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SURFACE WAVE PROCESSES ON THE CONTINENTAL 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.

SCIENTIFIC OBJECTIVES

- predict accurately the nonlinear shoaling transformation of waves over a gently sloping beach

- determine the effects of wave breaking on the directional properties of waves in shallow water

- predict accurately the nonlinear transfer of energy from wind waves to lower-frequency infragravity waves and the subsequent propagation and damping of these waves on the continental shelf

- determine the effects of refraction and bottom friction on the propagation of swell across a wide, shallow continental shelf

- determine the importance of resonant quartet interactions in the evolution of wind wave spectra on the continental shelf

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 and resonant quartet interactions. On beaches near-resonant triad interactions cause strong evolution of wave spectra over distances of only a few wavelengths. A new stochastic shoaling model is under development, based on the Boussinesq equations for weakly nonlinear, weakly dispersive waves, that can be applied to random, directionally spread wind waves propagating over a gently sloping beach with approximately straight and parallel depth contours. While the wind waves and associated high-frequency harmonics are mostly dissipated in the surf zone, the nonlinearly excited infragravity

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waves reflect from the beach and radiate seaward across the shelf as free waves. A spectral WKB approximation is used to describe the refraction and topographic trapping of infragravity waves radiated from shore.

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 coherent arrays of pressure sensors and current meters deployed near Duck, NC, Cape Canaveral, FL, Norfolk, VA, and Point Conception, CA, and single point wave measurements (pressure sensors and directional buoys) from numerous field sites. 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

The shelf-wide variability of swell (Herbers, Hendrickson, and O'Reilly, manuscript in preparation) and infragravity waves (Herbers, Evangelidis, and Jessen, manuscript in preparation) was investigated with measurements from a cross-shelf transect of ten pressure transducers, deployed on the seafloor of the North Carolina shelf during the DUCK94 experiment. The observations generally show weak variations in swell energy across the shelf during benign conditions, in qualitative agreement with predictions of an energy conserving spectral refraction model. However, strong attenuation of swell energy levels across the shelf (up to a factor 4) observed on a few occasions suggests that bottom friction is important in high-energy conditions. Larger cross-shelf variations in infragravity motions were observed, with energy levels near the shelf break typically 2 orders of magnitude smaller than the levels observed close to shore. The observed strong attenuation of infragravity waves across the sloping inner shelf is primarily the result of refractive trapping of waves radiated from shore at oblique angles, and is well described by a WKB model. Across the relatively flat (but irregular) outer shelf, the attenuation is weaker but increases with increasing swell energy. These results indicate that the attenuation of infragravity waves across the shelf is caused by a combination of trapping and damping effects.

RESULTS

A new stochastic Boussinesq model was developed that describes the shoaling evolution of random, directionally spread wind waves on a gently sloping beach (Herbers and Burton, 1997). Existing deterministic Boussinesq models (Freilich and Guza, 1984; and many others) describe accurately the nonlinear wave shoaling process, but require large computing resources and a detailed specification of incident waves at the offshore boundary of the model domain, that is often not available. The new stochastic formulation, based on a third-order closure for weakly nonGaussian statistics, yields a numerically efficient coupled set of evolution equations for the wave spectrum and bispectrum that smoothly matches (in the limit of weak nonlinearity) the well known third-order stochastic solutions of dispersive finite depth theory (Hasselmann et al., 1963). Predictions of both the new stochastic Boussinesq model and Freilich and Guza's deterministic Boussinesq model are in good agreement with field observations of wave shoaling collected by S. Elgar and R. T. Guza in the DUCK94 experiment (Figure 1, from Norheim et al., 1997).

The effects of wave breaking (not incorporated in the energy-conserving wave shoaling models) on the directional properties of shoaling waves were investigated with measurements from a cross-shore array of bi-directional current meters deployed by R. T. Guza and S. Elgar in the DUCK94 experiment (Figure 2, from Herbers, Elgar and Guza, manuscript in preparation). In benign conditions when most of the instruments were outside the surfzone, the observations show a decrease in directional spreading of wave energy toward the shore (squares) that is consistent with refraction toward normal incidence and nonlinear energy transfers to wave components that propagate in approximately the same direction as the incident waves. In energetic conditions with wave breaking on a shallow sandbar, the observed directional spreading of wave energy increases sharply in the surfzone (asterisks). This dramatic directional broadening, possibly a scattering effect associated with irregular wave breaking patterns, may have important implications for wave-driven longshore currents and sediment transport.

