Sediment Transport at Density Fronts in Shallow Water

David K. Ralston
Applied Ocean Physics and Engineering, MS #12
Woods Hole, MA 02543
phone: (508) 289-2587   fax: (508) 457-2194   email: dralston@whoi.edu

LONG-TERM GOALS

The goal of this research is to quantify through observations and modeling how density fronts in shallow estuarine flows impact the mobilization, redistribution, trapping, and deposition of suspended sediment.

OBJECTIVES

The objectives of this research program are to
- implement a high-resolution, 3-dimensional, finite-volume hydrodynamic model of tidal flats field site including advanced sediment transport algorithms,

- integrate and test a set of field instruments to measure density, velocity, and suspended sediment concentration at density fronts in shallow water (< 1 m),

- characterize flow and suspended sediment at a density front through the tidal inundation cycle as it travels across the intertidal zone, and

- combine the observations and model results to (1) quantify sediment suspension, trapping, and lateral circulation at the front and (2) evaluate and improve the sediment transport model.

APPROACH

The research approach combines observational and modeling techniques. In the field, we measured velocity and suspended sediment at high resolution in shallow flows, tracking the evolution of the salinity front through the tidal cycle. The instrumentation incorporates an acoustic Doppler current profiler (ADCP) to measure currents and a profiling conductivity-temperature-depth sensor (CTD) to measure water column salinity and density. Suspended sediment concentrations are based on a combination of acoustic and optical sensors, with calibration provided by gravimetric analysis of water samples taken during the surveys. A major field effort occurred in June 2009 on the Skagit Tidal flats in Puget Sound, coordinated with other researchers in the Tidal Flats DRI. Focused, Lagrangian observations of the shallow density front and its evolution through the tidal cycle were complemented by a large scale array of moored instruments deployed during the same period (Geyer, Traykovski, and Ralston).

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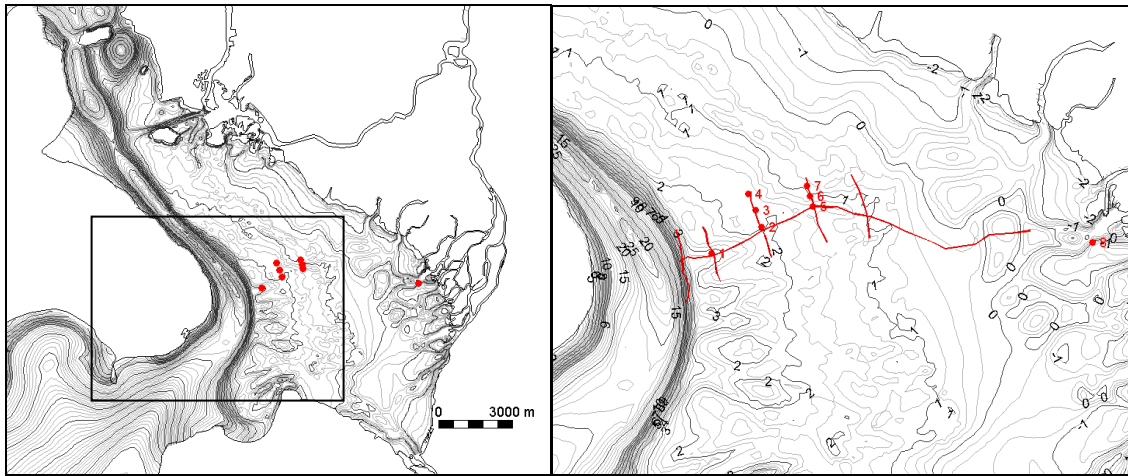| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Figure 1. Bathymetry of the Skagit Bay tidal flats (left) with a zoom on the study area on the southern flats (right). Red dots indicate frame locations, and lines show across-flats and across-channel survey lines.

