1999

Surface Wave Processes on the Shelf and Beach

Herbers, Thomas H.C.

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Thomas H. C. Herbers
Department of Oceanography, Code OC/He
Naval Postgraduate School
Monterey, California 93943-5122
phone: (831) 656-2917 fax: (831) 656-2712 email: herbers@oc.nps.navy.mil
Award Numbers: N0001499WR30012; N0001499WR30117; N0001499WR30011; N0001499WR30008; N0001499WR30009; N0001499WR20063; N0001499WR20157
http://cdip.ucsd.edu/showex

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 transformation of waves in shallow water
- predict accurately the nonlinear transfer of energy from wind waves to lower-frequency infragravity waves
- determine the effects of refraction and bottom friction on the propagation of swell across a wide continental shelf
- determine the importance of resonant quartet interactions in the evolution of wind wave spectra on the continental shelf
- improve the representation of nonlinear wave-wave interactions in operational wave prediction models
- determine the effects of wave nonlinearity and directional spreading on sea surface statistics

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

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 1999		**00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Surface Wave Processes On The Shelf And Beach**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Department of Oceanography,Code OC/He,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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 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

A new stochastic wave shoaling model was developed based on a third-order statistical closure of Boussinesq equations (Herbers and Burton, 1997). A one-dimensional version of the model for unidirectional waves was validated through comparisons with field data (Norheim et al., 1998). A two-dimensional implementation for directionally spread waves was completed and is currently evaluated with extensive directional wave measurements collected in the SandyDuck Experiment.

Direct estimates of the contribution of nonlinear wave-wave interactions to the spectral energy balance of breaking waves on a barred beach were obtained from measured wave spectra and bispectra based on a stochastic formulation of Boussinesq equations. 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 while dissipation appears to be confined to the high-frequency tail of the spectrum.

The effects of wave breaking 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. 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 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 surf zone. The dramatic directional broadening may have important implications for wave-driven longshore currents and sediment transport.

The evolution of swell across a wide continental shelf was investigated with measurements from a transect of ten bottom pressure transducers, deployed on the North Carolina shelf during the DUCK94 Experiment. The results of this study 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, large energy losses across the shelf (up to about 70 %) were observed when incident swell energy levels were higher, but not high enough to cause steepness-limited wave breaking. This strong attenuation is likely the result of energy losses in the bottom boundary layer. The observed damping rates suggest significantly larger bottom friction factors than are commonly used in wave prediction models.

In collaboration with W. C. O'Reilly a cross-shelf transect of 6 Datawell Directional Waverider buoys and a coherent array of 5 pressure transducers were deployed on the North Carolina shelf, as part of the ongoing ONR Shoaling Waves Experiment (SHOWEX). Additional geological data were collected in collaboration with T. Drake and J. McNinch, including measurements of small scale bathymetry, wave-induced ripples, and sediment samples. The combined data sets (including several major hurricanes) will be used to examine the effects of wave-bottom interaction processes on the attenuation and directional spreading of waves propagating across the continental shelf.

RESULTS

The nonlinear dispersion of random surface gravity waves in shallow water was investigated with Boussinesq theory and extensive 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 were estimated using four arrays of pressure sensors deployed by S. Elgar and R. T. Guza in 3-5 m depth during the SandyDuck experiment (Figure 1a). Observed wavenumbers deviate by as much as 20-30% from the linear dispersion relation and are in excellent agreement with the nonlinear Boussinesq theory predictions (e.g., Figure 1c-e). In high-energy conditions with breaking or nearly breaking waves the theoretical frequency and amplitude dispersion effects tend to cancel, yielding a nearly nondispersive wave field in which all components travel with approximately the shallow water wave speed, consistent with the observations (Figure 1).

IMPACT/APPLICATIONS

Results of this project have provided unique new insights in the statistical properties of ocean surface waves in shallow water and a numerically efficient approximation for nearshore surf prediction models.

