Tidal Flats and Muddy Seafloors

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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 FY09 are to collect observations of currents, waves, and bathymetry on tidal flats, and to develop, test, and improve models for tidal-flat processes and for mud-induced dissipation of waves in shallow water.

Specific goals relating 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.

Specific goals relating to waves over muddy seafloors are to:

- Extend existing wave models to account for damping by mud, and
- Use the observations and models to test hypotheses for mud-induced damping.

Additional goals in FY09 relating to sandy coasts include analysis of 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.

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WORK COMPLETED

i) Circulation and Morphological Change on Tidal Flats

In summer 2009, we deployed a two-dimensional array of tripods with sensors to measure water levels, currents, water density, and bathymetry from the subtidal to the upper intertidal regions on the north-central tidal flats in Skagit Bay near La Conner, WA (Figure 1). Pressure and velocity data were collected at 2 to 4 Hz to resolve both the wave and tidal flows and the combined wave-current bed stress. Five current profilers and colocated floating conductivity-temperature (CT) assemblies were positioned next to tripods, 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. Additional pressure-velocity sensors were deployed on the flats about 5 m from a tripod in a channel to examine channel-flat exchange and on the flats between two other tripods to examine smaller-scale spatial fluctuations in the circulation. 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 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).

During the study, water depths ranged from 0 to 400 cm, wind speeds ranged from 0 to 10 m/s, river discharge ranged from 20 kcfs in early July to 5 kcfs in late August, and near-bed current speeds ranged from 0 to 33 cm/s (Figure 2). Bed elevations changed by 15 to 20 cm in many locations as channels accreted and eroded (Figure 2).

