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Wave-Sediment Interaction in Muddy Environments: A Field Experiment

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This proposal is submitted pursuant to Broad Agency Announcement BAA #06-001

1. Summary

The long-term goal of the proposed work is to study and describe quantitatively the interaction between surface wave, currents and seabed sediments over a spatially heterogeneous littoral region that includes seabed areas of non-rigid, under-consolidated mud. The immediate goal is to participate in the planned Dalrymple-team MURI field experiment to study the effects of sediment state variability on wave propagation.

Technical approach. The Dalyrmple-team field experiment focuses on an area of western Louisiana where fluid muds (highly efficient in damping surface waves) are typical, associated with the progradation of a subaqueous mud clinoform delta at the mouth of the Atchafalaya Bay. However, on typical muddy coasts (e.g. Atchafalaya shelf) fluid mud layers are an episodic occurrence rather than a permanent defining characteristic. Muddy coasts also exhibit a spatially heterogeneous seafloor, with surficial sediments composed of different different mixtures of clay, silt, sand and particulate organic matter, with different degrees of consolidation, and characterized by widely different mechanisms of interactions with waves and wave-dissipation efficiency. Our wave observations to date on the Atchafalaya shelf show consistently strong swell damping, suggesting that other dissipation mechanisms might be active, in addition to fluid mud damping that will be the focus of the Dalrymple-team MURI field study.

The objective of our proposed work is to enhance the planned MURI field experiment and extend its scope by 1) increasing the shallow-water resolution of the Dalrymple-team observation array, and 2) expanding its physics and geographic coverage to the east (Atchafalaya shelf), into areas with different sedimentary characteristics.

During our previous, ONR-funded experiments on the Atchafalaya shelf (see Section 3) we have developed mobile instrument clusters and sampling methodologies designed to make high-resolution (time and vertical coordinate) observations of water column conditions (fluid, flow and suspended sediment properties)and seabed properties. The clusters have been deployed for multiple two-week cycles of continuous measurements, with 1 days turnaround between deployments for data downloading and instrument maintenance. The area and the range of processes covered by the MURI experiment will be extended by deploying the clusters in different along- and cross-shore configurations. A smaller "reference" (PUV sensor) cluster will be positioned to the east in a sandy environment to provide high-resolution comparative wave data. The proposed instrument system will have the unique advantage of producing synchronous, high-resolution observations of wave-current-sediment dynamics forced by the same atmospheric perturbation at locations characterized by different sediment types. The cluster deployments will be supported by seabed sampling during each two-week deployment to determine bed properties (e.g., grain size, rheology).

Anticipated outcome. The proposed work will provide high-resolution wave-current-sediment field data over heterogeneous sea beds of various degrees of consolidation (e.g. fluid muds, consolidated muds, fine sands). The mobility of the instrument clusters will facilitate observations particularly suitable for 1) model testing (e.g. cross-shore wave evolution), 2) understanding the effects of different sediment type on wave evolution, and 3) for developing a methodology for inferring bottom composition using remotely sensed wave data. The proposed work will generate an extensive observational database for additional model development, testing, and improvement. The observations will be made available on the WWW for all MURI researchers and will be published in peer-reviewed journals on a timely basis.

2. BACKGROUND

Limited laboratory and field observations show that waves propagating above muddy seafloors can be strongly dissipated. Laboratory experiments of wave propagation in the presence of a highly viscous bottom fluid-mud layer (Gade, 1958) showed about 80% wave energy loss over only 2.6 wavelength, for layer thickness of about 1.3 times the wave boundary layer thickness. In the field, Wells and Coleman (1981) observed more than 90% of the incident energy loss as waves propagated across the 20-km wide shallow mudflats off the coast of Surinam; (Mathew et al., 1995) report 95% of the incident energy was lost as waves crossed the 1.1 km-wide mudbanks off the coast of India. Mud-enhanced long-wave damping has been observed in water depths greater than 20 m near the Mississippi Delta (Forristall and Reece, 1985). By comparison, weaker dissipation effects (50% to 75% loss) have been observed across the much wider (100 km), sandy North Carolina shelf, attributed to the interaction of waves with bottom ripples (Ardhuin et al., 2002, 2003).

Direct Wave-sediment Interaction. Theoretical formulations of bed-induced wave dissipation are based on the assumption that wave motion reaches the bottom and interacts directly with bed sediments. A number of physical mechanisms for wave dissipation over muddy seabeds have been proposed over time, based on different models of sediment rheology. 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 Voigt solids (Jiang and Mehta, 1995, 1996), and non-Newtonian fluids (Chou et al., 1993; Foda et al., 1993). With the exception of liquefaction processes (Foda et al., 1993; deWitt, 1995), these models focus on a single, well-defined mud phase. The applicability of any of the models is constrained by properly matching the hypothesized dissipation mechanism to the actual sediment type and consolidation state.

The diversity of wave-sediment interaction mechanisms also suggests that the single, dominant-process approach should work if time/spatial scales of bed characteristics and the wave evolution are well separated. This is the case for a sandy beach: the physical properties of the bed on a sandy beach do not change significantly on the time scale of wave propagation – say, 10^2T or $10^2\lambda$, T and λ characteristic wave length and period.

Cohesive sediments, however, present the difficulty of evolving on a time scale comparable to that of wave evolution. Muds are sensitive to wave- and current-induced turbulence; the efficiency and characteristics of mud-induced wave damping depends 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 Shemdin, 1980; Shemdin et al., 1980; McPherson, 1980; Yamamoto and Takahashi, 1985; Lee, 1995). However, wave action liquefies bottom sediment by building up pore pressure and breaking the sediment matrix. The fluid-mud phase exhibits non-Newtonian characteristics at concentrations above ~5 kg/m^3, 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; Sheremet et al., 2005).