Extensive arrays of pressure sensors are currently deployed on the beach and inner continental shelf near Duck, NC (collaborative experiments with S. Elgar, R. T. Guza, B. Raubenheimer, and W. C. O'Reilly), to investigate in more detail the effects of nonlinear interactions and wave breaking on shoaling waves.

IMPACT/APPLICATIONS

The new nonlinear wave shoaling model developed in this project will be used extensively in numerical simulations of the transformation of ocean waves on beaches.

TRANSITIONS

The results of this research will be used in the new ONR Advanced Wave Prediction Program to improve the parameterizations of shallow water effects in operational regional wave prediction models.

RELATED PROJECTS

Wave-driven nearshore currents are investigated in a collaborative effort led by R. T. Guza (SIO). Observations of shear waves and infragravity waves in the surf zone are analyzed in collaboration with T. C. Lippmann (SIO) and E. B. Thornton (Naval Postgraduate School).

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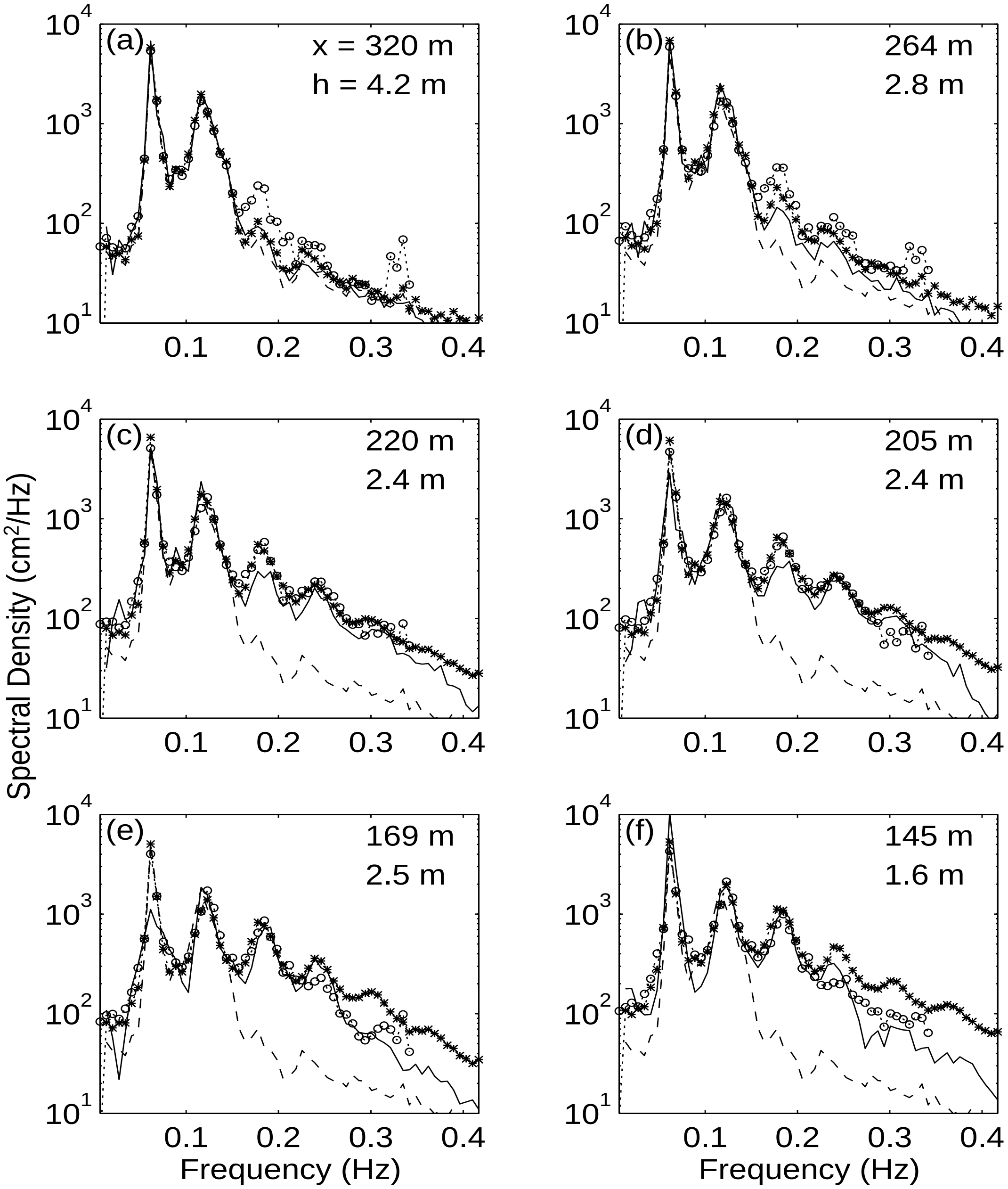

