

USING WAVE-CURRENT OBSERVATIONS TO PREDICT BOTTOM SEDIMENT PROCESSES ON MUDDY BEACHES

Alex Sheremet¹ and T.-J. Hsu²

1. Civil & Coastal Engineering, 365 Weil Hall, University of Florida, Gainesville, FL 32611 phone: (352) 392-9537/1429, email: alex@coastal.ufl.edu
2. Center for Applied Coastal Research, Civil and Environmental Engineering, 205 Ocean Lab. University of Delaware, Newark, DE 19716; thsu@udel.edu

Grant Numbers

UF: N00014-10-1-0363, N00014-11-1-0269, N00014-12-1-0220;
UD: N00014-11-1-0272.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2012		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Using Wave-Current Observations To Predict Bottom Sediment Processes On Muddy Beaches				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Civil & Coastal Engineering, 365 Weil Hall, University of Florida, Gainesville,FL 32611				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

LONG-TERM GOALS

The proposed work investigates quantitatively the interaction between wave, currents and seabed sediments in shallow water over a bed characterized by heterogeneous, mud-dominated sediments. The long-term goal of is to develop an approach to characterize accurately the state of a muddy sea bed, based on minimal prior information about bed sediment, and remote observations of surface waves and currents.

OBJECTIVES

This work is a collaborative study between University of Florida and University of Delaware (PI: T.-J. Hsu, N00014-11-1-0272). The objective of the project is to investigate the possibility to predict bottom sediment processes using field data collected during the MURI Wave-Mud experiment. The observational data will be used to identify typical, *predictable scenarios* (sequences of states) of the evolution of bed rheology under energetic waves. In parallel, we propose to develop a fully-physical, high-detail pilot model for wave-sediment interaction. The pilot model will have two components: a numerical models for small-scale bottom sediment transport Hsu et al., 2009, and a stochastic nonlinear wave propagation (Agnon and Sheremet, 1997; Sheremet et al., 2010). The data will be used to validate the model and propose simplifications for operational implementations. These goals are aligned with all three major ONR research thrust areas: nearshore, estuarine and riverine processes; remote sensing of the coastal environment; and sediment transport.

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). Many 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).

While linear rheology (simpler, e.g., shear modulus or shear viscosity independent of strain-rate amplitude) is typically preferred in models over complex of nonlinear models (Chou, 1989; Chou et al., 1993; Mei and Liu, 1987), field observations provided by the “Sub-bottom Field Experiment” (N00014-10-1-0363) and previous projects suggest that complex rheologies might be quite relevant for applications. A definite sequence of stages of bed transformation (see Section Figure 5) emerges from the analysis Sheremet et al., 2005; Jaramillo et al., 2008; Robillard, 2009; ?; ?. Under energetic waves, the stiff bed softens, liquefies, expands, and mixes with water. This mobilizes a surficial layer of sediment that is then rapidly resuspended by near-bed turbulence (a burst-like process), significantly increasing the suspended sediment concentration 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, lead-

ing to the formation of fluid-mud layers. Eventually, through de-watering and consolidation, the stiff bed state is reached again.

The proposed work is based on the following hypotheses:

1. Wave history drives the evolution of the wave/bed-sediment system.
2. Surface waves and the muddy seabed evolve as coupled systems.
Wave-induced bottom stress and turbulence (that drive bed evolution) is balanced by mud-induced wave dissipation (that controls bed stress levels).
3. The evolution of the bed follows predictable cycles.

The wave-sediment system is driven by waves, but its evolution path is determined by the coupling between wave and sedimentary processes. Different wave histories might therefore result in different evolution paths for bed reworking. 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.

The concept of typical scenarios for bed-rheology evolution during storms provides the basis for investigating bed responses to waves activity. A pilot wave-mud interaction model is being build as a loosely coupled wave-mud interaction model based on two existing codes: the numerical model for bottom sediment transport (Hsu *et al.*, 2009), and the stochastic nonlinear shallow-water wave propagation (Agnon and Sheremet, 1997; Kaihatu *et al.*, 2007; Sheremet *et al.*, 2010). The ongoing work has three directions of research:

Data analysis: reconstruct the sequence of bed states in storms captured in the field observations and identify typical scenarios for evolution of bed rheology.

Model development: improve existing wave and sediment transport model and combine them into a coupled wave-sediment system.

Model validation: simulate the collection of storms, to investigate the limitations of the model, as well as to understand typical evolution patterns of bed rheology.

WORK COMPLETED

Field experiment and data analysis: The “Sub-bottom Field Experiment” project provided information about the evolution of the bed under wave action. In support the data collection effort of the Traykovski/Trowbridge group, the project deployed instrumentation to capable of high-resolution measurements of full water column hydrodynamics and near-bed sediment dynamics. An example of an instrumented platform is shown in Figure (Figure 2). To investigate the sediment mass exchange between the bed and the water column, a new method for estimating the vertical profile of suspended sediment concentration was developed and tested using field observations collected in 2008 and 2010 (Sahin *et al.*, 2012b).

Model development: Both numerical components of the pilot numerical model – stochastic nonlinear wave propagation (Agnon and Sheremet, 1997), and small-scale sediment transport (Hsu *et al.*, 2009), were implemented and thoroughly tested on field observations collected during the 2008 and 2010 field experiments (e.g., Safak *et al.*, 2010; Sheremet *et al.*, 2010; Sahin *et al.*, 2012a,b). A typical bed evolution cycle has been identified and studied in detail (e.g., Sahin *et al.*, 2012b, see next section). An analysis of bed reworking during all observed storms is ongoing.

When the fluid mud model was originally developed Hsu et al. (2009), there was no available information on the mud rheological properties and an empirical closure used in Le Hir et al. (2001) was adopted. Consequently, the rheology closure used in Hsu et al. (2009) only allows qualitative understanding on the effect of rheology on fluid mud transport. Without detailed the information on mud rheology, it is not possible to rigorously validate the numerical model and to develop predictive capability. Hsu and his visiting scholar Mr. Wen-Yang Hsu, a PhD student of National Cheng-Kung University, Taiwan, further investigated this issue (see below). Mr. Wen-Yang Hsu was awarded a prestigious 9-month scholarship from National Science Council of Taiwan. The new formulation on rheological closure will be used in the numerical model to simulate field experiment.

RESULTS

Field Experiments: Figure 3 shows an example of observations of waves and bed state response (this case: a frontal storm observed in March 2008). 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), based on the location of maximum intensity. At P3, bed elevation changes by 10-15 cm, consistent with previous observations (Jaramillo et al., 2008; Sheremet et al., 2010), and suggesting a significant bed reworking and wave-sediment coupling.