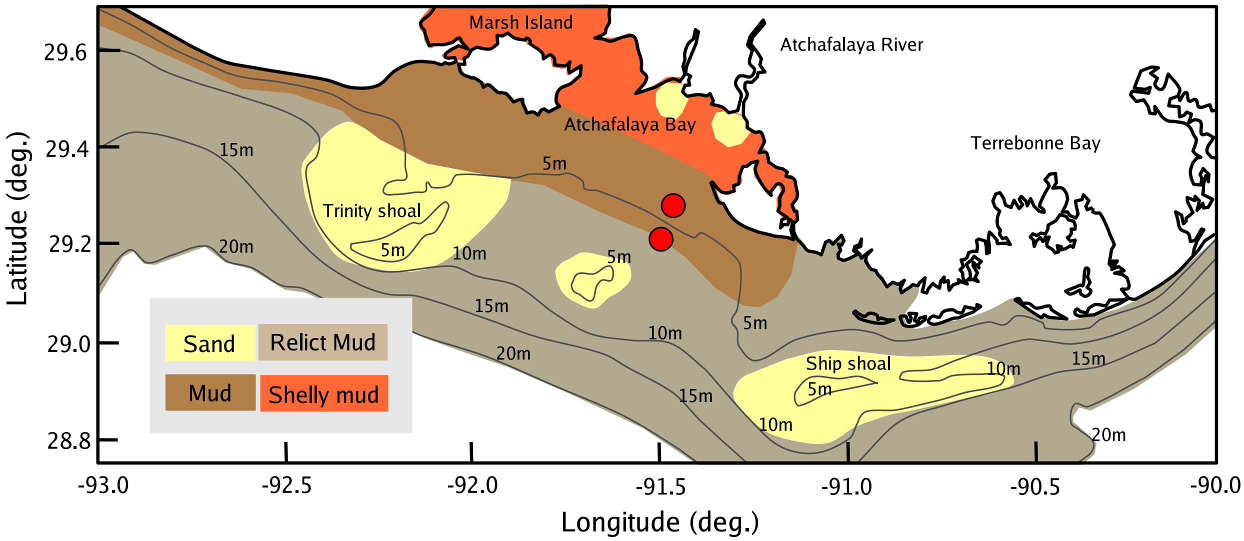


FIGURE 1. Facies map of the surficial sediments of the Atchafalaya inner shelf, Louisiana, USA (from Neill and Allison, 2005). Relict sediment units sometimes are mantled by thin (less than 20-cm thick), ephemeral modern mud. Red circles mark the location of tripods during the event of March 8-13, 2006 (Section 3).

Spatial heterogeneity of bed sediments, characteristic of the vast majority of littoral areas, adds another level of complexity to the problem of wave-sediment coupling, by introducing a spatial variation in the bed state, in addition to time variability. Figure 1 shows the general distribution of sediment type on the Atchafalaya inner shelf, Louisiana, USA.

Indirect Wave-sediment Interaction. On time/spatial scales comparable to those of wave evolution on a sandy beach ("short " scales, 10^2T or $10^2\lambda$), direct wave-bed interaction is arguably the dominant dissipation mechanism. However, many important cohesive-sediment littoral zones exhibit morphological characteristics that allow wave evolution and dissipation on much larger scales. At the widest point of the Atchafalaya shelf (Figure 1), the 10-m isobath is approximately 50 km offshore. Over such scales second-order, indirect interaction mechanisms can become important.

Surface waves interact resonantly with waves propagating at the water/mud interface (one surface mode can excite two non-collinear sub-harmonics at the interface, Hill and Foda, 1999; Jamali et al., 2003a,b). This suggests a path of energy transfer from surface to the soft bottom mediated by free and forced wave modes at the water/mud interface (Jiang and Mehta, 2000). Theoretical analysis (Jamali et al., 2003a,b), and laboratory experiments (Hill and Foda, 1999) using two fluids of different densities (not fluid mud) suggest this mechanism is possibly important.

A series of recent field experiments (Sheremet and Stone, 2003; Sheremet et al., 2005) on the Atchafalaya shelf (Figure 1) have raised questions about the possible role of surface-surface wave interactions in mediating short wave dissipation in cohesive sedimentary environments. The observations showed unexpected short-wave damping in areas with soft cohesive bed sediments, in contrast to normal (negligible dissipation) over areas with sandy bottoms. Later, sediment monitoring devices deployed at the same muddy site showed that strong spectrum-wide wave damping coincided with formation of a fluid-mud layer with sediment concentrations of over 10 kg/m^2.

On a typical sandy beach (slope $\simeq$1%) near-resonant three-wave interactions are known to cause significant energy transfers over a few wavelengths (Freilich and Guza, 1984; Elgar and Guza, 1985; Agnon et al., 1993; Herbers et al., 1995; Kaihatu and Kirby, 1995; Agnon and Sheremet, 1997; Herbers and Burton, 1997; Agnon and Sheremet, 2000 and many others). Nonlinear processes should be important over a 20-km wide, shallow (~5 m depth) muddy shelf. However, the combined effects of nonlinearities and frequency dependent damping on wave evolution has not been studied. Observed short-wave dissipation suggests that nonlinear energy transfer within the wave spectrum may be important, perhaps providing the coupling between the short- and long-wave spectral bands, allowing energy to flow toward long waves, where it can be efficiently dissipated via direct wave-bottom interaction. Numerical simulations based on nonlinear wave propagation models (Sheremet et al., 2005) are consistent with the field measurements.