Figure 1: Comparison of observed (solid curves) with predicted (asterisks = stochastic model, circles = deterministic model) wave spectra at 6 instrument locations on a natural ocean beach near Duck, NC. The distance x from shore, water depth h, and the initial spectrum at x = 480 m (dashed curve) are indicated in each panel. Both models predict accurately the observed strong nonlinear evolution of nonbreaking waves propagating over a shallow sandbar at x = 240 m (Figure 2).

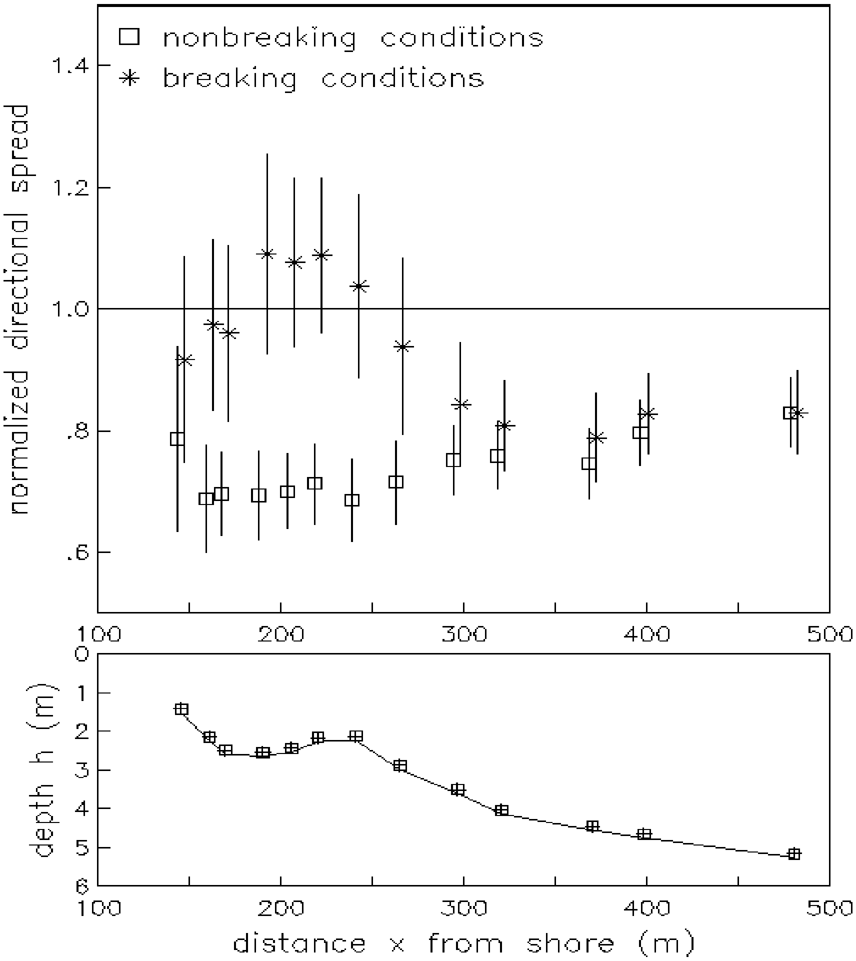

Figure 2: Observed directional spread (the width of the directional distribution of wave energy) versus cross-shore position x. The estimates, obtained from a transect of bi-directional current meters, are normalized by the incident wave directional spread estimated from an offshore array of pressure sensors in 8 m depth. Asterisks represent estimates from 304 data records collected in high-energy wave conditions with intense breaking on the sandbar. Squares represent estimates from 551 data records collected in low-energy wave conditions with small energy losses on the sandbar. Symbols and bars indicate the mean value and standard deviation of the estimates. A representative beach profile with the instrument locations is shown in the lower panel. Whereas directional spreads decrease toward the shoreline in non-breaking conditions, consistent with refraction of shoaling waves, directional spreads increase dramatically in breaking conditions with a maximum slightly inshore of the crest of the sandbar.