WAVE-SEDIMENT INTERACTION IN MUDDY ENVIRONMENTS: SUBBOTTOM FIELD EXPERIMENT

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LONG-TERM GOALS

The long-term goal of the proposed work is to study and describe quantitatively the interaction between wave, currents and seabed sediments in shallow water over a bed characterized by heterogeneous, mud-dominated sediments.

This report includes the projects: Project 1: "Wave-Sediment Interaction in Muddy Environments: A Field Experiment", PIs Sheremet and Allison (ending Sept 30, 2010), Project 2: "A Device For In-situ Observations Of Muddy-bed Response To Waves", PI Sheremet, (ending Sept 30, 2010), and Project 3: "Wave-Sediment Interaction in Muddy Environments: Subbottom Field Experiment", PIs Sheremet and Allison (ending Sept 30, 2011).

OBJECTIVES

The objectives of Projects 1 and 3 were to participate in the MURI-led field experiment on wave-sediment interaction on the Atchafalaya shelf. The major field experiment efforts were in spring 2008 and 2010. in each experiment, a total of 5 tripods were deployed at locations fronting the Atchafalaya shelf and further westward along the Chenier Coast near Freshwater Bayou. The tripods carried instrumentation for coherent measurements of waves and near-bottom sedimentary processes, including vertical structure of velocities and suspended sediment concentration, and lutocline position and motion. During the field experiment of 2010 near Freshwater Bayou, the instrumentation was supplemented with a pore-pressure and temperature array (built at U. Florida, Project 2) to monitor the evolution of bed characteristics during storms (pore pressure) in addition to deposition rate and stratigraphy. The projects represent a coherent effort to obtain detailed field observations (previously lacking) about the processes associated with fluid-mud layer formation and bed response to wave events, necessary for effective modeling of wave propagation over muddy shelves, as well as the role of wave activity on the processes related to the development of subaqueous clinoforms.

APPROACH

Laboratory and field observations show that soft muddy bottoms and near-bed fluid mud layers can dissipate as much as 80% of wave energy over a distance of just a few wave lengths (Gade, 1957; Jiang and Mehta, 1995; deWitt, 1995; Hill and Foda, 1999; Chan and Liu, 2009; Holland et al., 2009; and others).

To explain this process, several theoretical models of wave-mud interaction have been proposed, involving a range of rheologies and dissipation mechanisms. Mud has been described as a viscous Newtonian fluid (Dalrymple and Liu, 1978; Ng, 2000; deWitt, 1995); visco-elastic solid (Jiang and Mehta, 1995); visco-plastic Bingham material (Mei and Liu, 1987; Chan and Liu, 2009); or poro-elastic material (Yamamoto and Takahashi, 1985). Other processes, in addition to viscous dissipation in the mud layer, have been hypothesized to contribute to wave damping, such as nonlinear interactions between surface and interfacial waves at the water-mud separation surface (Jamali et al., 2003). So far, most applications have given preference to the linear rheology (simpler, e.g., shear modulus or shear viscosity independent of strain-rate amplitude) over complex of nonlinear models (Chou, 1989; Chou et al., 1993; Mei and Liu, 1987).

However, theoretical and laboratory evidence suggests that mud and wave processes evolve on comparable time and spatial scales, and are strongly coupled. On one hand, the efficiency and characteristics of mud-induced wave damping depends strongly on mud state. Smooth and hard consolidated mud dissipate waves at a similar, or even weaker, rate than sandy bottoms(Yamamoto and Takahashi, 1985). Over non-Newtonian fluid mud (concentrations >5 kg/m3), wave dissipation is significantly stronger (Chou et al., 1993; Foda et al., 1993). On the other hand, even under mildly energetic waves mud state can change from consolidated to fluid over the duration of one storm (Chou et al., 1993; Foda et al., 1993; deWitt, 1995). The similar scales of evolution and the strong coupling suggest that the applicability of the above models depends on the state of the bed, which evolves during a storm in response to wave activity. While it has been hypothesized that wave-sediment coupling should be active in the field (Allison et al., 2000; Sheremet and Stone, 2003, and others), this coupling had not been observed directly prior to these experiments.

The basic hypothesis of the proposed work (supported by our ongoing field experiments on the Atchafalaya shelf) is that wave damping by fluid mud is only one of several dissipation mechanisms that could be active on a muddy shelf. The Louisiana coast 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 MURI field experiment site covers only a small fraction of this diversity, both conceptually and geographically. Projects 1-3 enhanced the planned MURI field experiment by: a) increasing the resolution of the MURI observation array in intermediate and shallow water, and b) 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.

