

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

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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 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 (along with Geyer and Traykovski).

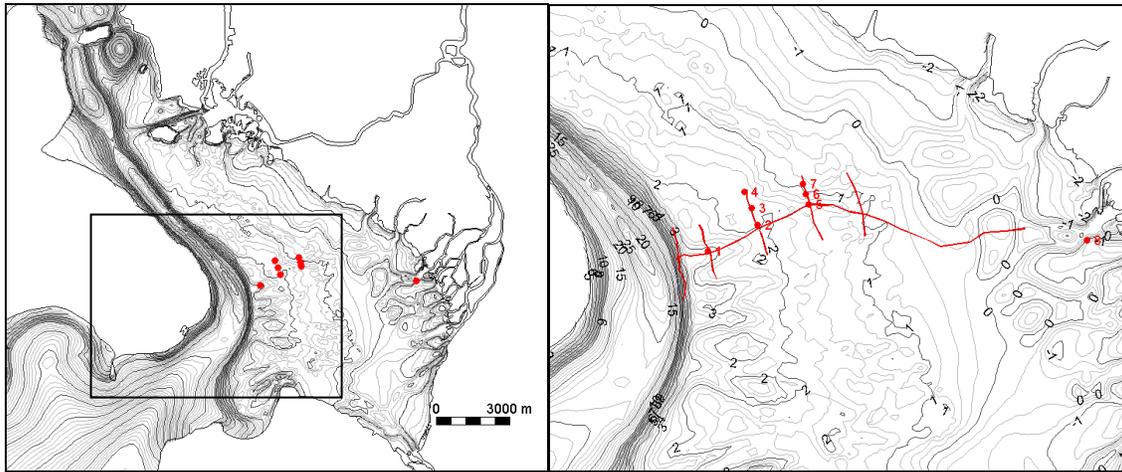


Figure 1. Bathymetry of the Skagit Bay tidal flats (left) with a zoom on the study area on the southern flats (right). Red dots indicate frame locations, and lines show across-flats and across-channel survey lines.

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 multiple 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 suspended sediment depend 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.

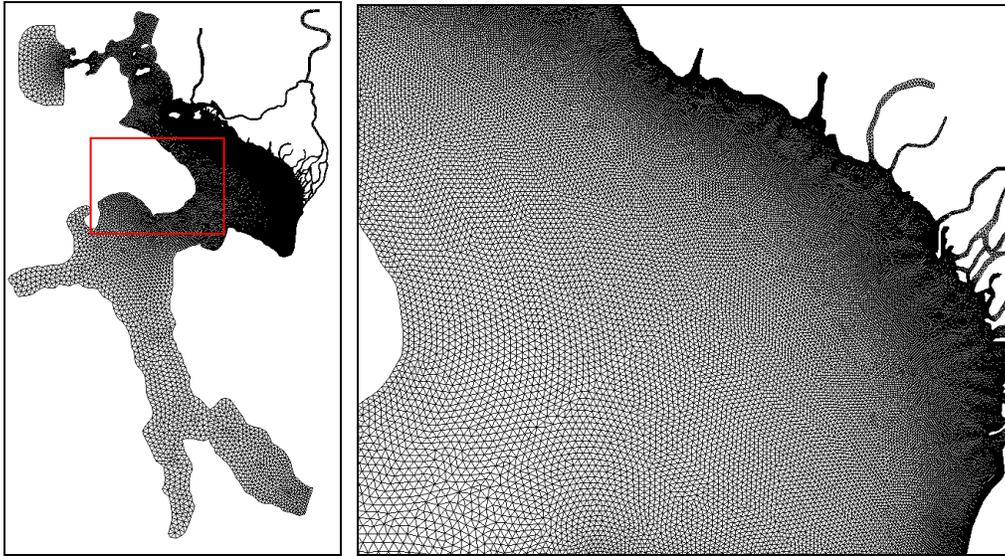


Figure 2. Model grid of Skagit flats and surrounding region: (left) full domain, with open boundaries are at southern end of Saratoga Passage, west of Deception Pass, and the northern end of the Swinomsih channel, and (right) zoom on southern tidal flats region shown in Fig. 1. Minimum horizontal grid 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 unstrucuted 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 obsevation. Additional bathymetric data were aquired from other investigators working in the area – jet ski surveys near the mouth of the North Fork (Raubenheimer and Elgar, WHOI) and aircraft surveys using LiDAR of the most of the intertidal region (Brozena, NRL). Data for boundary forcing of tides, river discharge, and winds were also 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.

