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Modeling wave-mud interaction on the central chenier-plain coast, western Louisiana Shelf, USA

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ABSTRACT

The strong coupling between hydrodynamics and seafloors on shallow muddy shelves, and resulting bed reworking, have been extensively documented. On these shelves, spectral wave transformation is driven by a complex combination of forcing mechanisms that include nonlinear wave interactions and wave energy dissipation induced by fluid-mud at a range of frequencies. Wave-mud interaction is investigated herein by using a previously validated nonlinear spectral wave model and observations of waves and near-bed conditions on a mildly-sloping seafloor off the muddy central chenier-plain coast, western Louisiana Shelf, United States. Measurements were made along a cross-shelf transect spanning 1 km between 4 and 3 m water depths. The high-resolution observations of waves and near-bed conditions suggest presence of a fluid mud layer with thickness sometimes exceeding 10 cm under strong long wave action (1 meter wave height with 7 s peak period at 4 meter depth). Spectral wave transformation is modeled using the stochastic formulation of the nonlinear Mild Slope Equation, modified to account for wave-breaking and mud-induced dissipation. The model is used in an inverse manner in order to estimate the viscosity of the fluid mud layer, which is a key parameter controlling mud-induced wave dissipation but complicated to measure in the field during major wave events. Estimated kinematic viscosities vary between 10^{-4}-10^{-3} m^2/s. Combining these results of the wave model simulations with in-depth analysis of near-bed conditions and boundary layer modeling allows for a detailed investigation of the interaction of nonlinear wave propagation and mud characteristics. The results indicate that mud-induced dissipation is most efficient when the wave-induced resuspensions of concentrations > 10 g/L settle due to relatively small bottom stresses to form a fluid mud layer that is not as thin and viscous as a consolidated seafloor in absence of wave action but also not as thick and soft as a near-bed high concentration layer that forms during strong wave action.

1. Introduction

In nearshore muddy environments, energetic surface waves have been observed to soften the initially consolidated seafloor and cause resuspension of sediment which finally settles to form fluid mud layers (e.g., Jaramillo et al., 2009; Sahin et al., 2012), the thickness of which depends on site-specific mud properties and hydrodynamic conditions. Interaction of waves with these high concentration mud layers causes significant wave energy dissipation (e.g., Sheremet et al., 2005). The dissipation rate was reported to be more significant during the phase of hindered settling of the resuspended material when a fluid mud layer forms (Sheremet et al., 2011a), and dramatically greater than that observed over sandy shelves (e.g., Ardhuin et al., 2003). Mud-induced wave energy dissipation is observed at both low frequencies and at the short wave band of the spectrum. This short wave band is not kinematically coupled to the seafloor; energy loss in this band was hypothesized to be due to nonlinear energy transfers across the spectrum, i.e., triad interactions (Sheremet and Stone, 2003).

An early study of wave propagation on muddy seafloors (Gade, 1958) considered a two-layer system consisting of water overlaying a viscous fluid representing the muddy seafloor. The resulting model of Gade (1958) is valid for long waves; with it, wave heights were seen to exponentially decay as waves propagate. This model was later improved with the inclusion of viscous effects in both layers, and an extension to dispersive waves (Dalrymple and Liu, 1978). An analytical limit to the model of Dalrymple and Liu (1978) was derived by Ng (2000). This simplification is valid when the thickness of the mud layer (h_o) is comparable to the Stokes'

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boundary layer thickness of the mud layer, $\sqrt{\frac{2\nu_m}{\omega}}$ (ν_m is the kinematic viscosity of the fluid mud layer, and ω is the wave radian frequency), and much thinner than the overlaying water layer. This simplification results in explicit expressions of wave dissipation rate and, therefore, computational efficiency. In these three studies, peak mud-induced wave energy dissipation was noted to occur when h_o is the same order of magnitude as, but slightly larger than, $\sqrt{\frac{2\nu_m}{\omega}}$ (20% in Gade, 1958; 30% in Dalrymple and Liu, 1978; 50% in Ng, 2000).

Other mud rheologies have been used such as visco-elastic (Hsiao and Shemdin, 1980; Liu and Chan, 2007; Mei et al., 2010) and visco-plastic models (Mei and Liu, 1987; Chan and Liu, 2009). Recently, viscous mud formulations have been incorporated into wave models; the formulation of Gade (1958) was modified for directional wave fields in a phase-averaged model (Winterwerp et al., 2007), and the formulation of Ng (2000) was implemented in a phase-resolving nonlinear wave model (Kaihatu et al., 2007).