During the field experiments two areas on the (extremely) wide Atchafalaya shelf were instrumented to monitor cross- and along-shore wave-current-sediment interaction: a) the subaqueous Atchafalaya clinoform (T1 to T4, Figure 1, in 2008), and b) in collaboration with the MURI experiment (2008-2010) on the beach at Freshwater Bayou (T5). The instruments were deployed for approximately two months and recorded continuously over two-week periods, with short instrument turnaround for offloading data, cleaning sensors and replacing batteries. The 2008 Freshwater Bayou platform (T5) was meant to support the data collection effort of the Elgar/Raubenheimer group (hydrodynamics and waves) with information about near-bed current-sediment dynamics. The instruments on T5 were configured to sample continuously for 4 weeks, coinciding with the activity of the Elgar/Raubenheimer cross-shore array.

All five platforms were equipped with instruments capable of high-resolution measurements of full water column hydrodynamics and near-bed sediment dynamics (Figure 2). Directional wave and current dynamics are monitored throughout the water column using an upward looking ADCP (at about 0.5-m vertical resolution), a downward looking PC-ADP which monitor near-bed flow (approximately 4-cm vertical resolution). A PUV gauge (co-located ADV and pressure sensor) are used for high resolution wave measurements. During our previous experiments we have developed a procedure to keep PC-ADP and the PUV recording continuously at 2 Hz for up to two weeks. Sediment dynamics (suspended and in-bed) are monitored with ABS (sediment layer dynamics), OBS-3 (relatively dilute suspended sediment), OBS-5 (high suspended sediment concentration), and LISST aggregate and discrete particle grain-size analyzer. Additional instrumentation, e.g., vertical arrays of ADVs (Sontek Hydra) was deployed during some of the 2-week experiment periods. The data collected during the field experiments of 2008 and 2010 (over 100 GB of data in total).

WORK COMPLETED

Two large scale field experiments were conducted in 2008 and 2010, in collaboration with the MURI team. Figures 3-4 show observations deep (7m; Fig. 3) and shallow water response during one of the largest frontal storm events observed in 2008 (storm from 6-9 March). Data presentation includes results of current (ADCP), wave (pressure sensor on the PC-ADP) and sea-floor evolution (PC-ADP and OBS) at tripods T1 and T3 during the frontal storm. Tripod T1 (Figure 3) is located on the foreset of the clinoform (in about 7 m of water). Tripod T3 is near the 4-m isobath, on the clinoform topset. Swell evolution shows an increase in wave dissipation during the storm. For example, the swell height peak on March 06 is approx. 0.85 to 1 m at T1 and T3 (Figure 3a and 4a), however, on March 7th the swell shows a decay from approx. 0.7 m at T1 to 0.45 m at T3. The event is associated with fairly energetic southward winds and currents which seem to be due to a superposition of low tide and the flushing of the coastal setup post-frontal storm passage. The sea-floor response can be inferred from the PC-ADP acoustic backscatter (Figures 3c-4c), based on the location of maximum intensity. While no significant changes are observed at T1 (7-m isobath), at T3 the position shows local variations (erosion/liquefaction and settling) of the order of 10-15 cm, with an overall drift (platform settling) of the order of centimeters. These results are consistent with previous observations (Jaramillo et al 2008; Sheremet et al. 2010) which suggest a significant change of wave dissipation regime during storms.

RESULTS

Evolution of bed sediment state: Our observations support the hypothesis that an effective coupling exists between surface waves and cohesive bed sediment. Based on acoustic backscatter records, several stages can be distinguished in the evolution of the bed: stiff mud at the beginning of the storm (density 1250-1450 kg/m^3 in surficial sediments from cores at the sites), liquefaction and rapid resuspension as the storm intensifies, followed by hindered settling (fluid mud formation).

Under energetic waves, the stiff bed softens, liquefies, expands, and mixes with water. Figure 6 illustrates the process, as recorded by the backscatter intensity of the PC-ADP. The mobilized surficial layer of sediment is then rapidly resuspended by near-bed turbulence (a burst-like process), significantly increasing the suspended sediment concentration (SSC) in the entire water column. In turn, increased SSC acts as a negative feedback that controls the further development of the process by dampening near-bed turbulence and suppressing mixing. As the storm wanes, decaying near-bed turbulence allows the suspended sediment to settle, leading to the formation of fluid-mud layers (Safak et al., in print; Sheremet et al., in review). Eventually, through dewatering and consolidation, the stiff bed state is reached again.