Initial comparisons between model results and observations indicated that local wind forcing was important for generating surface wind stress that affected mean currents and vertical mixing rates. The Skagit model was adapted to incorporate observed winds during the observation period, improving model skill for salinity and velocity at stations near the wind observations. However, analysis of wind observations at a multiple stations in the study region indicated that significant heterogeneity in the wind field that likely depended on the complex orography of Puget Sound (Giffen and Raubenheimer).

To address this issue, we developed an atmospheric model of the region using the Weather Research and Forecasting model (WRF) and coupled it to FVCOM. The atmospheric model was evaluated against observations and found to have good agreement, and coupled atmospheric-hydrodynamic runs were simulated for the period of the observations on the Skagit flats.

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 that 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 $930 \text{ m}^3 \text{ s}^{-1}$ in early June and about $450 \text{ m}^3 \text{ s}^{-1}$ 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 $10^{-6} \text{ m}^2 \text{ s}^{-1}$ and 0, respectively. Similarly, the bottom roughness (z_0) was set to 0.1 mm, representative of relatively small roughness elements on the flats. One somewhat surprising result was the importance of vertical resolution for simulating the observed salinity structure on the flats. Although the shallow water depths might suggest fewer vertical levels are necessary than in models with deeper domains, the sharp vertical gradients and the relatively steep topography bottom topography in the region combined with the sigma-coordinate system of FVCOM (and many similar coastal models) can lead to spurious vertical mixing that weakens vertical and horizontal gradients. For example, model runs with 20 sigma-levels had weaker stratification on the flats, a shorter salinity intrusion, and consequently different regions of sediment trapping than simulations with 30 levels.

The calibrated model results compare well with the moored time series of water surface elevation, velocity, salinity and stratification (Figure 3). 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. Critically for suspended sediment transport calculations, the bed stresses calculated in the model compare well with near-bed stresses calculated with ADVs, including ebb-flood asymmetries. Stratification modulates the tidal stresses, with higher stresses during unstratified flood tides, and weaker stresses during stratified ebbs up until the point that stratification breaks down. Similarly, comparisons between observed (through calibrated optical and acoustic measurements) and modeled suspended sediment show good agreement.

