Evolution of Fine-Grained Sediment Deposits over Moderate to Long Time Scales

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LONG-TERM GOAL

My long-term goal within the STRATAFORM program is to increase our understanding of the processes controlling the formation, reworking and preservation of event-scale stratigraphy on the continental shelf.

OBJECTIVES

The objectives of this project for FY00 have been to 1) develop a coupled model for resuspension, flocculation and consolidation of fine-grained shelf sediment; 2) apply our 2-dimensional shelf sediment transport model to the Eel shelf to understand patterns of net erosion and deposition and the evolution of bed surface texture on event time scales; 3) run my 1-dimensional shelf sediment transport model for the complete set of conditions recorded by the long-term tripod at Site S-60; and 4) compare transport on the Eel shelf to that on the Russian River shelf.

APPROACH

My approach combines model development and application with data analysis to better understand shelf sediment transport processes, facilitate data analysis, and improve our predictive capabilities. This approach yields insights into transport and bed processes at time scales of events, decades to a hundred years (~ period of record), and geological time scales (1000's years or more).

WORK COMPLETED

Model development during the past year has primarily focussed on developing a time-dependent shelf sediment transport model that includes flocculation and consolidation processes. The model is now operational using Paul Hill's formulation for flocculating suspensions and observed time-dependent critical shear stress profiles (Johansen et al., 1997) resulting from bed consolidation. Last year I developed a numerical model of bed consolidation. This fall, I will be fully coupling that to the resuspension and flocculation model.

We have used the two-dimensional, time-dependent model developed by Courtney Harris to quantify across-shelf transport, deposition and sorting during transport events on continental shelves (Harris and Wiberg, submitted). I have run my 1D model to calculate transport rates for all available data from the long-term tripod at Site S60 on the Eel shelf. I have also compared sediment transport and bed reworking on the Eel and Russian River shelves (Wheatcroft, Wiberg and Butman, in preparation).

RESULTS

Coupled model of resuspension, flocculation, and consolidation for fine-grained sediment

The coupled suspended sediment equations below, which follow a formulation suggested by Paul Hill, have been used to investigate time-dependent flocculation across size classes during resuspension events. These equations partition mass between two states, disaggregated and aggregated, for each size class *j*.

$$\frac{\partial Cs_j}{\partial t} = -B_j Cs_j \hat{N}f + kC_f - w_s \frac{\partial Cs_j}{\partial z} + \frac{\partial}{\partial z}\left(K \frac{\partial Cs_j}{\partial z} \right),$$
$$\frac{\partial Cf_j}{\partial t} = B_j Cs_j \hat{N}f - kC_f - w_f \frac{\partial Cf_j}{\partial z} + \frac{\partial}{\partial z}\left(K \frac{\partial Cf_j}{\partial z} \right).$$

Cs_j and Cf_j are the mass concentrations for sediment size class *j* in the disaggregated and aggregated (flocculated) state respectively. Flocculation of disaggregated particles is determined by the concentration of mass in the disaggregated state *Cs*, the estimated number of aggregates *Nf*, and a flocculation rate between aggregates and disaggregated particle of size class *j*. B_j is the flocculation rate based on the sum of shear induced scavenging of already existing flocs and scavenging due to differential settling, as formulated by Hill and Nowell (1995). The disaggregation rate *k* is poorly understood. Determinations of *k* based on shear velocity and local shear stress in the water column have been postulated to relate disaggregation to properties of the bottom boundary layer. Initial aggregate concentrations must also be specified. Currently, initial aggregation of particles is based on sediment concentrations in the water column and a flocculation time-scale. We are testing the sensitivity of the model to the initial aggregation formulation.

Fine-grained sediment consolidates following deposition. As porosity decreases with depth and time due to consolidation, the critical shear stress for sediment resuspension increases. Increases in critical shear stress below the bed surface limit sediment erosion rates and therefore reduce suspended sediment concentrations. The effects of consolidation on erosion rates are included in the model by imposing a time-varying critical shear stress profile in the bed surface layers based on observations by Johansen et al. (1997). Sediment that is exchanged with the bed during transport conditions is maintained in an unconsolidated, high porosity layer at the bed surface with a relatively low critical shear stress (~0.08Pa).