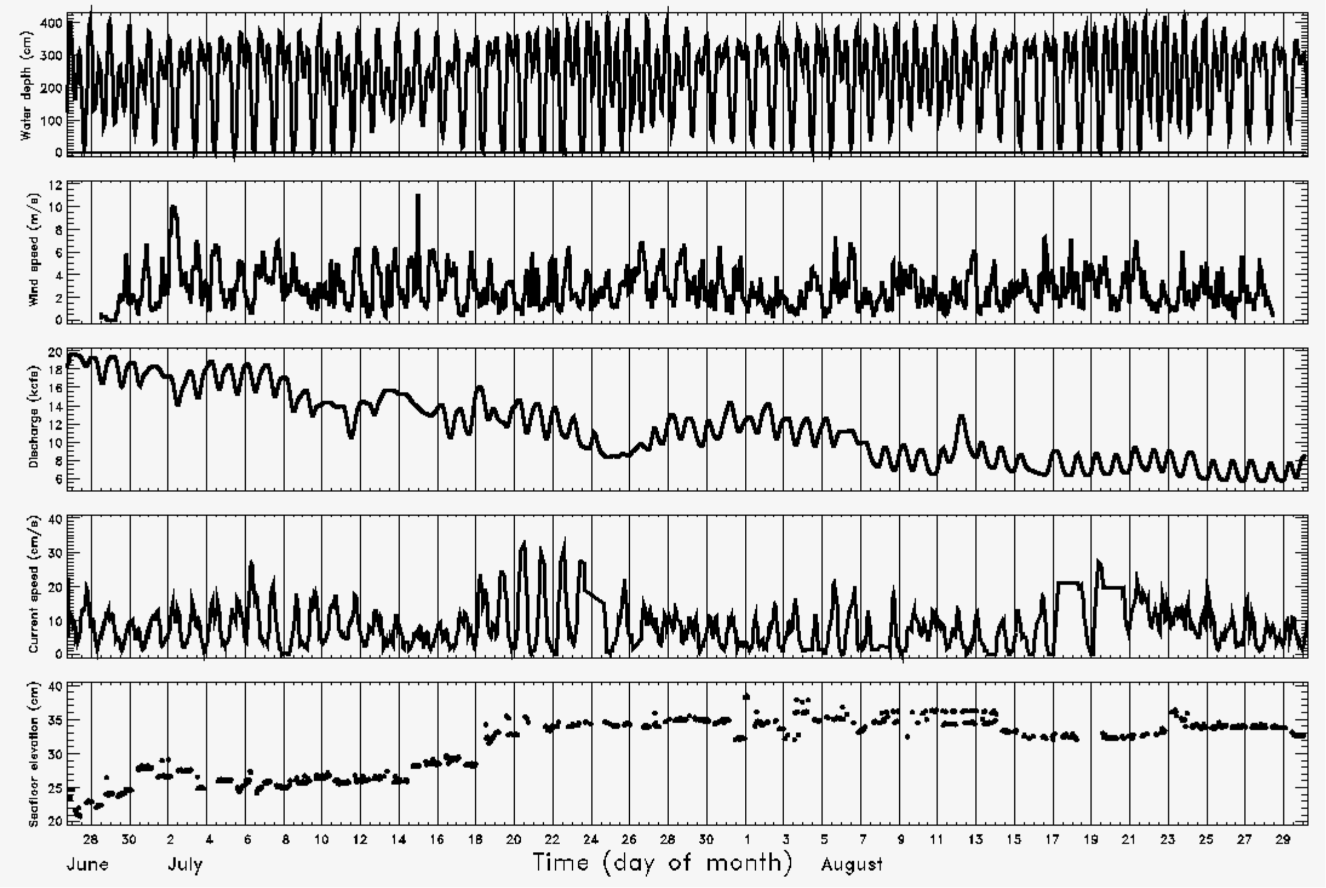

Figure 2: From top to bottom: Water depth, wind speed, Skagit River discharge, current speed, and seafloor elevation versus time for more than 60 days of observations on the Skagit Bay tidal flats in 2009. The water depth (or tide level) and current speed were observed at the offshore edge of the 25-element array, near the 7-m tall meteorological station. The seafloor elevation changed about 20 cm (erosion and accretion) as a river distributory channel migrated beneath the altimeter.

ii) Wave propagation over muddy seafloors

The mud-induced dissipation of the surface-gravity wave field observed on the muddy inner shelf offshore of Louisiana was shown to be strongly depth dependent, and the dissipation rate was shown to be largest at infragravity frequencies. By incorporating an empirical dissipation function determined from the observations into a nonlinear Boussinesq wave model, the strong attenuation of the wave field observed between 5- and 2-m water depths can be predicted accurately (Elgar & Raubenheimer 2008).

Although the dissipative Boussinesq model has high skill, there is some scatter. Model-data discrepancies may be caused by the neglect of wind input and whitecapping dissipation (although winds usually were light), the assumption that waves propagated along the axis of the array (the waves usually were nearly aligned with the transect, but had a small directional spread), and the relatively large distances between the sensors. These potential sources of error are being investigated with observations from a spatially dense array of about 16 sensors deployed in winter 2008. In addition, the 2008 observations include a wider range of conditions. Furthermore, in 2008 colleagues measured sediment properties with acoustic sensors mounted on nearby tripods and with shipboard surveys, allowing observations of wave dissipation to be combined with observations of the lutocline and of sediment characteristics. The wave data are being shared with collaborators.

iii) Wave propagation on sandy coasts (Nearshore Canyon Experiment)

A new formulation was developed for the free parameter used in many wave transformation models, and was shown to improve wave height predictions for most observations from 6 field experiments (Apotsos *et al.* 2008).

The momentum fluxes caused by strong alongshore pressure gradients that result from inhomogeneous incident wave fields onshore of a submarine canyon were shown to be important to the alongshore currents observed in the surfzone (Apotsos *et al*. 2008).

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).

Wave heights and directions observed between 1- and 5-m water depths near the head of the Scripps Submarine Canyon were shown to be predicted well by the SWAN wave numerical model (presented at the ONR DELFT3D meeting, Woods Hole, March 2009).