TRANSITIONS

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

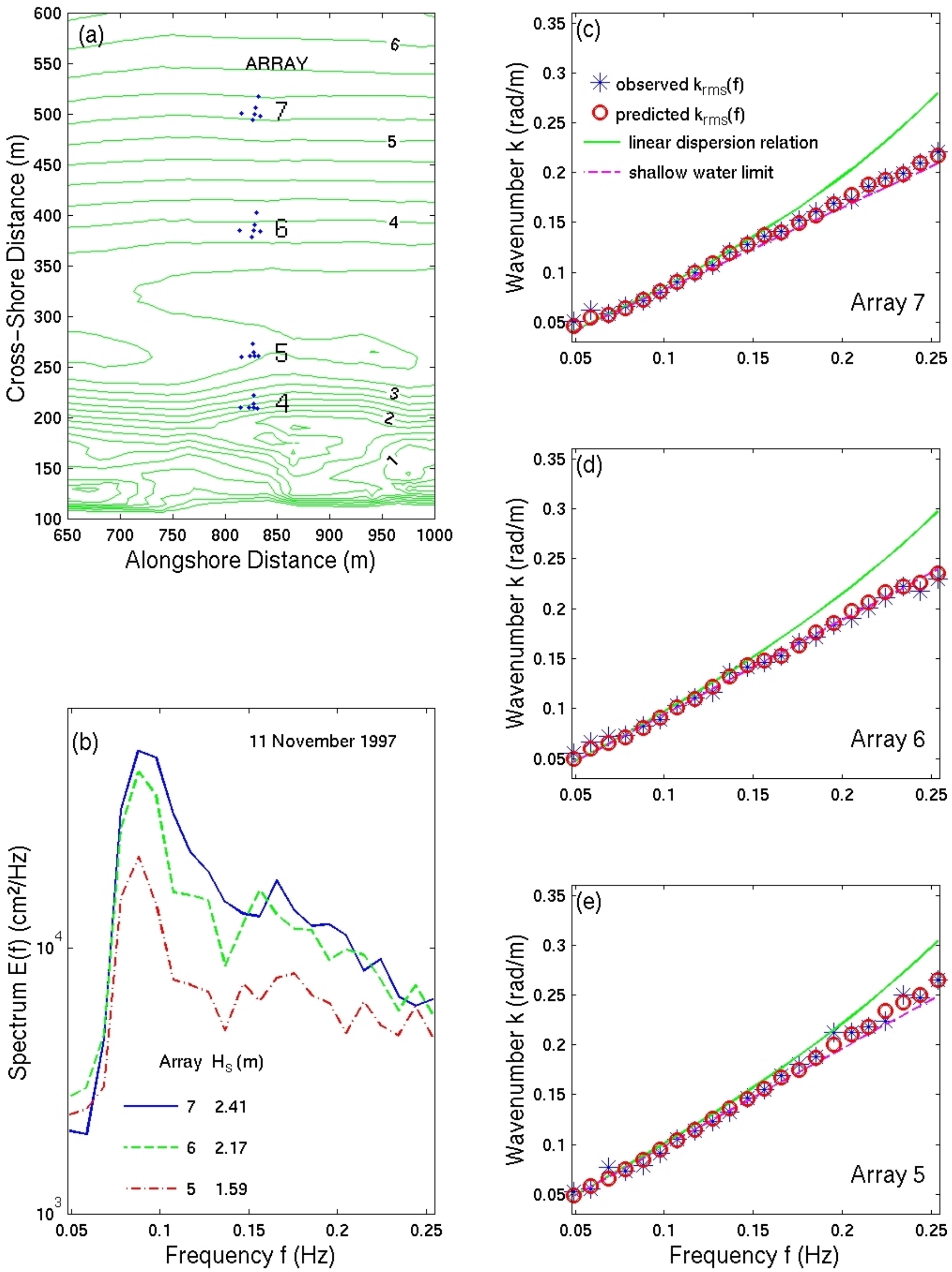

FIGURE 1. Wavenumbers of surface gravity waves observed in shallow water near Duck, NC, are compared with the linear dispersion relation and nonlinear Boussinesq theory predictions. (a) Bathymetry (depth contours in m) and locations of pressure sensor arrays. (b) Wave spectra at arrays 7, 6, and 5. (c-e) Observed and predicted dispersion relations at arrays 7, 6, and 5.

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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