Integration of an Analytical Model for Shelf Sediment Deposition into SedFlux

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LONG-TERM GOALS

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.

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 scientific objectives of our present project are (i) to develop and validate an analytically-based, physically realistic algorithm for shelf deposition due to wave-supported gravity flows and (ii) to help implement the resulting computationally efficient formulation into SedFlux.

APPROACH

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

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

where α is the shelf slope, B is the depth-integrated buoyancy anomaly due to suspended sediment, $c_d \approx 0.003$ to 0.005 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.

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

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

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 FY02 we published additional theory related to our shelf depositional model (Friedrichs, 2002a), used time-series and core data collected by STRATAFORM investigators to validate the model for the Eel shelf and explain the fundamental depositional processes occurring there (Scully, 2001; Scully et al., 2002a,b,c), experimented with the SedFlux model with our analytical model fully incorporated (Syvitski et al., 2002), developed new theory to further validate the theoretical underpinnings of our analytical model (Parsons et al., 2002), and applied our analytical solution to new environments other than the Eel Shelf (Friedrichs, 2002b; Wright et al., 2002).

RESULTS

Our analytical model has reproduced observed time-series of near-bed velocity and deposition 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 (Scully et al., 2002a). Analytic predictions of deposition suggest that the magnitude of wave energy is locally 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. Our model results also demonstrate that the bathymetry of the Eel margin plays a critical role in gravity-driven transport and deposition (Scully et al., 2002a,b). Close 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 via the Eel Canyon (Figure 1). 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.

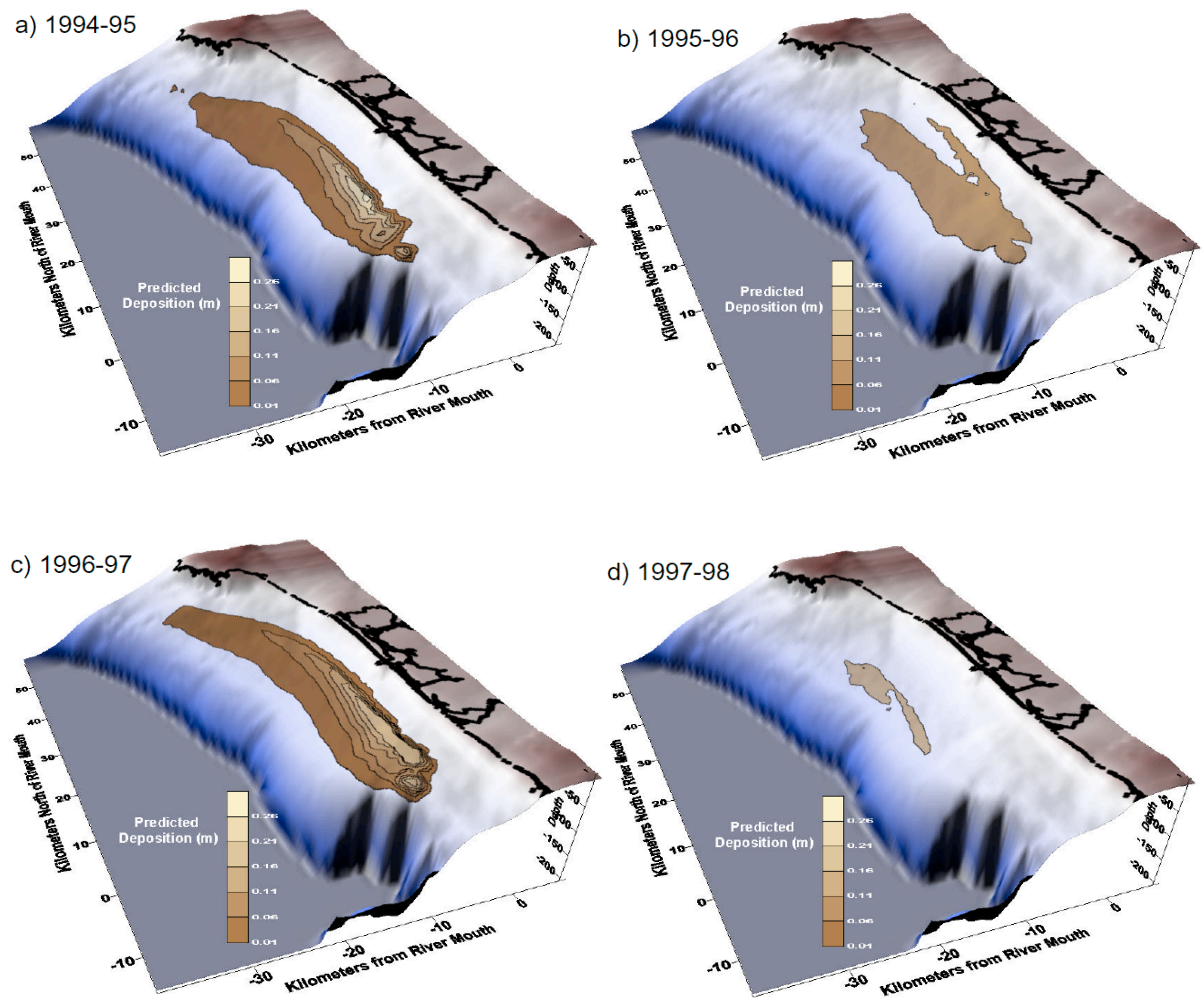

Figure 1. Winter flood season deposition on the Eel shelf for the first four years of STRATAFORM as predicted by the numerical algorithm for wave-supported gravity flows which has been incorporated into SedFlux (Scully et al., 2002b).

