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Tidal Flats, Muddy Seafloors, and Sandy Coasts

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LONG-TERM GOALS

The long-term goal is to develop field-verified models for the evolution of surface-gravity waves, circulation, sediment transport, and the subsequent morphological response in shallow, coastal waters.

OBJECTIVES

The objectives of our studies in FY10 are to analyze observations of currents, waves, and bathymetry on tidal flats, and to develop, test, and improve models for tidal-flat processes. Specific goals related to tidal flats are to:

- Investigate the relative importance to the circulation of riverine and tidal flows, and
- Estimate the bottom stresses owing to waves and tidal and subtidal flows on the flats.

Additional goals in FY10 include developing models for mud-induced dissipation of waves, planning a study of waves and circulation in the vicinity of a strong, narrow jet of water at an inlet, and analyzing waves, currents, and morphological change onshore of complex shallow-water bathymetry dominated by two submarine canyons that extend nearly to the shoreline.

APPROACH

Our approach is to collect field observations to test existing hypotheses, to discover new phenomena, and to calibrate, evaluate, and improve models for tidal flat hydrodynamics and morphological evolution and for waves propagating in shallow water across muddy and sandy seafloors.

WORK COMPLETED

i) Circulation and Morphological Change on Tidal Flats

In summer-fall 2009, we deployed a two-dimensional array of sensors to measure water levels, currents, and water density from the subtidal to the upper intertidal regions on the north-central tidal flats in Skagit Bay near La Conner, WA (Figure 1). Pressure, velocity, and conductivity data were collected at 25 locations to observe the wave and tidal flows, and to estimate combined wave-current bed stress. Five current profilers and colocated floating conductivity-temperature (CT) assemblies were positioned next to the fixed sensors, and were moved every two weeks to examine the spatial and temporal variability of the vertical profiles of currents and densities. Detailed measurements of the vertical and spatial density structure were collected via CTD casts from a small boat. Winds were measured at 3 locations on the north-central flats (Figure 1), and at 1 location on the south flats (by D. Ralston (WHOI), not shown). Bathymetric surveys were conducted throughout the 5 by 5 km study region along shore-parallel and shore-perpendicular lines (separated by about 100 m in the cross- and alongshore, respectively) using a GPS system mounted on a waverunner. Skagit River discharge was obtained from the U.S. Geological Survey Mount Vernon station.

Figure 1: Approximately 5 by 5 km array of 25 bottom-mounted tripods (green symbols, each with an acoustic current meter, pressure gage, and conductivity-temperature (CT sensor), 2 meteorological stations (white), 5 colocated current profilers and floating CTD stacks with sensors about 20 and 70 cm below the water surface (red), and 2 colocated current meters and pressure gages (yellow) deployed in 2009. A meteorological station also was deployed on Craft Is. by J. Thomson (UW-APL) (pink).

ii) Wave propagation over muddy seafloors

The effect of a muddy seafloor on wave dissipation and on fetch-limited wave generation is being studied by comparing SWAN numerical wave-model predictions with observations (Engelstad *et al.* 2010).

Comparisons of waves measured over a muddy seafloor with model predictions and with observations of the fluid mud layer thickness suggest that as wave energy decreases following the peak of a storm,

the fluid mud layer begins to consolidate, causing the viscosity and the mud-induced dissipation to increase (Safak *et al.* 2010).

iii) Wave propagation on sandy coasts (Nearshore Canyon Experiment)
The SWAN numerical wave model was shown to predict accurately the wave heights and directions observed between 1- and 5-m water depths near the head of the Scripps Submarine Canyon (Gorrell *et al.* 2010).

The effects of sediment-induced stratification on sediment transport and corresponding morphological change were investigated with observations from North Carolina and a 1-D General Ocean Turbulence model (Falchetti *et al.* 2009).

RESULTS

The observations collected in 2008 and 2009 on the Skagit tidal flats are being used to investigate processes affecting sediment transport, including bottom drag coefficients, the vertical structure of flows and water density, the depth-averaged circulation, waves in shallow water, and winds.