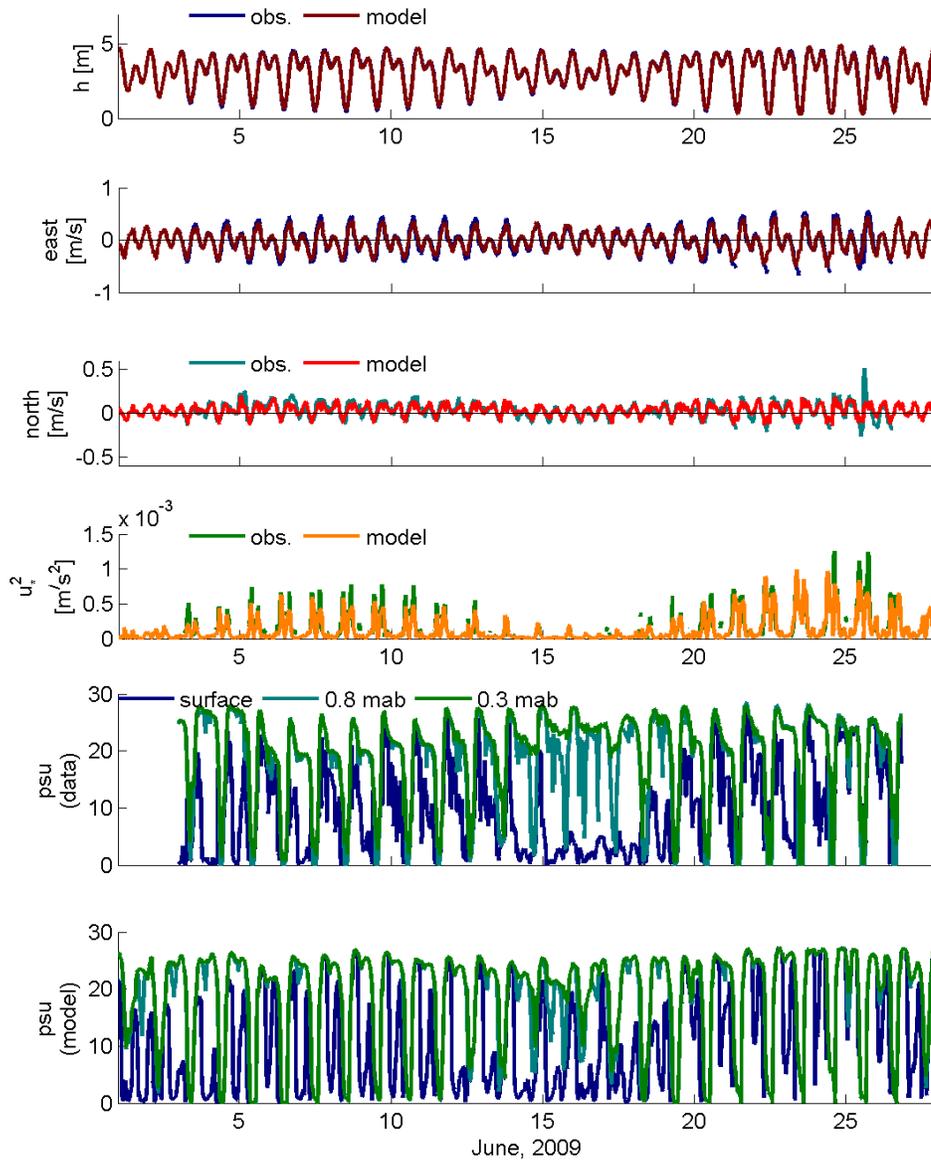


Figure 3. Comparison between observations and model results from a station mid-flats in a small distributary channel (station #5 in Fig. 1): [top panel] water surface elevation, [panel 2] east velocity (~cross-shore), [3] north velocity (~along-shore), and [4] near bottom stress (friction velocity), [5] observed salinity (at 3 elevations – surface, 0.8 m above the bed, and 0.3 mab), [6] modeled salinity at same 3 elevations.

An example from the model during an ebb tide with high river discharge illustrates the importance of stratification and baroclinicity to dynamics on Skagit tidal flats (Fig 4). 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 about 10 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. 4), with a region in between the mouths that is less stratified and higher salinity. Recent comparisons with observations from other researchers (Raubenheimer & Elgar group) has confirmed this spatial heterogeneity seen in the model, and the simulations are now being used to help interpret the 3d structure of the observed circulation and development and breakdown of stratification.

