Integration of an Analytical Model for Shelf Sediment Deposition into SedFlux

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LONG-TERM GOAL

The global objective of the Virginia Institute of Marine Science (VIMS) involvement in the STRATAFORM program is to improve understanding of the spatially and temporally varying mechanisms that suspend, transport, and deposit sediment specifically on the continental shelf in the vicinity of the mouth of the Eel River and generally on continental shelves that are accumulating fine sediment.

SCIENTIFIC OBJECTIVES

The Final STRATAFORM Modelers Meeting identified critical steps required to achieve an integrated continental margin modeling system. One of these critical steps is incorporation of an updated, process-oriented shelf sedimentation algorithm within the larger SedFlux model. During Phases III of STRATAFORM, gravity-driven flows of fluid mud within the wave boundary layer were identified as the dominant mode of across-shelf transport of fine sediment during flood years. Thus the primary scientific objectives of our present project are to develop, validate and help implement within SedFlux a simple, computationally efficient formulation for shelf deposition which includes the fundamental physical processes associated with wave-driven gravity flows.

APPROACH

Our analytical model is based on the following two relations (Wright et al., 2001):

$$\alpha B \approx c_d U u_{grav}, \qquad Ri_{cr} = U^2/B \qquad (1a,b)$$

where α is the shelf slope, B is the depth-integrated buoyancy anomaly due to suspended sediment, $c_d \approx 0.003$ is the bottom drag coefficient, U is the strength of waves plus current at the top of the wave boundary layer, u_{grav} is the across-shelf velocity of the gravity current within the wave boundary layer and $Ri_{cr} \approx 1/4$ is the critical gradient Richardson number. Eq. (1a) is the linearized momentum balance governing a sediment-laden gravity current within the bottom boundary layer, while (1b) determines the maximum amount of sediment which can be suspended by U. Eq. (1a) provides an advance over previous analytical treatment of the Chezy balance because it includes the effects of ambient waves and currents in providing the turbulence needed to support the gravity current while simultaneously enhancing the drag resisting down-slope motion. Eq (1b) is also a significant advance in that it employs a powerful negative feedback mechanism. The total sediment load is limited to $B = U^2/Ri_{cr}$ because additional suspension would shut down the generation of turbulence by shear instability.

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14. ABSTRACT

The global objective of the Virginia Institute of Marine Science (VIMS) involvement in the STRATAFORM program is to improve understanding of the spatially and temporally varying mechanisms that suspend, transport, and deposit sediment specifically on the continental shelf in the vicinity of the mouth of the Eel River and generally on continental shelves that are accumulating fine sediment.

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Combining (1a) and (1b) to solve for u_{grav} and across-shelf gradients in sediment transport give

$$u_{grav} = \alpha \ Ri_{cr} U/c_d, \qquad D = d/dx \{(g\rho_s/s) B u_{grav}\} \qquad (2a,b)$$

where D is the sediment deposition rate, g is 9.8 m/s^2, ρ_s = 2.65 g/cm^3 is the density of siliceous sediment, and $s = (\rho_s - \rho_{water})/\rho_{water} = 1.65$ (g, ρ_s and s are needed to convert B back to appropriate units of sediment mass). Shelf slope, the critical Richardson number and the drag coefficient are all reasonably constrained. U is often dominated by wave orbital velocity which can be easily predicted from observed or modeled wave height and period. Thus (1)-(2) give the sediment transport and deposition rates associated with gravity currents within the wave boundary layer without needing any information about the sediment itself. The only other assumption employed in our basic formulation is that sediment supply is locally unlimited. If the supply of available sediment cannot provide a concentration sufficient to reach Ri_{cr}, then the above theory locally predicts D = 0.

WORK COMPLETED

In FY01 we presented and published the theory behind our shelf deposition model (Friedrichs et al., 2000; Wright et al., 2000, 2001) and used time-series and core data collected by STRATAFORM investigators to validate the model for the Eel shelf (Friedrichs et al., 2001a, Scully et al. 2000, 2001a,b,c,d). A paper documenting our model-data comparison using a 1-D (across-shelf) formulation (Scully et al., 2001a) was submitted for publication during the summer of FY01. A draft of a second paper comparing observations and model results in 2-D (across- and along-shelf) was completed (Scully et al., 2000b) and is to be submitted for publication soon after Malcolm Scully has defended his Masters thesis in September 2001 (Scully, 2001). Our validation results were also presented during FY01 at the Chapman Conference (Friedrichs et al., 2001a; Scully et al., 2001c,d).

