OVERALL OBJECTIVES AND APPROACH

The primary objective is to develop field-verified models for the evolution of surface-gravity waves propagating over a muddy seafloor, allowing more skillful predictions of wave fields on continental shelves, and enabling the estimation of characteristics of the seafloor from wave observations. The approach is to investigate empirical and theoretical expressions for mud-induced damping by comparing field observations with numerical model simulations. The damping caused by a muddy seafloor will be 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 will 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 will be investigated.

SPECIFIC GOALS FOR FY07-FY09

The primary specific goal for the next few years is to obtain field observations to test and improve models for wave propagation over muddy seafloors. We propose to

- Observe waves along a cross-shore transect spanning several km of the Louisiana inner shelf between about 7- and 1-m water depth,
- Extend existing wave models to account for damping by mud,
- Test hypotheses for mud-induced damping, and
- Calibrate, test, and improve the models by comparing the predictions with the observations.

The proposed transect (Figures 1 and 2) will enhance the observations to be obtained with the 3 MURI tripods, and will extend the observations obtained with the tripods and with the buoys deployed in deeper water (proposed by Herbers and O'Reilly) into shallower water where wave dissipation and nonlinear energy transfers are strongest. Close collaboration with the MURI investigators will allow new findings about mud-induced dissipation to be included in wave models. In addition, collaboration with Herbers and O'Reilly will result in wave measurements and modeling that span a continental shelf with a muddy seafloor, and thus will provide a unique database for additional model tests and calibrations.
Figure 1. Lower: Map of the Louisiana coast (contours are labeled with water depth in m). Triangles are approximate locations of the MURI tripods. Upper: Expanded view of the “boxed” area in the lower panel showing the high-spatial-resolution wave array (thick red line between approximately 7- and 1-m water depth) superposed on aerial photographs of the Louisiana shelf near the MURI tripods (triangles) (contours are labeled with water depth in m). The high-spatial-resolution array will consist of colocated pressure gages and 3-axis acoustic Doppler current velocimeters mounted on low-profile, trawl-proof seaspiders and jetted pipes at approximately 20 locations near (surrounding) and onshore of the shallowest MURI tripod (see Figure 2 for array details).


BACKGROUND

Observations show that waves propagating above muddy seafloors can be dissipated strongly. More than 90% of the incident energy was dissipated as waves propagated across the 20-km wide shallow mudflats off the coast of Surinam (Wells and Coleman 1981), and 95% of the incident energy was lost as waves crossed the 1.1 km-wide mudbanks off the coast of India (Mathew et al. 1995). Mud-enhanced damping has been observed in water depths greater than 20 m near the Mississippi Delta (Forristall and Reece 1985), and between 16- and 12-m water depths over muddy sections of the Louisiana shelf (e.g., Figure 1). However, the strongest dissipation occurs in shallower water, with more than an order of magnitude reduction in wave energy observed between 12- and 2-m water depth (Higgins 2002 and Figure 2 of the Dalrymple et al. MURI proposal).

The physical mechanisms causing wave dissipation over muddy seabeds are unknown. Hypotheses include damping by the soft bottom (Sheremet et al. 1980), interactions between waves and viscous fluidized muds (Dalrymple and Liu 1978), suspension of mud (Sheremet and Stone 2003), formation of a high-density near-bottom mud layer (Sheremet et al. 2005), and generation of waves (Hill and Foda 1999) and turbulent motions (Mehta and Srinivas 1993) on the fluid-mud interface. Even though high-frequency (>0.4 Hz) waves attenuate over the water column before reaching the seafloor, observations suggest significant dissipation of high-frequency components of a wave field propagating over a muddy bottom (Sheremet and Stone 2003), possibly caused by nonlinear energy transfers to lower-frequency components of the wave field, some of which subsequently are damped by the mud or the fluid-mud interface.

