Wave Propagation Across Muddy Seafloors

Steve Elgar
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
phone: (508) 289-3614 fax: (508) 457-2194 email: elgar@whoi.edu

Grant numbers: N00014-07-10461, N00014-02-10145, & N00014-05-10755
http://science.whoi.edu/users/elgar/main.html

Britt Raubenheimer
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
phone: (508) 289-3427 fax: (508) 457-2194 email: britt@whoi.edu

Grant numbers: N00014-07-10461, N00014-03-10447, & N00014-05-10755

LONG-TERM GOALS

The long-term goal is to develop field-verified models for the evolution of surface-gravity waves, allowing more skillful predictions of wave fields on continental shelves and enabling the estimation of characteristics of the seafloor from wave observations.

OBJECTIVES

The objective of the Wave Propagation Across Muddy Seafloors project is to develop, test, and improve models for mud-induced dissipation of waves in shallow water. Specific goals are to:
- Observe waves along a cross-shore transect spanning several km of the Louisiana inner shelf between about 5- and 1-m water depth,
- Extend existing wave models to account for damping by mud,
- Use the observations and models to test hypotheses for mud-induced damping, and
- Calibrate, test, and improve the models by comparing their predictions with the observations.

Additional objectives in FY07 included analysis of waves, currents, and morphological change onshore of complex shallow-water bathymetry dominated by two submarine canyons that extend nearly to the shoreline (the Nearshore Canyon Experiment, NCEX).

APPROACH

The approach is to investigate the evolution of surface-gravity wave fields by comparing field observations with numerical model simulations. The damping caused by a muddy seafloor is being investigated by simultaneously observing surface waves, near-bottom currents, and in collaboration with MURI investigators, characteristics of the mud layer and associated sediments. The field observations allow testing of existing hypotheses for mud-induced damping of the wave field, as well as development of new formulations and parameterizations for the dissipation that can be used in both research and operational wave models. By extending the observations into shallow water, the combined effects of mud- and wave-breaking-induced dissipation can be investigated.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Wave Propagation Across Muddy Seafloors**		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) **Woods Hole Oceaographic Institution,360 Woods Hole Rd,Woods Hole,MA,02543**		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)**	**8**	

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

WORK COMPLETED

i) *Wave propagation over muddy seafloors*

Pressure gages and current meters were deployed along a cross-shelf transect between approximately 5- and 2-m water depth on the muddy seafloor of the Gulf of Mexico (Figure 1).