Bottom drag coefficients C_d were estimated from the depth-averaged cross-shore momentum balance (Figure 2, red symbols). The nonlinear advection, Coriolis, and mixing terms are small, and the acceleration term did not affect the results significantly, and thus these terms were neglected. Squared correlations r^2 between the pressure gradient terms (barotropic and baroclinic) and the velocity term estimated using nearbed flows typically were greater than 0.6, and C_d ranged from 0.003 to 0.009, roughly consistent with prior results. Estimates of C_d using depth-averaged velocities were 20-50% smaller than estimates of C_d using nearbed velocities. Drag coefficients estimated with logarithmic and vertical-velocity-variance (Nezu and Rodi 1986, assuming that vertical velocity fluctuations are a proxy for turbulence) methods were similar to those estimated with the momentum balance (Figure 2).

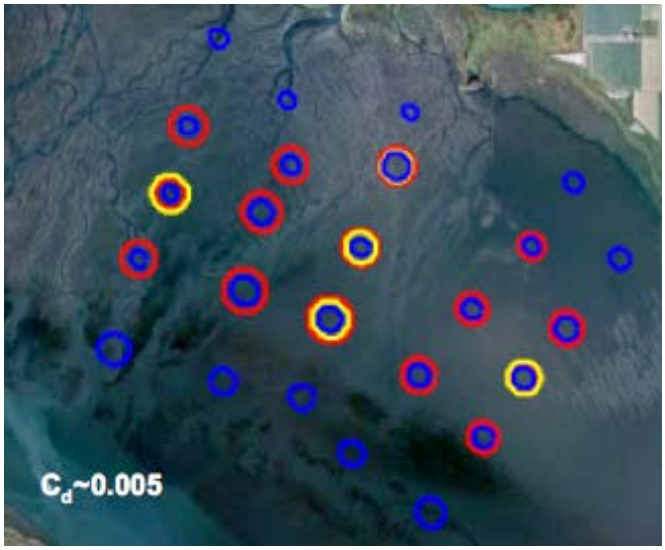

Figure 2: Google Earth image of Skagit Bay with circles representing bottom drag coefficients estimated with the momentum balance (red), the logarithmic layer (yellow), and the vertical-velocity-variance (blue) methods. The area of each circle is proportional to the bottom drag coefficient. Values of C_d ranged from 0.001 to 0.01. Mean values and 95% confidence limits were 0.0056 ± 0.0003 for the pressure method, 0.0055 ± 0.0034 for the log layer method, and 0.0040 ± 0.0009 for the vertical-variance method.

Although visual observations on daily hikes across the flats and a bathymetric survey conducted with a GPS system mounted on a wave runner suggest that bedforms ranged from 15-cm high ripples and numerous shallow (about 30-cm deep) channels at the northwest edge of the study region (near the main river channel) to a relatively smooth bed spotted with clam shells at the southeast edge (far from the river), the C_d did not have a significant dependence on along- or cross-flat location or on distance from the main river channel. However, flow magnitudes and bottom drag coefficients were different on the flats than in the channels. In particular, pressure and velocity sensors deployed about 0.13 m above the flats and about 0.13 m above the bed of a nearby channel showed that flows were about 30% smaller in the channel than on the flats, drag coefficients were about 70% larger in the channel than on the flats, and turbulence is greater near the channel floor than near the flat bed for water depths greater than about 1 m (Elgar and Raubenheimer 2010). For currents flowing primarily across the channel, the ratio of current speed (defined as the square root of the sum of the squared along- and across-channel flows) observed 0.13 m above the bed on the flat, U_f, to that observed 0.13 m above the bed in the channel, U_c, increases as the depth increases (Figure 3a). The increase of U_f/U_c with depth is accompanied by an increase in the relative amount of turbulence (parameterized by the variance of the vertical velocity fluctuations) near the channel bed (Figure 3b), consistent with previous observations of flows across a channel. Drag coefficients estimated with the vertical-velocity-variance method suggests $C_d \approx 0.003$ on the tidal flat and $C_d \approx 0.005$ in the channel. Visual observations suggest the tidal flat bed was smooth, whereas the channel had numerous randomly aligned bedforms and algal mats with heights of up to about 0. 25 m. Thus, the higher turbulence levels and larger drag coefficients in the channel relative to the flats may be related to the channel roughness. The ratio U_f/U_c observed for along-channel flows (Figure 3c) is consistent with a cross-shore momentum balance. For an average