The combined flocculation/consolidation model was tested using a time series of flow and suspended sediment concentration from Site S60 on the Eel River shelf (Figure 1). In the absence of flocculation and bed consolidation (and effects of stratification), large deviations exist between measured and calculated concentrations 0.3m and 1.0 m above the bed (mab). Including flocculation draws down the calculated concentrations to values more in line with measured values. Including a realistic profile of critical shear stress for a consolidated bed of fine-grained sediment yielded significantly better estimates of sediment concentrations than those obtained with or without flocculation (Figure 1).

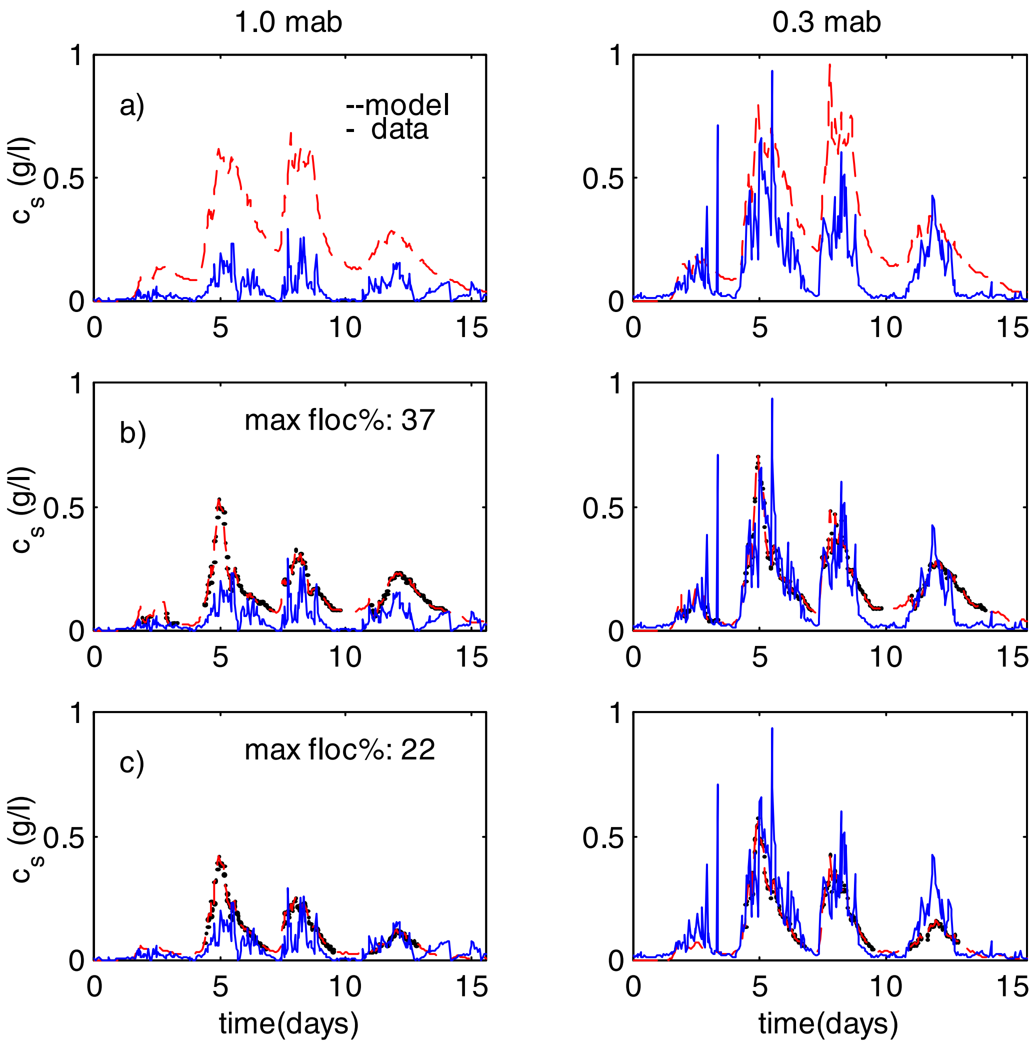

Figure 1. Calculated suspended sediment concentrations 0.3m and 1.0m above the bed (mab) for a series of wave resuspension events at Site S60 on the Eel shelf in the fall of 1995. (a) no flocculation or consolidation; (b) flocculation but no consolidation; (c) flocculation and consolidation. Maximum floc percentage in the water column is indicated for cases (b) and (c).