Wave dissipation mechanisms: An inverse modeling approach based on the nonlinear wave model developed by Agnon and Sheremet (1997) was used to investigate net wave dissipation (Sheremet et al., 2010, Figure 4). The dominant wave dissipation mechanism is wave-bottom interaction, and that the process is triggered by the reworking of bed sediment by waves. Wave dissipation increases during a storm, as the bed is softened by waves and sediment is re-suspended. Maximum of mud-induced dissipation (about 50% loss of incoming energy flux loss over approx. 4-km propagation distance) is observed at the end of the storm, over under-consolidated (gelling) bed sediment (Figure 5b, 8a).

The contribution of the nonlinear interactions is expressed in transfers from the peak of the spectrum toward higher and lower frequencies, resulting in an increased apparent dissipation of the spectral peak and net growth in the high and low frequency bands. This trend is not captured by the linear model, which suggests that neglecting the effect of wave nonlinearity can lead to aliasing nonlinear energy transfers into dissipation effects, distorting the representation of mud-induced dissipation.

Bed Evolution: Under energetic waves (Figure 5, P3) the stiff bed softens, liquefies, expands, and mixes with water. The mobilized surficial layer of sediment is then rapidly resuspended significantly increasing the suspended sediment concentration in the entire water column. Increased (SSC-induced) stratification controls the process by dampening near-bed turbulence and suppressing mixing (Safak et al., 2010; Sahin et al., 2012a). As the storm wanes, decreasing near-bed turbulence allows settling, and the formation of fluid-mud layers (Safak et al., 2010; Sheremet et al., 2010). Eventually, through de-watering and consolidation, the stiff bed state is reached again.

Vertical profile of suspended sediment concentration: The new method was proposed by Sahin et al. (2012a) for estimating the vertical profile of SSC based on the acoustic backscatter. The method was used to reconstruct the evolution of the suspended sediment mass (Figure 6b). In addition to flow velocity,

the SSC profiles can be used to constrain the fine-scale sediment transport model of Hsu et al. (2009). In turn, the model output provides quantities that are difficult to observe directly, such as the near-bed turbulent stress (Figure 6d). The numerical model suggests a threshold bed-stress value of 0.52-0.75 Pa for bed mobilization (Atchafalaya mud). This value is itself dependent of the wave activity history.

Bed hysteresis and mass balance: The storm cycle is analyzed in Figures 7 and 8 (?) in terms of the mass exchange between bed and the observable water column (the first approximately 1 mab). The transfer function that maps the the water-column mass flux (rate of suspended sediment mass change per unit time and unit horizontal area) onto the bed volume flux (rate of volume change per unit time and unit horizontal area) is the bed concentration. If during the event the bed concentration were constant and the evolution of the bed and water column sediment content were controlled strictly by bed/water-column mass exchange, the shapes of the two curves would be identical.

An estimate of the bed density derived by directly dividing the two fluxes is shown in Figure 8 (circles). The density has singularities for the zeros of the bed flux (i.e., corresponding to moments when the water-column mass changes but the bed position is constant). Because the estimate is also distorted by possible lateral advection of sediment, the periods with significant advective contribution (green segments, Figure 7 and 8) should be discarded. (Advection however, is estimated to contribute less than 10% of the suspended sediment mass.) During the event, the density of the bed stays consistently lower than the gelling density for Atchafalaya mud, but within ranges that cannot be described as a purely Newtonian viscous fluid. Toward the end of the event, the density increases steadily toward and past the gelling point, consistent with inverse modeling results reported by Sheremet et al. (2010).

Modeling of Wave-bed coupling: Field observations of the vertical structure of the flow velocity during the March 2008 storm suggest that a surficial bed layer as thick as 20 to 30 cm oscillates with the waves (maximum RMS horizontal velocity observed during the most active period is of the order of 20 cm/s) while also sliding down-slope with a mean velocity of the order of 5 cm/s (similar to that observed by Jaramillo et al., 2008). The fact that wave-induced oscillations of the bed (which in turn contribute to wave dissipation) are associated with high-density mud layers suggests that complex, nonlinear mud rheologies (visco-elastic/plastic or Bingham type) might play a role in modeling wave-bed interaction (mud-induced wave dissipation, and wave -induced bed-reworking).

Most numerical model of wave-mud interaction lack of detailed model-data comparison, especially concurrent validation of free-surface damping rate and velocity profiles in the mud layer. As part of his PhD study, Mr. Wen-Yang Hsu has carried out a comprehensive series of laboratory experiments on wave propagation over a bottom mud layer (kaoline mud). In addition to the surface wave field and bottom velocity profiles in the mud layer, detailed rheological properties (viscosity and yield stress) of the kaoline mud are also measured via a rheometer. Measured rheological properties were used in the 2DV numerical model of wave-mud interaction (Torres-Freyermuth and Hsu 2010), which solve mud transport and nonlinear wave propagation, to simulate the flume experiments and demonstrate good agreement between the model-predicted and measured wave shapes and dissipation. Experimental data, rheology data, linear model of Dalrymple and Liu (1978), and the nonlinear model of Torres-Freyermuth and Hsu (2010) were adopted to carry out forward and backward modeling of wave-mud interaction. Measured rheology of kaoline exhibits hybrid properties of Bingham and pseudo-plastic fluid. Moreover, measured time-dependent velocity profiles in the mud layer revealed that the shear rate under wave loading is highly phase-dependent. Measured shear rate and rheological data allow for back-calculating the time-dependent viscosity of the mud layer under various wave loading, which also fluctuates up to one order

of magnitude during one wave period. However, the resulting time-dependent bottom stress was shown to fluctuate only within 25% of its mean. Measured wave-averaged bottom stress was correlated with wave damping rate in the intermediate wave energy condition.

Commonly adopted constant viscosity assumption was then evaluated via linear and nonlinear wave-mud interaction models. When driving the models with measured wave-averaged mud viscosity (forward modeling), wave damping rate was generally over-predicted for low wave energy condition. On the other hand, when a constant viscosity is chosen to match the observed wave damping rate (backward modeling), the predicted velocity profiles in the mud layer are not satisfactory and the corresponding viscosity is lower than the measured value. These discrepancies are less pronounced when waves become more energetic. Differences between the linear and nonlinear model results become significant in low energy condition, suggesting an amplification of wave nonlinear effect due to non-Newtonian rheology. In general, the constant viscosity assumption for modeling wave-mud interaction is only appropriate for more energetic wave condition. A manuscript summarizing our main finding was submitted for publication.