Another major focus this year was incorporating the code for our analytical model for mid-shelf mud deposition into James Syvitski's SedFlux code. To help accomplish this task, Scully spent a week during spring FY01 in Boulder, Colorado, working with James Syvitski and Eric Hutton at INSTAAR. We purchased time on "Deep Purple", the super computer at INSTAAR funded by ONR, and familiarized ourselves with Deep Purple's operation while performing 2-D model simulations of gravity-induced deposition on the Eel Shelf. We delivered a preliminary version of our code to Syvitski's group in January 2001, delivered an updated version during Scully's visit to INSTAAR in May, and discussed the SedFlux code further with Syvitski at the Chapman Conference in June. In summer FY01, Syvitski and Hutton finished incorporating the May 2001 version of our code into SedFlux, and in September Syvitski presented results of gravity-driven shelf deposition using our contributions to SedFlux at the 2001 IAMG Conference in Cancun, Mexico (Syvitski et al., 2001). Our own preliminary results of 1-D simulations on geological time-scales were presented at the 2001 Chapman Conference (Friedrichs et al., 2001b).

RESULTS

Our 1-D analytical model has reproduced observed time-series of near-bed velocity and deposition (Figure 1) on the mid-shelf following Eel River flood events under conditions where sufficient fine sediment was available from river floods to critically stratify the wave boundary layer. If insufficient sediment is delivered to cause critical stratification, energetic waves enhance drag and retard down-slope transport and limit deposition. Analytic predictions of deposition suggest that the magnitude of wave energy is more important than the magnitude of the flood event in controlling the thickness of mid-shelf gravity-driven deposition following floods of the Eel River. This provides an explanation for why the largest flood during the STRATAFORM program did not produce the thickest observed mid-shelf flood layer. Higher wave energy increases the capacity for critically stratified gravity flows to transport sediment to the mid-shelf and results in greater gradients in flux and hence deposition. Instead, flood magnitude determines how close to shore the flood deposit begins and how far along-shelf it extends.

Our 1-D model results also demonstrate that the bathymetry of the Eel margin plays a critical role in gravity-driven transport and deposition. Analytic predictions indicate that gravity-driven deposition on the mid-shelf begins roughly 7-8 km north of the river mouth. Closer to the river mouth, the seaward increasing mid-shelf slope associated with the convex upward subaqueous delta causes gravity-driven flux divergence, preventing significant mid-shelf gravity-driven deposition and favoring sediment bypassing. Seaward decreases in shelf slope in the vicinity of the observed flood depo-center lead to greater flux convergence by gravity-driven flows, and hence greater deposition. Farther north, the supply of sediment diminishes sufficiently to prevent significant gravity-driven deposition. The analytic predictions of mid-shelf mud deposition are spatially and temporally consistent with field observations and provide strong evidence that gravity-driven processes control the emplacement and location of the Eel margin flood deposit.

We used our two-dimensional numerical model to more accurately predict large-scale gravity-driven deposition on the continental shelf for four consecutive flood seasons of the Eel River using realistic bathymetry, waves and river forcing. During two of these years (Figure 2), the Eel River experienced large flood events that left distinct deposits of fine sediment on the mid-shelf. The predicted magnitude and distribution of gravity-driven deposition of river-derived sediment on the mid-shelf are consistent with field observations. Greatest deposition on the mid-shelf is predicted well north of the river mouth despite greater sediment input near the river mouth. As in the 1-D case, 2-D numerical model results indicate that wave intensity and the bathymetry of the Eel shelf are the dominant factors controlling the observed pattern of deposition. Both gradients in the along-shelf and across-shelf bed slope favor mid-shelf deposition in the region 10-35 kilometers north of the river mouth. The thickest mid-shelf deposition is predicted to occur following large floods with the highest associated wave energy. Large wave energy also allows significant amounts of sediment to escape the shelf as gravity-driven flows. The greatest amount of sediment is predicted to leave the shelf from the region off-shelf of the river mouth where inshore sediment input is high and the concave downward bathymetry associated with the Eel River subaqueous delta prevents significant gravity-driven deposition.

The implementation of our analytical solution within the SedFlux code has been used by James Syvitski's group to investigate the role of sediment supply on the stratigraphic evolution of continental margins over geologic time scales. Their preliminary results suggest that margins with large sediment loads and small waves develop narrower shelves than margins with smaller sediment loads and large waves. This is because our analytical approach predicts that under small wave/large supply conditions the wave boundary layer will be overwhelmed by sediment and deposit material close to shore, whereas under large wave/small supply conditions the wave boundary layer will be overwhelmed and deposit far from shore.