The efficiency and characteristics of mud-induced wave damping depend on mud state. Over smooth and hard consolidated muds, wave dissipation can be similar or even weaker than over sandy bottoms (Yamamoto et al. 1978; Hsiao and Sheremt 1980; Sheremt et al. 1980; MacPherson 1980; Yamamoto and Takahashi 1985; Lee 1995). However, wave action fluidizes bottom sediment by building up pore pressure and breaking the sediment matrix. The fluid-mud phase exhibits non-Newtonian characteristics at concentrations above 1 kg/m³, with significantly higher wave dissipation than caused by a consolidated mud bottom (Gade 1957; Chou et al. 1993; Foda et al. 1993). Under energetic waves the sediment matrix can collapse completely, leading to massive submarine landslides (Sterling and Strohbeck 1975). Near-bottom high-density suspensions (fluid-mud layers) also can form from hindered settling in the wake of a high wave-activity event (e.g., from a frontal passage, Wells and Kemp 1984; Allison et al. 2000; Winterwerp 2001; Sheremt et al. 2005; and others).

The diversity of mud states and corresponding beds include poro-elastic solids (Yamamoto et al. 1978; Yamamoto and Takahashi 1985), viscous Newtonian fluids (Dalrymple and Liu 1978), Bingham fluids (Mei and Liu 1987), generalized Voight solids (Jiang 1993; Jiang and Mehta 1995), and non-Newtonian fluids (Chou et al. 1993; Foda et al. 1993). Models for the behavior of these idealized muds in the presence of waves and currents have been extended to include the effects of wave nonlinearity (Jiang and Mehta 1996; Ng 2000). Surface waves interact with waves on the interface separating the upper water column from the fluid-mud layer (the lutocline), resulting in Kelvin-Helmholtz-like shear instabilities (Mehta and Srinivas 1993), turbulent eddies, and resonant nonlinear energy transfers, all of which can cause significant dissipation of the surface wave field (Hill and Foda 1999; Jamali et al. 2003a, 2003b).

Models for idealized muds may be of limited application to natural muds, which contain organic materials. Additionally, with the exception of fluidization processes (Foda et al. 1993), each model focuses on a single, well-defined mud phase, and different models may be applicable in different situations (Mei and Liu 1987). The models predict greatly differing damping effects, and observations of the frequency dependence of the damping could be useful to determine which (if any) theories provide reasonable damping estimates for specific wave and bottom conditions.
HIGH-SPATIAL-RESOLUTION FIELD EXPERIMENT

Waves and currents will be observed along an approximately 10-km long transect offshore of Atchafalaya Bay, between 7- and 1-m water depths (red line in Figure 1, shown in detail in Figure 2). We expect most of the dissipation of the wave field to occur in these depths where wave nonlinearities and interactions with the seafloor are strongest. In addition, extending the array into water as shallow as 1-m depth allows investigation of wave breaking on a muddy seafloor, and of the wave- and current-driven transport of suspended sediments that has been hypothesized to bring large amounts of mud onto the shoreline during storms (Draut et al. 2005).

![Figure 2](image)

**Figure 2.** Schematic of the high-spatial-resolution array (expanded view of the red line in Figure 1). Thick black curves are depth contours, labeled in m. Colocated pressure gages and current meters (red ovals) will be deployed close to the MURI tripod (magenta triangle) in 5-m water depth, and in shallower water. Four sensors will be deployed alongshore of the main transect to allow investigation of directionally spread wave fields. The array will extend Herbers and O’Reilly’s array of wave sensors and buoys (eg, blue circle) into shallow water.

We hypothesize that as long waves interact with the seafloor and dissipate, energy is transferred from higher-frequency short waves across the spectrum to the lower-frequency long waves. Other nonlinear interactions may transfer energy from waves at the primary spectral peak frequency to higher-frequency harmonics. We hypothesize that the nonlinear transfer rates are such that the wave field evolves toward nearly equal spectral levels across a wide range of frequencies. Thus, as has been found over sandy beds, the nonlinear-transfer and dissipation rates are related to each other.

Observations made with our high-spatial-resolution array in shallow water (red line in Figure 1
and red symbols in Figure 2) will be used to resolve the expected strong wave dissipation and nonlinear energy transfers, which lead to significantly different spectral evolution than observed on a sandy bottom (and thus potentially are particularly useful to distinguish bottom characteristics). Comparisons of the observations with our nonlinear-wave-model simulations will allow empirical determination of the damping as a function of frequency. These empirical frequency-dependent dissipation functions can be used in wave models, and, with constraints on the mud properties, can be used to determine which (if any) theories provide reasonable damping estimates. The observations proposed here also will allow high-resolution estimates of the unknown spatial scales over which significant dissipation occurs. Additionally, observations of lutocline and mud properties (collected by us and by the MURI team) concurrent with our observations of energy fluxes near a MURI tripod will provide information for testing theoretical expressions for the effects of a muddy seafloor on the wave field.