Bed Sediment Processes: 1D vs. 3D Modeling Observations and numerical simulations (Sheremet et al., 2010) show that the various transient states of the bed during this reworking cycle are relevant for wave dissipation processes (Dalrymple and Liu, 1978; Mei and Liu, 1987; Maa and Mehta, 1990; Jiang and Mehta, 1995)

The process of sediment mobilization through bed reworking by hydrodynamics suggests that the seabed might play the role as a sediment source. This alternative was investigated by Safak et al. (2010); Sahin et al. (2012a,b), using field observations collected during the ONR-supported MURI wave-mud experiments of 2008 and 2010. In their preliminary analysis, Sahin et al. (2012b) used the 1D vertical model developed by Hsu et al. (2009). They note that the sediment balance is typically dominated by the mass exchange between the bed and the water column, with the important exception of water fronts passing over the observation site, likely associated with of freshwater plumes originating from the nearby river. The fronts produce a transient lateral (horizontal) convergence of sediment-flux (Figure), that cannot be captured by a 1D vertical model. Sahin et al. (2012b) hypothesize that water fronts are shore-duration processes, and overall the balance remains 1D, even when the plume passes over the site.

The apparent contradiction between the good performance of 1D models and the existence of strong-but-transient 3D processes such as fronts pose an important problem for sediment transport: What are the dominant sources of sediment on a shallow shelf, and under what conditions are they active? The issue is important for modeling and prediction, obviously, because 1D modeling is lighter/faster, and *local* – i.e., requires only knowledge of the local flow/sediment/bed conditions. However, 1D modeling is predicated on the assumption of non-essential horizontal flux convergence.

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.

One of the direct implications of the present research is the developing the foundation for the development of a coupled hydrodynamic-seafloor prediction model for muddy environments.

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 near-shore 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 field experiment 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 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 also benefits from, and enhances, 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.

The bottom boundary layer fluid mud modeling component of the proposed work also benefits from, and enhances parallel research (Hsu) funded by ONR to develop multidimensional, turbulence resolving model for fine sediment transport driven by waves and tidal currents.

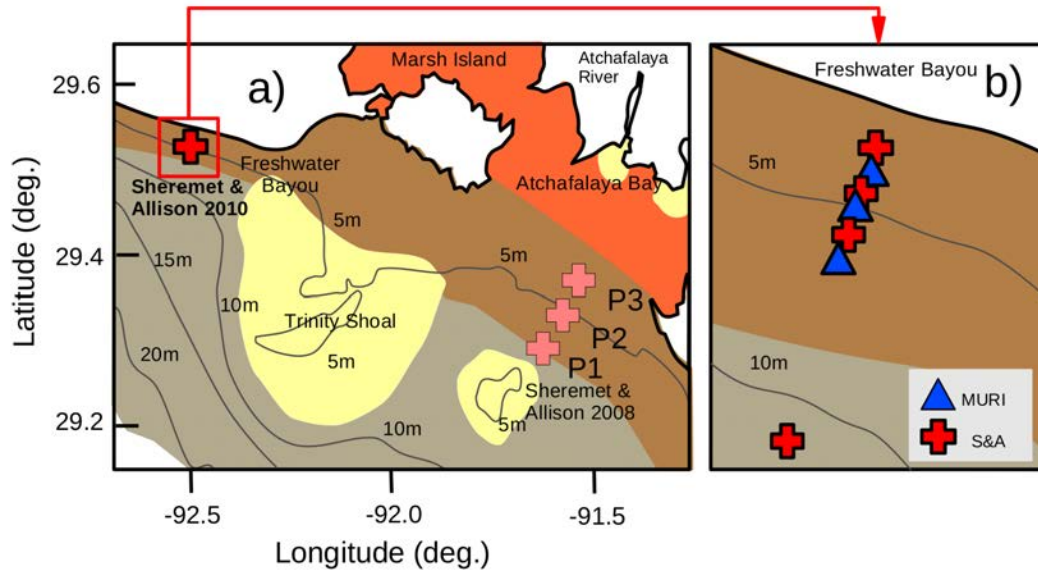


Figure 1: a) Plan view of the Atchafalaya shelf showing the location of the experiments conducted in 2008 (light red crosses, platforms P1-3) and 2010 (MURI) red cross. b) Magnified area of the 2010 MURI experiment with the locations of the three MURI platforms (blue triangles) and Sheremet & Allison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

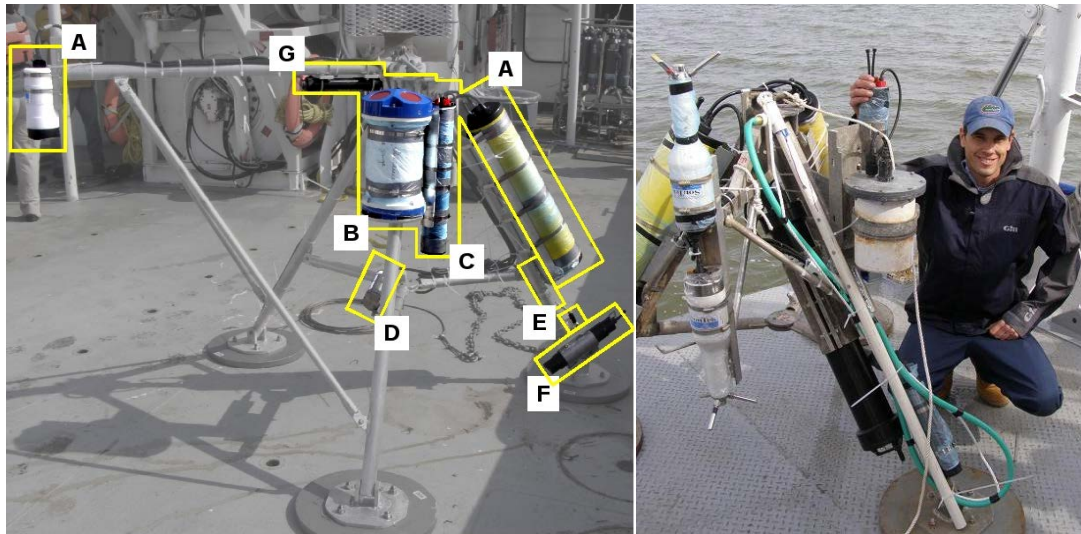
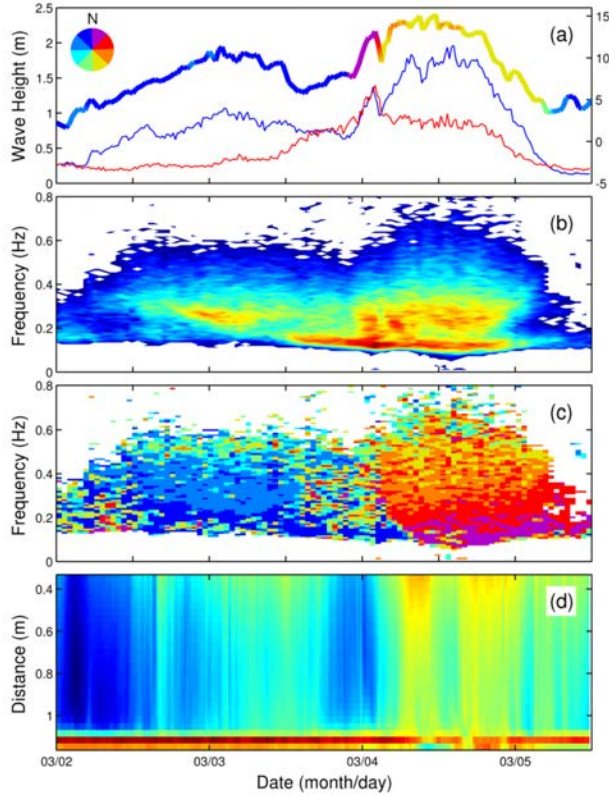
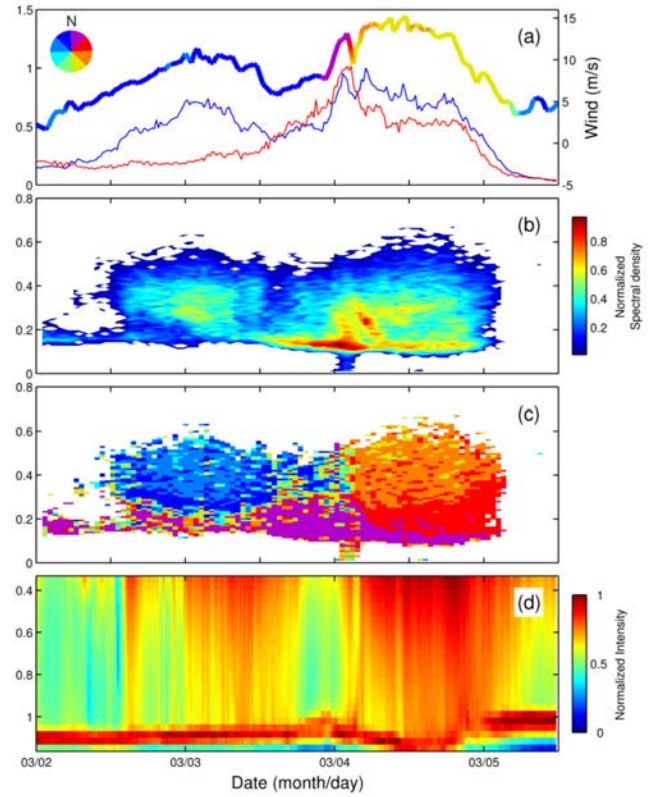