This sequence exhibits two interesting features: a) it has been seen repeatedly in our data, suggesting a predictable bed-reworking pattern; b) some stages seem to match some of the proposed theoretical models. For example, the mechanism for bed softening under waves loosely matches the threshold principle of the Bingham model: indeed, weaker storms do not appear to produce a resuspension burst.

Wave dissipation mechanisms: The dominant wave dissipation mechanism is wave-bottom interaction; the process is triggered by the reworking of bed sediment by waves. Wave dissipation typically increases during a storm, as the ber is softened by waves and sediment is re-suspended. The maximum of mud-induced dissipation (about 50% loss of incoming energy flux loss over approx. 4-km propagation distance) is attained typically at the end of the storm, when the bed sediment in a soft, under-consolidated state, likely close to gelling. However, nonlinear three-wave interactions play an crucial role in the interpretation of the frequency distribution of net wave dissipation (Figure 5). Neglecting the effect of nonlinearities leads to aliasing nonlinear energy transfers into dissipation effects, and distorts the representation of mud-induced dissipation.

Predictability of bottom state: One of the more intriguing questions raised by this study is the predictability of bed-sediment state. While accurate in-situ bed-state information is complex and hard to obtain, especially during storms, wave observations are comparatively simple and readily available for Navy operations, either through numerical forecasting or even remote sensing. Is it possible to predict the characteristics of bottom sediment processes (e.g., bed stiffness, presence of fluid-mud layers), based only on surface-wave observations?

However, the simple prolem "Estimate the present state of the bed using currently observed waves" is insufficiently constrained as it implicitly assumes that the bed is in a well-defined, non-evolving state that can be recognized by examining the wave dissipation rates. This is not usually true, as different bed rheologies might result in indistinguishable dissipation rates for waves.

The observed bed-reworking cycle (Sheremet et al., 2005; Jaramillo et al., 2008; Robillard, 2009; Sahin et al., in prep.), illustrated in Figure 6, suggests that the uncertainty could be eliminated if the prediction problem is reformulated as "Estimate the present state of the bed using the observed *wave history*."

Recent progress in numerical modeling of wave-mud interaction (Hsu et al., 2009; Torres-Freyermuth and Hsu, 2010; Safak et al., in print; Sheremet et al., in review), and the comprehensive field observations collected during the MURI field experiment, provide an excellent basis for addressing the complexities of modeling wave-mud interaction.

The inverse modeling approach of Rogers and Holland (2009), modified for using a nonlinear wave model that accounts for triad interaction (Agnon and Sheremet, 1997) was used to investigate this hypothesis. While the wave-sediment system is driven by waves, any particular evolution path it takes is determined through the internal coupling between wave and sedimentary processes. Different wave histories might therefore result in different bed-rheology evolution paths. These paths can be investigated and categorized using observations and numerical models. Because waves are the main driving factor, a coupled wave-sediment numerical model driven by wave evolution can be developed to forecast the state of bed sediment.

Ultimately, in an operational version, a wave model could be equipped with different wave dissipation modules, and the set of typical scenarios would provide an algorithm for swapping them.

IMPACT/APPLICATIONS

Much of the present and near-future Navy capability on predicting regional and nearshore processes assumes a sandy (non-cohesive) sedimentary environment. The present research enhances this capability by providing field data essential for model validations and by identifying processes and developing mechanisms which allow expansion into areas with significantly different characteristics.

RELATED PROJECTS

The project represents a convergence of several directions of research (near-shore wave modeling, cohesive sediment transport, the development of operational forecasting tools for nearshore circulation and waves, increase use of remote sensed information, etc) and etc), and collaboration efforts circumscribed by the MURI-lead effort to understand wave-mud interaction.

The project is coordinated in collaboration with other MURI related projects. The scope and approach of the present research builds on the strong, ongoing collaboration between U. Florida and U. Texas and U. Delaware, illustrated by a number of papers in print and in preparation. The field work was coordinated with with the MURI group of researchers, especially regarding observational data sharing (boundary layer and bed sediment characteristics, Traykovski, Kineke, Dalrymple), and other researchers that participated in the MURI-lead field experiment (Elgar, Raubenheimer, Allison). The work represents a natural continuation and expansion of the PIs ongoing research projects. The proposed work also builds on our previous collaborations on wave modeling with Kaihatu (Texas AM).

This research will also benefit from, and enhance, parallel research (Sheremet) funded under NOPP to improve existing operational wave-forecasting systems (WaveWatch III, SWAN, etc) by developing and implementing numerical modules for wave-mud interaction and nonlinear waves physics.

