Nonlinear and Dissipation Characteristics of Ocean Surface Waves in Estuarine Environments

James M. Kaihatu
Zachry Department of Civil Engineering, Texas A&M University
3136 TAMU
College Station, TX 77843-3136
phone: (979) 862-3511 fax: (979) 862-8162 email: jkaihatu@tamu.edu

Alexandru Sheremet
Department of Civil and Coastal Engineering, University of Florida
P.O. Box 116580
Gainesville, FL 32611
phone: (352) 392-9537 fax: (352) 392-3394 email: alex@coastal.ufl.edu

Jane M. Smith
Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center
3909 Halls Ferry Rd.
Vicksburg, MS 39180
phone: (601) 634-2079 fax: (601) 634-4314 email: Jane.M.Smith@usace.army.mil

Hendrik L. Tolman
National Center for Environmental Prediction, National Oceanic and Atmospheric Administration
5200 Auth Rd. Rm 209
Camp Springs, MD 20746
phone: (301) 763-8133 x7253 fax: (301) 763-8545 email: Hendrik.Tolman@noaa.gov

Award Number: N00014-10-1-0389 (TAMU); N00014-10-1-0805 (UF)
https://ceprofs.civil.tamu.edu/jkaihatu/research/proj.html

LONG-TERM GOALS

The overall goal of this work is the development of computational modules for the dissipation of surface wave energy due to expanses of bottom mud and marshland vegetation. The computational modules would represent both the dissipative effects on the surface waves and the effects of dissipation on other processes of wave transformation and evolution. In addition these modules would allow for feedback between the surface wave and the energy dissipating feature.

OBJECTIVES

1) Develop processes models of the physics of dissipation in estuarine areas.
2) Use optimized ensemble simulations to represent effects of dissipation on wave processes.
3) Develop and test low-dimension, reduced representations of estuarine effects for inclusion into operational wave models.
4) Develop experimental versions of operational wave models.

APPROACH

We will first work to develop computational models for detailed, phase-resolved predictions of wave dissipation in estuarine areas. These models will include various mud proxy models (viscous fluid, viscoelastic semi-rigid bed, Bingham plastic) for wave/mud interaction and mud-induced dissipation. These proxy models for mud dissipation have fairly broad-banded responses over a large swath of wave frequencies, so they can be expected to inhibit various nonlinear interactions in the random wave field. The task here will be to surmise whether this frequency dependence is scalable or self-similar over a range of frequencies, conditions or proxies. In addition the feedback between surface and lutocline waves will be investigated to determine whether or not these interactions have an effect on surface wave energy; allowing for surface-lutocline interaction can potentially *redirect* surface wave energy rather than simply dissipate it. A similar line of inquiry will be performed for wave-vegetation interaction, though the expected parameter space for this phenomena may be significantly reduced compared to mud dissipation. These models will be validated with available data.

To make this suitable for a random wave spectral model (as most operational wave models are), we must find ways of randomizing our results with the deterministic models. One possible method would be the use of a neural network approach, which uses data from the models to establish a "training set" which helps predicts future behavior. The neural network mapping strategy of Krasnopolsky et al. (2002) will be one candidate for use; it was used for the Wavewatch-III © model, and should be available for use here.

In addition, and in concert with the project "Development of Numerical 3-Wave Interactions Module for Operational Wave Forecasts in Intermediate-Depth and Shallow Water" (PI: Sheremet; co-PI: Kaihatu) we will investigate physically-justifiable reduced dimension models which will retain the dominant components of wave-mud-vegetation interaction but will also allow for more expedient calculation. Furthermore, for further application of the model to a wider range of areas, we are also investigating the dissipation of waves over steep bathymetry, such as reefs.

Finally we will make use of the models developed above to create experimental versions of operational models. This will allow us to test the physics in the developed models while using the general framework of operational wave models. We will conduct robustness tests of the system to determine the conditions under which the new models exhibit sub-optimal behavior. We will also work with the NCEP and NAVO (if available) operational forecasters, as well as the scientific community at the Naval Research Laboratory (NRL) and Engineering Research and Development Center (ERDC) to insure smooth incorporation of these developments into their operational run stream.