Figure 2: Left: An instrumented platform. Instrumentation includes a PC-ADP (A), an ADCP (B), an ABS (C), a CT probe (D), turbidity sensors one OBS-5 (F), and two OBS-3 (E, partially visible behind the OBS-5), and an acoustic pinger (G). Right: Pore-pressure array ready to be deployed (Spring 2010) and his designer, Uriah Gravois (U. Florida graduate student). Black cylinder contains electronics (Onset Computer Corporation Tattletale 8 Data logger, Persistor Memory Expansion (Paroscientific Pressure Sensor included in the housing). The white cylinder is the probe, (4 pore-pressure/thermistors). Two Sontek Hydra ADVs and their battery canister (large white cylinder) can also be seen.



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



(b) P3 (29 deg 15.574, 91 deg 34.267 W), 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, $f \leq 0.2$ 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 some “significance threshold” (arbitrary). (d) Normalized acoustic backscatter records of the downward-looking PC-ADP.

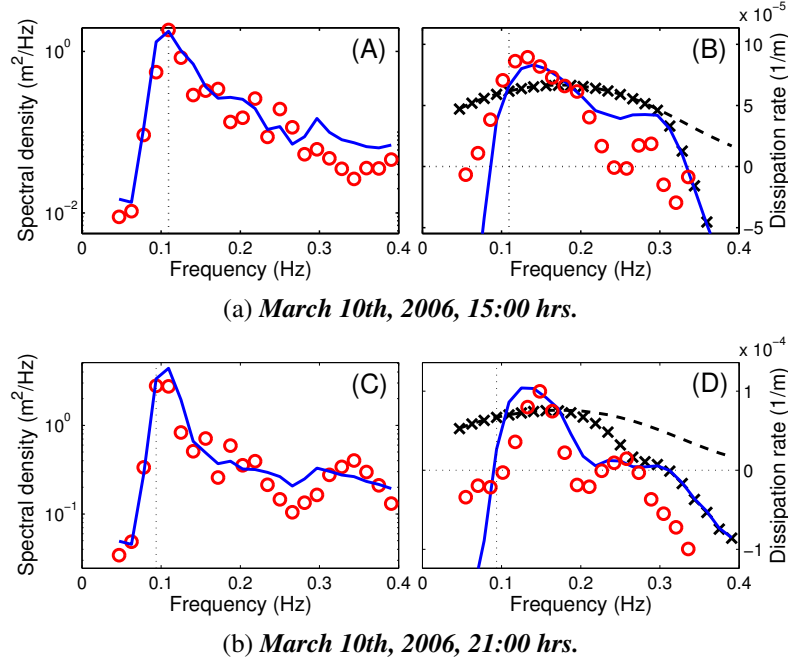


Figure 4: Example of numerical simulations of wave spectrum evolution (a,c) and dissipation rates (b,d) for the storm of March 10-11th 2006 (red – observations; blue – model; black dashed – mud-induced dissipation rate, Ng, 2000; crosses – net “linear” dissipation rate, including wind input, white-capping, 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 net growth rates for higher and lower frequency bands. Nonlinear wave-wave interaction conserves energy, therefore it does not contribute to the bulk (frequency integrated) wave dissipation/growth.