3. Motivation and Previous Work

Fluid muds, arguably producing the most spectacular wave dissipation effects, dominate the western Louisiana coast due to rapid depositional events associated with the progradation of a subaqueous mud clinoform delta at the mouth of the Atchafalaya Bay ((Neill and Allison, 2005)) and along the adjacent muddy chenier coast shoreface ((Allison et al., 2000; Draut et al., 2005)). This area is the chosen site of the Dalyrmple-team field experiment.

The sedimentary structure of the Atchafalaya shelf, however, is more complex than its western chenier plain segment, with large adjacent patches of different sediment characteristics (see Figure 1), with a large-scale gradation of grain size from clay-rich, cohesive sediments in the west to silts and fine-medium sands to the east. Associated with winter frontal events on 3-10 day timescales, on this shelf fluid-mud layers are episodic occurrences with durations of about 12 hours and thickness < 30 cm. Our previous work suggests that the mechanisms of wave dissipation active in these areas have a higher degree of complexity, involving different sediment states, and, consequently, different wave-bed interaction mechanisms. The physics of these processes are not well understood.

As a part of the ONR-sponsored project “Coupled Dynamics of Waves and Fluid-mud Layers" (PIs Sheremet and Allison), two instrumented bottom tripods were deployed for over two months during Spring 2006 on a very flat section (mean gradient approximately 10^{-4}) of the inner Atchafalaya shelf, Louisiana (Figure 1). The instruments were deployed for 2 weeks at a time, with a turnaround time of a couple of days used for data downloading and cleaning of the instruments. A schematic and description of the clusters is given in Figure 3.

Figure 2 shows observations of current velocity and wave spectrum evolution during the passage of a cold front, from March 8 to 13, 2006, which generated fairly intense wave activity, with 2-m, 10-s swells. At that time, the instrument clusters were deployed (Figure 1) along the 5-m and 3-m isobaths, respectively, at a distance of approximately 10 km from each other. Wave spectrum evolution is typical for a frontal passage, with an initial short wave pulse (noon of March 8th) followed by the arrival early on March 9th of fairly long (for the area) and energetic swells. The currents (Figure 1C-D) follow a tidal cycle of shore-normal flows amplified by the storm-associated circulation. A strong (up to 35 cm/s) shoreward flow (toward NE, magenta) coincides with the onset of the storm. About the time of the arrival of the swells (typically late in the storm development, e.g. Sheremet and Stone, 2003), the direction of the flow switches to seaward

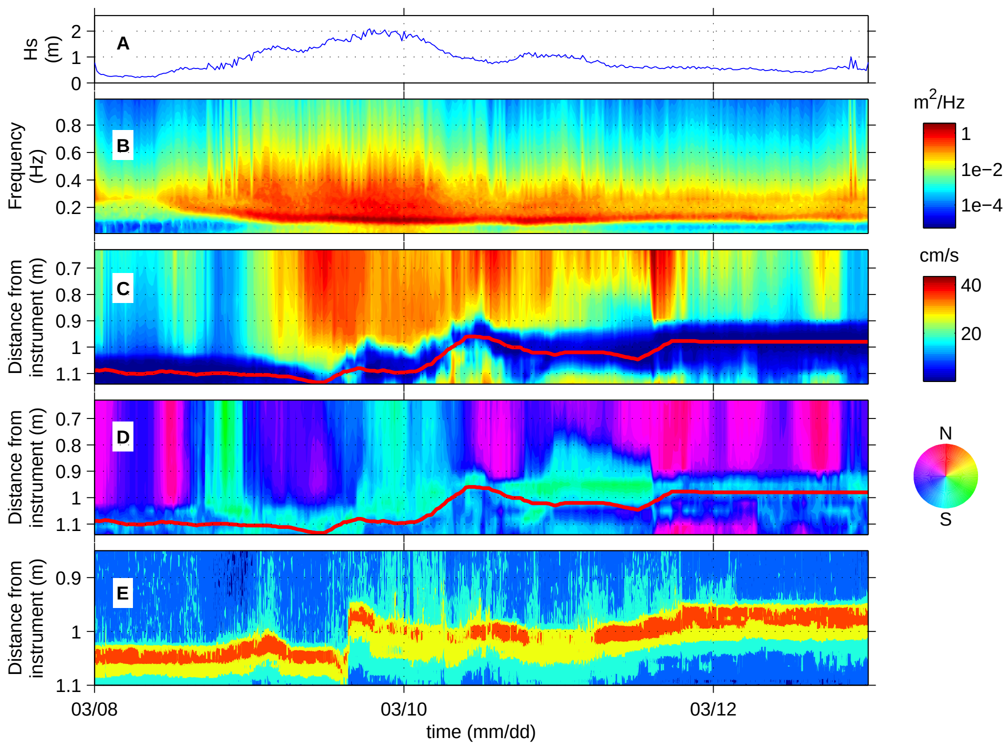


FIGURE 2. Current and wave observations vs. time during a frontal passage, March 8-13, 2006. A) evolution of significant wave height; B) Evolution of wave frequency spectrum; C) PC-ADP measurements (16-minutes average) of current velocity (instrument head is located at 1.12 m above the platform foot); D) Horizontal velocity direction as function of the distance from the instrument head. Directions shown here are flow directions (to, not from). The estimated position of the bed, defined by the position of the signal minimum separating near-bed horizontal velocity measurements from spurious bed reflections, is marked by a red line. E) Intensity of ABS reflected signal (arbitrary units) at the 3-m site. Maxima (yellow-red) indicate the position of the bottom.