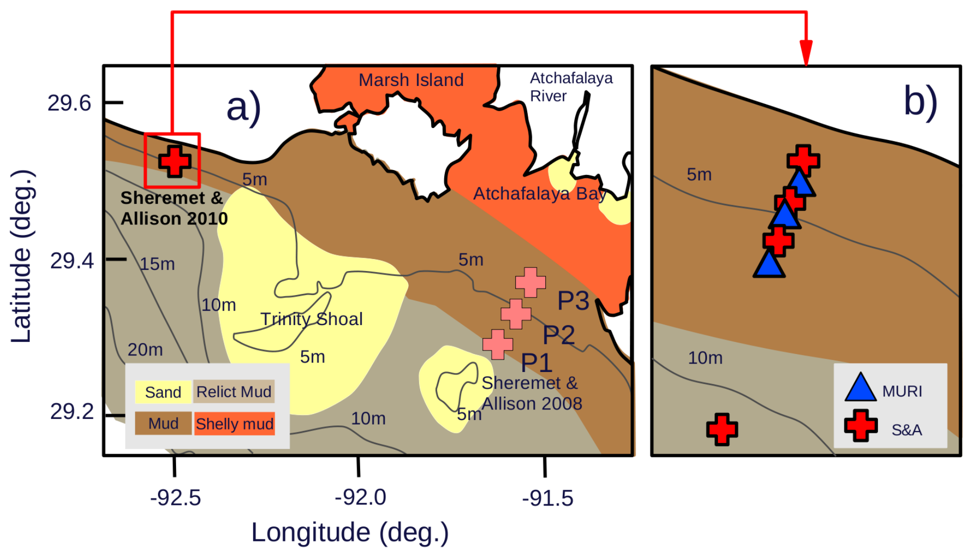


Figure 1: a) Plan view of the Atchafalaya shelf showing the location of the experiments conducted in 2008 (light red crosses, platforms P1-3) and 2010 (MURI) red cross. b) Magnified area of the 2010 MURI experiment with the locations of the three MURI platforms (blue triangles) and Sheremet & Allison array (red crosses). An ADCP and a pressure sensor were deployed farther offshore (approx. 18-m depth) to provide boundary conditions for wave propagation.