In parallel with the observations, we are developing and analyzing a numerical modeling of the Skagit tidal flats. The model uses the Finite Volume Coastal Ocean Model (FVCOM), but has been modified to incorporate recent advancements in sediment transport modeling through code from the Community Sediment Transport Model System (CSTMS). The unstructured grid of FVCOM allows the model to simulate conditions broadly across the Skagit flats and surrounding region, but with focused grid resolution near the observations. The observations are being used to calibrate the model and to evaluate how well the model resolves sharp salinity gradients at fronts, both across the tidal flats and at lateral fronts coinciding with channel-shoal bathymetry. Collectively, analyses of the observations and model are being used to quantify how local frontal processes on scales of 10's to 100's of meters impact retention, redistribution, and export of sediment over tidal flats on scales of kilometers.

WORK COMPLETED

A major field effort was conducted in June 2009. We deployed an array of instrument platforms on Skagit flats (Fig. 1) designed to measure the flow and sediment-transport processes on the flats. After instrument deployment and just before recovery (approximately 5 days each period), we conducted high-resolution surveys of the currents, density, and suspended sediment distributions on the flats over mulitple tidal cycles. Surveys (locations shown in Fig. 1) were designed to characterize the cross-flat structure of the salinity front, and how the lateral distribution of density, currents, and supendeds sediment dependend on the structure of distributary channels on the flats.

The instrumentation at the quadpod stations measured acoustic profiles and optical point measurements of suspended sediment concentration, bed elevation, horizontal and vertical velocity, conductivity, temperature and depth. The acoustic profiles of sediment concentration and bed elevation were measured with Acoustic Backscatter Sensors (ABSs) and Pulse Coherent Doppler profilers. Each of the pods had 1 or 2 near-bed Acoustic Doppler Velocimeters (ADVs, with pressure sensor) for measurements of tidal currents, waves and turbulence. The stations had accompanying surface moorings with TS/OBS sensors, to quantify vertical and horizontal salinity and sediment gradients.
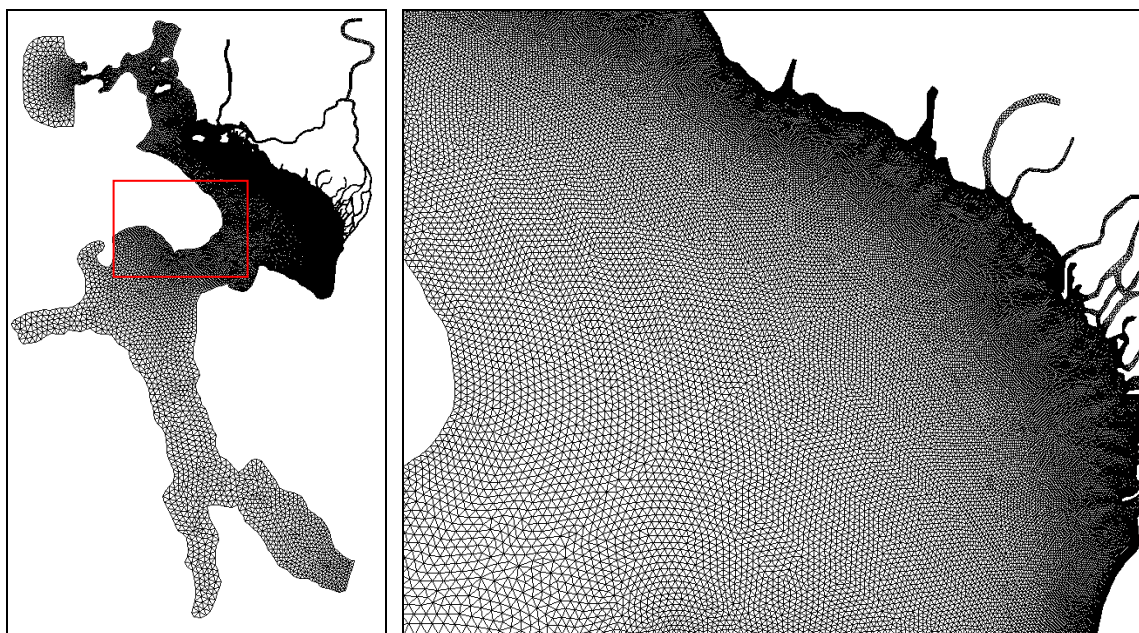
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Figure 2. Model grid of Skagit flats and surrounding region: (left) full domain, with open boundaries are at southern end of Saratoga Passage, west of Deception Pass, and the northern end of the Swinomsih channel, and (right) zoom on southern tidal flats region shown in Fig. 1. Minimum horizontal grid scale is about 10 m.