To obtain regional-scale observations of wave evolution over a muddy seafloor, Herbers and O'Reilly propose to deploy instruments offshore of our high-spatial-resolution array, including buoys to estimate the frequency-directional spectrum of the incident wave field. The proposed arrays will form a cross-shelf transect of buoys, pressure gages, and current meters that will provide observations of the evolution of the wave field over the muddy seafloor from deep water nearly to the shoreline. These wave observations will produce a database to test wave propagation (forward) models and inverse models that estimate sediment characteristics from observations of wave evolution.

Measurements will be made during winter, when cold air outbreaks generate energetic waves (significant wave heights of a few m). Although maintenance of sensors in shallow, biologically rich waters is labor intensive, we will maintain the high-spatial-resolution array for about 2 months, simultaneous with the MURI tripod deployments, ensuring a wide range of wave conditions. Sidescan sonar surveys and bottom sampling will be conducted prior to instrument deployments by the MURI team. In addition, during our deployment, turn-around, and recovery cruises, acoustic sensors operated from ships and small boats (in shallow depths) will be used to estimate the thickness of the mud layer. We will work with MURI investigators to select optimal locations for the sensors and the dates of deployments.

SITE MAPPING AND SEDIMENT CHARACTERISTICS

The range of dissipation mechanisms on any particular muddy bottom emphasizes the importance of monitoring seabed and suspended sediment properties, the depth of the mud layer, and motions of the fluid-mud interface during wave propagation studies. Although field observations of motions of cohesive sediments have been difficult owing to the paucity of field-capable instruments (and also to the low visibility, rapid bio-fouling, and other logistical difficulties associated with muddy environments), our array of wave sensors (Figure 1) will be aligned with (and will surround) the MURI-team tripods that will measure properties of the mud layer and bottom sediments concurrent with our observations of the evolution of the wave field. Additionally, we will collect information about the bottom properties near our sensors during deployment, turn-around, and recovery of our sensors.

Extensive information about the sedimentary structure of the experiment site is available (Neill and Allison 2005; Draut et al. 2005; Allison, unpublished data), and the distribution of sediment types on the Atchafalaya shelf is known qualitatively (Figure 3). The Atchafalaya subaqueous delta is characterized by soft muds caused by rapid sedimentation. The Atchafalaya Bay head deltas and the deltaic shoals are sand (Figure 3). Relict prodeltas are hard mud (several thousand years old) that can fluidize under intense wave-current action. The shelly bay mud is a continuation (top set) of the soft mud of the Atchafalaya subaqueous delta, but has some shell material that may affect its behavior in waves. Sidescan sonar surveys and bottom sampling will be conducted during the pilot deployment (2007) by the MURI team, and during deployment, turn-around, and recovery cruises of the main experiment (2008) by the MURI team and by our team (Elgar & Raubenheimer and Herbers & O’Reilly).
Shipboard acoustic systems will provide estimates of the thickness of the mud layer immediately prior to deployment of our sensors, as well as during the turn-around and recovery cruises. In addition, SCUBA divers will obtain surface samples and visual estimates of the mud layer depth at the start, middle, and end of our field deployment. At sites too shallow for a large ship, smaller, hand-held acoustic systems will be used to estimate the mud layer thickness. In addition, SCUBA divers will obtain cores (vibracores and pushed-by-hand samplers) and sediment samples at the sensor locations. As described below, testing of hypothesized damping coefficients requires knowledge of the water depth, mud layer thickness, and the density and viscosity of the mud. The proposed sampling scheme, combined with the extensive observations made by the MURI team at three locations, should provide sufficient information.

Figure 3. Facies map of the surficial sediments of the Atchafalaya area. Both modern and relict (Holocene) age units are shown (from Neill and Allison, 2005). Relict units sometimes are mantled by thin (less than 20 cm) ephemeral muds. The exact location of the array will be determined after pilot work in 2007, and will be selected in collaboration with the MURI team. The thickest mud deposits usually are found in depths less than about 7 m or greater than 20 m.