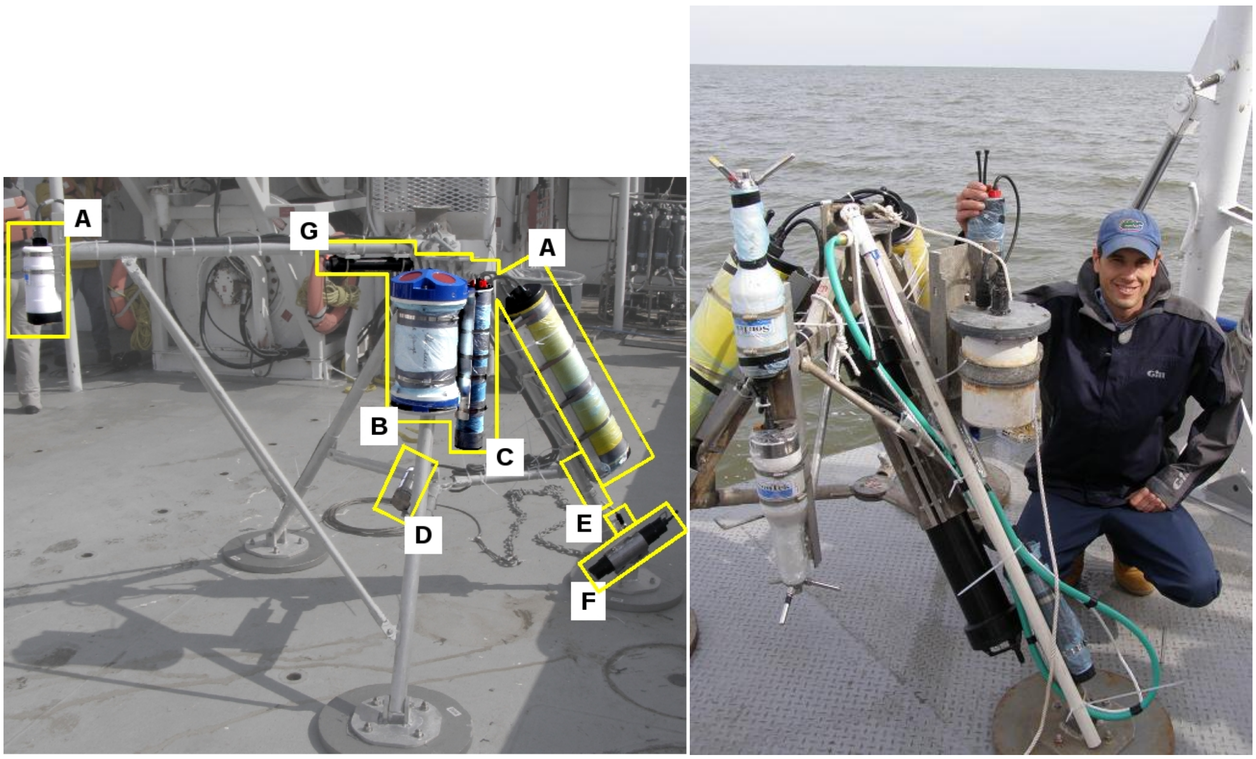
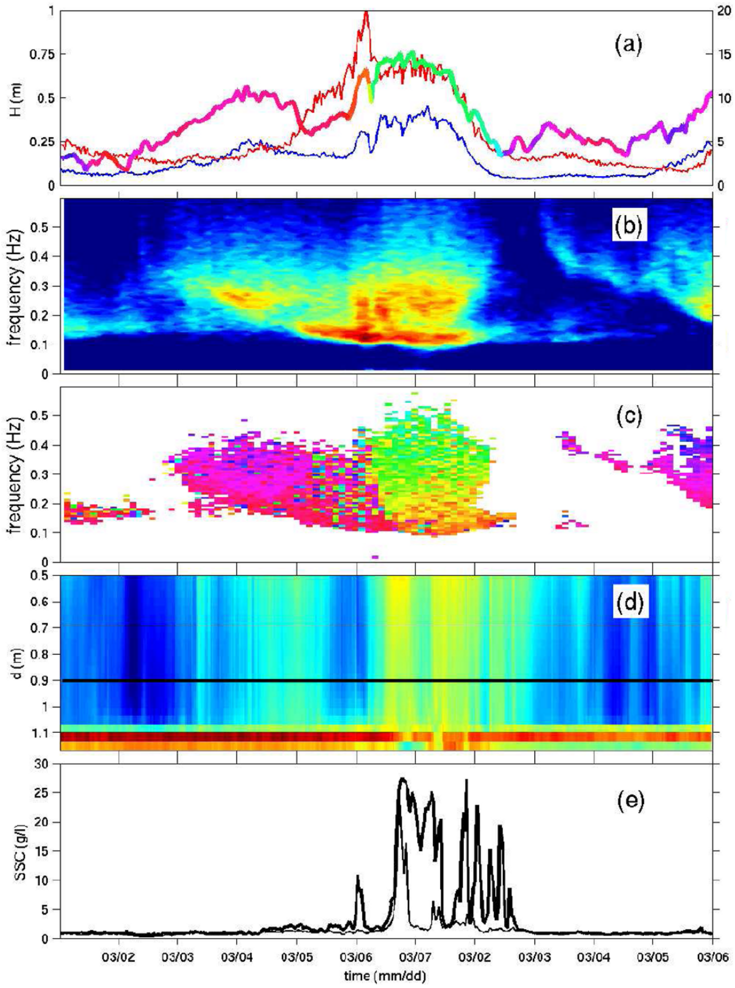
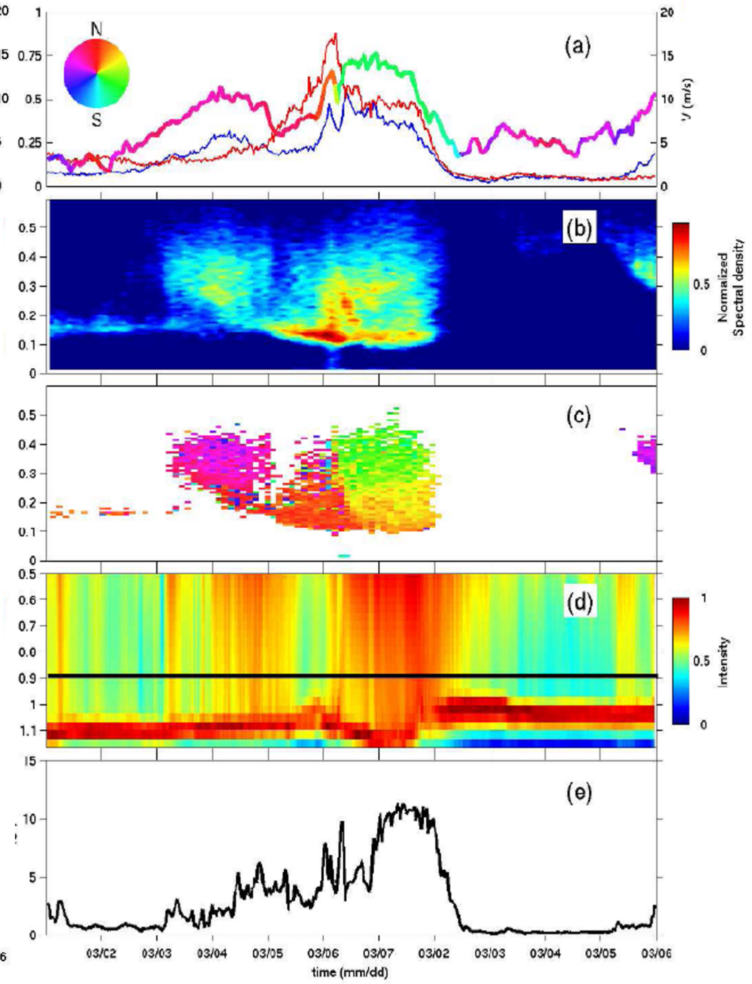