water depth on the flat of 1.2 m, a 0.3 m deep channel, and drag coefficients of 0.003 on the flat and 0.005 in the channel, the momentum balance suggests $U_f/U_c \approx 1.2$, similar to the observed ratio.

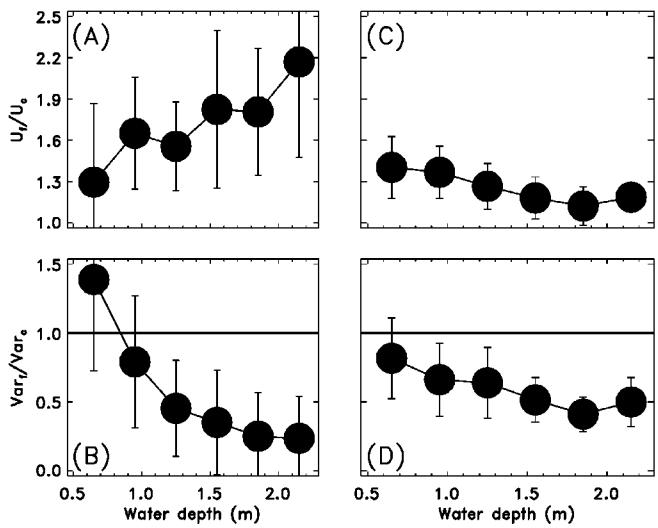

Figure 3: Ratio of current speed and vertical velocity variance observed on the flat to that observed in the channel versus water depth on the flat for (A-B) flow directions greater than 60° relative to the channel axis (across-channel flow) and (C-D) flow directions within 40° of the channel axis (along-channel flow). Bars are 1 standard deviation. [For across-channel flows, flow (variance) ratios increase (decrease) from about 1.3 to 2.2 (1.4 to 0.2) with increasing depth. For along-channel flows, flow (variance) ratios decrease slightly with increasing depth from about 1.4 to 1.1 (0.8 to 0.5).]

Nearbed flows, and thus bottom stresses, also may be affected by the fresh-river-water-induced density stratification that is modulated at tidal frequencies by the sheared currents (Figure 4). In particular, ebb velocities are significantly smaller than flood velocities, at least partly owing to a tidal dependence of the stratification.

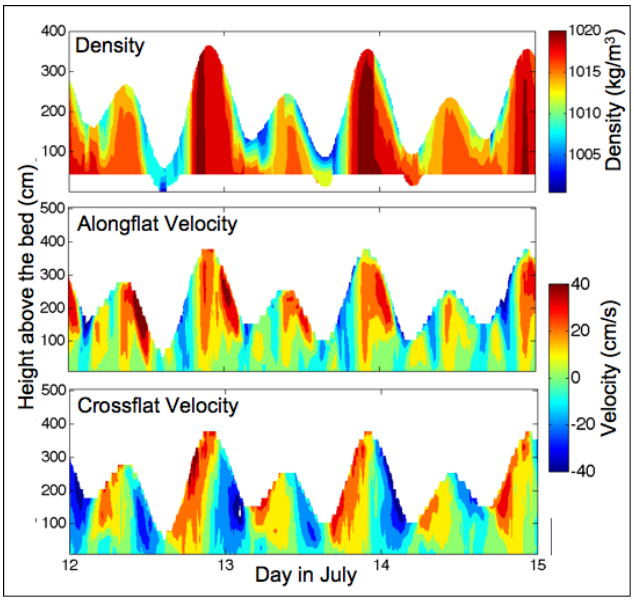

Figure 4: Vertical profiles of density (top), and along- and cross-flat velocity (middle and bottom) versus day from July 12 to 15, 2009. [Water density is well-mixed during strong floods, but the water column becomes stratified (surface to bottom density differences of up to about 15 kg/m^3) during ebbs. Similarly, the along- and cross-flat velocities often are more sheared during ebbs (surface to bottom flow differences of up to 40 cm/s).]