As detailed in the MURI team proposal, sediment sampling will include high-resolution sub-bottom profiles (acoustics) and analysis of box cores (to estimate density grain size distribution, viscosity, and sedimentary bedding and structures). The range of errors in the sediment (mud) information obtained at our wave sensors in shallower water will be determined by comparison of the detailed sediment properties acquired by the MURI team with estimates made at our nearby sensors. In shallow water, the theoretical damping formulations simplify greatly (discussed below), reducing sensitivity to details of the mud layer. Even if mud characteristics change significantly between the times samples are obtained by SCUBA divers, there will be accurate information at least 3 times during the deployment, providing a database adequate for testing hypotheses. Even if there is no information about certain aspects of the mud for times between visits by divers, the data can be used to develop and test damping parameterizations used in wave propagation models.
WIND AND WHITE CAPS

Although shoaling, nonlinear energy transfers, and mud-induced damping are the primary mechanisms influencing wave propagation in the study area (plus wave breaking in the shallowest depths), the effect of wind (a source of energy) and white capping (a sink of energy) will be considered. Wind and atmospheric properties will be measured by existing buoys in the area and by the MURI team at their tripods. Mesoscale atmospheric models (e.g., COAMPS) will be used to provide additional estimates of the wind field. These observations will be used to drive SWAN model simulations to estimate the effects of winds and white capping. Additionally, wind and white capping terms can be included in the Boussinesq model (described below) to estimate the fluxes of momentum and buoyancy (likely not important in the shallow depths) (Fairall et al. 2003), and to estimate the effects of energy input from wind and dissipation from white caps (Janssen 2004). Furthermore, over the deployment period there will be times during which winds are light and white capping is negligible, allowing hypothesis and model testing without the influence of wind or white capping.

MODELING WAVES PROPAGATING OVER A SHALLOW, MUDDY SEAFLOOR

Models for waves shoaling on sandy beaches are well developed. When initialized at the seaward edge of the shoaling region (typically 6-8 m depth, O(1) km from shore), Boussinesq equation-based models accurately predict the observed evolution of non-breaking waves (Freilich and Guza 1984; Elgar and Guza 1985a; and many others). Boussinesq-type models have been extended to include directionally spread waves (Herbers and Burton 1997; Herbers et al. 2003), alongshore-bathymetric variations and arbitrary depths (Janssen et al. 2006), and heuristic descriptions of surfzone (Mase and Kirby 1992; Kaihatu and Kirby 1995; Kirby and Kaihatu 1996; Elgar et al. 1997; Chen et al. 1997; Herbers et al. 2000; Herbers et al. 2003, Kaihatu 2003) and viscous (laboratory side walls) (Elgar et al. 1992a) dissipation.

The Boussinesq equations for weakly dispersive, weakly nonlinear, shallow water waves are (Peregrine 1967)

\[
g \eta_x + u_x + \frac{1}{2} (u^2)_x = \frac{1}{2} h(u_t h)_x - \frac{1}{6} h^2 u_{xxx}
\]

\[
\eta_t + (hu_x)_x + (\eta u_x)_x = 0
\]

where \( g \) is gravitational acceleration, \( \eta \) is the sea-surface elevation, \( u \) is the depth–averaged velocity potential, \( h \) is the water depth, and the subscripts \( x \) and \( t \) indicate differentiation with respect to space and time, respectively. The sea-surface elevation has the Fourier representation

\[
\eta = \sum_{n=1}^{N} a_n(x) \cos(\Phi_n(x) - \omega_n t)
\]

where the radian frequency \( \omega_n = n \Delta \omega \), with \( \Delta \omega \) the frequency resolution. The small amplitude (linear) wavenumber, \( k_n \), consistent with the Boussinesq approximations is given by

\[
(\Phi_n)_x = k_n = (\omega_n / (gh)^{1/2}) [1 + h\omega_n^2 / (6g)]
\]