Application of the two-dimensional, time-dependent shelf transport model

During wave-driven transport events, decreasing wave orbital velocity with increasing depth leads to a cross-shelf gradient in bed shear stress. High bed shear stresses on the inner shelf lead to winnowing of the seabed within a few hours of the onset of energetic waves. As fine sediment is removed from the bed and advected downstream, the seafloor becomes unable to supply fine-grained sediment to the suspended load. Flux convergence and decreases in bed shear stress below the critical shear stress allows the fine sediment to deposit primarily on the mid and outer shelf. The resulting cross-shelf variations in sediment size are most pronounced on narrow, steep shelves where flux gradients are stronger and advection can transport sediment over a larger range of water depths. Cross-shelf textural variations in turn affect fluxes. Suspended sediment calculations that neglect seabed winnowing and, on narrow shelves, advection, will be inaccurate within hours of the onset of resuspension.

The characteristics of the storm beds produced by a wave-driven resuspension event reflect cross-shelf patterns in transport and deposition. On the inner shelf, the storm beds are predominantly coarse layers of reworked sediment that are 1-2 cm thick for storm events observed at the STRATAFORM site. The maximum depth of reworking depends on the maximum bed stresses reached during a transport event. As water depth increases, the depth of reworking decreases and the proportion of fine sediment in the reworked layer increases. On narrow shelves, the thickness of mid-shelf storm beds can be augmented by net deposition due to cross-shelf advection and flux convergence. Net deposition added up to 0.5 cm to the thickness of mid-shelf storm beds calculated for the narrow-shelf transect. On less steep slopes, net deposition is minimal and the depth of reworking is responsible for determining event bed thickness. In all cases, there was net erosion in the inner shelf.

The cross-shelf gradient in wave-generated bed shear stress, combined with fluctuations in cross-shelf current velocity provides a net drift of sediment towards deeper water. Over time, this acts to remove fine-grained sediment from inner and mid-shelf regions and deliver it to the outer-shelf and continental slope. The presence of fine-grained sediment deposits at mid-shelf depths on many shelves implies that other processes, such as consolidation, bioturbation, and the addition of new sediment through river flooding, act to retain fine sediment in these areas.

Transport calculations for the Eel shelf and comparison to the Russian shelf

Measured suspended sediment concentrations 0.3m above the bed at site S60 (long-term tripod) on the Eel shelf reveal a marked difference during times of high and low river discharge (Figure 2). During low discharge, average concentration as a function of wave condition is consistent from year to year and is well captured by my 1-dimensional sediment transport model. However, when discharge is high, measured suspended sediment concentrations are higher and much more variable. The model accounts only for local resuspension from the bed, so the introduction of sediment from the river plume or from gravity flows of fluid muds are not represented in the model. One effect that presently is being included is the increased mobility of newly deposited sediment that has not had time to consolidate. This will increase calculated suspended concentrations during high discharge conditions.

Suspended sediment concentrations and fluxes during transport events depend on wave and current conditions and on bed sediment properties. The relative importance of these factors on concentration and flux were determined for a resuspension event in April 1988 for which wave and current data at water depth of 90 m are available for both the Eel and the Russian River shelf. Calculated suspended sediment concentrations 1.0 mab during the resuspension event are 2.5-3 times higher on the Eel shelf than the Russian shelf; suspended sediment flux is 4 times larger. Of the difference in flux, about 5-10% is attributable to differences in bed sediment (slightly finer on the Eel shelf); 15-20% each to differences in waves (~20% higher on the Eel shelf) and to subtidal currents (comparable at the two site), and 55-60% to differences in tidal currents (about twice as large on the Eel shelf). The contribution of each factor to differences in suspended sediment concentration 0.3 mab is similar, except that the effect of wave differences increases to about 35% and the effect of tidal current differences decreases to about 40%.