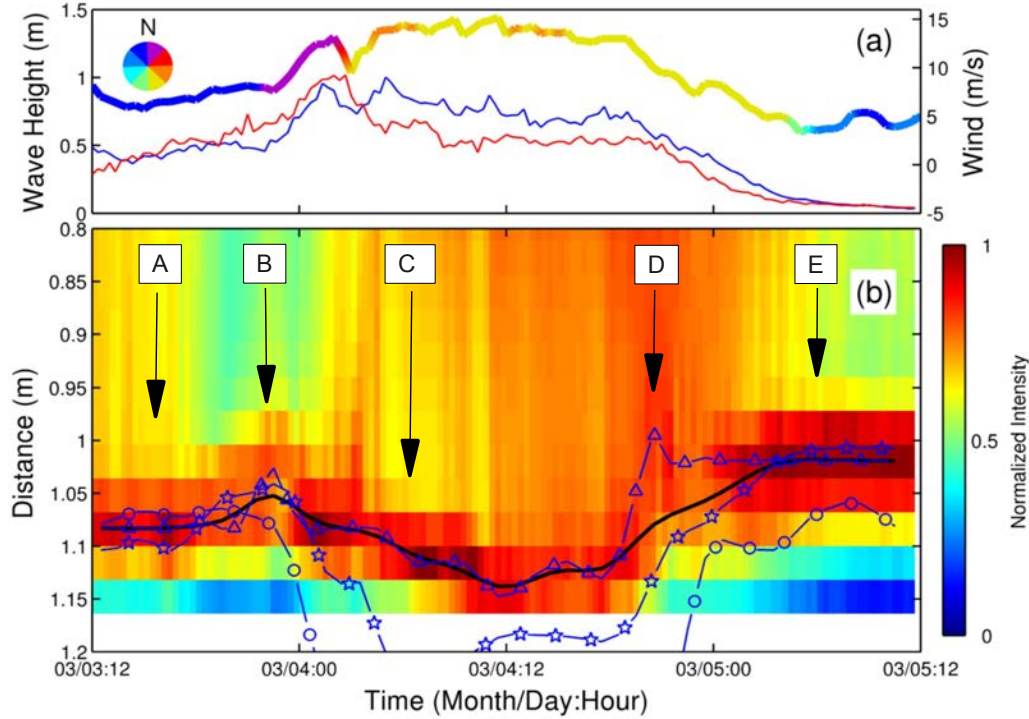


Figure 5: Analysis of PC-ADP backscatter showing a 20-30-cm thick surficial layer of the bed oscillating and sliding down-slope during the storm. a) Significant wave height (blue: short waves, red: swell); and wind speed and direction (color code indicated the direction the wind blows toward).

b) Normalized PC-ADP backscatter intensity. The lines represent the location of: maximum backscatter intensity (triangles); zero mean horizontal velocity (stars), and zero RMS horizontal velocity (circles). The continuous thick line is a smoothed estimate of the bed position. A surficial bed layer of approximately 20-30 cm oscillates with the waves and slides down-slope. Arrows mark the hypothesized stages of bed evolution: (A) solid bed; (B) breaking of the bed matrix and water absorption (liquefaction/fluidization/expansion); (C) bed erosion; (D) settling and bed accretion; (E) formation of fluid muds. The process is followed by eventual de-watering/consolidation (not shown).

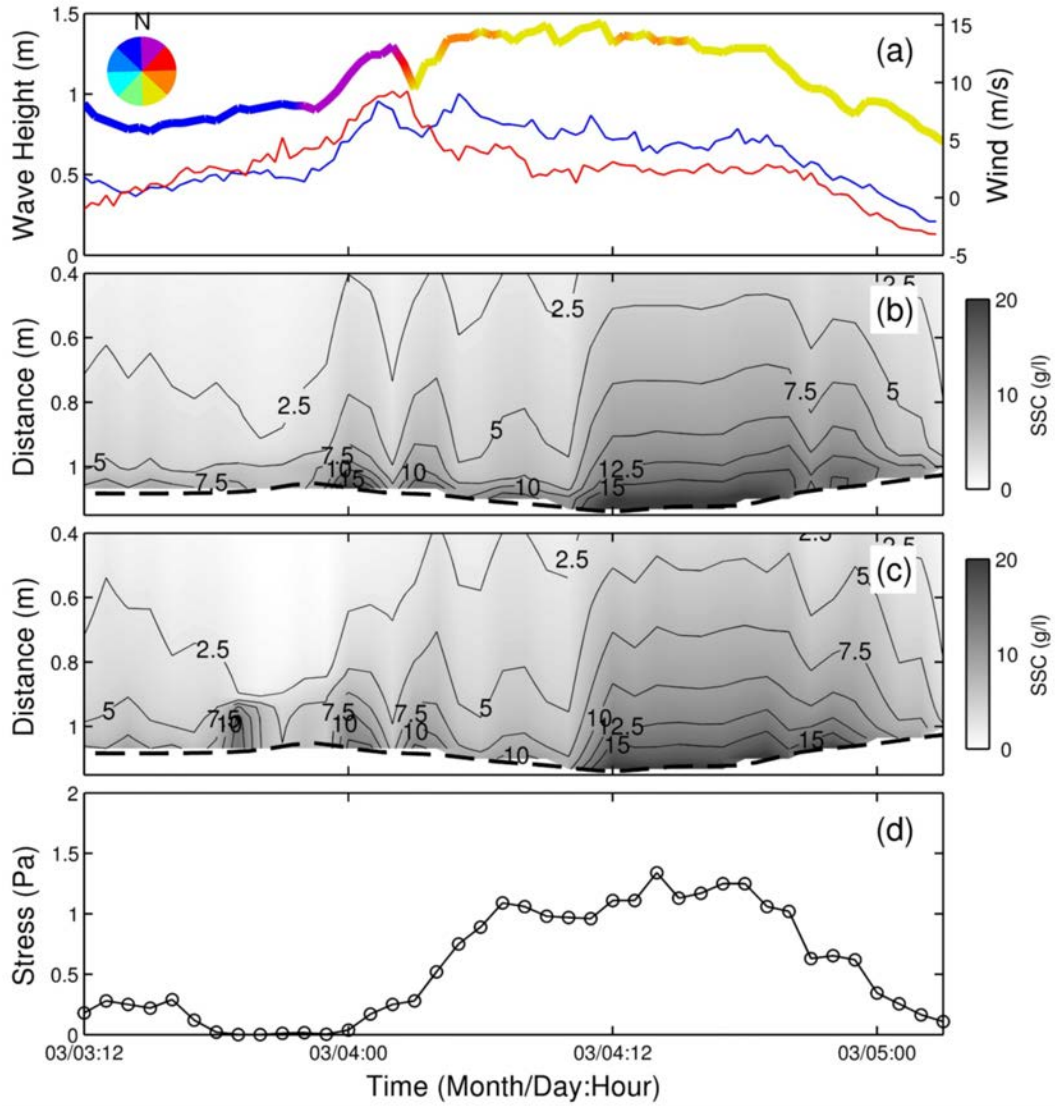


Figure 6: A reconstruction of the evolution of the vertical profile of the suspended sediment concentration during the storm of March 2008. a) estimates based on inverting the PC-ADP backscatter intensity (Sahin et al., 2012a), and numerical simulations using the model of Hsu et al. (2009) of b) suspended sediment concentration profile, and c) bottom shear stress.