The TAMU team consists of the PI (Kaihatu); a (former) Ph.D. student, Mr. Navid Tahvildari, who had developed models and analysis for investigating the interactions between surface and interfacial waves, and two M.S. students (Mr. John Goertz and Mr. Aravinda Venkattaramanan). Mr. Goertz is quantifying the dissipation which occurs over steep bathymetry. Mr. Venkattaramanan (funded under a teaching assistantship) is investigating nonlinear wave processes through vegetation. (Dr. Tahvildari graduated in December 2011).The UF team consists of Alex Sheremet (PI), Miao Tian and Cihan Sahin (Ph.D. students) who are working on modeling nonlinear wave evolution in dissipative environments (mud), and the response of sea bed to wave action.

WORK COMPLETED

We have investigated the dissipation process of wave propagation over steep bathymetry by focusing on the deduction of the instantaneous dissipation and comparing its bulk statistics to those from probabilistic models. We have also begun expanding our work into the area of vegetation-induced dissipation by coding up small process models for this dissipation, with the eventual goal of including them into the nonlinear wave models.

We have also outlined the development of a frequency domain model (derived from the Boussinesq equations) for nonlinear wave-wave interactions between surface and interface modes. The interaction coefficients for temporal growth of interface modes have been derived, and we have extended this to include temporally periodic, spatially evolving interactions between both resonant triads at the interface and surface and near-resonant triads at each surface. The resulting equations account for interactions betweeen nine different frequencies at the surface, interface, and between both surface and interface.

We have also used data from a field experiment conducted at Atchafalaya Bay, Louisiana in February 2008 to investigate the dynamics of wave-sediment interaction on the muddy shelf at the 4m isobath. Instrumentation deployed for the experiment included a downward-pointing pulse-coherent acoustic Doppler profiler) (PC-ADP), an upward-pointing acoustic Doppler current profiler (ADCP), and an optical backscatter sensor (OBS). Acoustic backscatter measurements were used to determine suspended sediment profiles, while the velocity profiles were deduced by the application of a one-dimensional vertical bottom boundary layer model to estimate parameters such as shear stress. The temporal evolution of the surface waveheights were correlated to that of suspended sediment concentration in order to determine the dynamics governing the surface wave dissipation.

RESULTS

Reef Wave Breaking and Dissipation: Wave breaking processes over the reef were studied using data from the Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, which consisted of random waves propagated over a short 1:5 or a 1:2.5 slope leading to a long flat section representing the top of the reef. Waves breaking over the steep slope would generate long waves which would propagate over the top of the reef. We used the methodology of Kaihatu et al. (2007) to investigate the individual dissipation events and check their statistical characteristics against those of more established models (e.g. Battjes and Janssen 1978; Thornton and Guza 1983). One central feature of the Kaihatu et al. (2007) methodology was the instantaneous eddy viscosity dissipation mechanism of Zelt (1991), within which the eddy viscosity mixing length was scaled to the breaking criterion for a solitary wave. Use of this scaling overestimated the bulk dissipation (when integrated over the individual events) far above those from probabilistic models calibrated to these data. We determined that alteration of this scaling (via adjustment of the breaking criterion) reduced the resulting bulk dissipation down to the levels seen in the calibrated models. This is significant in that the potential for adjustment of this criterion was not recognized by Zelt (1991), nor of many of the ensuing time-domain models which have used this mechanism as a breaking mechanism (e.g. Kennedy et al. 2000). Figure 1 shows the impact of the adjustment of this breaking criterion on ensuing bulk dissipation estimates.

Nonlinear Surface-Lutocline Coupling: Our ongoing efforts to investigate the nonlinear coupling between the free surface waves and interfacial waves have been expanded to include the effects of near-resonant interactions at the individual surfaces. Absent the near-resonant interactions, the resonant surface-interface interactions lead to temporal evolution characteristics for the surface and interface waves which have remarkable temporal periodicity. However, the addition of the near-resonant interactions on each surface affect the temporal evolution of surface and interface amplitudes in drastically different ways. Figure 2 shows a comparison between the temporal evolution characteristics with and without the inclusion of near-resonant interactions.