In shallow water three-wave interactions are nearly resonant, and the slow spatial evolution of the Fourier amplitudes \( a_n \) and phases \( \Phi_n \) of the wave field is given by (Freilich and Guza
Although these models usually have been applied to moderately sloped sandy beaches, and hence

\[
\dot{a}_n = \sum_{j=1}^{n-1} a_j a_{n-j} R_{jn} \sin(\Phi_j + \Phi_{n-j} - \Phi_n) \\
+ \sum_{j=n+1}^{N} a_j a_{n-j} R_{jn} \sin(\Phi_j - \Phi_{j-n} - \Phi_n) \\
+ \sum_{j=1}^{N-n} a_j a_{n+j} R_{jn} \sin(\Phi_{n+j} - \Phi_j - \Phi_n) \\
- \kappa_n a_n \\
\dot{\Phi}_n = \sum_{j=1}^{n-1} \frac{a_j a_{n-j}}{a_n} R_{jn} \cos(\Phi_j + \Phi_{n-j} - \Phi_n) \\
- \sum_{j=n+1}^{N} \frac{a_j a_{n-j}}{a_n} R_{jn} \cos(\Phi_j - \Phi_{j-n} - \Phi_n) \\
- \sum_{j=1}^{N-n} \frac{a_j a_{n+j}}{a_n} R_{jn} \sin(\Phi_{n+j} - \Phi_j - \Phi_n)
\]

where \( N \) is the number of modes, the overdot indicates differentiation with respect to the propagation direction, and the coupling coefficients \( R_n \) are functions of depth and frequency (given explicitly in Freilich and Guza [1984] equations (21)-(24)).

Dissipation (discussed below) is given by the last term \((-\kappa_n\)\) in the equation for the evolution of the amplitudes.

These equations are the many mode generalization of the evolution equations for a monochromatic wave and its harmonic (Armstrong et al. 1962, Mei and Unluata 1972, Lau and Barcilon 1972, Bozcar-Karakiewicz and Davidson-Arnott 1987). Although extensions to two-dimensions (eg, for a directionally broad banded wave field) are straightforward (Herbers et al. 2002), the one-dimensional version will be used here to simplify the discussion. The effects of wind and white capping can be included in the expressions for the evolution of the Fourier amplitudes.

The Boussinesq equations also can be expressed in a stochastic formulation (Herbers and Burton 1997) that has been adapted to include a dissipation function (Herbers et al. 2000, 2003). The stochastic model requires less computational time than the deterministic model (above), and is more easily extended to account for directionally broad band wave fields (Herbers et al. 2003). We plan to collaborate with Herbers on comparisons of the observations with stochastic model predictions.

An alternative approach is to use the mild slope equations (Agnon and Sheremet 1997, Agnon and Sheremt 2000), which are identical to the Boussinesq equations in shallow water, but may allow more accurate modeling of higher-frequency components in deeper water. High-frequency components also can be included in the Boussinesq equations by using higher-order dispersion relationships. Changes in the dispersion relationship owing to the presence of a mud layer (Dalrymple and Liu 1978, Ng 2000) can be included in the wave models. We plan to collaborate with Alex Sheremt (U. Florida) to compare mild-slope and Boussinesq model simulations with each other and with observations. Details of the dissipation \( \kappa \) induced by the muddy bottom can be investigated with either model.

Although these models usually have been applied to moderately sloped sandy beaches, and hence
to relatively short propagation distances, they also have been used to investigate nonlinear interactions that occur when waves propagate long distances over a shallow flat bottom. Numerical simulations suggest that narrow band swell initially transfers energy to harmonics, as seen on natural beaches, followed by additional nonlinear transfers resulting in a broad, featureless spectrum at large distances (Figure 4) (Elgar et al. 1990). We hypothesize that on the nearly flat Louisiana shelf energy will be transferred from a broad frequency range of motions to motions at those frequencies for which dissipation is strongest (e.g., theoretical damping functions predict strong dissipation in a narrow frequency range between approximately 0.01 and 0.14 Hz for conditions typical of the Louisiana shelf).

The numerical results are consistent with laboratory observations of waves propagating many wavelengths over a shallow flat bed (Elgar et al. 1990, 1992a), including viscous dissipation from interactions between the waves and the walls and floor of the laboratory tank. However, there are few, if any, observations of ocean waves propagating long distances over a muddy bottom, and thus it is not known how mud-induced dissipation will affect the nonlinear energy transfers and the evolution of the energy spectrum.