(southward, green) and the cycle repeats itself once more during the storm with weaker current velocities.

The most remarkable feature in Figures 2C,D, and E is the change in the position of the bottom with respect to the instrument head. The observations show what appear to be weak bed erosion/accretion cycles. Overall, sensor-measured distance to the bottom decreases by 10-15 cm during this event. The return ABS signal at the 3-m site exhibits a very similar trend. Changes in the position of the bottom are likely due to the combined effect of 1) platform sinking due to local liquefaction of the muddy bed, and 2) burial by fluid mud advected from inshore, or formed by settling of suspended sediment (in the waning wave phase in the event). Liquefaction might play the most important part in the initial change, as the largest decrease in distance to bed (second peak of red line) is seems to be associated with the period of energetic swell activity (around noon March 11). Advection and settling probably become important in the wake of the storm, when wave and current activity die down. Once fluid-mud is formed, waves and the fluid-mud layer evolve in a manner consistent with previous observations (e.g. Sheremet et al., 2005): wave energy decays at all frequencies, turbulence also decreases and the layer grows (possibly due to settling of suspended sediment). The full dataset recovered for this is still being processed and analyzed.

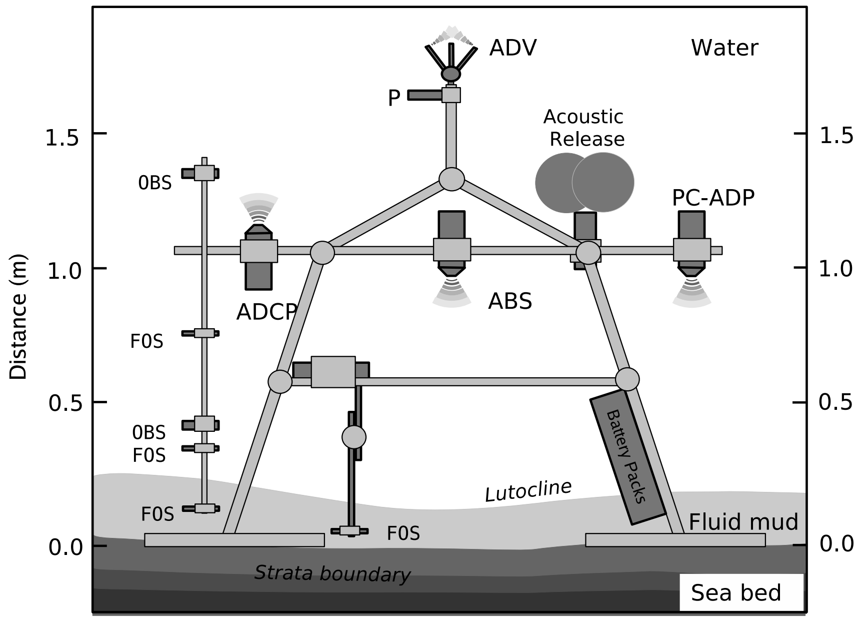
The above example illustrates the complexity of the coupled wave-current-sediment processes in an area of the Atchafalaya shelf that can be characterized as muddy but has decadal linear sedimentation rates of only 1-2 cm/y ((Neill and Allison, 2005)). It also demonstrates the potential of our experimental approach based on mobile instrument clusters providing coherent high-resolution measurements of near-bottom hydrodynamics and sediment motion, coupled with detailed wave information. Near-bottom current and sediment observations allow for effective modeling of local sediment transport processes and accurate diagnosis of sediment state. In turn, sediment information (e.g. fluid-mud layer thickness) together with very detailed wave data collected at several locations (in this example in the cross-shore) can be used for modeling wave evolution over beds of various sedimentary states.

4. Technical Approach

4.1. **Instrument Cluster.** Our observations on the Atchafalaya shelf support the hypothesis that cohesive sedimentary environments evolve on time scales comparable to that of wave evolution. Understanding the coupling of wave, current and cohesive-sediment dynamics requires *coherent observations* of all three types of processes, which in turn requires clustering a significant number instruments on the same platform.

During the ONR-sponsored project "Coupled Dynamics of Waves and Fluid-mud Layers" we have developed a methodology based on mobile instrument clusters. A schematic of the cluster is shown Figure 3. At a minimum, each cluster will include 1 ADCP, 1 ABS, 1 PC-ADP, 2-3 OBS units and independent pressure sensors. The instruments record continuously at wave-resolving sampling rates for the entire duration of the deployments (2 weeks in the case of the Spring 2006 experiment). At the end of each deployment, a one-day turnaround time is needed for cleaning, maintenance and data downloading, after which the clusters are ready to be redeployed. This approach allows for achieving some critical spatial coverage by moving the clusters, and seems to work particularly well in the Atchafalaya spring climate, when cold front outbreaks occur roughly once every two weeks.