Wave-Mud Interaction and Dissipation: Analysis of the PC-ADP data revealed that three significant current pulses, flowing toward the SSW, occurred as a storm event on 26 February 2008 began its initial development. Temperature and salinity measurements in the area showed a decrease in both quantities; correspondingly suspended sediment concentration (SSC) also increased during this time. This indicates the movement of sediment-loaded fresh water past the station. The particular event of interest occurred 27 February 2008, as the highest SSC and strongest waves and currents were measured then.This event eroded the bed (position deduced from the maximum acoustic backscatter return). As the current speeds fall, deposition occurs and the bed level rises until the beginning of the third current pulse (approximately 10 hours after the first pulse), at which point significant resuspension of sediment occurs. The SSC in the water column decreases as the current speeds and wave energy fall until it is almost free of sediment (about 21 hours after the first pulse). Using estimated SSC profiles (Sahin et al., in review) and measured current profiles, the bottom stress and the temporal evolution of the bed density were calculated from a constrained 1D vertical boundary layer model. The data suggests a softening of the bed in the early stages of erosion, with consolidation occurring as the bed accretes and stiffens (rise in shear stress) as the wave energy and current speeds decline. Figure 3 shows the evolution of the bed density and position with the changes in wave energy.

IMPACT AND APPLICATIONS

National Security

The present reserch extends the predictive capability of the Navy's wave forecasts by treating areas that are far removed from the non-cohesive sedimentary environments which have underpinned work in wave propagation. These mechanisms, when incorporated into operational Navy wave prediction models, can improve operational predictions in shallow, muddy areas or areas with steep bathymetry.

RELATED PROJECTS

This work is done in collaboration with ONR funded research (PI: Sheremet) to develop sediment transport forecasting capabilities for muddy areas.

REFERENCES

Battjes, J.A., and Janssen, J.P.F.M. (1978) Energy loss and setup due to breaking of random waves. Proceedings of the 14th International Conference on Coastal Engineering, ASCE, Hamburg, Germany, 466-480.

Kaihatu, J.M., Veeramony, J., Edwards, K.L., and Kirby, J.T. (2007) Asymptotic behavior of frequency and wave number spectra of nearshore shoaling and breaking waves. Journal of Geophysical Research, 112, doi: 10.1029/2006JC003817.

Kennedy, A.B., Chen, Q.J., Kirby, J.T., and Dalrymple, R.A. (2000) Boussinesq modeling of wave transformation, breaking and runup. I: One dimension. Journal of Waterway, Port, Coastal and Ocean Engineering, 126, 39-47.

Sahin, C., Safak, I., Hsu, T.-J., and Sheremet, A. (2012) Observations of sediment stratification on the muddy Atchafalaya shelf, Louisiana, USA, in review.

Thornton, E.B., and Guza, R.T. (1983) Transformation of wave height distribution. Journal of Geophysical Research, 88, 5925-5938.

Zelt, J.A. (1991). The run-up of breaking and nonbreaking solitary waves. Coastal Engineering, 15, 205-246.

PUBLICATIONS

Goertz, J.T. (2012) Long wave breaking effects on fringing reefs. M.S. thesis, Zachry Department of Civil Engineering, Texas A&M University, 51p [in press].

Goertz, J.T., Kaihatu, J.M., Sheremet, A., Smoth, E.R., and Smith, J.M. (2012) Long wave breaking effects on fringing reefs. Proceedings of the 32nd International Conference on Coastal Engineering, Santander, Spain [in press].

Sheremet, A., Kaihatu, J.M., Su, S.-F., Smith, E.R., and Smith, J.M. (2011) Modeling of nonlinear wave propagation over fringing reefs. Coastal Engineering 58, 1125-1137 [published].

Tahvildari, N. 2011. Nonlinear interactions between long waves in a two-layer fluid. Ph.D. dissertation, Zachry Department of Civil Engineering, Texas A&M University, 112p [published].