**DETERMINING MUD-INDUCED DISSIPATION**

Our previous work has shown that as waves shoal outside the surfzone, energy is transferred from energetic swell (the primary power spectral peak) to higher frequency harmonics (Elgar and Guza 1985a, 1985b; Elgar et al. 1990, Freilich et al. 1990, Elgar et al. 1992a, 1992b, Elgar et al. 1997, Norheim et al. 1998, Herbers et al. 2000, 2002, 2003, and many others). In the surfzone, nonlinear interactions continue to transfer energy to higher frequency motions, where presumably the energy is dissipated during breaking (Herbers et al. 2000). Similarly, the observed energy loss of lower-frequency infragravity waves in the surfzone has been explained as the result of nonlinear interactions between infragravity waves and swell that transfer energy to higher frequencies, where it is dissipated (Thomson et al. 2006, Henderson et al. 2006). In both cases, energy continuously is transferred to frequencies where it is dissipated. The greater
the dissipation, the greater the transfer.

We hypothesize that similar nonlinear interactions are important to the dissipation of waves propagating over shallow muddy seafloors. Observations of waves on the Louisiana shelf show significant dissipation across a wide range of frequencies. However, the higher-frequency waves are too short to reach the seafloor where mud-induced dissipation occurs. Instead, nonlinear interactions likely result in energy transfer from the short, high-frequency waves to longer wavelength, low-frequency motions that interact with the seafloor and dissipate. As the energy levels of the low-frequency motions decrease, nonlinear interactions between higher-frequency waves may continue to transfer energy to the long waves that are dissipated by the mud. Thus, as waves propagate in shallow water, nonlinear interactions could continually transfer energy to motions where dissipation occurs. The theoretical expressions for the damping coefficient \( \kappa \) depend on the wave frequency, as well as properties of the mud layer (Gade 1957, 1958, Dalrymple and Liu 1978, Jiang and Mehta 1992 1995, Ng 2000, and others), with a sharp peak in dissipation between about 0.10 and 0.14 Hz for conditions typical of the Louisiana shelf. We hypothesize that as waves propagate over a muddy bottom, energy continually is transferred to motions near those frequencies that preferentially are dissipated, resulting in energy loss across a wide range of frequencies. This process is similar to the transfers from swell to higher frequencies during breaking and to the transfers from low-frequency to swell motions that reduce infragravity energy near the shoreline.

A primary objective is to develop numerical models that describe the evolution of a wave field propagating over a shallow muddy seafloor. The Boussinesq equations (or, equivalently the mild-slope equations) also provide a tool to investigate the combination of nonlinear energy transfers and frequency-dependant energy losses. Non-dissipative wave models will be initialized with observations at one sensor, and run to the next sensor shoreward, yielding a prediction of the wave field in the absence of dissipation, but accounting for nonlinear energy transfers (as well as the effects of wind and white capping if appropriate). Differences between the modeled and observed energy spectra will provide a frequency-dependent estimate of the dissipation. This approach has been used to estimate the frequency-dependent dissipation that occurs when waves break in the surfzone (Kaihatu and Kirby 1995, Elgar et al. 1997, Herbers et al. 2000), and when infragravity waves loose energy near the shoreline (Thomson et al. 2006).

Alternatively, the damping coefficient can be investigated directly from the observations. The frequency-dependent energy transport equation can be expressed as a balance between the cross-shore gradient of the energy flux spectrum, \( F_x \), a nonlinear source term \( S_{nl} \) (eg, nonlinear wave-wave interactions), input owing to wind \( S_w \), energy loss owing to white caps \( S_{wc} \), and a dissipation term \( \kappa \) that accounts for mud-induced damping (and can be extended to include breaking-induced dissipation) given by:

\[
F_x(\omega) = S_{nl}(\omega) + S_w(\omega) + S_{wc}(\omega) + \kappa(\omega)
\]

The energy flux spectrum is given by \( F_x(\omega) = C_g \rho g E(\omega) \), where \( C_g \) is the wave group speed, \( \rho \) is the density of seawater, and \( E(\omega) \) is the sea-surface elevation spectrum. In the Boussinesq approximation, energy is transmitted with the shallow water group speed \( C_g = \sqrt{gh} \). The energy flux gradient \( \frac{dF_x}{d\omega} \) can be evaluated from differences in energy flux measured at adjacent instrument locations in the array (see Herbers et al. [2000] for details).