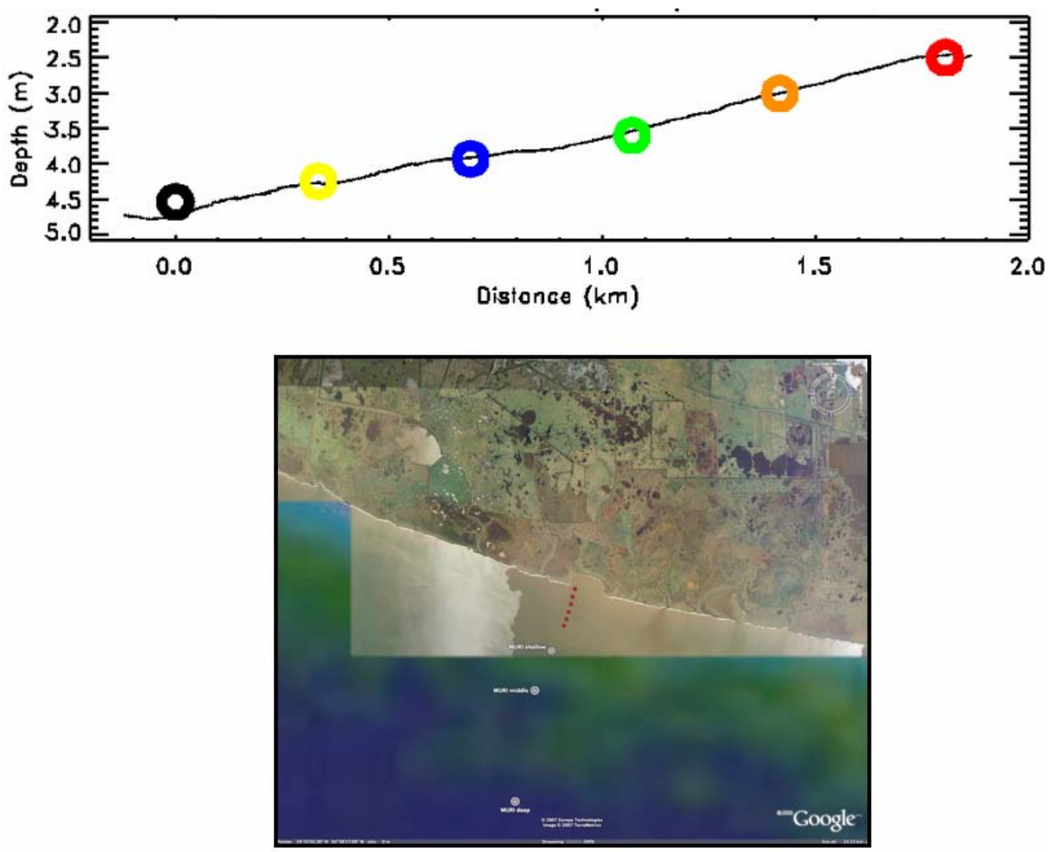

Figure 1. Upper: Depth (curve) of the muddy seafloor versus distance from the most offshore sensor measured during a shipboard acoustic survey (provided by G. Kineke). Symbols are colocated pressure gages and current meters. Lower: Aerial view of the Louisiana coast and the sensors (red symbols) shown in the upper panel, as well as the 3 tripods deployed by the MURI team (white symbols). [Six sensors were deployed across 1.8 km of the muddy seafloor between about 5- and 2-m water depths (slope is 1/1000).]

ii) *Nearshore Canyon Experiment*

The loss of infragravity wave (periods of a few minutes) energy observed in the surfzone was shown to be the result of nonlinear interactions with higher frequency swell (Henderson *et al*., 2006).

The effect of bottom stress was included in a model for wave-induced setup, resulting in improved predictive skill, especially near the shoreline. The effects of rollers on setup were shown to be small (Apotsos *et al*., 2007).

A new formulation was developed for the free parameter used in many wave transformation models, and was shown to improve wave height predictions for most observations from 6 field experiments (Apotsos *et al*., in review).

The momentum fluxes caused by strong alongshore pressure gradients that result from inhomogeneous incident wave fields onshore of a submarine canyon were shown to be important to the alongshore currents observed in the surfzone (Apotsos *et al*., in review).

Reflection from steep bathymetric features was shown to be important to the propagation of infragravity waves observed on the inner shelf near two submarine canyons (Thomson *et al*., in press).

RESULTS

As part of a pilot test, observations of waves were collected for 24 days in March and April 2007 along the transect shown in Figure 1. The seafloor was covered with a 30-cm thick layer of yogurt-like mud (density about 1.6 g/l [G. Kineke and S. Bentley]) that caused significant dissipation of the wave field, as shown in Figure 2. For example, during a small storm (waves were 1 m high in 5-m water depth) on day 22, there was a 70% reduction in energy flux (a quantity that is conserved in the absence of dissipation) as waves propagated 1.8 km between about 5 and 2 m depth (Figure 2, compare the black curve (most offshore sensor in Figure 1) with the red curve (most onshore sensor in Figure 1)).