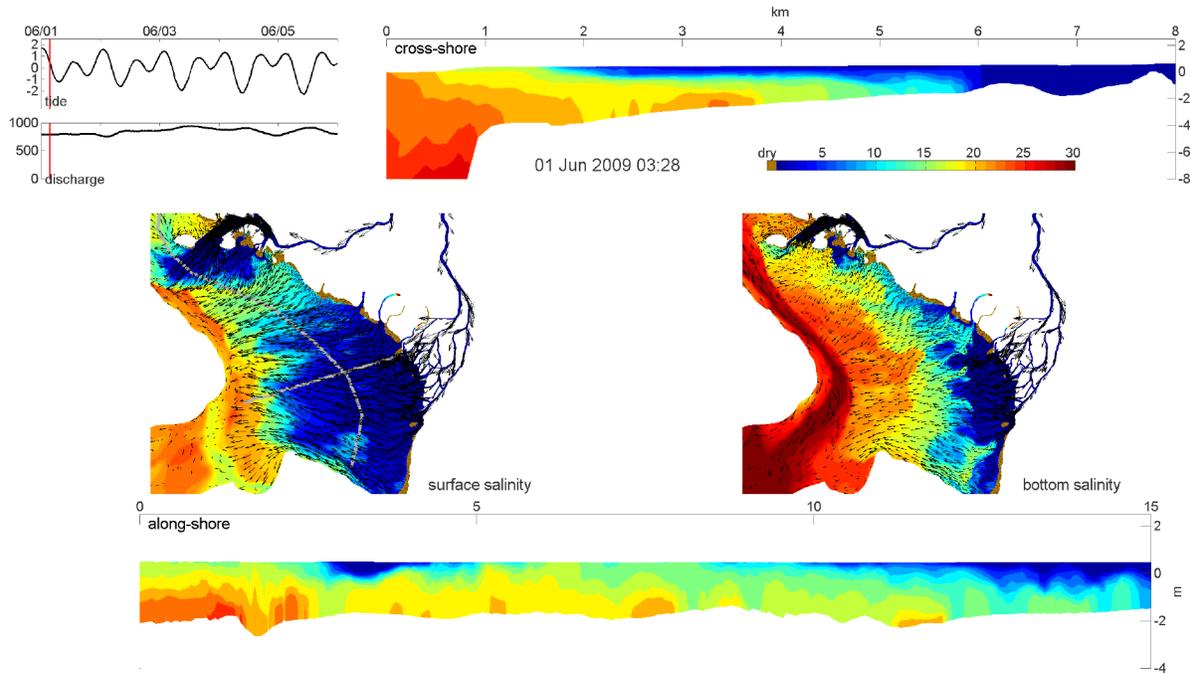


Figure 4. Model results with realistic forcing from early June 2009, when tides were moderate (between spring and neap) and river discharge was high ($\sim 950 \text{ m}^3 \text{ s}^{-1}$). Maps of surface (left) and bottom (right) salinity are shown with across-flat (top) and along-shore (bottom) vertical 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.

A fundamental question then is how the tidal variability in baroclinicity and stratification affects sediment transport across the tidal flats. Alternatively, is it necessary to resolve the density structure in these shallow environments to accurately simulation the sediment fluxes? The model results from the Skagit indicate that it is. The baroclinic forcing and stratification generate asymmetries in bottom stress and consequently in sediment transport. During flood tides, the baroclinic pressure gradient at the salinity front enhances the bottom stress and during ebbs stratification suppresses turbulence and sediment resuspension. In a time series from a transect across the south Skagit flats, stratification is strongest and bottom stresses are weakest during neap tides (Figure 5). During spring tides stratification develops and persists during the weaker tides around high water, but maximum stresses occur during the stronger diurnal flood and ebb.