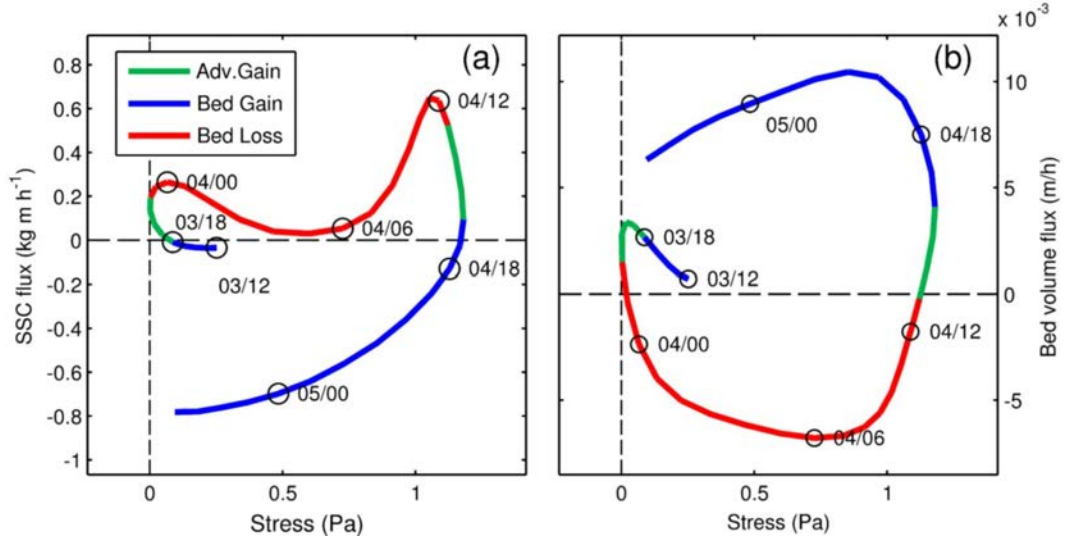


Figure 7: Sediment mass balance between the water-column and the sea bed during the bed-reworking cycle: sediment flux vs. bed stress. a) water column: ter-column and bed sediment flux vs. bed stress. The colors marks time intervals that can be identified as dominated by bed/water-column mass exchange, or by lateral advection. The transfer function that maps the curves in panels a) and b) into each other is the bed concentration. If during the event the bed concentration were constant and the evolution of the bed and water column sediment content were controlled strictly by bed/water-column mass exchange, the shapes of the two curves would be identical.

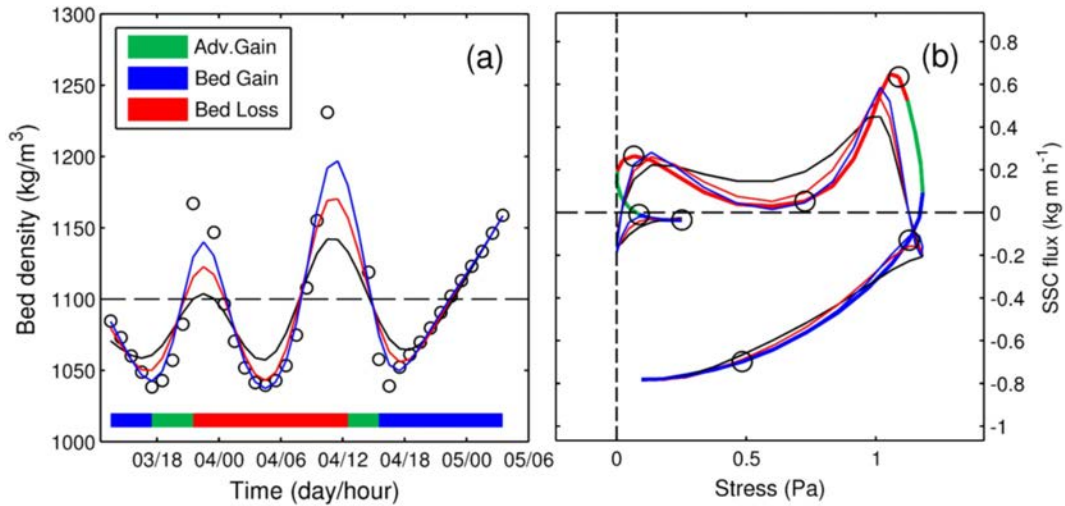


Figure 8: a) Estimates of bed concentration vs. time. b) Corresponding water-column hysteresis curves (compare with Figure 7a). The circles represent the bed concentration values derived directly from Figure 7, by dividing the two fluxes; lines represent estimates based on various degrees of smoothing of the direct estimate. In a), the dashed line marks the gelling density for the Atchafalaya mud (Robillard, 2009).

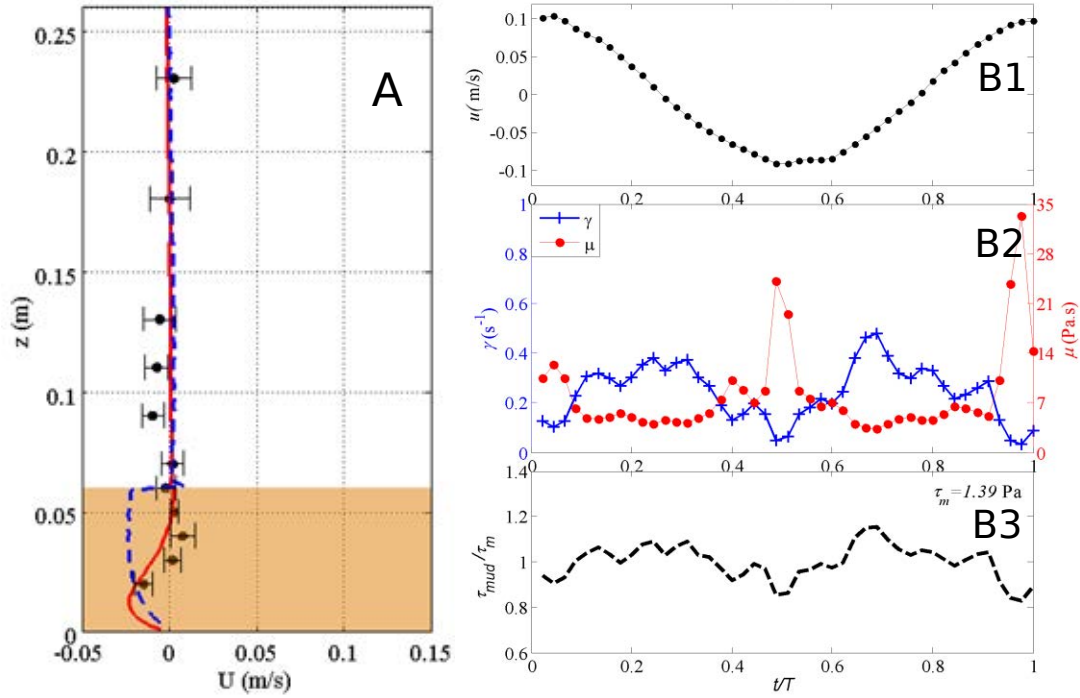


Figure 9: Laboratory experiment of wave-mud interaction (in collaboration with W.-Y. Hsu and H.-H. Hwung, NCKU, Taiwan) reveal insights in the mud layer driven by surface waves (depth=24 cm, wave height=4 cm, mud thickness =6 cm). (A) Measured velocity profile during flow reversal agrees with nonlinear model results (red curve). However, model results are sensitive to the viscosity used (see blue curve when viscosity is increased by 5 times). (B) Measured viscosity in the mud layer (see B2) changes by one order of magnitude during the wave passage (see (B1) for free-stream velocity). However, measured shear stress only changes within 20% of its mean value (see B3).

