Muddy Seafloors and Tidal Flats

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LONG-TERM GOALS

The long-term goal is to develop field-verified models for the evolution of surface-gravity waves, circulation, sediment transport, and the subsequent morphological response in shallow waters on sandy and muddy coasts and on macrotidal flats.

OBJECTIVES

The objective of our studies in FY08 is to develop, test, and improve models for mud-induced dissipation of waves in shallow water, and for circulation, sediment transport, and morphological change on macrotidal flats.

Specific goals relating to waves over muddy seafloors 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.

Specific goals relating to macrotidal flats are to:

- Investigate the relative importance to the circulation of riverine and tidal flows,

- Test and improve models for circulation, sediment transport, & morphological evolution,

- Evaluate assumptions and semi-empirical formulations underlying theories for circulation and sediment transport on tidal flats, and

- Examine the processes leading to channel migration.

Additional goals in FY08 relating to sandy coasts include analysis of waves, currents, and morphological change onshore of complex shallow-water bathymetry dominated by two submarine canyons that extend nearly to the shoreline.

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APPROACH

Our approach is to collect field observations to test existing hypotheses, to discover new phenomena, and to calibrate, evaluate, and improve models for waves propagating across muddy seafloors and for tidal flat hydrodynamics and morphological evolution.

WORK COMPLETED

i) Wave propagation over muddy seafloors

Pilot observations collected in 2007 of waves dissipating across the muddy Louisiana coast were analyzed (Elgar and Raubenheimer, 2008). Results are discussed below.

In 2008, pressure gages and current meters were deployed along a cross-shelf transect between approximately 5- and 1-m water depth on the muddy seafloor of the Gulf of Mexico (Figure 1).

Figure 1. Locations of colocated pressure gages and current meters (red circles) deployed between 5- and 1-m water depth on the Louisiana coast in winter-spring 2008. The seafloor near the study area is muddy, resulting in strong dissipation of sea and swell. The blue triangle is a tripod with sediment sensors (Sheremet and Allison). [Map of the Louisiana coast showing the locations of 16 wave and current sensors deployed along a 3-km-long cross-shore transect offshore of Flat Lake.]

ii) Wave propagation on sandy coasts (Nearshore Canyon Experiment)

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.,* 2008).

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*., 2008).

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*., 2007).

The effects of sediment-induced stratification on sediment transport and corresponding morphological change were investigated with observations from North Carolina and a 1-D General Ocean Turbulence model (Falchetti *et al.*, 2008)

iii) Circulation and Morphological Change on Macrotidal Flats

A pilot project in August 2008 in Skagit Bay, near the north fork of the Skagit River, La Conner, WA was completed successfully (Figure 2). Eleven tripods with colocated pressure sensors, current meters, and conductivity-temperature (CT) sensors were deployed across the tidal flat. Bathymetric surveys of the flat were obtained with a GPS and a personal watercraft equipped with an acoustic altimeter. Meteorological data were collected nearby by a colleague (Thomson, UW APL). Pressure, flows, and water density were measured at 2 Hz for approximately 10 days.
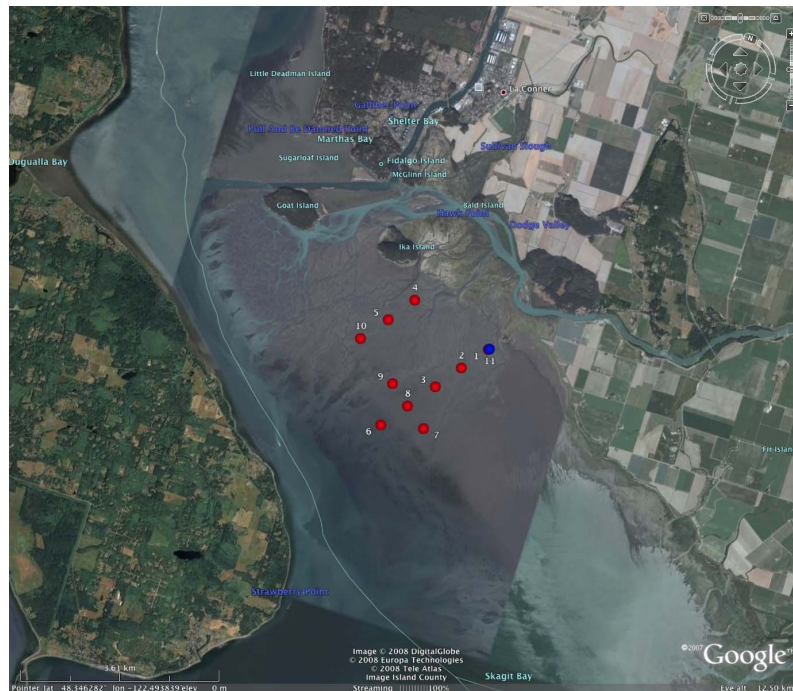

Figure 2. Locations of colocated pressure gages, current meters, and CTs (red & blue circles) deployed on a macrotidal flat in Skagit Bay in August 2008. The tide range was approximately 5 m, and the seafloor at the sensor locations was dry at low tide. The area was surveyed with GPS and a sonar mounted on a personal watercraft. [The map of a 10 x 10 km area of Skagit Bay shows the locations of 11 instrument tripods extending from the marshes to the offshore edge of the intertidal region.]