Figure 2: Right: An instrumented platform ready for deployment. Deployed instrumentation included downward-looking PC-ADP (A), upward-looking ADCP (B), an ABS (C), a CT probe (D), turbidity sensors – one OBS-5 (F), and two OBS-3 (E, one is partially visible behind the OBS-5). An acoustic pinger (G) is used to locate the deployed tripod. Left: the pore-pressure array ready to be deployed (Spring 2010) and his designer, Uriah Gravois (U. Florida graduate student). The black cylinder contains the electronics (Onset Computer Corporation Tattletale 8 Data logger, Persistor Memory Expansion (Paroscientific Pressure Sensor included in the housing). The long white cylinder is the probe, containing 4 sets of pore-pressure sensors and thermistors. Two Sontel Hydra ADVs and their battery canister (large white cylinder) can also be seen mounted on the tripod.



(a) P1 (29 deg 11.815, 91 deg 36.731 W), 7-m depth.



(b) P3 (29 deg 15.574, 91 deg 34.267W), 4-m depth.

Figure 3: Observations of waves and suspended sediment concentration (SSC) at two platforms (P1 and P3, see Figure 1). (a) Significant wave height of sea (blue, f>0.2 Hz) and swell (red, f≤0.2 Hz) bands. Multi-color curve shows the wind speed and direction. (b) Normalized spectral density of the sea surface elevation. (c) Peak wave propagation direction for each frequency band in the power spectrum (for both winds and waves, the directions indicate where the flow is toward, i.e., N means toward North). The wave directions are shown only for frequencies with spectral density above a lower limit. (d) Normalized acoustic backscatter records of the downward-pointing PC-ADP. The two lines indicate the locations of the sediment concentration gauges. (e) Suspended sediment concentration at 18 cm above bed (thick line) and 40 cm above bed (thin line).