The implementation of our analytical solution within the SedFlux code has been used in collaboration with James Syvitski to investigate the role of sediment supply on the stratigraphic evolution of continental margins over geologic time scales. Initial results from numerical experiments using SedFlux suggest that margins with large sediment loads and small waves develop narrower shelves than margins with smaller sediment loads and large waves (Syvitski et al., 2002). This encouraged us solve for equilibrium shelf profiles based on our analytical solution alone. If one assumes that equilibrium depositional shelves prograde until wave-supported gravity currents are just able to bypass the inshore supply of sediment, Q, during large river events, then Eqs. (1) and (2) lead to the following relation for equilibrium shelf slope, □:

$$(\square Ri_{cr}/c_d)\ (1 - (\square Ri_{cr}/c_d)^2)^{-3/2} = 8Qsg/(\square_s Ri_{cr})\ (\sinh kh/H\square)^3 \qquad (3)$$

where k is wave number, h is water depth, H is wave height and □ is radian wave frequency. This equation does a good job of reproducing the observed slope of the mid-shelf (50 m to 100 m water depth) off the Eel River (Figure 2). Equilibrium shelf slope is predicted to decrease farther from the mouth of the Eel because sediment supply from the river plume also decreases with distance from the river mouth. Preliminary results suggest Eq. (3) applies well to other shelves with high riverine sediment loads such as the Waiapu shelf in New Zealand (Friedrichs, 2002b). Off the Waiapu, smaller waves and a larger sediment load result in a steeper equilibrium shelf closer to shore.

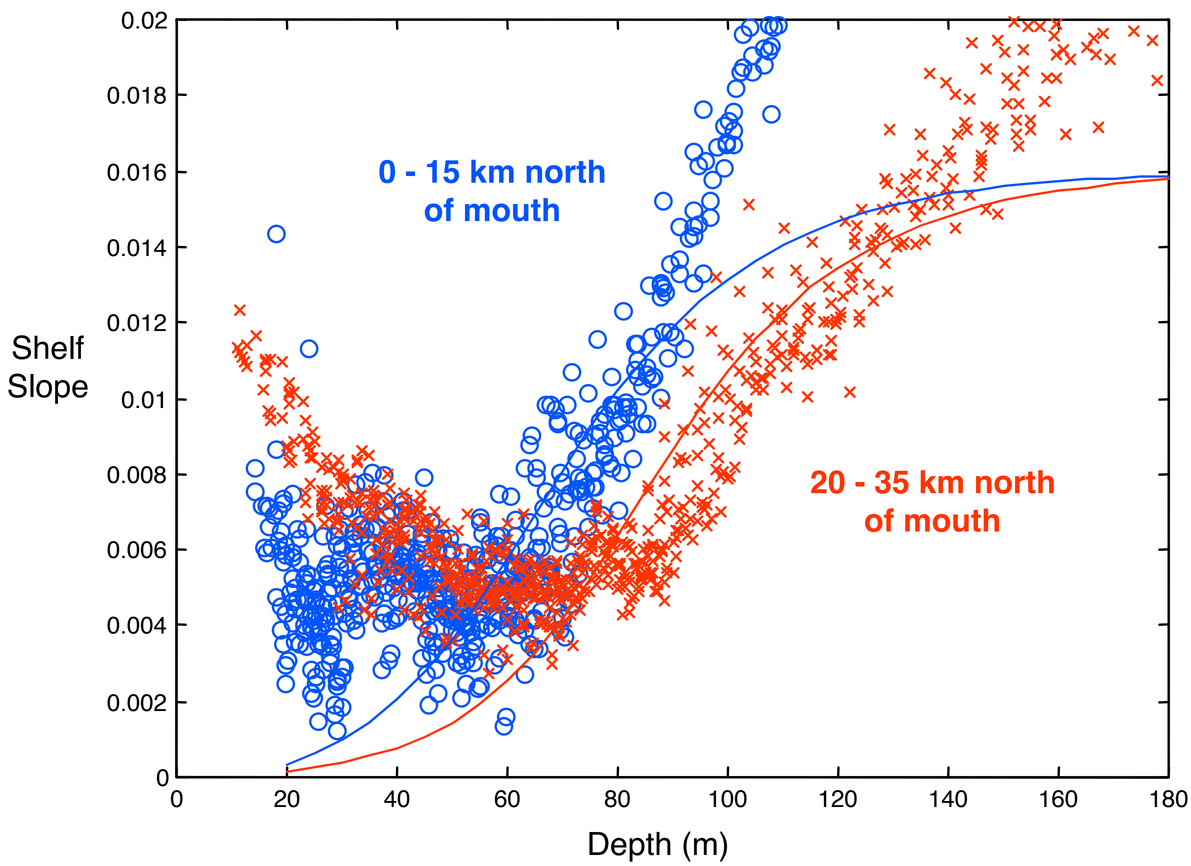

Figure 2. Comparison of observed Eel Shelf slope (o,x) with that predicted by Eq. (3) (curves). Discharge and waves are based on values characteristic of large events such as the January 1995 and January 1997 floods.

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, 2002). 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 active projects involving Friedrichs also focus on coastal sediment transport:

1. Upscaling Simple Models for Energetic Shelf Sediment Transport. Office of Naval Research (www.vims.edu/physical/projects/CHSD/projects/Euro).

2. Forecasting Scour Related Mine Burial Using a Parameterized Model. Office of Naval Research (www.vims.edu/physical/projects/CHSD/projects/MBP).

3. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (www.vims.edu/physical/projects/CHSD/projects/CAREER).

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