The clusters is designed to maximize the vertical and temporal resolution of flow and sediment motion measurements throughout the water column, with moderate redundancy built-in for some of the highest priority measurements (e.g. pressure). Currents are monitored over the water column by acoustic Doppler profiling velocimeters. The downward-looking PC-ADP measures current velocities almost to the bottom, allowing detailed analysis of boundary layer dynamics and bed evolution (e.g. Section 3). The upward looking ADCP measures currents in the water column above the tripod. Suspended sediment concentrations (SSC) are monitored using a combination of point (OBS on each tripod) and depth-integrated (ABS and ADP/ADCP) measurements, independently calibrated using *in situ* samples obtained with peristaltic pump-bag samplers mounted on the tripods and with bottom sediments collected at the tripod sites (for large-volume laboratory calibration). The downward-looking ABS and PC-ADP units measure the motion of the fluid-mud interface. In-sediment conditions will be measured with the 700 kHz ABS, which can map the motion of the non-rigid seabed (stratal interfacial motion) to depths of about 50 cm below the seafloor.



Instrument	Target	Operation	Output
PC-ADP	Water	Sampling: 2 Hz Bin height: 0.02 m	u, v, w profiles
ADCP	Water	Sampling: 2 Hz Bin height: 0.35 m	u, v, w profiles
ABS	Fluid-mud layer Bed	Sampling: 80 Hz Bin height: 0.0025 m	SSC strata boundary, lutocline motion
ADV	Water column	Sampling: 2 Hz	p, u, v, w 1 point
OBS	Water column Fluid-mud layer	Sampling: 0.1-2 Hz Saturation: ~5 kg/m^3	1 point, SSC
FOS	Water column Fluid-mud layer	Sampling 0.1 - 2 Hz Saturation: ~100 kg/m^3	1 point, SSC

FIGURE 3. Schematic of a tripod showing a deployment configuration of the instruments. The table summarizes the capabilities and sampling schemes of the instruments. SSC is suspended sediment concentration, and P and UVW are pressure and horizontal and vertical velocity components. A conductivity-temperature sensor (not shown) is located near the ABS. The single FOS underneath the tripod is robot arm-operated. Not all the instruments shown will be deployed on every tripod.
Abbreviations: ABS (Acoustic Backscatter Sensor), PC-ADP (Pulse-Coherent Acoustic Doppler Profiler), ADCP (Acoustic Doppler Current Profiler), FOS (Fiber Optics Scatterometer), OBS (Optical Backscatter Sensor), ADV (Acoustic Doppler Velocimeter), and P (pressure sensor).

An additional automated profiling fiber optic scatterometer (FOS, Allison) system will be available. This unit, developed under ONR support, has one 400 μm diameter, multispectral backscatterance probe on a profiling unit that can map lutocline and sub-seabed sediment concentrations over an 80-cm vertical range. Three other FOS sensors can be deployed at fixed depths in concert with the OBSs. A single laser in-situ scattering and transmissometry (LISST-100X, Sequoia Scientific) unit is available for one tripod to look at aggregate (floc) grain size of suspended material in situ. This unit also provides an independent optical measurement of suspended sediment concentration and measures conductivity/temperature.

At this time ONR-funded instrumentation is available to outfit two complete instrument clusters. We request funds for building two additional large clusters and a smaller "reference" wave sensor (see below).

4.2. **Seabed Sampling .** Bottom tripod deployments will be supplemented with box coring at each tripod site at the beginning and end of each two-week deployment. Cores will be sub-cored using Plexiglas trays that will be X-radiographed to examine near-surface (<50 cm) sediment stratigraphy and event layer formation. Additional sub-cores will be sub-sampled onboard ship to collect sediments for grain size, bulk properties, geochronology using short-period radioisotopes (7Be, 234Th), and laboratory rheological experimentation.

The surficial sediment will be characterized by density, grain size settling velocity and rheology.

Density profiles (probably the most important state variable required) will be derived from in situ measurements of sediment concentration provided by robotic-arm FOS. Near bed SSC will be derived from acoustic (ABS, PC-ADP) and optical (OBS, FOS) measurements calibrated using in situ water and sediment samples. Basic SSC sampling (OBS) will be done at the same rate at three levels above the lutocline, and the FOS unit will provide sediment concentration information within the fluid mud layer. ABS data can also be used to estimate the position of the lutocline and concentration of the fluid mud layer. Density profiles of bottom surficial cores of up to 45 cm height will also be obtained using gamma-ray transmissometer in the UF laboratory , which has the lab facilities for this purpose.

Grain size will be measured with standard sand (automated settling column) and mud (Sedigraph, Coulter Counter) analysis methodology. Pumped, large volume water samples will be used to obtain sufficient suspended sediment to determine disaggregated grain size in support of the LISST measurements. Grain-size distribution of sandy material will be obtained in automated settling columns. Settling velocity of sand will be estimated from size. Settling velocity of silt/clay material (mud) will be derived from combining the acoustic backscatter strength from in situ ADV (or PC-ADP) to estimate turbulent diffusivity and in situ SSC (Kwon, 2005). LISST data will be utilized to examine aggregate grain size, providing floc parameters necessary to the estimates of settling velocities.

Our sediment sampling using box cores, will enable us to tie water column processes to seabed response, and will provide opportunities to directly examine seabed bulk, grain size and rheological properties. Sediment porosity will be calculated using wet and dry weights. Sediment samples will be used to measure relevant mud rheologic properties such as grain size, shear strength, etc, in the UF laboratory. The rheology of samples of fluid mud will be measured in a Bohlin Gemini HRNano rheometer using the controlled-stress mode (UF) (Jiang and Mehta, 1994, 1995).