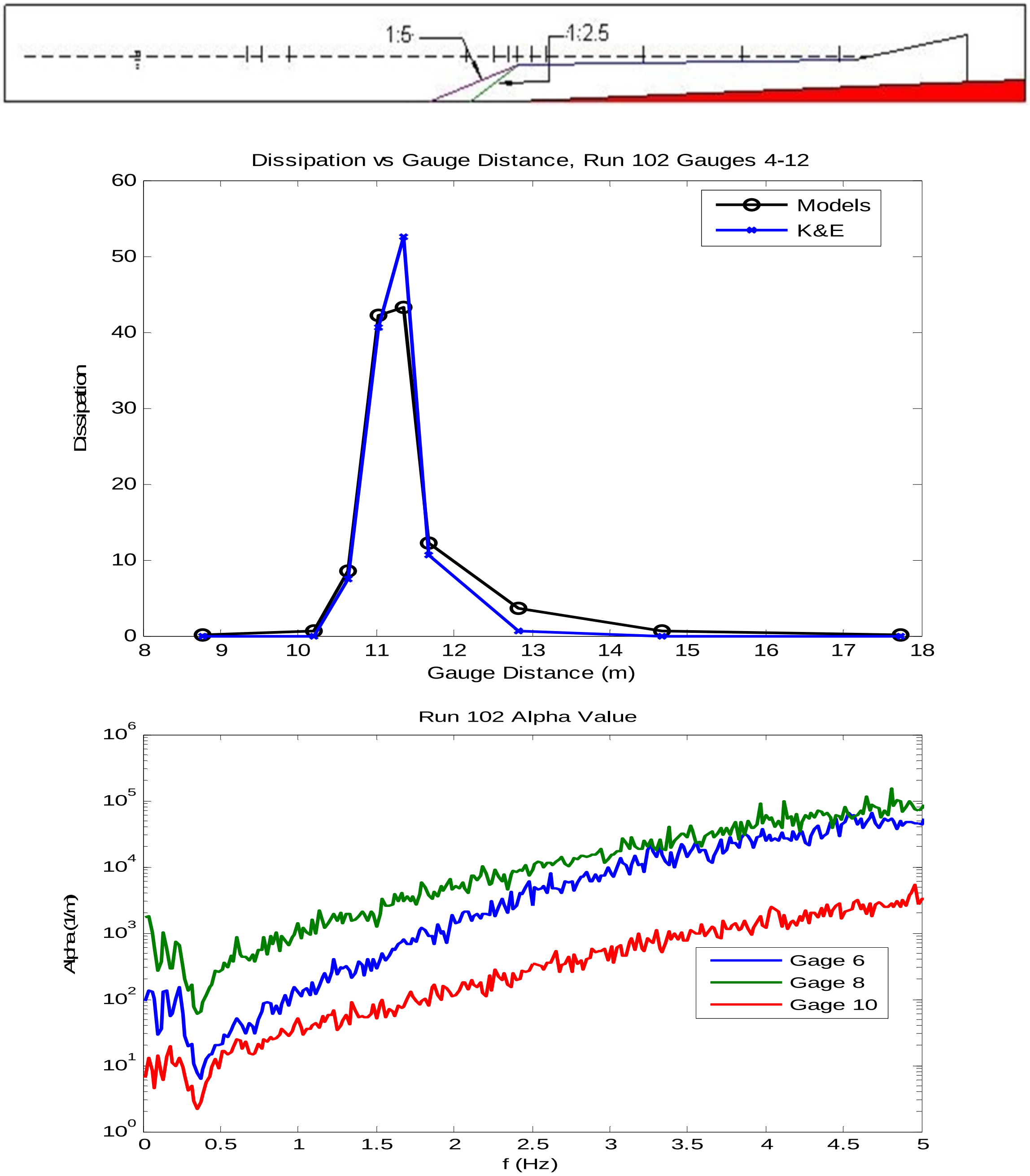

Figure 1: Breaking wave dissipation analysis of waves propagating over a steep reef. Top: Experimental layout with both slopes shown. Middle: Dissipation estimates using methodology of Kaihatu et al. (2007) with adjustment of breaking length scale (blue line) compared to calibrated probabilistic estimates (black line). Bottom Dissipation rate for three gages over the steep slope as a function of frequency.