Field observations and Finite Volume Coastal Ocean Model (FVCOM) simulations (in collaboration with D. Ralston (WHOI)) are being used to examine the processes governing the temporal evolution of the stratification-induced potential energy anomaly (Φ) (Burchard and Hofmeister 2008), which may result from tidal straining (an effect of sheared flows and horizontally varying water density) of the depth-averaged and vertically-dependent densities, along- and across-flat advection, vertical advection, surface and bottom buoyancy fluxes, mixing, changes in water depth, and turbulent transport. Preliminary results near the middle of the flats suggest that although tidal straining and mixing are the largest terms, they roughly balance, and thus advection is important (Figure 5). However, model results suggest that the relative importance of the terms depends on proximity to the main river channel, river discharge, and tidal range (e.g., spring versus neap tides).

Bottom stresses also may be affected by winds, which generate waves and which may enhance mixing or straining (by increasing current shear). Additionally, spatial variability of winds may be important to the waves, circulation, and the resulting sediment transport on the flats. Correlations between wind speeds and directions observed along the flats decrease exponentially with separation distance (Figure 6). For the 3 to 5 km distances between the north and south Skagit towers, r^2 is about 0.2. Prevailing winds at the mid-flat tower are from the northwest, whereas prevailing winds at the south Skagit tower are from the southwest, suggesting the low correlations between wind speeds and directions are at least partly owing to the influence of regional topography on the wind field.

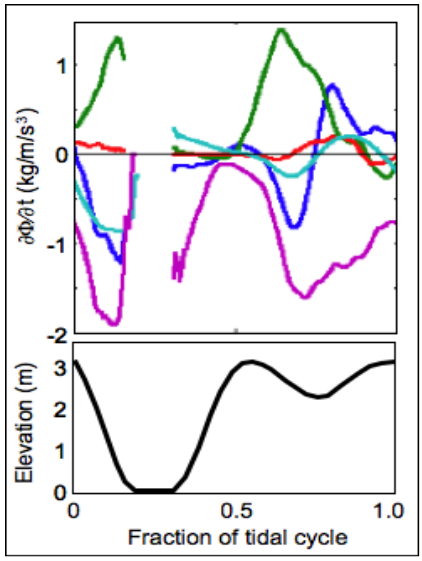

Figure 5: Phase-averaged (over similar tides) estimates of terms in the equation for ∂Φ/∂t (top), including straining of the depth-averaged (green curve) and vertically dependent density (red), mixing (pink), and cross-flat (dark blue) and vertical advection (light blue), and tidal elevation (bottom) versus fraction of tidal cycle. [Increases of ∂Φ/∂t owing to straining of the depth-averaged density are roughly balanced by decreases owing to mixing. Cross-flat and vertical advection cause decreased ∂Φ/∂t on the strong ebb and increased ∂Φ/∂t on the weak flood.]