RESULTS

The observations from the cross-shore transect of 16 sensors deployed along the muddy Louisiana coast (Figure 1) are being analyzed, and compared with the observations made the previous year in the same location (Figure 3). The pilot observations made on a macrotidal flat (Figure 2) are being analyzed, and will be used to design a larger experimental program for 2009.

Observations of waves were collected for 24 days in March and April 2007 with 6 sensors deployed along the transect shown in Figure 3. 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 (Figure 3c). 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 3c, compare the black curve (most offshore sensor in Figure 3) with the red curve (most onshore sensor)).
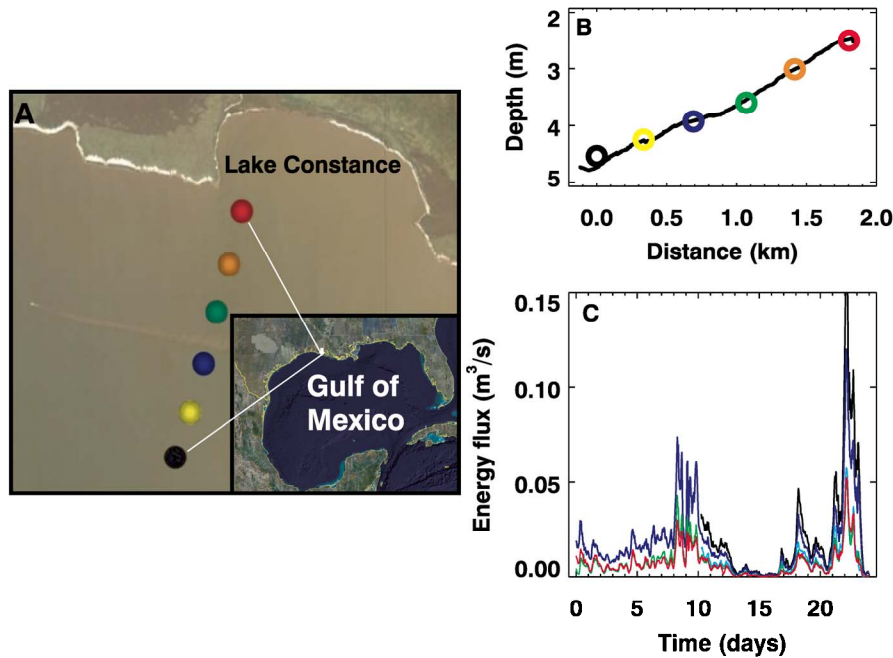

Figure. 3 (A) Sensor locations (colored symbols) superposed on an aerial photo of the Louisiana coast (inset shows location within the Gulf of Mexico). (B) Depth of the seafloor (curve, estimated from a shipboard survey 100 m west of the sensors) and locations of colocated pressure gages and current meters (symbols) versus distance from the deepest (black circle) sensors. (C) Energy flux (integrated over the frequency range 0.05 < f < 0.30 Hz) versus time (days since Mar 23, 2007). The black (distance = 0 km in B), blue (distance = 0.7 km), and red (distance = 1.8 km) curves are observed energy fluxes. The turquoise and green curves are energy fluxes predicted by the dissipative Boussinesq model at the shallowest sensor (distance = 1.8 km) initialized with observations at distances = 0 and 0.7 km, respectively. [Two plots show the locations of the 6 wave sensors that were deployed on a cross-shore transect extending from about 5- to 2-m water depth over a 2 km distance, and a third plot shows that the onshore decrease of energy density is predicted well by the numerical Boussinesq model.]

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The observed dissipation is a strong function of depth (Figure 4). 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.
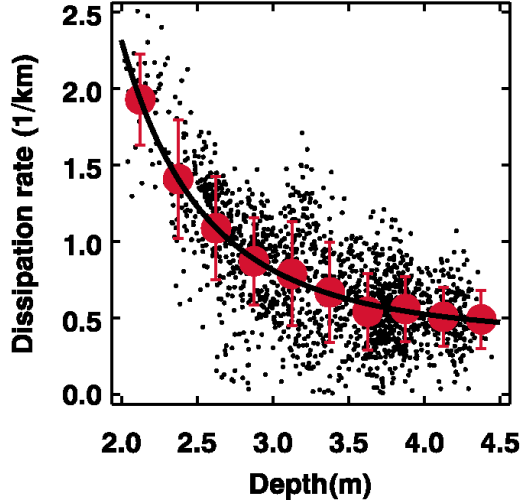

Figure 4. Dissipation rate versus water depth for the 24 days of data obtained during the pilot experiment in spring 2007. Significant wave heights at the most offshore sensor ranged from 0.1 to 1.0 m. The tide range was about 1 m. The black dots are individual 1-hr data runs, and the red circles are 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
[Dissipation rate decreases from 0.5/km to 2/km between 4.5 and 2.0 m water depth.]