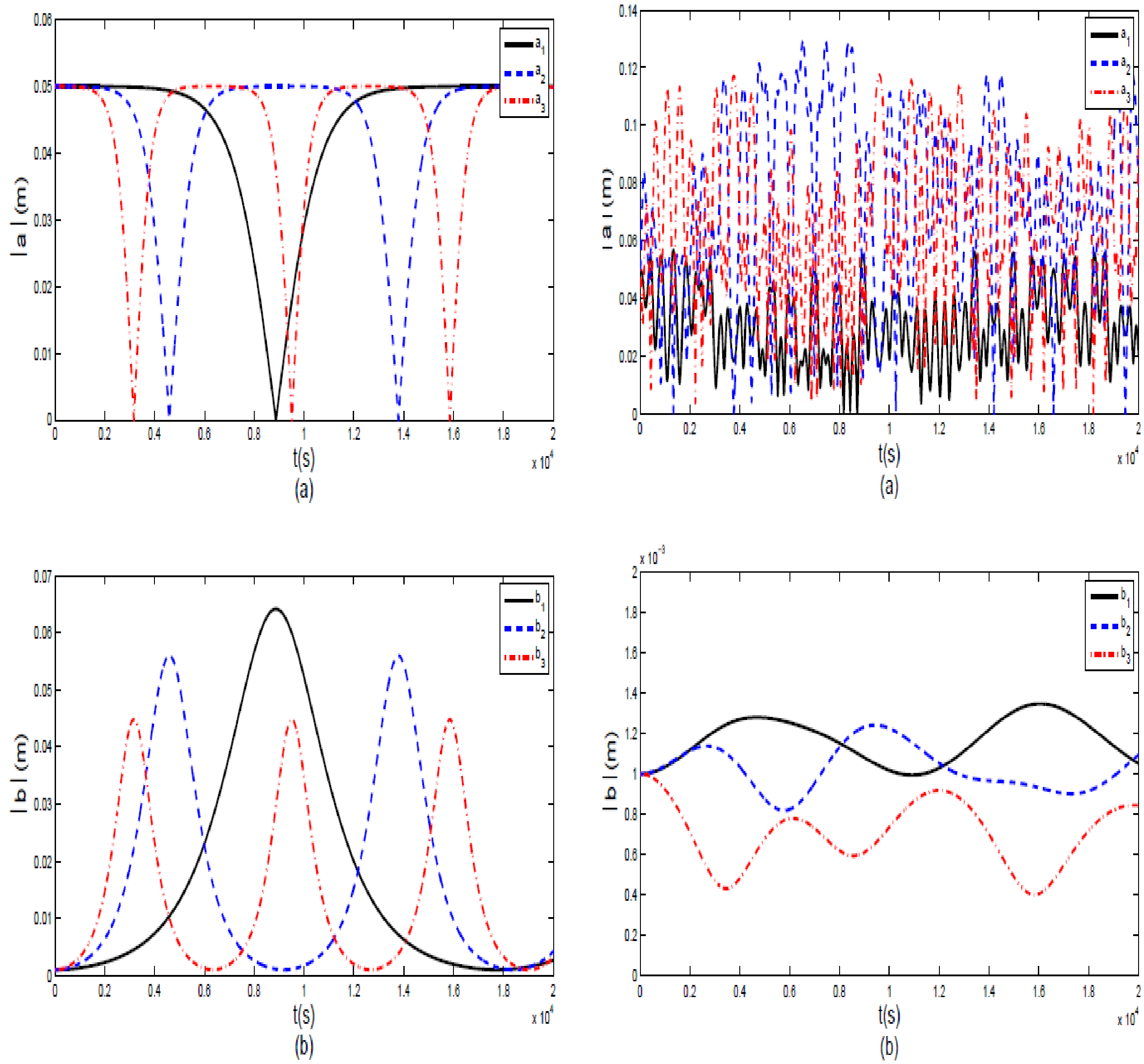

Figure 2. Temporal evolution of resonant surface – lutocline wave interaction with and without near-resonant interactions at interface and surface. Left: Temporal evolution of triad amplitudes at the surface (top) and interface (bottom), in which each surface-interface triad shown is resonant and uncpupled from other triads. Right. Temporal evolution of triad amplitudes at the surface (top) and interface (bottom) in which near-resonant interactions are also allowed to occur between frequencies in triads.

