

Surface Wave Processes on the Continental Shelf and Beach

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Award Numbers: N0001401WR20026, N0001401WR20030
N0001401WR20024, N0001401WR20022, N0001401WX20499, N0001401WR20031
<http://www.oc.nps.navy.mil/wavelab/>

LONG-TERM GOALS

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 surface waves 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 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 interactions (e.g., wave-bottom triads and wave-wave quartets), and bottom friction. A different approach is used near the shore where near-resonant wave-wave triad interactions cause a rapid transfer of energy to

harmonic components and lower-frequency infragravity waves. A new model is developed, based on a stochastic closure of Boussinesq theory, that predicts the nonlinear shoaling transformation of a random, directional wave field across a beach. 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. 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

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 (Herbers et al., 2000). 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 nonlinear dispersion of a random, directional wave field in shallow water was investigated with Boussinesq theory and field data (Herbers et al., in press). 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 nonlinear theory predictions.

A cross-shelf transect of six Datawell Directional Waverider buoys and a high-resolution coherent array of five bottom pressure sensors 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 and side-scan sonar surveys of wave-induced sand ripples. Graduate student Fabrice Ardhuin used these data sets in conjunction with a new spectral wave prediction model to examine swell damping across the shelf (Ardhuin et al., 2001; submitted). 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). Predicted strong damping of energetic swell across the shelf is in good agreement with the observed swell decay. 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.

RESULTS

Waves propagating across a continental shelf are affected by bottom topography with a wide range of scales. At the largest scale (nominally 1-100 km) the shelf slope and features such as submarine shoals and canyons, islands, bays and headlands cause shoaling, refraction, and diffraction. The effects of depth variations with smaller scales (nominally 10 m – 1 km), comparable to the wavelengths of swell and sea, are less well understood. The dominant wave-bottom interaction mechanism at these scales is believed to be the Bragg resonance between two surface wave components with wavenumbers \vec{k} and \vec{k}' and the same frequency $f = f'$, and a bottom undulation with the difference frequency (0) and wavenumber $\vec{k}_b = \vec{k} - \vec{k}'$. This triad interaction causes an exchange of energy between surface waves of the same frequency that travel in different directions. Hasselmann (1966) developed a statistical theory for the scattering of random waves by an irregular

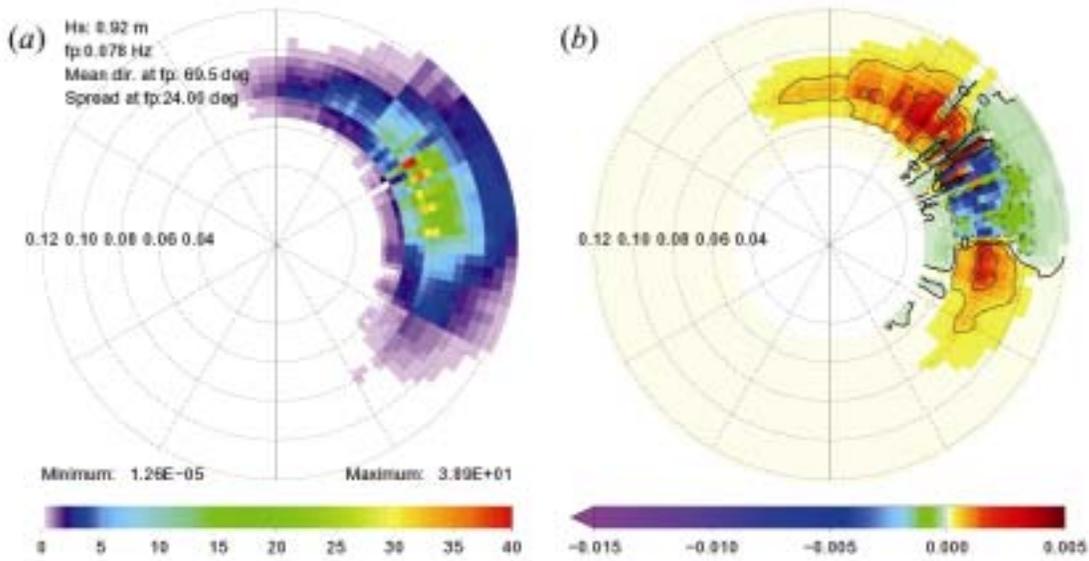


Figure 1. Spectrum $E(f, \theta)$ (left panel) and corresponding bottom scattering source term $S_{Bragg}(f, \theta)$ (right panel) predicted in a swell hindcast in 20 m depth on the inner shelf offshore of Duck, NC. The radial axis indicates the frequency f in Hz. The arrival direction θ is displayed in compass coordinates. Yellow-red and green-blue colors in (b) indicate positive (energy gain) and negative (energy loss) source term values, respectively. The predicted three-lobe structure of $S_{Bragg}(f, \theta)$ indicates that the dominant energy transfers are from the spectral peak to neighboring directions, causing an increase in directional spread.