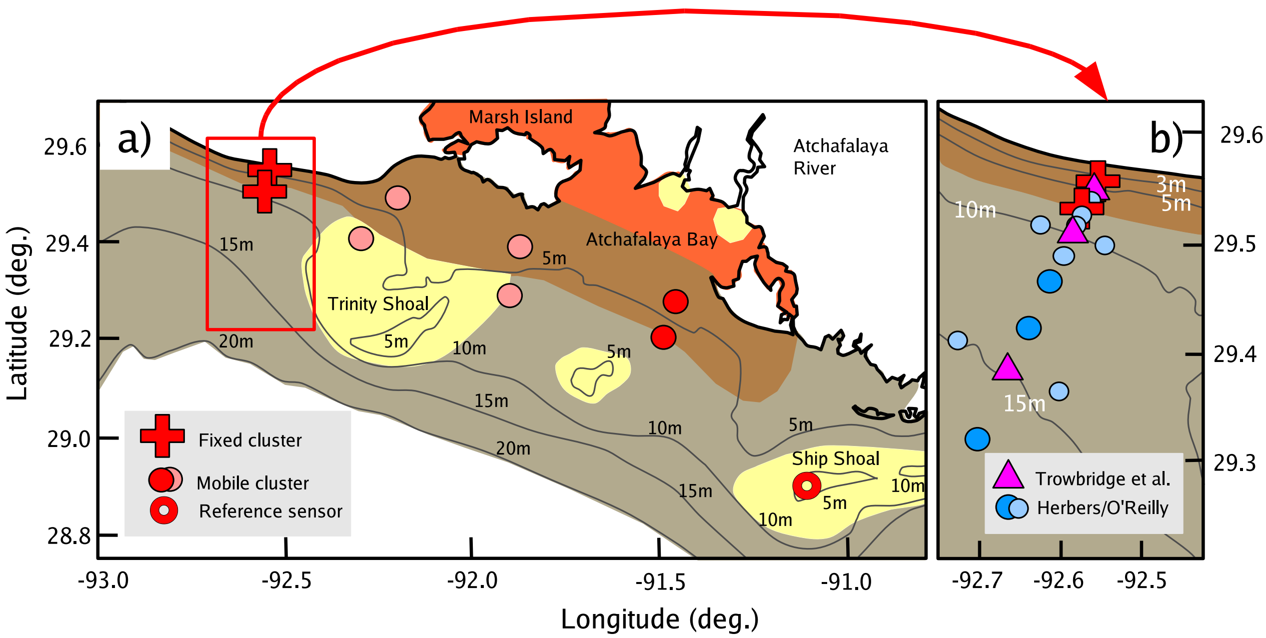


FIGURE 4. a) Plan view of the Atchafalaya shelf with the proposed deployment locations. b) Magnified area of the MURI experiment with the locations of the three MURI platforms (magenta triangles) and Herbers/O'Reilly PUV tripods (light blue circles) and buoys (dark blue circles). Elgar/Raubenheimer array, located between the 6- and 1-m isobaths, is too small to be reproduced here. The proposed location (6 and 4 m) of the two fully instrumented clusters (red crosses) will overlap with both Elgar/Raubenheimer and Herbers/O'Reilly arrays. The configuration shown for the mobile clusters is that of Spring 2005. Other possible configurations are shown (pink circles).

4.3. **Work plan.** The basic hypothesis of the proposed work is that wave damping by fluid mud is only one of several dissipation mechanisms that could be active on a muddy shelf. Much like any muddy coast, Atchafalaya shelf exhibits a gradation of sediment age, type and grain size, from soft muds in the west, to more consolidated mud and fine sands to the east. The planned Dalrymple-team MURI field experiment site covers only a small fraction of this diversity, both conceptually and geographically (rectangle in Fig4A, and Figure 4B). We propose to enhance the planned MURI field experiment by:

(1) Increasing the intermediate/shallow-water resolution of the Dalrymple-team observation array, and introducing other data collection instrumentation not present on the MURI array (e.g., LISST, FOS, ABS of different frequency);
(2) Expanding its physics and geographic coverage to the east (Atchafalaya and Terrebonne shelf), to examine wave dissipation in areas with different sedimentary and morphological characteristics.

Increased spatial resolution: The planned MURI instrument array specifies three instrumented platforms to be deployed in 2008 on the western Louisiana shelf at the 15-m, 10-m and 5-m isobaths (triangles in Figure 4B). Since soft muds are primarily confined within the 5-m isobath in this region, we propose to deploy two *fixed* clusters at additional locations, near the 6-m isobath and

4-m isobath (red crosses in Figure 4A-B). The exact locations of the clusters will be determined taking into account also other instrument arrays to be deployed. Preliminary discussions with collaborators (Herbers/O'Reilly and Elgar/Raubenheimer teams) suggested an arrangement which overlaps with their proposed arrays. This will complement their observations, focused exclusively on wave propagation processes, with observations of boundary layer wave-current-sediment dynamics.

Expanded coverage: To obtain regional-scale observations of wave evolution over a range of sediment types, water depths, and wave conditions, we propose to deploy two additional *mobile* clusters along several cross-shelf transects on the Louisiana coast, parallel to the fixed clusters deployed at the MURI site. The cross-shelf transect used in Spring 2006 (red circles) as well as other possible configurations (pink circles) are shown in are shown in Figure 4A. Such configurations can range from a few km to tens of km when covering from 3 to 10 m water depth areas and will provide observations of the evolution of the wave field over muddy, mixed mud and sand, sandy, and hard, relict mud seafloors. By comparing and contrasting wave evolution observed in areas with different sediments, the effects of seafloor-induced dissipation will be isolated from those of regional-scale processes (*e.g.*, wind, interaction with large-scale circulation). The high-resolution data collected will be suitable for both classical linear (second order) and nonlinear (higher order) spectral wave analysis, and will be particularly useful for testing direct and inverse wave models that estimate sediment characteristics from observations of wave evolution.