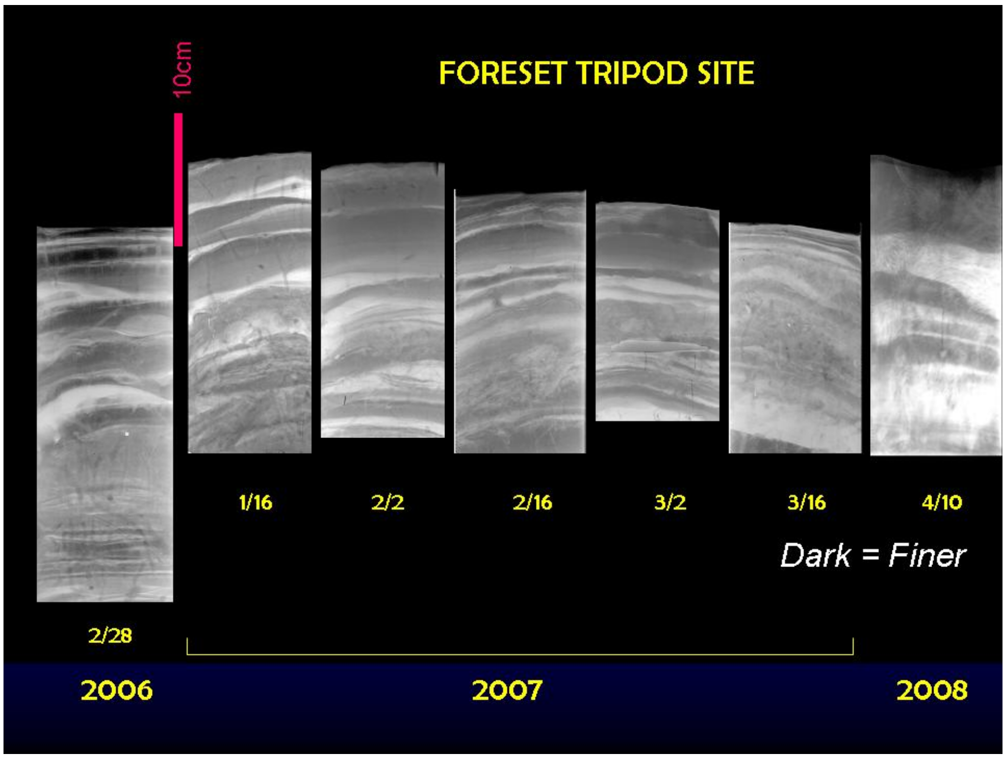
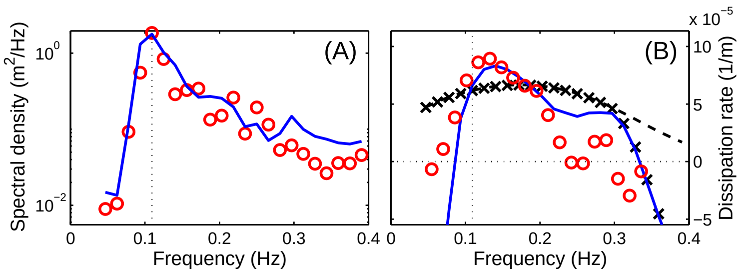
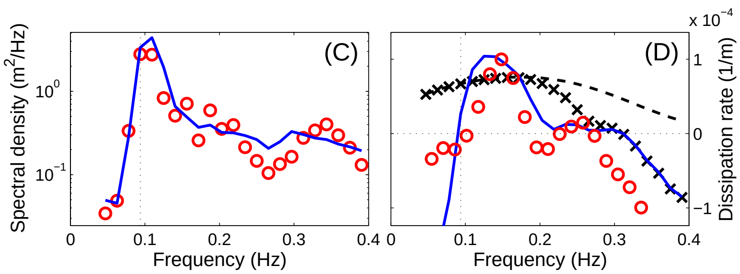


Figure 4: X-radiograph positives (dark=finer sediment) of upper seabed stratigraphic evolution at the foreset (T1) site taken from cores collected during two week turnarounds of the tripods. Only one date is shown in 2006 and 2008, while all the 2007 dates are shown. These data demonstrate the complex response of upper seabed stratigraphy to the multiple frontal storms experience yearly and are likely a combination of normal resuspension-deposition cycles (smaller events) and fluid-mud depositional events (larger events).



(a) March 10th 15:00 hrs



(b) March 10th 21:00 hrs

Figure 5: Example of numerical simulations of wave spectrum evolution (a,c) and dissipation rates (b,d) for the storm of March 10-11th 2006 (red – observations; blue – model; black dashed – mud-induced dissipation rate, Ng, 2000; crosses – net “linear” dissipation rate, including wind input, whitecapping, and mud-induced dissipation). The nonlinear transfer of energy from the peak toward higher and lower frequencies appears to increase the net dissipation of the spectral peak and results in a net growth in higher and lower frequency bands. In fact nonlinear interaction conserve energy.