Assuming that the Boussinesq equations describe the wave evolution, the nonlinear source term \( S_{nl}(\omega) \) represents the net transfer of energy to waves with frequency \( \omega \) via near-resonant triad interactions, and can be expressed in terms of the imaginary part (IM) of the bispectrum \( B(\omega',\omega) \) of the wave field (Herbers et al. 2000) as:
\[
S_{nl} = IM \left\{ \frac{3\omega}{2h} \rho g \left[ \int_0^\infty d\omega' B(\omega', \omega - \omega') - 2 \int_0^\infty d\omega' B(\omega', \omega) \right] \right\}
\]

Thus, the nonlinear source term can be estimated directly from the observations. The energy sources owing to wind (Fairall et al. 2003) and white capping (Jannsen 2004) can be estimated from meteorological observations, or neglected when winds are light.

The true damping coefficient as a function of frequency \( \kappa(\omega) \) can be estimated by ascribing differences between gradients in energy flux \( F_s(\omega) \) (and the wind terms if appropriate) and nonlinear interactions \( S_{nl}(\omega) \) to dissipation.

The estimates of the damping function \( \kappa(\omega) \) obtained from the observations and from the differences between observations and non-dissipative Boussinesq or mild slope equation model predictions will be used to test theories for mud-induced damping. Theoretical studies suggest that damping depends on the density and viscosity of the water and the mud, the depth of water, the wave frequency, wavelength, and amplitude, and the thickness of the mud layer (Gade 1957, 1958, Hunt 1959, Liu 1973, Mei and Liu 1973, Dalrymple and Liu 1978, MacPherson 1980, Jiang and Metha 1992, 1995, 1996, Jiang and Watanabe 1996, Ng 2000, and many others). For example, the damping function for a thin mud layer in shallow water can be expressed as (Ng 2000)

\[
\kappa(\omega) = -\frac{\delta_m(B_r + B_i)k^2}{\sinh(2kh) + 2kh}
\]

where \( \delta_m = \sqrt{2\nu_m / \omega} \) is the frequency-dependent Stokes’ boundary layer thickness, with \( \nu_m \) the viscosity of the mud, \( k \) the first-order wavenumber (neglecting the mud layer), and \( h \) the water depth. The constants \( B_r \) and \( B_i \) (given in the Appendix of Ng (2000), equations A1-A8) are functions of the wavenumber, the Stokes’ boundary layer thicknesses of the mud and the water, the ratio of the mud and water densities, and the mud layer thickness. This expression for the damping is the shallow water limit of Dalrymple and Liu (1978), and simplifies further if the mud is much more viscous than the water, in which case the damping is maximum when the mud layer is approximately 1.5 times the Stokes’ boundary layer thickness, consistent with empirical (Gade 1958) and numerical results (Dalrymple and Liu 1978).

The parameters necessary to test these theories will be obtained from the shipboard surveys, box cores, diver-obtained samples, and from the densely instrumented tripods deployed by the MURI team. Thus, initial tests will be conducted along the portion of the array that surrounds a MURI tripod (Figure 2). If the theories for damping are shown to be accurate near the tripods, we will extend the hypothesis tests to shallower depths, using parameters estimated from box cores, acoustics from small boats, and diver-obtained samples.

In the absence of adequate information to test the theoretical damping coefficients, the dissipation estimated from differences between model predictions and observations can be used to determine (in an inverse approach) the values of the unknown parameters (for example, the depth of the mud layer), and to verify whether or not the estimated values are reasonable.

Regardless of the veracity of the theoretical expressions for damping, the dissipation function estimated from differences between model and data can be incorporated into the wave model, which is then doubled-checked by rerunning the dissipative model between the two sensor locations and comparing with the observations.

Preliminary numerical simulations using the Boussinesq equations with a simple expression for dissipation suggest that in 5-m water depth nonlinear interactions result in significant energy transfers and evolution of the wave field over distances of a few wavelengths (hundreds of
meters, Figure 4). To resolve the spatial scales over which dissipation occurs, and to avoid aliasing of results, we propose a densely spaced array of wave sensors (Figure 2). The array will be designed in collaboration with the MURI team to allow detailed testing of the theoretical expressions for damping near their tripod. For conditions typical of the Louisiana shelf, the damping is maximum for 7 to 10 s period waves (frequencies from 0.10 to 0.14 Hz). In 5-m water depth, these waves have 50 to 70 m long wavelengths, and there can be significant reductions in wave energy over a few hundred m of propagation distance. Thus, we propose to deploy wave sensors within a few hundred m of a MURI tripod (Figure 2), with exact distances based on results from the pilot experiment, numerical model simulations, and needs of other investigators. The spacing between sensors in shallower water will be based on numerical simulations, the pilot results, shallow-water scaling (eg, scaling by \(kh\) has been used in laboratory studies of waves propagating over a shallow flat bottom \[Elgar et al. 1992a\]), and in collaboration with other investigators in this project.