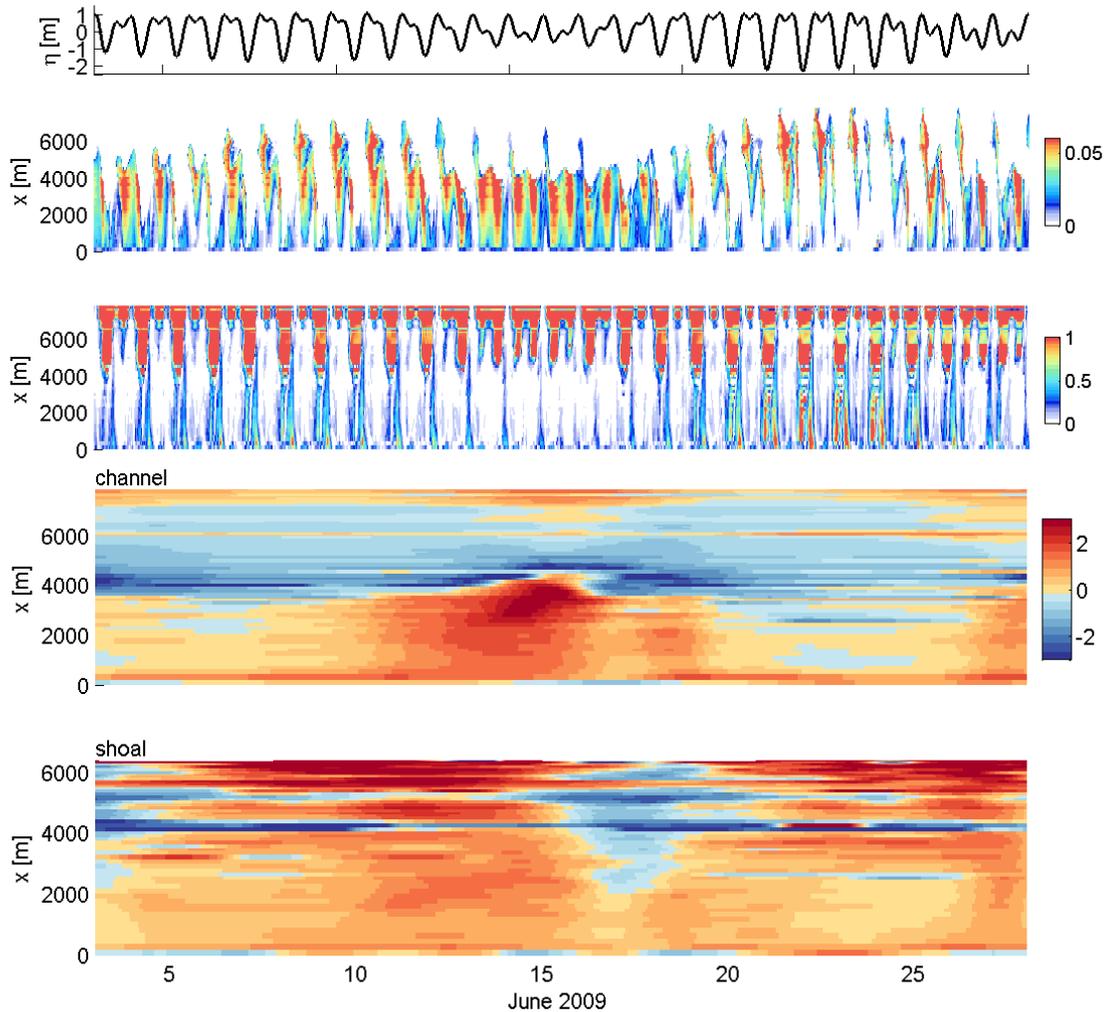


Figure 5. Model results of stratification, stress, and stress asymmetry in a section across the south Skagit tidal flats (location shown in Fig 1): [top panel] water surface elevation, [panel 2] stratification (buoyancy frequency) as a function of distance across the flats and time (s^{-2}), [panel 3] bottom stress ($N m^{-2}$), [panel 4] stress asymmetry in a tributary channel (skewness, with flood-directed asymmetry > 0 and ebb-directed < 0), [panel 5] stress asymmetry on tidal flats adjacent to the tributary channel shown in [4].

An important distinction is that the transect shown in all but the bottom panel of Figure 5 follows one of the distributary channels flowing across the flats from the mouth of the south fork of the Skagit River. At low tidal stage, river discharge continues to flow in the channel, and the channel in the upper part of the transect has a period each tidal cycle when high stresses associated with the river flow are ebb directed. In contrast, the lower flats remain inundated except for the most extreme low tides, and the stress asymmetry created by the baroclinic pressure gradient and the stratification remains flood dominant. Here we have quantified tidal stress asymmetry with the skewness, with positive values indicative of flood-dominant stresses. The lower channel (below the low tide elevation) is flood dominant, with the strength of the asymmetry increasing during neap tides, but the upper channel is largely ebb dominant due to the river flux. In contrast, a section taken adjacent to the channel (only

500 m to the north) shows that without the ebb-directed stresses of the river discharge, the flats are even more flood dominant. These sections suggest that (1) stratification and baroclinic pressure gradient at the tidal salinity front enhance stress asymmetry and consequently sediment trapping even in shallow water, and (2) that sediment transport in the distributary channels across the flats provide the primary means for sediment export, with the net flux strongly dependent on tidal forcing and the river discharge.