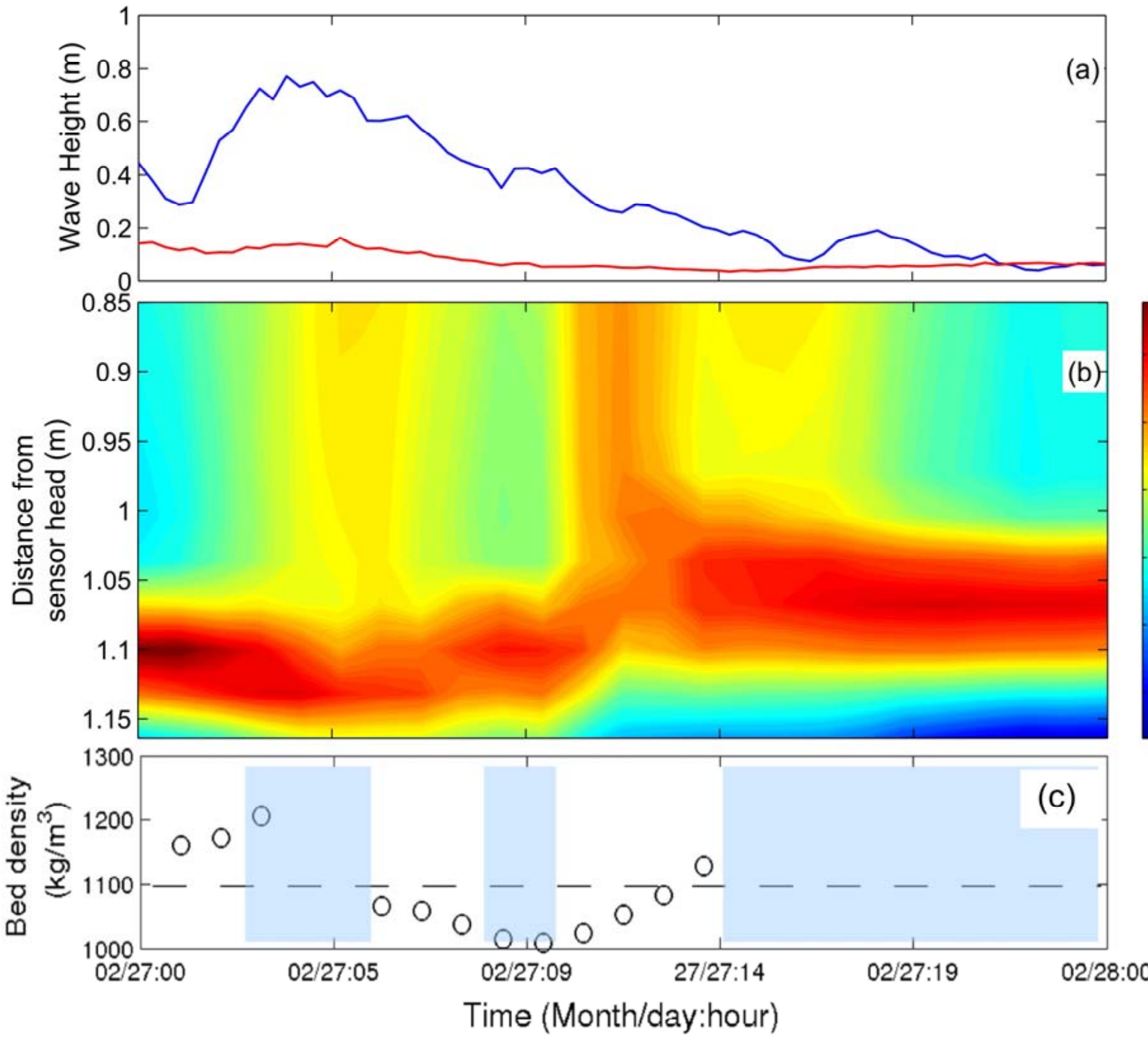

Figure 3. Bed reworking cycle during the storm of 27-28 February 2008. Top: Significant wave height (short wave: blue; swell: red). Middle: PC-ADP acoustic backscatter intensity – maximum return is likely position of bed. Bottom: Density of eroded/accreted bed layers based on mass conservation. Areas in blue denote times when mass was not conserved between bed and water column, indicative of sediment influx from the Atchafalaya River.