In the shallowest depths there may be depth-limited wave breaking. The effects of mud-induced damping on breaking waves are unknown. We hypothesize that similar nonlinear energy transfers are important to the evolution of the wave field, and that energy is dissipated at both low frequencies (via mud-induced damping) and at high frequencies (via wave-breaking induced dissipation). Nonlinear interactions will transfer energy from the most energetic parts of the spectrum to motions where dissipation occurs, possibly resulting in complex evolution of the wave field as different damping mechanisms become dominant. By comparing model predictions with observations of waves propagating across the shallow, muddy seafloor that are dissipating owing to both mud-induced damping and wave breaking, the frequency dependent dissipation can be estimated. Boussinesq models are ideal to investigate the evolution of the wave field in shallow depths. Models based on the shallow-water equations (eg, RBREAK, \[Kobayashi et al. 1989, Raubenheimer et al. 1995, 1996, Raubenheimer and Guza 1996\]) also will be used to investigate the processes dominating the evolution of the wave field in shallow depths.

**ANTICIPATED RESULTS**

The comparisons of observations with model simulations of waves propagating across the shallow, muddy seafloor into shallow water will allow investigation of the processes important to the evolution of the wave field. In particular, the nonlinear interactions that transfer energy from waves over a wide range of frequencies to motions where dissipation occurs will be quantified. In addition, the validity of theoretical expressions for mud-induced damping will be examined. Moreover, the field observations allow determination of parameterizations for mud-induced damping that can be incorporated into operational wave models. By extending the observations into shallow depths where depth-limited breaking occurs, the effect of a muddy bottom on wave breaking can be investigated, and the differences between mud- and breaking-induced dissipation can be quantified.

**COLLABORATIONS AND PROVISION OF SUPPORTING DATA**

Although the proposed investigation of wave evolution over a muddy seafloor is self-contained, it also provides opportunities for collaboration with other investigators. A companion proposal by T. Herbers (NPS) and W. O'Reilly (SIO) describes investigations of wave evolution across the shallow muddy seafloor offshore of our proposed array of wave and current sensors. The cross-shelf transects incorporate the 3 densely instrumented tripods to be deployed by the MURI team. We plan to collaborate closely with the MURI team (www.ce.jhu.edu/dalrymple/MURI) and with T. Herbers and W. O'Reilly.

The combined wave evolution measurements, geological surveys, and direct measurements of fluid-sediment interactions will provide a test bed for different approaches to infer bottom characteristics from surface-wave observations and for testing operational wave propagation models. To facilitate collaborations, we will distribute our observations via the WWW within one year of the field experiment, similar to the public distribution of data we have collected over the last decade (http://science.whoi.edu/PVLAB/index.html). The WWW site includes files with
highly processed products (means, variances, spectra, bathymetry), as well as time series for every instrument for every data run from each experiment. README files explain the data formats, and are accompanied by example plots and a list of publications with additional figures and details.

We plan to continue collaborating with NCEX colleagues (principal investigators, post-doctoral researchers, and students), including testing models for surface gravity wave propagation (T. Herbers, R. Guza (SIO), W. O'Reilly, J. Kaihatu (NRL)), infragravity wave generation (J. Thomson (UW), T. Herbers, E. Thornton (NPS), J. MacMahan (U Del.)), and internal wave evolution (S. Lentz (WHOI)) near and across the abrupt canyon bathymetry. In addition, we plan to collaborate on studies of inner shelf (S. Lentz), surf (R. Guza, S. Henderson (SIO), J. Kaihatu, T. Ozkan-Haller (OR State)), and swash (R. Holman (OR State), T. Hsu (U. FL), S. Lentz, T. Maddux (OR State), A. Reniers (Delft)) circulation, wave breaking (T. Lippmann (OH State), R. Holman), and morphological evolution (T. Lippmann, R. Holman, T. Holland (NRL)). Students and colleagues will lead most of these studies, and our role will decrease with time, especially as we increase our commitment to studies of processes in shallow water with muddy bottoms.
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