An estimate of the frequency dependence of the mud-induced dissipation (Figure 5) 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.

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 5, 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 3) and 1.2 (blue symbol in Figure 3) km offshore of the shallowest sensor (red symbol in Figure 3), 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 3c).

Based on the estimated dissipation function (Figure 5) and the fidelity of the dissipative Boussinesq wave model (Figure 3c), 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.
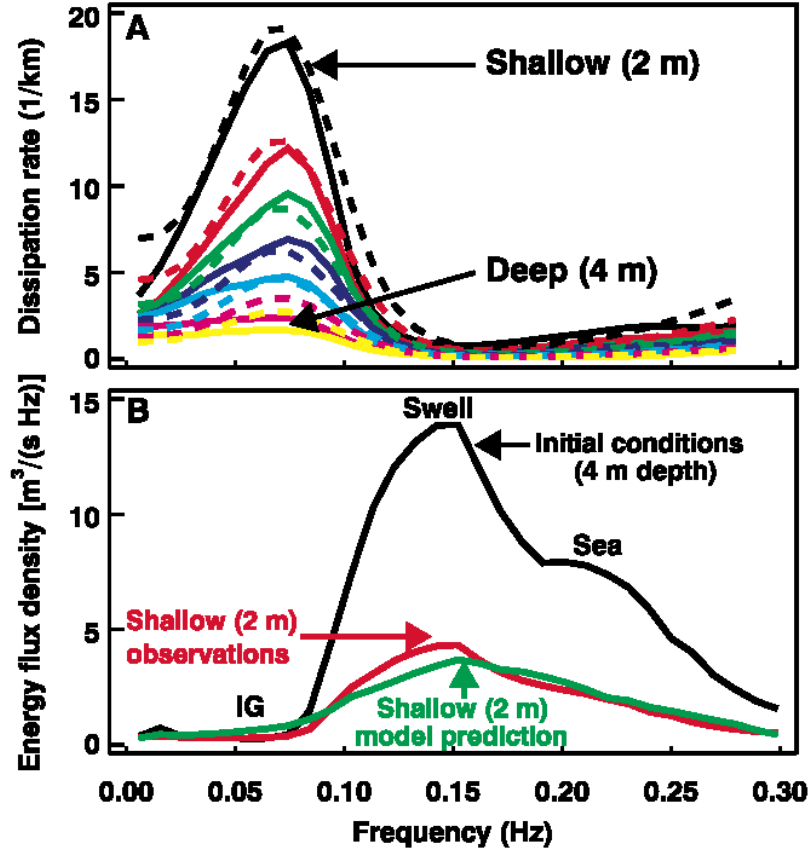

Figure 5. (A) Dissipation rate versus frequency. Solid curves are differences between the nondissipative Boussinesq model and the observations averaged over all 51-min-long runs in 0.3-m wide depth bins from approximately 4 (yellow) to 2 m (black) depth. The dashed curves are based on a least squares fit (of a Gaussian function combined with a quadratic) to the solid curves that accounts for the observed $h^{-3.4}$ depth dependence, and are given by:

$$\kappa = 31h^{-3.4}\left[6.2\exp\left\{-1/2\left((f-0.07)/0.03\right)^2\right\}\right]+2.5-27f+82f^2.$$ *(B) Energy flux density versus frequency observed at the deepest (≈ 4 m depth, black curve) and shallowest (≈ 2 m depth, red) sensors, and predicted by the dissipative Boussinesq model in 2 m depth (green). The model was initialized with the ≈ 1 m high waves observed in 4 m depth between 0300 and 0351 hrs CST Apr 14, 2007 (day 22 in Figure 3). [Dissipation increases with increasing frequency until about 0.075 Hz, and then decreases to nearly zero by 0.15 Hz. The curve is close to a 'bell shape'. Spectral levels of storm-induced swell waves decrease significantly as the waves propagate into shallower water across the mud, whereas infragravity energy levels remain nearly constant. The Boussinesq model predicts the observed decrease of swell energy.]*

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 4).

Although the dissipative Boussinesq model has high skill, 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 the spatially dense array of about 16 sensors deployed in winter 2008 (Figure 1). In addition, the 2008 observations include a wider range of conditions. Furthermore, in 2008 colleagues measured sediment properties with nearby tripods and shipboard surveys, allowing observations of wave dissipation to be combined with observations of the lutocline and of sediment characteristics.

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.

Our observations on the macrotidal flat are part of a larger effort to investigate and model physical, geological, and morphological processes on tidal flats. As part of the Tidal Flats DRI we are providing bathymetric surveys to all DRI team members, and ground truth (currents, water temperature, salinity) to colleagues investigating remote sensing techniques on tidal flats.

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 2008.

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

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