Considering these cross-flats slices alone would suggest that the stress asymmetry and sediment trapping at the salinity front would lead to significant sediment retention on the Skagit flats. However, bed sediment observations (by Nittrouer group) suggest that relatively little of the sediment associated with the spring freshet is retained for extended periods on the tidal flats, and that instead much of the sediment is exported to the deeper basins to the south (Saratoga Passage) and north (Deception Pass). The realistic bathymetry and forcing of the model helps to resolve this discrepancy. Much of the observational effort discussed here focused on the broad southern Skagit flats with its network of small distributary channels. In contrast, the northern fork of the Skagit discharges over a much narrower intertidal region due to bathymetric constraints of Whidbey Island. The flats of the north fork are more channelized and have a steeper bed gradient, and thus are more efficient at moving sediment seaward during the period around low water. Additionally, the combination of tidal rectification of the along-shore currents and tidal amplification that generates a pressure gradient between Saratoga Passage and Deception Pass produces a net northward flux on the flats, seen in both the observation and the model. This along-shore current provides a mechanism for moving sediment from the south to the northern flats where it is efficiently moved into Whidbey Channel and then out Deception Pass or into Saratoga Passage. Net fluxes calculated along isobaths in the model demonstrates the discrepancy in transport pathways between freshwater (approximately evenly split between north and south) and sediment (moved off the flats predominantly in the north, while the southern flats are retentive) (Figure 6). The results also provide support for the importance of numerical modeling with realistic bathymetry to understand complex natural systems. Constructing models with sufficient resolution to capture the relevant processes remains a computational challenge, as evidenced by the importance of the small tributary channels across the flats that likely remain under-resolved by both the model grid and available bathymetric data.

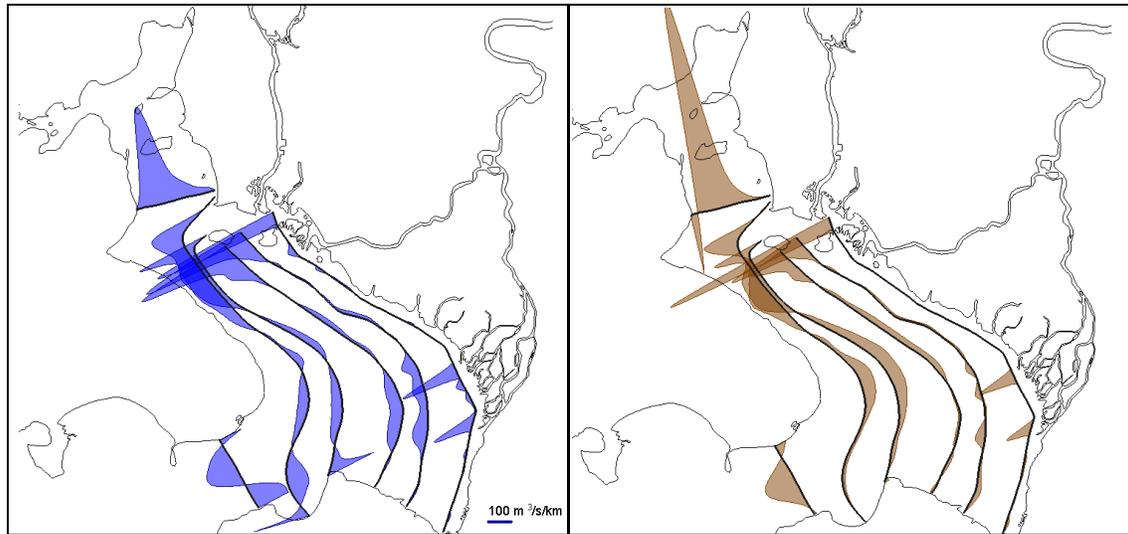


Figure 6. Maps of freshwater transport (left) and sediment flux (right) from the model. Sections are taken along isobaths and averaged over 3 diurnal tidal cycles (June 22-24, 2009). While freshwater flux is roughly evenly split between the north and south fork, sediment is exported only from the north fork where channelization and bed slopes are greater than on the southern flats.

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 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 other investigators in the Tidal Flats DRI. The field efforts on the Skagit were done in conjunction with Geyer and Traykovski. The model and grid development has been in collaboration with Geoff Cowles. Collaborations with others involved in the DRI include Raubenheimer and Elgar (for bathymetry, observations for model calibration, and use of the model to interpret their water column and wind observations), Lerczak (model simulations at seasonal time scales), Signell and Sherwood (CSTM implementation), and Thomson and Chickadel (bathymetry). Currently one post-doc (Nick Nidzieko at WHOI) and one student (Vera Pavel at WHOI) are working with Ralston on results from this modeling, although neither is directly funded by the project.