It has been suggested (Sheremet and Stone, 2003) that, due to the very mild bathymetry of the Louisiana shelf, useful comparisons can be made between measurements at locations as far apart as Atchafalaya and Terrebonne Bay. We propose to take advantage of this by deploying an additional wave sensor (ADCP or ADV) on Ship Shoal, west of Terrebonne Bay (red ring, Figure 4A) to provide reference data from a sandy environment.

The mobile clusters will be deployed from UNOLS vessels. The fixed shallow water cluster deployed at the MURI experiment site will require a vessel (Tulane University's R/V Eugenie) capable of deploying tripods in water depths too shallow for UNOLS vessels.

4.4. **Data Analysis and Modeling.** Nonlinear models for wave shoaling on sandy beaches are well developed and predict accurately the observed evolution of non-breaking waves (*Freilich and Guza* 1984; *Elgar and Guza* 1985; Agnon et al., 1993; Agnon and Sheremet, 2000 and many others). However, observations of ocean waves propagating long distances over a muddy bottom are scarce, and thus it is not known how mud-induced dissipation will affect the nonlinear energy transfers and the evolution of the energy spectrum. Models for the expected strong nonlinearity and damping in shallow water will be based on the mild-slope approach (Agnon and Sheremet 1997; Agnon and Sheremet 2000) which accounts for wave-wave and wave-bottom interactions (Sheremet et al., 2005b). Regardless of the specifics of the formulation, a phase-resolving, quadratic spectral model for shallow-water wave evolution has the form:

$$(1)\qquad \frac{dB_j}{dx} = iK_jB_j + \sum_{p,q} T_{j,p,q}\, B_pB_q\;\; \delta(\sigma_j - \sigma_p - \sigma_q),\ \text{with } B_j = a_j\, C_j^{1/2} \exp ik_jx,$$

where for mode j, $K_j = k_j + i\kappa_j$, with κ_j is the dissipation coefficient, a_j the complex modal amplitude, $|B_j|^2$ the modal energy flux, and $T_{j,p,q}$ the interaction coefficient depending on the frequency σ, wave number k and group velocity C of each mode in the triad (j, p, q). The Kronecker δ

symbol selects the interacting modes. The local water depth is h. Note that the dispersion relation typically changes in dissipative media, so that k_j is *no longer* given by the non-dissipative linear dispersion relation $\sigma_j^2 = k_j \tanh k_j h$ (e.g. Dalrymple and Liu, 1978).

To be useful for validating wave models like (1) the experimental data must allow for accurate estimates of

(1) modal energy flux amplitude B_j at several (at least 2) cross-shore locations, and
(2) modal complex wavenumber $K(\sigma)$ as a function of frequency , i.e. the modified wavenumber $k(\sigma)$and the dissipation rate $\kappa(\sigma)$.

The dataset provided by the proposed field experiment will allow for highly complex validation tests of the wave propagation part of models like (1). Continuous 2-week recording at 2 Hz time series of pressure and velocities will allow for high-resolution spectral and bispectral analysis, providing accurate estimates of the modal energy flux $|B_j|^2$ for model input and output comparison. The resulting spectral and bispectral estimates will be used to study of dissipation patterns in a wide frequency range, as well as the efficiency of nonlinear coupling and the combined effects of dissipation and nonlinear interactions on wave evolution in different frequency bands (Sheremet et al., 2005b). Synchronized, parallel wave observations (one at MURI site and one mobile), together with the reference sandy site wave sensor will provide unprecedented insight into wave dissipation as a function of different mud state (the clusters will collect mud state observations coherent with hydrodynamics measurements).

An essential element of the proposed work is the derivation of accurate estimates of the dissipation rate κ and wavenumber k, i.e. the linear dispersion relation. Based solely on the low horizontal resolution of the proposed array of instrument clusters, this is a challenging task.

We propose to develop a collaboration with sediment transport modelers (Hsu, University of Florida), to model the vertical distribution of sediment concentration. Our instruments will provide long high-resolution time series of both hydrodynamic parameters (PUVW) in the first 50 cmab with a vertical resolution of about 2 cm (e.g. Figure 2). The PC-ADP bin located highest above the bed (about 0.5 m), or the ADV (higher in the water column) will provide 2 Hz time series of free flow velocities which can be used for boundary layer forcing (Sections4.1). Sediment analysis will provide relevant mud rheologic properties such as SSC, grain size, shear strength (Section 4.2). The data will be used to validate the model. The model will then be used to "interpolate" and "extrapolate" the measurements into the near-bed section of the water column and provide values for parameters relevant to wave dynamics (e.g. thickness and viscosity of fluid mud layer). We are in a continuous dialog with Hsu to insure that our data collection approach addresses his needs.

Remote sensing offers a potentially more rapid and large spatial-scale assessment of wave dissipation phenomenon that is complementary to our small-scale, bottom monitored approach. The linear dispersion relation could be derived based on a combination of information about the position and the state of the sea bed, waves, and water column conditions produced by our instruments with estimates of wavenumber spectra derived from remote sensing, and inverse modeling. We are highly interested in collaborating with ONR-funded remote sensing research on this topic.