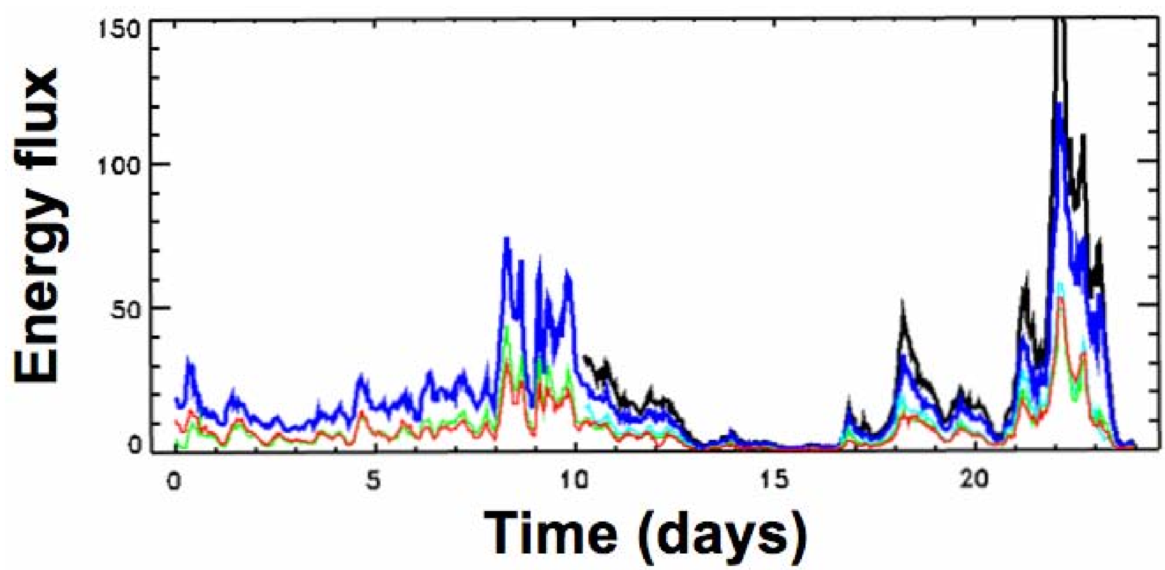

Figure 2. Energy flux versus time. Thick black and blue curves are the energy fluxes (m^3/s) observed in approximately 5- and 4-m water depths (same colors as symbols in Figure 1). The red curve is the energy flux observed in approximately 2-m depth (red symbol in Figure 1), 1.8 and 1.2 km onshore of the black and blue curves, respectively. Energy fluxes at the shallowest sensor (red symbol in Figure 1) predicted by a nonlinear Boussinesq wave model that includes an empirical mud-induced dissipation function are shown by the thin turquoise (initialized 1.8 km away) and green (initialized 1.2 km away) curves. If the model were perfect, the thin turquoise and green curves would overlay the red curve. [Energy fluxes decrease as waves propagate from 5- to 2-m water depth for all data sets during the 24-day observational period. A Boussinesq wave model that includes an empirical dissipation function predicts the decrease accurately.]

The observed dissipation is a strong function of depth (Figure 3). For these data, the energy flux decreased as $h^{-3.4}$, where h is water depth. This strong depth dependence of mud-induced dissipation has not been observed previously, possibly because most observations have been made in deeper water.

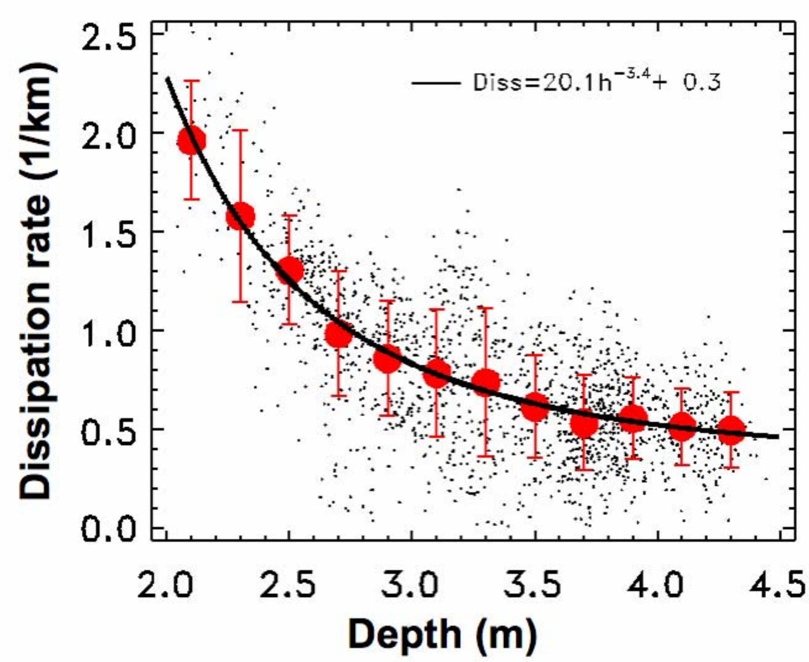

Figure 3. Dissipation rate versus water depth for the 24 days of data obtained during the pilot experiment in spring 2007. Significant wave heights at the most offshore sensor ranged from 0.1 to 1.0 m. The tide range was about 1 m. The black dots are individual 1-hr data runs, and the red circles are averages within 25-cm-wide depth bins (+/- 1 standard deviation is shown as vertical bars). The black curve is a fit through the data, which gives dissipation = 20.1 $h^{-3.4}$ +0.3. [The dissipation rate increases with decreasing depth as $h^{-3.4}$ from about 0.5/km in 5 m depth to about 2.5/km in 2 m depth.]