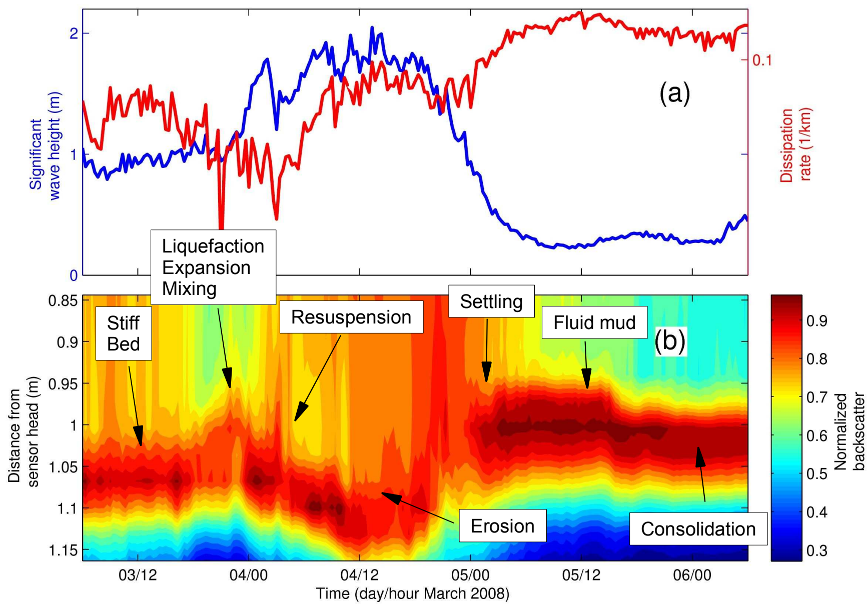
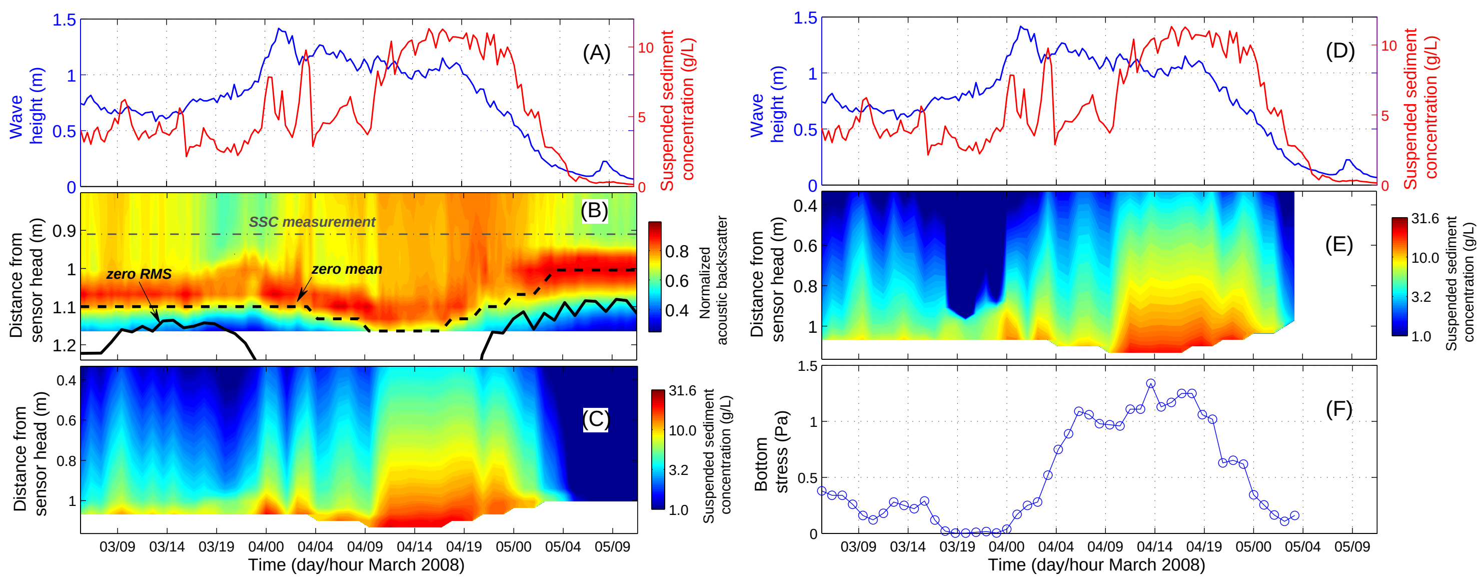


Figure 6: Typical evolution of a muddy bed during the March 03-05, 2008 storm (Platform P3 on Atchafalaya Shelf, Figure 3; Jaramillo et al., 2008; Safak et al., in print; Sahin et al., in prep.). a) Swell significant wave height (blue), and and swell dissipation rate (red). b) Vertical structure of PC-ADP backscatter intensity. High intensity backscatter values are indicative of high suspended sediment concentration.



(a) Analysis of PC-ADP backscatter: a,d) Significant wave height (blue), and SSC (red) observations at approx. 20 cmab (thin dashed line in b). b) PC-ADP backscatter intensity (zero mean current – thick dashed line; zero RMS velocity – thick continuous line). c) Estimates of suspended sediment concentration based on PC-ADP backscatter.

(b) Numerical modeling using the model of Hsu et al. (2009): D) Significant wave height (blue), and SSC (red); E) Numerical simulation of SSC evolution based on measurements of waves, currents, and mud characteristics, and F) bottom shear stress.

Figure 7: Example of reconstruction of SSC evolution based on the PC-ADP backscatter and numerical modeling. Observations collected at P3 on the Atchafalaya Shelf during the storm of March 03-05, 2008 (Sahin et al., in prep., see also Figure 6).

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