5. Timeline and Expected Results

We propose to deploy existing instrumentation at the MURI test site and elsewhere in Spring FY07, during the pilot experiment. We have included optional items in the budget for additional instrumentation. However, anticipating that requested instrumentation will not become available within the short time until Spring 2007 we will use existing resources and will borrow any additional critical instrumentation. Preliminary discussions have indicated that some instruments (PC-ADPs, and ADVs, Elgar/Raubenheimer, WHOI and Holland, NRL) will be available for February-March 2007. It total, anticipate that we will be able to outfit for the pilot experiment three clusters, and the reference sandy-site pod, even without the additional instrumentation requested in the present proposal. The availability of this borrowed instrumentation is problematic for the field effort beyond Spring FY07.

Summer and Fall 2007 will be used for the analysis of the data collected during the pilot experiment and for the preparations for the full one in Spring 2008. We will purchase the additional instrumentation requested as soon as funds are released. We propose to participate in the main field experiment in Spring 2008 with four clusters and the reference pod. FY09 will be used for data analysis and modeling. The proposed work will generate an extensive observational database for additional model development, testing, and improvement. The observations will be made available on the WWW to all researchers involved in the MURI Atchafalaya project. .

6. Collaborations

The entire scope and approach of the proposed work is based on a strong collaboration with the MURI field effort and other NRL and ONR-funded teams that will participate in the experiment.

The proposed work represents also a natural continuation and expansion of two ongoing research projects (Sheremet and Allison; and Sheremet, Stone and Kaihatu).

A close collaboration is planned with Holland's team of researchers from NRL Stennis. The proposed work is synergistic with, and reflects ideas formulated in, Holland's (NRL) "Heterogeneous Coasts" research initiative. Holland has provided significant support for our previous field experiments. Holland's team of researchers with UF student support (S. Jaramillo) will carry out in May 2006 a geological survey (grab samples, acoustic sediment classification system, and sidescan sonar) on the Atchafalaya shelf. The effort was coordinated with UF and Tulane to cover the locations where Sheremet and Allison deployed instruments during the ONR-supported field experiment (February-March 2006) and earlier (Neill and Allison, 2005) sites. The data will provide complementary information about the geology of the sites, in preparation for the work proposed here.

Modeling effort within the proposed work represents either a continuation and/or collaborative work with Kaihatu (NRL), Kirby (U Delaware), Hsu (U Florida). Hsu has developed a simplified two-phase formulation for fluid mud hydrodynamics that is computationally efficient and accounts for essential mechanisms such as fluid-sediment interaction and intergranular rheology. Field data collected during the proposed work will be used to calibrate the new fluid mud model. The calibrated model will be further used to study wave/mud interaction under various wave conditions and sediment properties.

7. Tasking

The project is a collaborative effort, with all three PIs involved in various degrees in all the activities of the project. Sheremet will manage the project and the UF component of the field effort, work on data analysis and modeling. Allison will plan and coordinate with UF the Tulane field effort to measure BBL and water column and sedimentological/geochronological properties of the bed. Allison will also serve as the overall field coordinator in Louisiana, supervising shipping, deployment, and retrieval of instrumentation. Mehta will collaborate in the planning of the field experiment and data analysis.

8. Budget Justification

Salaries include fringe benefits and university indirect costs. The project requires about 40 days of UNOLS ship (R/V Pelican) time for deployment, bi-weekly turnaround and retrieval of instruments.

University of Florida. We requesting support for two field technicians (Schofield and Adams) for the first two years (FGY07 and FY08) of the project, who will construct and participate in the deployment of the UF clusters and for a graduate student who will participate in the field experiment and data analysis and modeling.

Funds are also requested to purchase the necessary instruments to outfit an additional instrument cluster and supplement existing instrumentation (2 ADCPs, 1 PC-ADP, 1 ABS and 6 self contained OBS). We believe we will will be able to borrow some of these instruments (from NRL and WHOI) for the pilot experiment scheduled in 2007, but most will not be available for 2008. We also request funds for the purchase of a Bohlin Gemini constant-stress rheometer, which will be used for the lab analysis of sediments sample rheometrical properties (e.g. shear strength).

Domestic travel funds are also requested for travel to the site of the field experiment and UF-Tulane work meetings. Funds requested to support international travel to one international conference per year by two PIs (Sheremet and Mehta).

An ONR-funded Beowulf cluster will be used for all numerical applications (modeling and data analysis). We are requesting funding for the maintenance of the computer cluster (replacement parts) and the associated software (MATLAB and FORTRAN) licenses.

Tulane University. One month of summer salary per year is requested for the PI (Allison) who will participate in all phases of the project and coordinate the Tulane effort. We are requesting 5 mo of support for a technician (Duncan) for all three years of the project, who will construct and maintain the Tulane clusters and aid in the fieldwork and data processing. Funds are also requested for a graduate student who will participate in the field effort and utilize the results toward the thesis/dissertation for a graduate degree. Fringe benefits are requested at Tulane rates for PIs, technicians, and graduate students.

Optional funds are also requested to purchase the necessary instruments to outfit an additional instrument cluster (see above for list). Funds are requested for eight days of ship time in FY07 and FY08 (16) on the Tulane 60-ft vessel R/V Eugenie at a rate of $1,900/day. This vessel usage is for tripod deployment and recovery (and supplementary bottom sampling) at sites that are too shallow (<5 m deep) for UNOLS vessel access.

Travel funds are requested in all three years of the project for the PI and graduate student to attend conferences (AGU or equivalent) for presentation of results. These are requested as international funds to allow possible attendance at overseas meetings as well as domestic. Materials and supplies funds are requested for maintenance and minor equipment for the instrument clusters, disposable field supplies for coring, etc., and laboratory analyses for grain size, instrument calibration, etc. These funds will also be utilized for software licensing.

Tulane University overhead is requested at the federally negotiated rate of 49%.

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