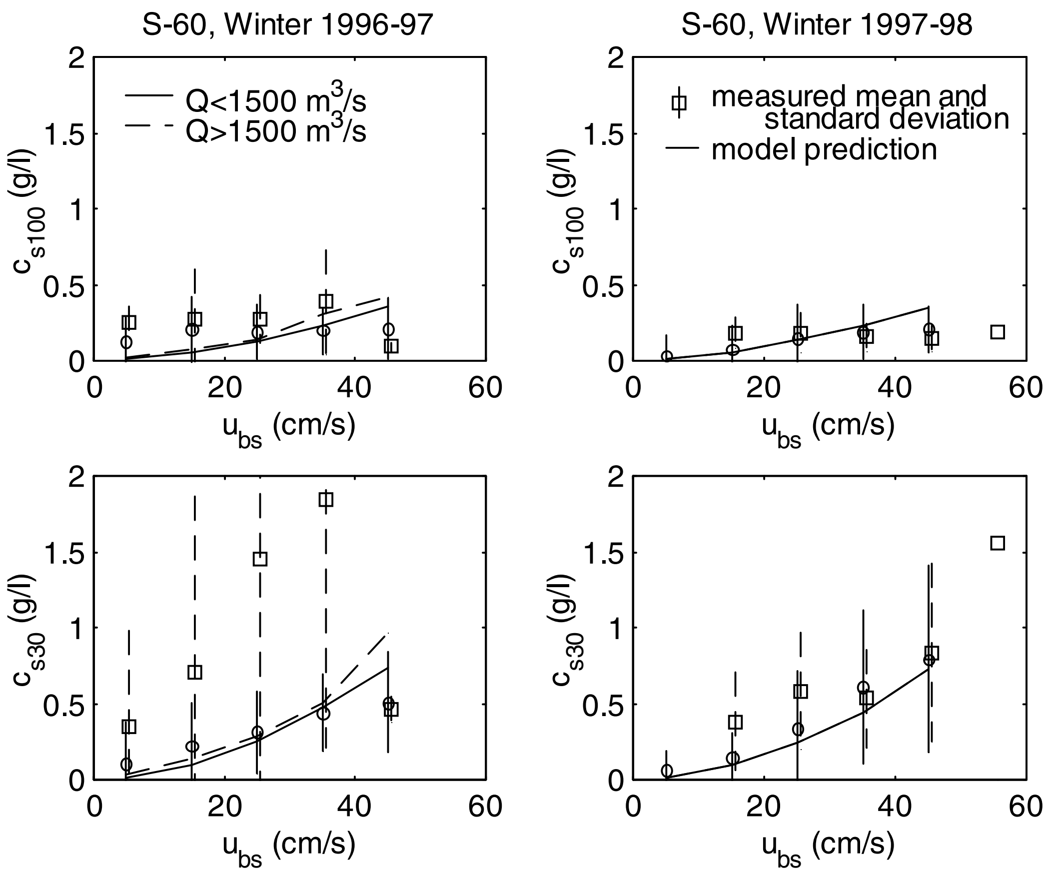

Figure 2. Comparison of average measured and predicted suspended sediment concentrations 30 cm and 100 cm above the bed as a function of near-bed wave orbital velocity, u_{bs}, at Site S60 on the Eel shelf; data and calculations are separated by high and low discharge of the Eel River.

IMPACT/APPLICATION

The results of the coupled resuspension, flocculation, and consolidation model and the two-dimensional sediment transport model indicate that bed consolidation and resulting decreases in entrainment rates are of primary importance in maintaining mud deposits on the shelf. Large storms on the Eel shelf could have removed the deposits of the 1995 and 1997 floods if consolidation had not reduced the mobility of these fine-grained deposits.

TRANSITIONS

I am going to work with Courtney Harris on incorporating effects of consolidation in her 3D sediment transport model calculations. Consolidation-related effects may also play a role in mine burial prediction. I have proposed testing this model as part of the Mine Burial Prediction program.

RELATED PROJECTS

The coupled resuspension, flocculation, and consolidation model is an important element in my Harbor Processes study, where we are using it to determine desorption rates during resuspension events.

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