An estimate of the frequency dependence of the mud-induced dissipation (Figure 4) was obtained by comparing the observations with predictions from a nondissipative nonlinear Boussinesq wave model. The model was initialized with observations at each sensor location, and integrated to the next sensor shoreward. Differences between model predictions and observations at the shoreward sensor are attributed to dissipation. A nonlinear wave model is required because in these water depths nonlinear interactions can result in large transfers of energy between waves with different frequencies that otherwise might be incorrectly attributed to dissipation. By reinitializing the model at each sensor location, accumulation of model errors is reduced.

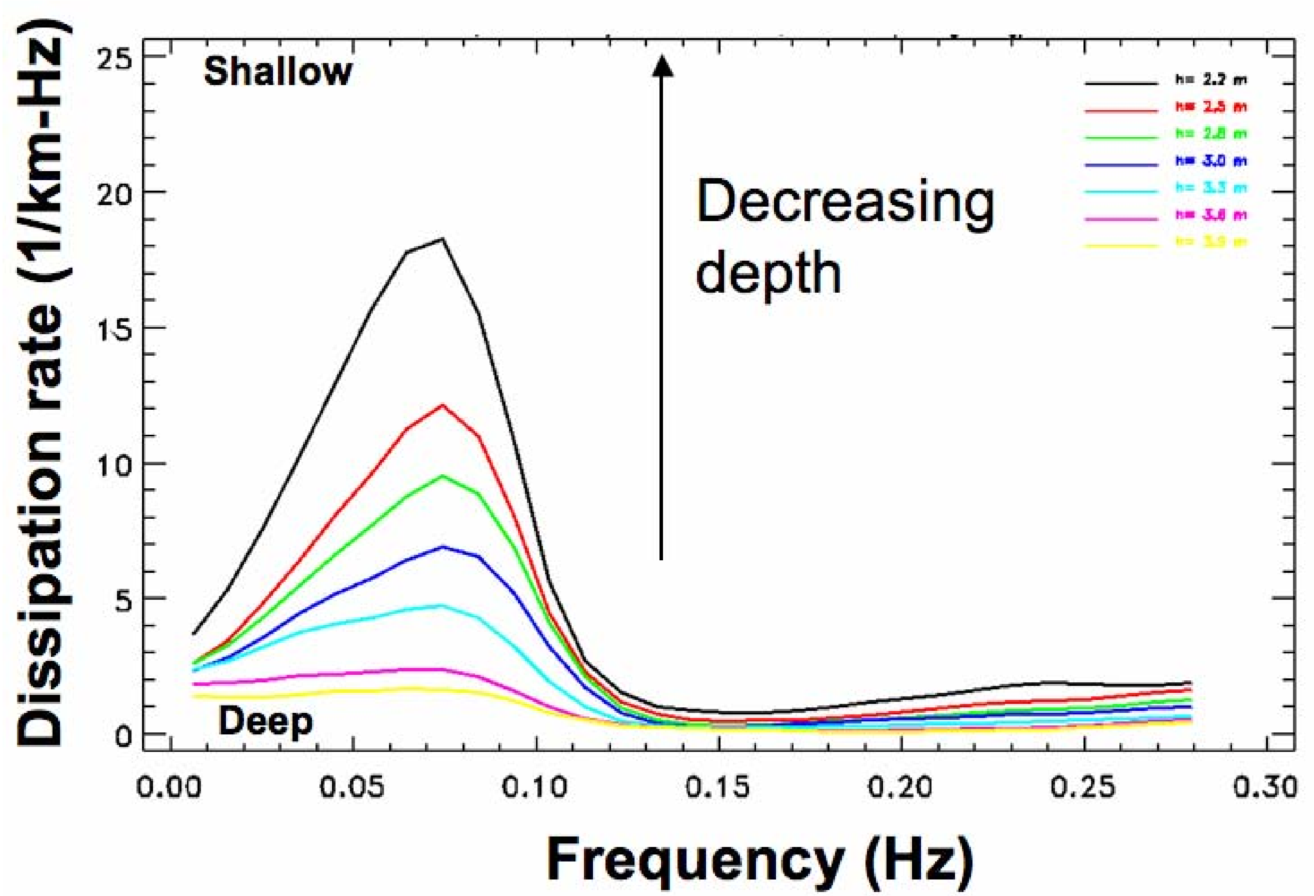

Figure 4. Dissipation rate density inferred from differences between a nondissipative nonlinear Boussinesq wave model and observations versus frequency. The different color curves are the inferred dissipation for all data runs averaged over 30-cm-wide depth bins (depths are given in the legend). [The dissipation rate is low (< 4/km-Hz) for the lowest frequencies, increases to a maximum at about 0.07 Hz, decreases to low values (< 2/km-Hz) at about 0.12 Hz and increases slightly (up to about 2/km-Hz) from 0.12 to 0.28 Hz. The curves have a Gaussian (bell curve) shape between 0 and 0.12 Hz. The maximum dissipation rate (at 0.07 Hz) increases from about 1/km-Hz in 3.9 m depth to about 18/km-Hz in 2.2 m depth.]

A curve consisting of a Gaussian function (dominates the shape between 0 and 0.12 Hz) plus a quadratic (dominates between 0.12 and 0.28 Hz) was fit to the frequency-dependent empirical curves shown in Figure 4, and combined with an $h^{-3.4}$ term to produce one curve that describes the inferred dissipation as a function of frequency and depth. This empirical dissipation function was used in the nonlinear Boussinesq model to simulate the wave field.

The dissipative Boussinesq wave model was initialized with observations at the sensors located 1.8 (black symbol in Figure 1) and 1.2 (blue symbol in Figure 1) km offshore of the shallowest sensor (red symbol in Figure 1), and integrated shoreward. The model-predictions of the overall energy fluxes are similar to those observed at the shallow sensor (compare thin turquoise and green curves with the red curve in Figure 2, and Figure 5).