Extensive efforts have gone into development of a high-resolution numerical of the Skagit tidal flats and surrounding region. Bathymetry was collected from multiple sources and combined to create an unstrucutred model grid (Figure 2). Grid resolution ranged from about 10 m on the flats in the study region to over 500 m in more distant parts of the domain. The bathymetry and grid in the distributary network of the Skagit were refined basd on surveys of depth and discharge in the river during the June 2009 obsevations. Data for boundary forcing of tides, river discharge, and winds were aquired and input into the model. In addition to the grid and forcing, the hydrodynamic code (FVCOM) had to be modified and tested for this implemetnation. A sediment transport module that incorporates the latest verion of the CSTMS has been implemented into FVCOM, and simulations have been run for test cases and for the Skagit domain. FVCOM was also modified to incorporate the most recent version of the Generalized Ocean Turbulence Model (GOTM), allowing application of different turbulent closure schemes and parameters to the simulations than then default Mellor-Yamada scheme. The flexibility to evaluate different turbulence closures is particular important in a highly stratified environments like the Skagit and for sediment transport calcuations that are sensitive to the calcuation of near-bed turbulence.

RESULTS

Model simulations were run with realistic forcing (tides, river discharge) corresponding with the observation period in June 2009. Comparisons between observed and model salinity, velocity, and water surface elevation were used to adjust key model parameters. An important result of the calibration process has been to show the importance of low background mixing and bottom friction to accurate simulations. The Skagit flats were strongly stratified at times due to the spring freshet, with river discharge ranging between 930 $m^3 s^{-1}$ in early June and about 450 $m^3 s^{-1}$ by the end of the month.

To maintain sharp horizontal and vertical salinity gradients, the background values for turbulent and horizontal diffusivity were set to 10^{-6} m^2s^{-1} and 0, respectively. Similarly, the bottom roughness (z_0) was set to 0.1 mm, representative of relatively small roughness elements on the flats. Calibration and model refinement remains on-going, but results to date are encouraging. The model results compare well with the moored time series of water surface elevation, salinity and stratification, and velocity profiles. The model reflects the observed diurnal tidal pattern of extreme variability in stratification: unstratified during the strong floods, stratifying at high water and remaining stratified through the weaker ebb and flood, and mixing midway through the strong ebb. Similarly, comparisons with ADCP data show that both the magnitude and vertical structure of velocity are well-resolved in the model. Direct comparisons between observed and simulated suspended sediment concentrations have not yet been done, but will be evaluated pending processing of the field samples. Additionally, in-situ observations from other parts of the Skagit flats collected by DRI collaborators (Raubenheimer, Elgar, and colleagues) will be used to independently assess the model skill and to evaluate the spatial heterogeneity across the flats.