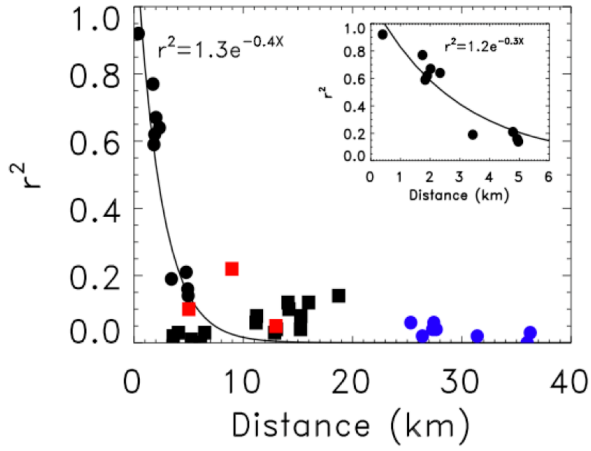

Figure 6: Correlation squared (r^2) of wind speeds between all pairs of towers on the flats (black circles), between flat and inland towers (black squares), between pairs of inland towers (red squares), and between towers on the flats and the Smith Island tower (blue circles) versus distance. The inset shows only flat towers. The best fits (black curves) show that r^2 values decrease exponentially with separation distance.

The North American Meteorological 12 km Weather Research and Forecasting model (NAM 12km) was used to predict the wind speeds and directions on the Skagit flats (the 12-km resolution encompasses both the north and south flat locations) and at Smith Island at 3-hour intervals (not shown). The model predicts the predominance of low wind speeds and the lack of northeasterly winds on the Skagit flats, but underpredicts the highest winds in the mid-flat region. However, the correlations between the predictions and observations are small.

IMPACT/APPLICATIONS

Tidal-flat bottom drag coefficients C_d estimated for nearbed flows are about 0.005 (for depth-averaged flows $C_d \approx 0.003$). Although the results from this study are preliminary, it appears that drag coefficients are higher in channels than on the flats, and that tidally dependent stratification may cause tidal fluctuations in bottom stresses. Spatially variable winds may result in spatial variations of waves, mixing, and wind-induced straining, which could cause spatial and temporal variability of bottom stresses.

Field observations on sandy beaches have been used to test and improve model predictions for nearshore and surfzone waves, circulation, and morphological changes. Results from model-data comparisons have increased our ability to predict refraction of waves over submarine canyons and nearshore bathymetric change, including the migration of sandbars across the surfzone.

RELATED PROJECTS

Our observations on the tidal flat are part of a larger effort to investigate and model physical, geological, and morphological processes on tidal flats. As part of the Tidal Flats DRI we are providing bathymetric surveys to all DRI team members, and ground truth (currents, water temperature, salinity) to colleagues conducting numerical model simulations and investigating remote sensing techniques.

The observations of mud-induced dissipation of surface-gravity waves are part of a study that includes colleagues from several other institutions. Our spatially dense observations of waves and currents were part of a larger array of wave sensors spanning many km of the continental shelf, and part of an array that included intensely instrumented tripods with sensors to measure the lutocline and mud properties. To provide additional information about the sediment and water column properties, MURI-supported colleagues have performed cross-shelf shipboard surveys near all the sensors deployed in this project. Our data are being used in several ongoing collaborations.

Many investigators are using our observational databases to test components of models (eg, the NOPP nearshore community model, DELFT3D, nonlinear wave propagation schemes) for nearshore waves, currents, and bathymetry, and as ground truth for remote sensing studies. Almost 100 scientists, engineers, postdoctoral researchers, and students, have accessed our data distribution WWW site (http://science.whoi.edu/users/elgar/main.html) since 2006 to download time series and processed data products for their studies. In 2010 more than 40 people (including investigators from U.S. and international universities, government and DoD laboratories, and private companies) downloaded data from the Duck94, SandyDuck, NCEX, SWASHX, WORMSEX, and STIFEX projects.

The studies of tidal flats, mud-induced dissipation, and nearshore processes are in collaboration with NSF projects funding studies of water level setup, numerical modeling, and undergraduate fellows.

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PUBLICATIONS

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2. Elgar, S., and B. Raubenheimer, 2010 Currents in a small sandy tidal channel, *Continental Shelf Research, sub judice*. [submitted, refereed].

3. Gorrell, L., B. Raubenheimer, S. Elgar, and R.T. Guza, 2010 SWAN Predictions of Waves Observed in Shallow Water Onshore of Complex Bathymetry, *Coastal Engineering, sub judice*. [submitted, refereed].

HONORS/AWARDS/PRIZES

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