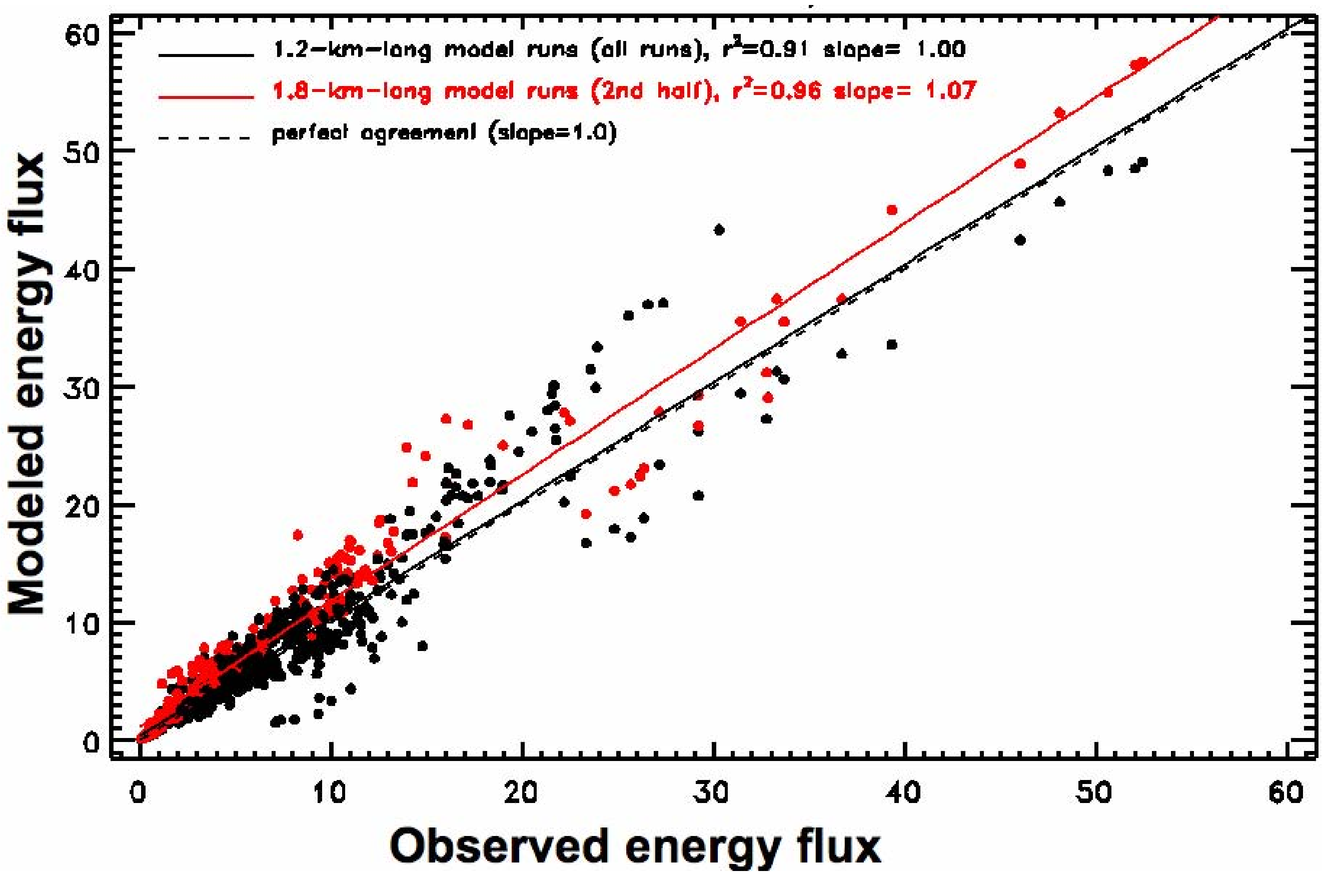

Figure 5. Energy flux (m^3/s) predicted by the dissipative Boussinesq wave model versus energy flux observed at the shallowest sensor. Black symbols are model simulations initialized 1.2 km offshore of the shallowest sensor, and red symbols are simulations initialized 1.8 km offshore. The dashed line is a 1-1 (perfect) fit, the black line (slope is 1.00, correlation coefficient is 0.91) is the fit through the points initialized 1.2 km offshore, and the red line (slope is 1.07, correlation is 0.96) is the fit through the points initialized 1.8 km offshore. [Scatter plot of model predictions versus observations of energy flux show the model has high skill, with correlations greater than 0.9 and best-fit line slopes close to 1.]

Based on the estimated dissipation function (Figure 4) and the fidelity of the dissipative Boussinesq wave model (Figures 2 & 5), we hypothesize that waves with frequencies near 0.07 Hz dissipate via interactions with the muddy seafloor. As these infragravity waves dissipate, their energy is replaced via nonlinear difference interactions between higher frequency waves (eg, between sea and swell), resulting in a nearly constant energy level at low frequencies (less than 0.1 Hz) and decreasing energy levels at higher frequencies. Bispectra of the observations are consistent with nonlinear difference interactions transfering energy from sea and swell to infragravity waves. As the infragravity waves dissipate, more energy is transfered from higher frequencies to infragravity motions. The nonlinear transfers increase as the water depth decreases, explaining the strong depth dependence of the dissipation rate (Figure 3).

Although the dissipative Boussinesq model has high skill (Figures 2 & 5), there is some scatter. Model-data discrepancies may be caused by the neglect of wind input and whitecapping dissipation (although winds usually were light), the assumption that waves propagated along the axis of the array (the waves usually were nearly aligned with the transect, but had a small directional spread), and the relatively large distances between the sensors. These potential sources of error will be investigated with observations from a spatially dense array of about 16 sensors planned for deployment in winter 2008. In addition, the 2008 observations will span a longer time period and thus a wider range of conditions. Colleagues will measure sediment properties with nearby tripods and shipboard surveys.

IMPACT/APPLICATIONS

Although the results from the pilot experiment in the Gulf of Mexico are preliminary, it appears that the mud-induced dissipation of the surface-gravity wave field is strongly depth dependent, and that the dissipation rate is largest for infragravity frequencies. By incorporating the empirical dissipation function determined from the pilot observations into a nonlinear Boussinesq wave model, the strong attenuation of the wave field observed between 5- and 2-m water depths can be predicted accurately.