An example of the model results is shown in Figure 3 during an ebb tide with high river discharge. The snapshot illustrates the importance of stratification and baroclinicity to dynamics on Skagit tidal flats. The cross-flat section shows strong stratification extending over nearly the entire width of the tidal flats. As the water level falls later in the ebb, the stratification is mixed away. During strong flood tides that inundate the flats, the salinity front is well mixed. At the grid resolution of about10 to 20 m in the study region, the model reproduces many of the features observed in cross-flat transects. Additionally, the model provides information on the spatial structure of the currents and freshwater that is not possible to measure synoptically in the field. For example, the North and South Forks of the Skagit each have distinct regions of influence of the flats (see salinity maps and along-shore transect in Fig. 3), with a region in between the mouths that is less stratified and higher salinity. The currents over the flats are complex due to the phasing of the tide between Deception Pass and Saratoga Passage. Model results and in-situ observations indicate a mean transport toward the north and Deception Pass that varies with tidal amplitude. Surface fronts corresponding with convergence of different water masses (e.g., outflow from the North and South Forks) were observed in the field and also appear in the model.
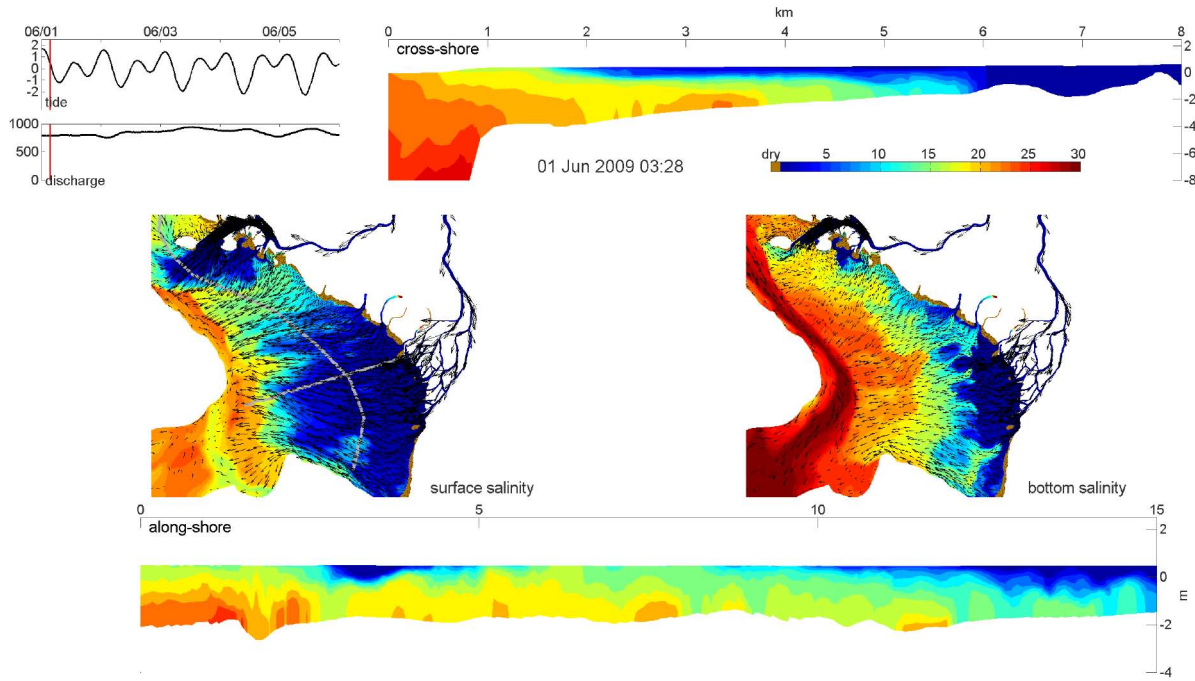
Figure 3. Model results with realistic forcing from early June 2009, when tides were moderate (between spring and neap) and river discharge was high (~950 m³s⁻¹). Maps of surface (left) and bottom (right) salinity are shown with across-flat (top) and along-shore (bottom) vertical sections. During ebbs, strong stratification extended over most of the tidal flats. During flood tides (not shown), the water column was well mixed as the salinity front moved across the flats with the rising tide.