Although these studies have helped to quantify wave energy dissipation due to mud, they have generally assumed temporally-constant rheological properties for the mud layer. However, under wave forcing changing throughout a storm, rheology of a muddy seafloor is likely to vary. The complexity of observing the properties of muddy seafloors throughout wave-energetic periods precludes the direct evaluation of wave propagation in muddy environments and limits the applicability of wave-mud interaction formulations in operational wave models. Therefore, wave models have been recently used in an inverse manner in order to infer properties of mud layers that control frequency-dependent wave dissipation, such as thickness and viscosity. One initial inversion study was based on implementation of the model of Ng (2000) into SWAN (Rogers and Holland, 2009). The same mud dissipation formulation was implemented into nonlinear wave models (Sheremet et al., 2011a; Tahvildari and Kaihatu, 2011) with rigorous formulations of nonlinear triad interactions (Agnon and Sheremet, 1997; Kaihatu and Kirby, 1995) rather than the related parametrizations in SWAN. By comparing the results of linear and nonlinear models, Sheremet et al. (2011a) demonstrated the importance of accounting for nonlinear triad interactions in controlling the frequency distribution of wave energy dissipation. Their nonlinear model captured both the enhanced dissipation at the spectral peak due to energy transfers to higher and lower frequencies, and the resulting overall growth at these frequencies; neither effect is captured by linear wave transformation models (Agnon and Sheremet, 1997; Kaihatu et al., 2007; Elgar and Raubenheimer, 2008). This reveals that a nonlinear wave model is necessary in order to extract accurate properties of muddy seafloors in an inverse manner and, therefore, obtain a better representation of wave-mud interaction processes. Based on wave measurements collected nearby during a previous field effort (Section 3.1), Elgar and Raubenheimer (2008) developed a depth- and frequency-dependent formulation of mud-induced dissipation. The differences between the measured energy flux and estimates from a nondissipative nonlinear Boussinesq model were attributed to mud-induced dissipation only, with no allowances for other potential sources of dissipation (breaking, whitecapping, etc.). Despite the dependence on mud dissipation, no quantitative properties of the muddy seafloor were discussed or deduced from the data in their study.

In this study, we use wave, current, suspended sediment and seafloor observations to infer properties of the bottom mud layer. These measurements, taken along a cross-shelf transect on the muddy central chenier-plain coast, western Louisiana Shelf, United States during an energetic wave period (Section 3), are used herein to model wave propagation across the muddy seafloor and bottom boundary layer processes with two previously validated models. A nonlinear wave model (Agnon and Sheremet, 1997, Section 2.1) is used in an inverse manner to estimate evolution of viscosity of the muddy seafloor throughout the event of interest. The model used herein includes both mud induced (Ng, 2000) and breaking induced (Sheremet et al., 2011b) dissipation, therefore, distinguishes between these two mechanisms. Our approach follows Sheremet et al. (2011a) and is tested herein under different forcing conditions, as a step towards building a methodology to forecast bed reworking by waves. Compared to the study site used by Sheremet et al. (2011a), the study site herein is a plane shelf (Section 3.1) and better suited. In addition, near-bed conditions are investigated in more detail (sediment concentration, bottom shear stress) in this study. Measured profiles of acoustic backscatter are used to estimate vertical structure of suspended sediment concentration (Section 3.1, Appendix). These estimates are then used, together with the observed flow conditions, to run a bottom boundary layer model for muddy environments (Hsu et al., 2009, Section 2.2). Evaluation of the results of the wave model and the boundary layer model together allows to gain more insight into wave-mud interaction (Section 4).

2. Models

2.1. Nonlinear wave model

The spectral wave model is based on the nonlinear Mild Slope Equation and accounts for the interactions and spectral energy transfers among Fourier modes (Agnon et al., 1993; Agnon and Sheremet, 1997). The model is derived from the boundary value problem for water waves, with boundary conditions expanded to second order in ka, where k is the wavenumber and a a representative amplitude. The model thus describes both linear wave transformation effects and nonlinear wave–wave interactions; these interactions are expressed as coupled Fourier modes which govern the strength of the energy transfer. The phase-resolving evolution equations of this model are then averaged; the resulting equations represent the evolution of spectra in terms of bispectra. Bispectral evolution equations are then required, and the system truncated and closed. The ‘sum’ and ‘difference’ interactions represented in these coupled modes are associated respectively with the generation of both harmonics of the spectral peak and energy transfers toward lower frequencies, which impact processes in the nearshore environment (Sheremet et al., 2011a). The stochastic (phase-averaged) and unidirectional version of the model is modified to account for the dissipative processes. A mud-induced dissipation formulation that treats the fluid-mud layer as a viscous Newtonian fluid (Ng, 2000, Section 1) is used. The mud-induced dissipation rate is a function of wave frequency, mud thickness, density, and viscosity. Depth-induced breaking is represented with a lumped probability-based breaking mechanism (Thornton and Guza, 1983) with a ratio of breaking wave height to breaking depth, i.e., breaker index, of γ=0.7 and a breaking intensity parameter set to B = 1. The dissipation is assumed to be constant over the frequency range; this is expected to only affect predictions of third moment statistics (skewness and asymmetry) but not spectral levels (Chen et al., 1997). Energy input due to winds is not included given the relatively weak winds during the modeled period and small distance along the cross-shore transect considered. The dissipation effects are included in the spectral but not in the bispectral evolution. The resulting model is integrated to obtain the cross-shore evolution of the modal energy flux, accounting for nonlinear interactions, shoaling, and dissipation, represented by the net modal dissipation rate κ_j (see in Eq. (2) the net wave dissipation rate of flux integrated over the frequencies). See Appendix B