto the ray trajectories. This method has the important advantage that refraction effects by sub-grid-scale depth variations are evaluated accurately using pre-computed rays, and thus the model can be applied with relatively coarse source term grids to large coastal areas. The model was implemented for the North Carolina shelf region including the transects instrumented during DUCK94 and SHOWEX (Figure 1).

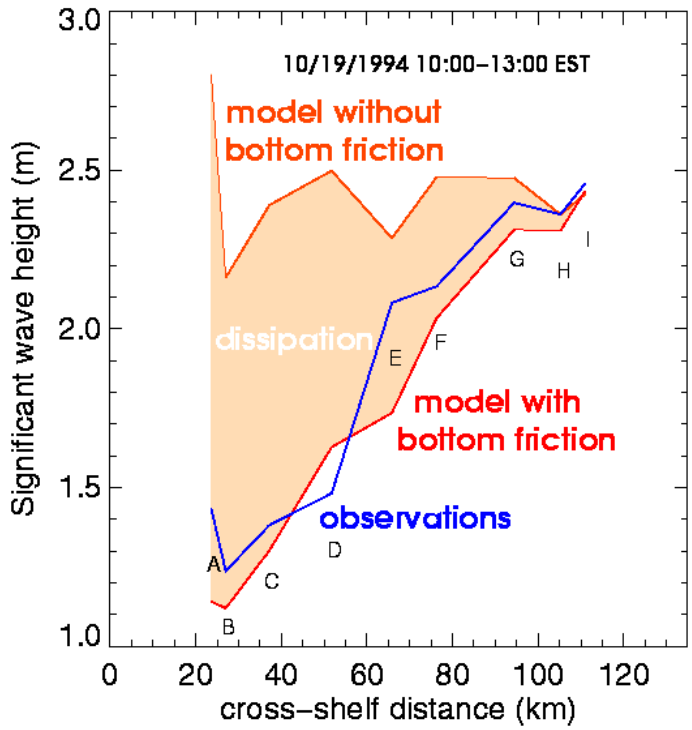

FIGURE 3. Observed and predicted swell decay across the shelf when the offshore wave height was maximum (vertical line in Figure 2). Observed wave heights are in good agreement with model predictions that include bottom friction. The large difference in wave heights predicted by model runs with and without bottom friction indicates that the observed decay is primarily caused by bottom friction. Labels A-I correspond to the sensor locations in Figure 1.

Dissipation of wave energy by bottom friction was represented in the energy balance with a source term given by Tolman (1994), based on models and laboratory measurements of the drag induced by wave-formed sand ripples (Grant and Madsen, 1979; Madsen et al., 1990). Moderately energetic waves can mobilize the seabed into steep vortex ripples that strongly enhance the bed rougness and wave dissipation. An example hindcast of swell decay across the shelf observed during DUCK94 is shown in Figures 2 and 3 (from Ardhuin et al., in press). In low wave conditions the observed and predicted damping is weak (e.g., 21 October, Figure 2). Active vortex ripples and large friction factors (0.06-0.12) are predicted on the entire shelf on 19 October when the swell energy was maximum. The predicted wave height decay (about a factor 2 between the shelf break and the inner shelf) is in good agreement with the observed decay (Figures 2 and 3).

A comprehensive validation of bottom friction source terms is planned using the more extensive SHOWEX data set. Initial analysis shows consistent strong damping of energetic swell across the shelf. Widespread sand ripples observed in the side scan sonar images of the sea floor support the hypothesis that the damping is caused by enhanced bottom friction over rough bed forms.

IMPACT/APPLICATIONS

Results of this research confirm the critical importance of rough bed-forms in swell transformation across a wide continental shelf. Analysis of swell decay on the North Carolina shelf shows that as much as 80% of the incident wave energy flux can be dissipated on the shelf and the variable dissipation rates appear consistent with existing movable bed roughness models. This dramatic sheltering of a coastline with a wide, sandy shelf has important implications for nearshore hydrodynamics and sediment transport.

TRANSITIONS

Results of the field experiments and modeling efforts are used in the ONR Advanced Wave Prediction Program to improve the parameterizations of shallow water effects in operational wave prediction models.

RELATED PROJECTS

Nearshore and inner shelf currents are investigated in collaborative efforts led by R. T. Guza and S. J. Lentz. The effects of nonlinearity and directional spreading on sea surface statistics are investigated in collaboration with S. Elgar. The stochastic Boussinesq model for shoaling waves developed in this project will be integrated in a comprehensive nearshore community model under sponsorship of the National Ocean Partnership Program (PI: J. Kirby).

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