IMPACT/APPLICATIONS

A present limitation in long-term modeling of continental margin evolution is realistic inclusion of hydrodynamic processes driving shelf deposition. Based on field observations collected over the last

20 years, complex wave-averaged currents driven by winds and pressure gradients have been thought to be mainly responsible for cross-shelf sediment transport and flux convergence on energetic accretionary shelves. Unfortunately, it may be exceedingly difficult to predict wind- and pressure-driven near-bed currents with sufficient accuracy to produce realistic deposits over geological time-scales. The ONR STRATAFORM project, however, recently identified a distinctly different mechanism for across-shelf mud transport associated with gravity-driven flows of fluid mud within the wave boundary layer. Gravity flows within the WBL can be realistically modeled based on knowledge of fine sediment supply, approximate wave height and bathymetry if one assumes that the critical Richardson number within the WBL determines the maximum capacity of the gravity flow to transport mud. Complex, externally forced mean currents do not appear to play a critical role in this newly identified transport mechanism. Thus the analytical model presented here has the potential to greatly reduce the complexity and computational limitations presently limiting our ability to perform realistic long-term simulations of the geologic evolution of many continental margin environments.

TRANSITIONS

Our data on bed stresses and resulting sediment resuspension from earlier years of this project have been made available to modelers and other STRATAFORM investigators and are being used to verify bottom boundary layer and sediment transport models. Our data can easily be accessed via data reports (which include data summaries on diskettes) and via the VIMS STRATAFORM website. Published papers by others which have directly utilized VIMS data include Morehead and Syvitski (1999), Ogston et al. (1999, 2000), Reed et al. (1999) and Zhang et al. (1999). Additional papers by non-VIMS authors incorporating VIMS data are in preparation. Our analytical formulation for sediment flux and deposition by critically-stratified, gravity flows has already been incorporated into long-term simulations of margin stratigraphic development by James Syvitski's ONR-funded group (Syvitski et al., 2001). Our analytical approach has also been made available to other STRATAFORM modelers, such as Fan, Harris, Niederoda, Reed, Swift, and Traykovski, all of whom are at various stages of incorporating gravity flows into more complex numerical simulations of shelf sedimentation.

RELATED PROJECTS

The following projects involving Friedrichs and/or Wright also address fine sediment transport and accumulation in coastal environments:

1. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (Marine Geology and Geophysics).

2. A Review of the Present Knowledge of Mine Burial Processes. Office of Naval Research (Marine Geosciences).

3. Spatially Complex Shoreface Roughness in Sediment Transport and Deposition, A New Zealand Case Study and Model Development. National Science Foundation (International Programs).

4. How Do Estuarine Turbidity Maxima Entrap Particles, Retain Zooplankton, and Promote Recruitment of Fish? National Science Foundation (Biological Oceanography).