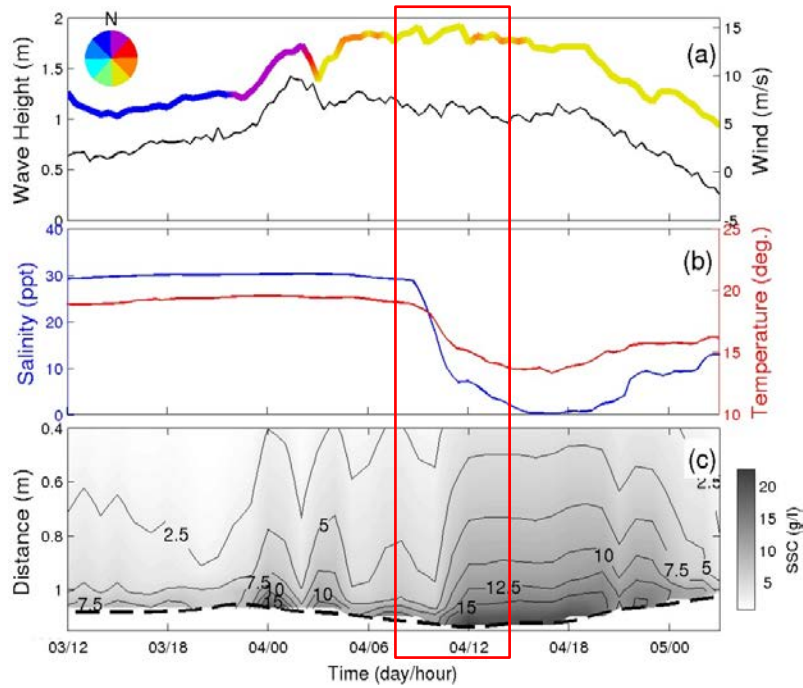


Figure 10: Observations of the passage of a fresh-water front over the experiment site during the storm of March 3rd to 5th, 2008. a) Wind speed and direction, and significant wave heights (short-wave: blue and swell: red); b) Salinity (blue) and temperature (red) at 55 cmab; c) Vertical profile of SSC estimated based on the PC-ADP backscatter. The red rectangle marks the approximate sediment-flux convergence moment. During this period, a 1D vertical bed-water column sediment balance model is likely invalid.

References

- Agnon, Y. and A. Sheremet (1997). Stochastic nonlinear shoaling of directional spectra, *J. Fluid Mech.* 345, 79-99.
- Allison, M.A., G.C. Kineke, E.S. Gordon, and M.A. Goni (2000). Development and reworking of a seasonal flood deposit on the inner continental shelf off the Atchafalaya River, *Continental Shelf Res.* 20, 2267-2294.
- Chan I.-C., and P.L.-F. Liu (2009). Responses of Bingham-plastic muddy seabed to a surface solitary wave, *J. Fluid Mech.* 618, 155-180.
- Chen, Y., R.T. Guza, and S. Elgar (1997). Modeling spectra of breaking surface waves in shallow water", *J. Geophys. Res.* 102/C11,25,035-25,046.
- Chou, H.-T. (1989). Rheological Response of Cohesive Sediments to Water Waves, Berkeley, California: University of California at Berkeley, Doctoral thesis, 149p.
- Chou, H.-T., M.A. Foda, and J.R. Hunt (1993). Rheological response of cohesive sediments to oscillatory forcing", In: *Nearshore and Estuarine Cohesive Sediment transport*, Coastal Estuarine Sci., 42, A.J. Mehta ed., 126-148, AGU, Washington DC.
- Dalrymple, R.A. and P.L.-F. Liu (1978). Waves over soft muds: a two-layer fluid model, *J. Phys. Oceanogr.* 8, 1121-1131.
- De Witt, P.J. (1995). Liquefaction of cohesive sediments caused by waves, *Delft Studies in Integrated Water Management* 6, Delft University Press.
- Elgar, S., and B. Raubenheimer (2008). Wave dissipation by muddy seafloors, *Geophys. Res. Lett.* 35/7, L07611.
- Foda, A.M., J.R. Hunt, and H.-T. Chou (1993). A nonlinear model for the fluidization of marine mud by waves, *J. Geophys. Res.* 98, 7039-7047.
- Foda M.A. and S.Y., Tzang (1994). Resonant fluidization of silty soil by water waves, *J. Geophys. Res.* 99(C10), 20463-20475.
- Freilich M.H. and R.T. Guza (1984). Nonlinear effects on shoaling surface gravity-waves, *Phil. Trans. Royal Soc. London Series A* 311, 1-41.
- Gade, H.G. (1957). Effects of a non-rigid impermeable bottom on plane surface waves in shallow water, Ph. D. Thesis, Texas A&M University, 35 pp.
- Hill, D.F. and M.A. Foda (1999). Effects of viscosity on the nonlinear resonance of internal waves, *J. Geophys. Res.* 104, 10951-10957.
- Holland K.T., S.B. Vinzon, L.J. Calliari (2009). A field study of coastal dynamics on a muddy coast offshore of Cassino beach, Brazil, *Cont. Shelf Res.* 29, 5035-5044.
- Hsu, T.-J., C.E. Ozdemir, and P.A. Traykovski (2009). High-resolution numerical modeling of wave-supported gravity-driven mudflows, *J. Geophys. Res.*, 114, C05014, doi: 10.1029/2008JC005006.