Additionally, field observations on sandy beaches have been used to verify and improve models for nearshore and surfzone waves, circulation, and morphological change, and to ground truth remote sensing techniques to estimate nearshore currents. The comparison of model predictions with observations has increased our ability to predict nearshore bathymetric change, including the migration of sandbars across the surfzone.

RELATED PROJECTS

The observations of mud-induced dissipation of surface-gravity waves are part of a study that includes MURI-funded investigators, as well as colleagues from other institutions. Our spatially dense observations of waves and currents were part of a larger array that included intensely instrumented tripods with sensors to measure the lutocline and mud properties. To provide additional information about the sediment and water column properties, MURI-supported colleagues have performed cross-shelf shipboard surveys near all the sensors deployed in this project.

Many investigators are using the Duck94, SandyDuck, and NCEX observations to test components of the NOPP nearshore community model, as well as other models (eg, DELFT3D) for nearshore waves, currents, and bathymetry. Dozens of scientists, postdoctoral researchers, and students have accessed our data distribution WWW site [http://science.whoi.edu/users/elgar/main.html] over the past few years to download time series and processed data products for their studies. For example, NCEX observations are being used in collaboration with modeling studies and as ground truth for remote sensing of nearshore waves and currents. More than 20 researchers (from US universities, Navy laboratories, and American engineering companies, as well as from European institutions) have downloaded data from the NCEX data distribution site in 2007.

The studies of nearshore waves, currents, and morphology are in collaboration with NSF projects funding swashzone research, numerical modeling, and undergraduate fellows.

REFERENCES

Apotsos, Alex, Britt Raubenheimer, Steve Elgar, R.T. Guza, and Jerry Smith, 2007 The effects of wave rollers and bottom stress on setup, *J. Geophysical Research* **112**, C02003, doi:10.1029/2006JC003549

Apotsos, Alex, Britt Raubenheimer, Steve Elgar, and R.T. Guza, Testing and calibrating parametric wave transformation models on natural beaches, *Coastal Engineering*, **in review**.

Apotsos, Alex, Britt Raubenheimer, Steve Elgar, and R.T. Guza, Wave-driven setup and alongshore flows observed onshore of a submarine canyon, *J. Geophysical Research*, **in review.**

Henderson, Stephen, R.T. Guza, Steve Elgar, T.H.C. Herbers, and A.J. Bowen, 2006 Nonlinear generation and loss of infragravity wave energy, *J. Geophysical Research* **111**, C12007, doi:10.1029/2006JC003539.

Thomson, Jim, Steve Elgar, T.H.C. Herbers, Britt Raubenheimer, and R.T. Guza, Refraction and reflection of infragravity waves near submarine canyons, *J. Geophysical Research,* **in press**.

PUBLICATIONS

1. Henderson, Stephen, R.T. Guza, Steve Elgar, T.H.C. Herbers, and A.J. Bowen, 2006 Nonlinear generation and loss of infragravity wave energy, *J. Geophysical Research* **111**, C12007, doi:10.1029/2006JC003539. [published, refereed]

2. Apotsos, Alex, Britt Raubenheimer, Steve Elgar, R.T. Guza, and Jerry Smith, 2007 The effects of wave rollers and bottom stress on setup, *J. Geophysical Research* **112**, C02003, doi:10.1029/2006JC003549. [published, refereed]

3. Thomson, Jim, Steve Elgar, T.H.C. Herbers, Britt Raubenheimer, and R.T. Guza, Refraction and reflection of infragravity waves near submarine canyons, *J. Geophysical Research,* **in press**. [in press, refereed]

4. Apotsos, Alex, Britt Raubenheimer, Steve Elgar, and R.T. Guza, Testing and calibrating parametric wave transformation models on natural beaches, *Coastal Engineering*. [submitted, refereed]

5. Apotsos, Alex, Britt Raubenheimer, Steve Elgar, and R.T. Guza, Wave-driven setup and alongshore flows observed onshore of a submarine canyon, *J. Geophysical Research*. [submitted, refereed]