The strong density gradients seen in the model were also observed in the field, coinciding at times with strong gradients in acoustic and optical backscatter. An example from late June is shown for an ebb during spring tides with moderate river discharge (~500 m³s⁻¹) (Figure 4). Early in the ebb (transect 1), strong stratification extends over the flats, velocity is highly sheared, and backscatter (indicative of suspended sediment concentration) is relatively low. Mid-ebb (transect 2), water level has fallen and the stratification has mixed on the upper flats but remains strong on the lower flats. In the unstratified region, velocities are more vertically uniform and backscatter is much higher, consistent with increased bottom stress and resuspension in the absence of stratification. By transect 3, the entire transect is well-mixed with high sediment concentrations. The transition from the stratified, low-sediment water to the well-mixed, high sediment concentrations was visible at times from the survey vessel (depending on sea state) as a change in water properties. Work is on-going to collaborate with DRI participants (Chickadel and Thomson) who were taking simultaneous aerial visible and infrared images to see how the transition in water properties appears in remote images. Initial comparisons between the model results and the frontal locations observed from the small boat are encouraging. The model provides the opportunity to resolve the 3-d structure of these features that is not possible from the field transects alone.
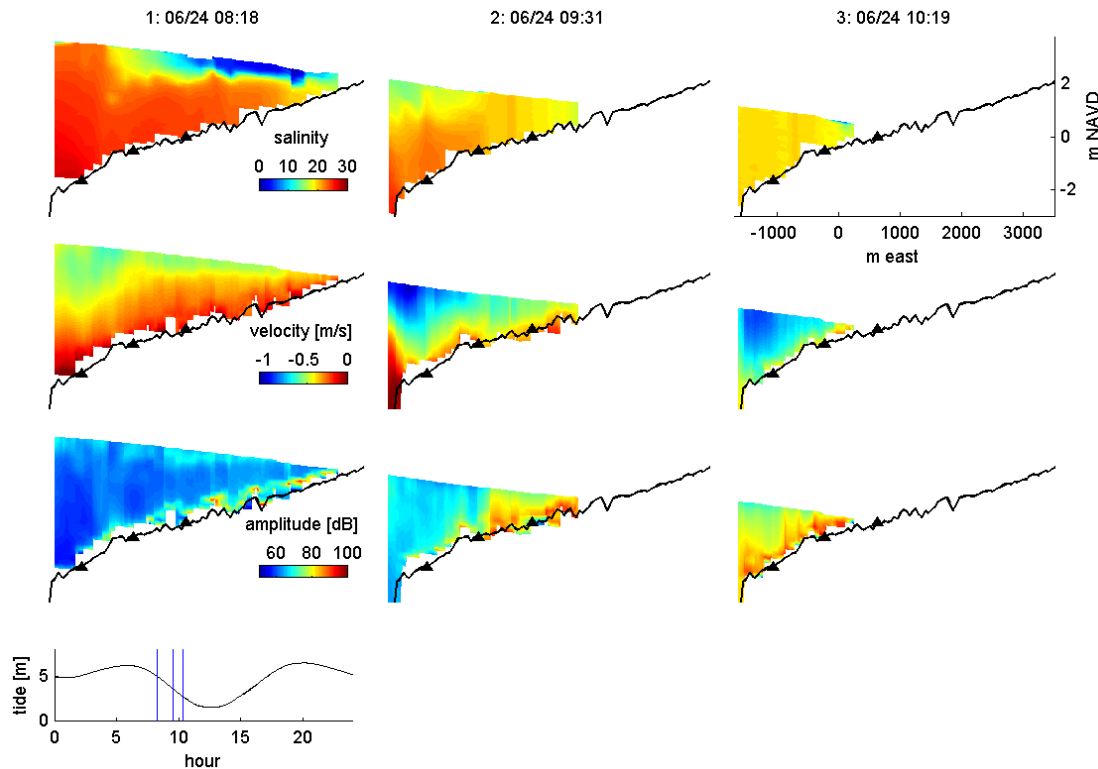
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Figure 4. Three across-flats surveys of salinity (top), velocity (middle), and acoustic backscatter (bottom) during a spring ebb tide on June 24. Tidal elevation time series is shown in the inset with the survey times indicated; positions of moored instruments at stations 1, 2, and 5 are marked with triangles on the transects. The sloping water surface reflects the change in water elevation during each transect.

IMPACT/APPLICATIONS

Results from this project may be used to enhance morphological models of coastal regions near river mouths, with applications to environmental assessment for the Navy.   Trapping and deposition of sediment associated with density fronts could introduce significant spatial and temporal variability in bed consolidation and bathymetric relief on tidal flats. The project will also help to evaluate the skill of coastal hydrodynamic models at resolving narrow density fronts, including the surface expression of such fronts that can be assessed with remote sensing observations.

RELATED PROJECTS

The work here is closely linked to several investigators in the Tidal Flat DRI. The field efforts on the Skagit were done in conjunction with Geyer, Traykovski, and Ralston ("Sediment Flux and Trapping on the Skagit Tidal Flats"). The model and grid development has been in close collaboration with Geoff Cowles. Collaborations with others involved in the DRI include Signell and Sherwood (CSTM implementation), Thomson and Chickadel (bathymetry), Raubenheimer and Elgar (bathymetry and observations for model calibration), and Lerczak (model development).

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