- Jamali, M., B. Seymour, and G. Lawrence (2003), Asymptotic analysis of a surface-interfacial wave interaction, *Phys. Fluids* 15, 47-55.
- Jaramillo, S., A. Sheremet, M. Allison, and K.T. Holland (2009). Wave-mud interactions over the muddy Atchafalaya subaqueous clinoform, Louisiana, United States: Wave-supported sediment transport, *J. Geophys. Res.*, 114, C04002, doi:10.1029/2008JC004821.
- Jiang F. and A.J. Mehta (1995). Mudbanks of the Southwest Coast of India IV: Mud viscoelastic properties, *J. Coastal Res.* 11, 918-926.
- Kaihatu J.M., A. Sheremet, and K.T. Holland (2007). A model for the propagation of nonlinear surface waves over viscous muds, *Coastal Engineering* 54, 752-764.
- Le Hir, P., P. Bassoulet, and H. Jestin (2001), Application of the continuous modeling concept to simulate highconcentration suspended sediment in a macrotidal estuary, in *Coastal and Estuarine Fine Sediment Processes*, edited by W. H. McAnally and A. J. Mehta, Elsevier, Amsterdam.
- Maa, J. P.-Y., and A.J. Mehta (1990), Soft mud response to water waves, *J. Wtrwy., Port, Coast. and Ocean Engrg.*, ASCE, 116 (5), 634-650.
- Mei, C.C. and P.L-F. Liu (1987). A Bingham-plastic model for a muddy seabed under long waves", *J. Geophys. Res.* 92, 14,581-14,594.
- Ng, C.-O. (2000). Water waves over a muddy bed: a two-layer Stokes's boundary layer model, *Coastal Engineering*, 40, 221-242, 2000.
- Robillard, D., (2008). A Laboratory Investigation Of Mud Seabed Thickness Contributing To Wave Attenuation, PhD. Dissertation, Online: <http://purl.fcla.edu/fcla/etd/UFE0024823>, University of Florida, Gainesville, FL, 2008.
- Rogers, E., and K.T. Holland (2009). A study of dissipation of wind-waves by viscous mud at Cassino Beach, Brazil: prediction and inversion, *Cont. Shelf Res.* 29, 676-690, 2009.
- Safak, I, A. Sheremet, M.A. Allison, and T.-J. Hsu (2010). Bottom turbulence on the muddy Atchafalaya Shelf, Louisiana, USA, *J. Geophys. Res.*, 115, C12019, doi:10.1029/2010JC006157.
- Sahin, C., I. Safak, T.-J. Hsu, and A. Sheremet (2012), Observations of sediment stratification on the muddy Atchafalaya Shelf, Louisiana, USA, submitted to *J. Geophys. Res.* (in print).
- Sahin, C., I. Safak, A. Sheremet, and A.J. Mehta (2012), Observations of sediment stratification on the muddy Atchafalaya Shelf, Louisiana, USA, submitted to *Marine Geo.* (in review).
- Sheremet, A. and G.W. Stone (2003). Observations of nearshore wave dissipation over muddy sea beds, *J. Geophys. Res.* 108, DOI 10.1029/2003JC001885.
- Sheremet A., A.J. Mehta, B. Liu, and G.W. Stone (2005). Wave-sediment interaction on a muddy inner shelf during Hurricane Claudette, *Est. Coastal Shelf Sci.* 63, 225-233.
- Sheremet, A., S. Jaramillo, S.-F. Su, M.A. Allison, and K.T. Holland (2011). Wavemud interaction over the muddy Atchafalaya subaqueous clinoform, Louisiana, United States: Wave processes, *J. Geophys. Res.*, 116, C06005, doi:10.1029/2010JC006644.

- Torres-Freyermuth, A., and T.-J. Hsu (2010). On the dynamics of wave-mud interaction: a numerical study, *J. Geophys. Res.*, 115, C07014, doi:10.1029/2009JC005552.
- Yamamoto, T. and S. Takahashi (1985). Wave damping by soil motion”, *J. Waterway, Port, Coastal, and Ocean Eng.* 3, 62-77.

PUBLICATIONS

Refereed Publications

1. Safak, I., M.A. Allison, and A. Sheremet, Observations of flocc variability under changing turbulent stresses and sediment availability conditions on a wave energetic muddy shelf, *Cont. Shelf. Res.* [submitted, refereed].
2. Safak, I., C. Sahin, J.M. Kaihatu, and A. Sheremet, Modeling wave-mud interaction on the Atchafalaya shelf, Louisiana, USA, *Ocean Modelling* [submitted, refereed].
3. Hsu, W. Y., Hwung, H. H., T.-J. Hsu, Torres-Freyermuth, A., Yang, R. Y., An experimental and numerical study on wave-mud interaction, *J. Geophys. Res.* [submitted, refereed].
4. Sahin, C., I. Safak, T.-J. Hsu, and A. Sheremet, Observations of Sediment Stratification on the Muddy Atchafalaya Shelf, Louisiana, USA, *Marine Geo.* [submitted, refereed].
5. Sahin, C., I. Safak, A. Sheremet, and A.J. Mehta (2012). Observations of Bed Reworking by Waves, Atchafalaya Shelf, Louisiana, USA, *J. Geophys. Res.* [published, refereed].
6. Sheremet, A., S. Jaramillo, S.-F. Su, M.A. Allison, and K.T. Holland (2011). Wavemud interaction over the muddy Atchafalaya subaqueous clinoform, Louisiana, United States: Wave processes, *J. Geophys. Res.*, 116, C06005, doi:10.1029/2010JC006644 [published, refereed].
7. Safak, I, A. Sheremet, M.A. Allison, and T.-J. Hsu (2010). Bottom turbulence on the muddy Atchafalaya Shelf, Louisiana, USA, *J. Geophys. Res.*, 115, C12019, doi:10.1029/2010JC006157 [published, refereed].

Conference papers

1. Kaihatu, J.M. , N. Tahvildari, C. Sahin, and A. Sheremet, Verification of Wave-Mud Interaction Models with Field Data, 12th International Workshop on Wave Forecasting and Hindcasting and 3rd Coastal Hazards Symposium, Hawaii 2011.
2. Sahin, C., I. Safak, A. Sheremet, and J. M. Kaihatu, Coupled wave-bed dynamics, Atchafalaya shelf, Louisiana, 12th International Workshop on Wave Forecasting and Hindcasting and 3rd Coastal Hazards Symposium, Hawaii 2011.
3. Sahin, C., I. Safak, A. Sheremet, M.A. Allison, Bed-sediment response to energetic waves, Atchafalaya inner shelf, Louisiana. *Coastal Sediments 2011*, Miami, FL.
4. Safak, I., C. Sahin, A. Sheremet, M.A. Allison, Observations and modeling of cohesive seafloor response to energetic surface waves on the Louisiana Shelf. *CSDMS 2010: Modeling for Environmental Change*, San Antonio, TX.
5. Sahin, C., I. Safak, A. Sheremet, M.A. Allison, Bed-sediment response to energetic waves, Atchafalaya inner shelf, Louisiana. *AGU Fall Meeting*

6. Sheremet, A., M.A. Allison, I. Safak, S.-F. Su, Wave-sediment interaction on the Atchafalaya Shelf, Louisiana, USA, AGU Ocean Science Spring Meeting, Oregon, Portland 2010.
7. Sahin, C., I. Safak, A. Sheremet, and M.A. Allison, A method for estimating concentration profiles for suspended cohesive sediment based on profiles of acoustic backscatter, AGU Ocean Science Spring Meeting, Oregon, Portland, 2010.
8. Safak, I., A. Sheremet, S. Elgar, B. Raubenheimer, Nonlinear wave propagation across a muddy seafloor, AGU Ocean Science Spring Meeting, Oregon, Portland, 2010.
9. Safak, I., A. Sheremet, S. Elgar, and B. Raubenheimer, Nonlinear wave propagation on a muddy beach, West Louisiana, USA, International Conf. On Coastal Eng., 2010.
10. Allison, M.A., Sheremet, A., Safak, I., and Duncan, D.D., Floc behavior in high turbidity coastal settings as recorded by LISST: the Atchafalaya delta inner shelf, Louisiana. AGU Ocean Sciences Meeting, Portland, Oregon, February, 2010.