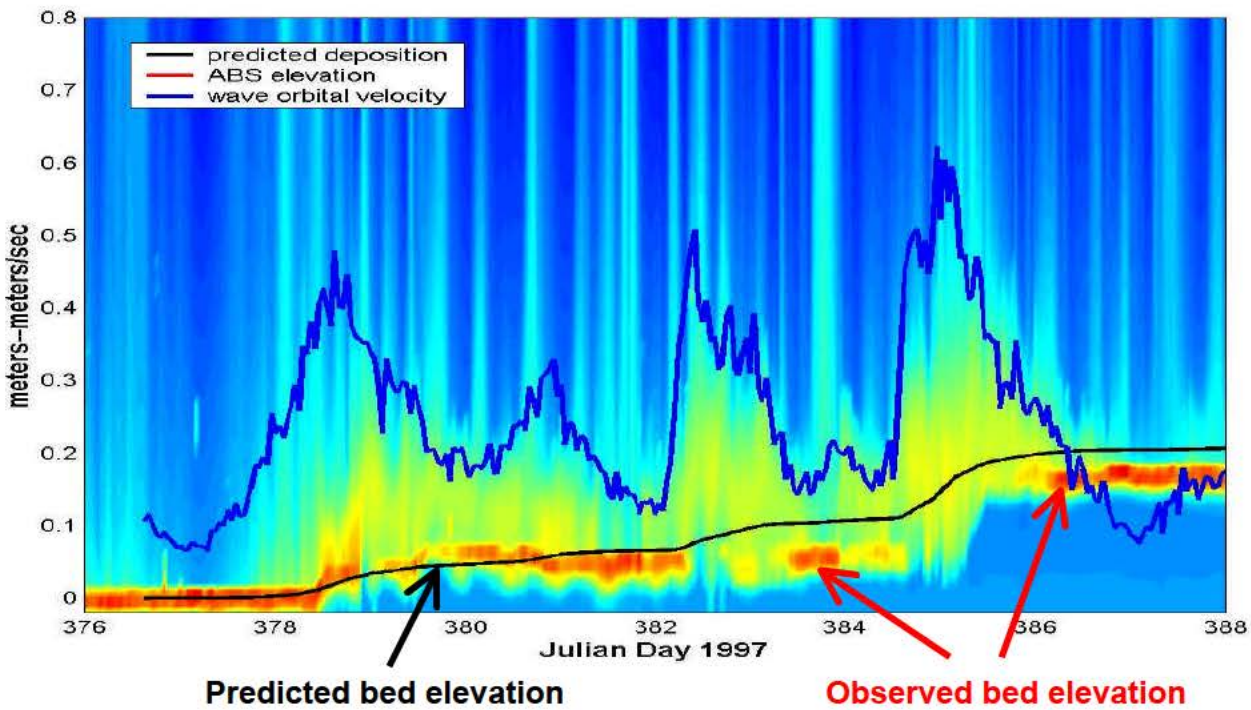

Figure 1. Predicted deposition at K-line 60-m site based on 1-D analytic solution for wave-induced gravity flows (Scully et al., 2001a). Observations from Traykovski et al. (2000).

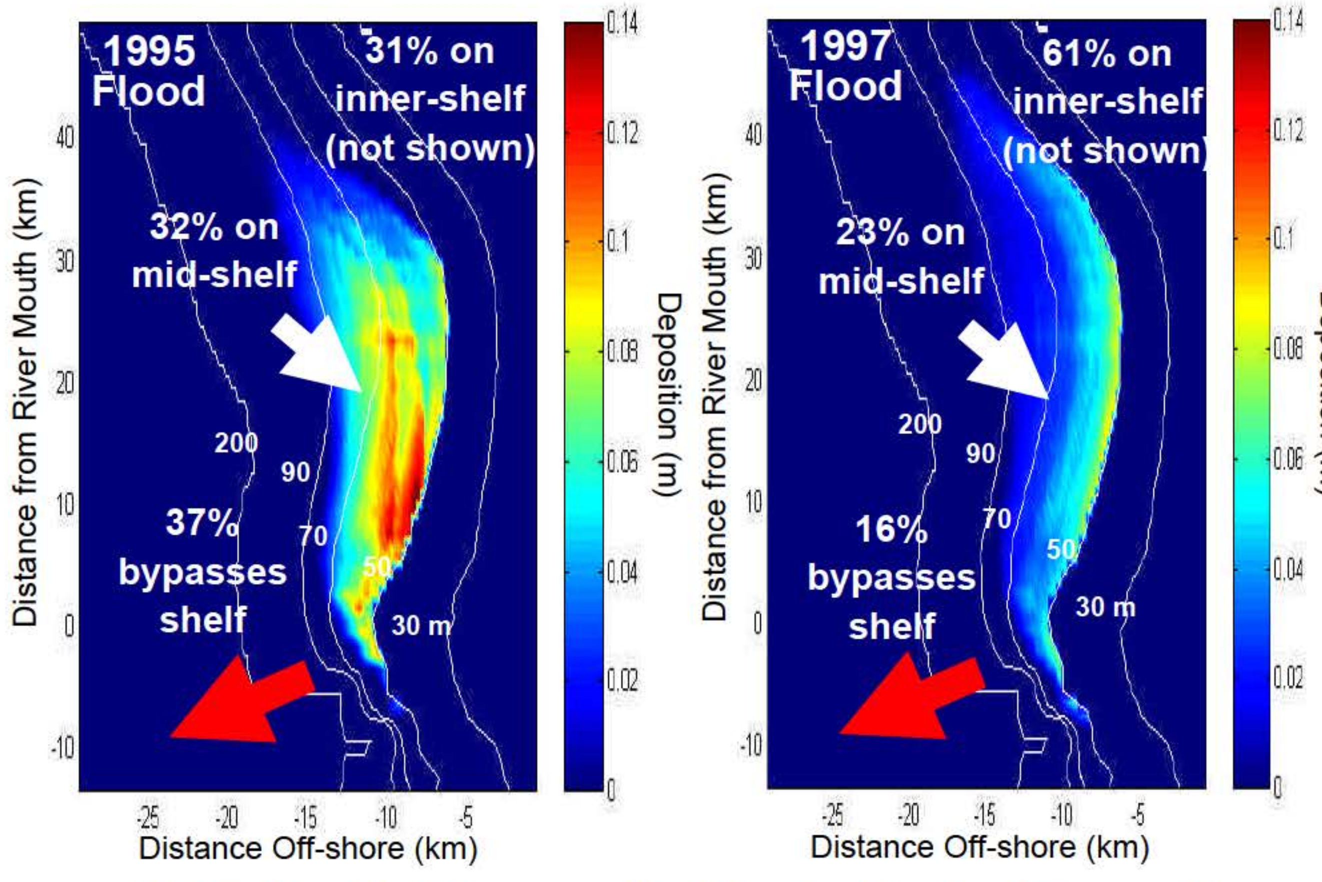

Figure 2. 1995 and 1997 flood deposition on Eel Shelf predicted by 2-D model numerical for wave-induced gravity flows (Scully et al., 2001b).

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