sea floor. The net energy transfer to waves with wavenumber \vec{k} can be expressed in the form of a source term S_{bragg} that involves an integral over all triads that satisfy the resonance rule:

$$S_{bragg}(\vec{k}) = \int_0^{2\pi} D_{bragg}(\vec{k}, \vec{k}') E_b(\vec{k}_b = \vec{k} - \vec{k}') [E(\vec{k}') - E(\vec{k})] d\theta'$$

where E and E_b are the wavenumber spectra of the surface and bottom, θ' is the propagation direction of component \bar{k}' , and D_{bragg} is a coupling coefficient that depends on the water depth. Graduate student Fabrice Ardhuin extended Hasselmann's theory to random bottom undulations superimposed on a sloping continental shelf, and evaluated the scattering effects for the North Carolina shelf (Ardhuin and Herbers, in press). Whereas earlier studies focused on the backscattering of waves by bottom undulations with wavelengths of about half the surface

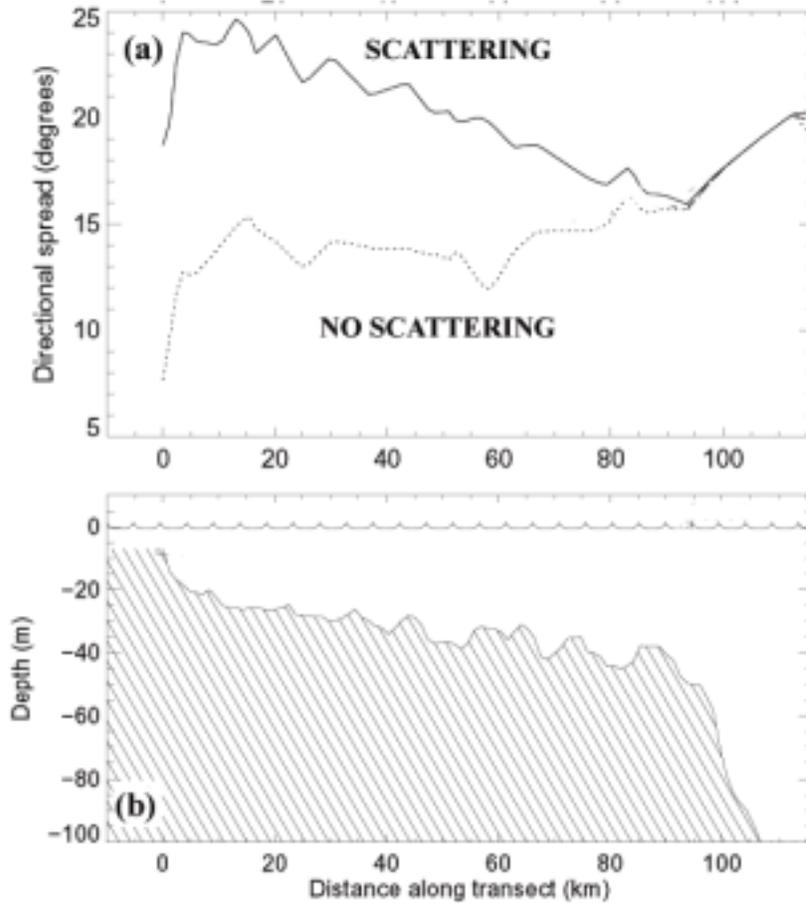


Figure 2. (a) Predictions of the evolution of the directional spread of swell across the North Carolina shelf. The dotted curve, a model prediction that accounts for refraction by the large scale shelf topography but neglects scattering by smaller-scale topography, shows the expected directional narrowing of a broad offshore spectrum owing to refraction toward shore-normal propagation. The solid curve, a prediction that includes both refraction and wave-bottom scattering, shows the initial narrowing of the spectrum across the shelf break followed by a gradual broadening owing to scattering. (b) Cross-shelf bottom profile.

wavelength ($\bar{k}' \approx -\bar{k}$, $\bar{k}_b \approx 2\bar{k}$) (e.g., Long, 1973), our results indicate that the back-scattered energy is small at this site owing to the sharp roll-off of the bottom spectrum E_b at high wavenumbers. The

predicted S_{bragg} is dominated by longer wavelength sand ridges ($|\vec{k}_b| < |\vec{k}|$) that cause energy exchanges between waves traveling in approximately the same directions ($\vec{k} \approx \vec{k}'$) (Figure 1). This forward scattering mechanism essentially diffuses wave energy about the mean wave direction, causing a gradual broadening of the directional wave spectrum. Preliminary calculations for the North Carolina shelf demonstrate that wave-bottom scattering is an important process that can significantly increase the directional spreading of swell near the shore (Figure 2), in qualitative agreement with observations.

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

Results of this research are adapted and implemented in a comprehensive nearshore community model that is being developed under sponsorship of the National Oceanographic Partnership Program (NOPP) (Lead-PI: J. T. Kirby). The effects of abrupt shelf topography on nearshore waves and currents are investigated in the Nearshore Canyon Experiment (NCEX) project led by S. Elgar.

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