RESULTS

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

Prior studies have suggested that waves can have a significant effect on intertidal flows and bathymetric evolution, even in protected embayments and for small wave heights. During the 2008 pilot study, when winds were alongshore (from the southeast) at about 11 m/s, wave heights (estimated from the bottom pressure measurements using linear theory) grew to more than 60 cm in 400 cm water depth and decreased monotonically onshore (Figure 3). During another storm, with 9 m/s winds from the west, wave heights were less than 20 cm, with the maximum wave height in about 200 cm water depth near the middle of the flats. In both cases, the wind speed and direction remained approximately constant for at least 4 hours. The observations are consistent with empirical formulas for fetch and depth-dependent wave generation based on observations in a long, shallow lake of uniform depth and depending on the wind speed, water depth, and fetch length (Figure 3). The formulas show that the wave heights are smaller for onshore winds than they are for alongshore winds primarily owing to the shorter fetch (not shown). However, the formulas tend to underpredict the largest wave heights (in deep water for alongshore winds), and overpredict the wave heights in shallow water depths.

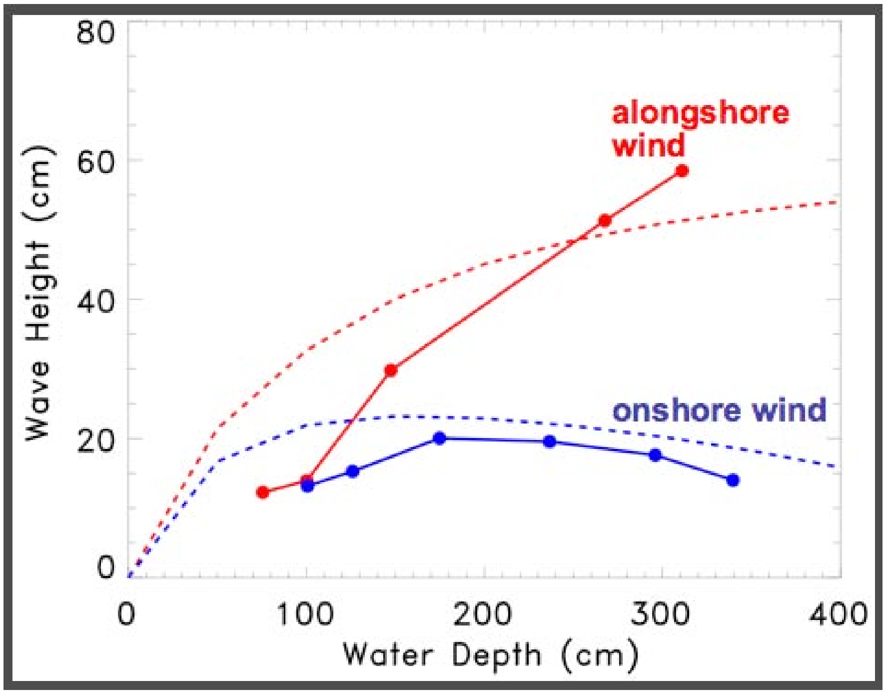

Figure 3: Wave heights observed during the 2008 pilot study versus water depth for 11 m/s alongshore (solid red curve) and 9 m/s onshore (solid blue curve) winds are predicted qualitatively well by empirical formulas (dashed red and blue curves, Young and Verhagen 1996).

The evolution of locally generated waves depends on energy sources and sinks (including input from wind stress and the dissipation owing to whitecapping and bottom friction) and the energy transfers owing to nonlinearities. To evaluate formulations commonly used in the SWAN wave numerical model, the total source plus sink terms (total input) for the alongshore (red in Figure 4) and onshore (blue in Figure 4) wind events are compared with the energy flux gradients integrated over frequency (so nonlinear transfers need not be considered) (Figure 4). Wave energy, direction, wavelength, and centroidal frequency were determined from colocated bottom pressure and velocity measurements, and wind speed and direction were estimated from anemometer data collected about 20 m above the tidal flats converted to 10-m winds. Discrepancies between the total input and the energy flux gradients may be owing to 5° errors in the relative angle of the wave propagation and the wind (not shown). Examination of the individual source and sink terms suggests that whitecapping dominates the dissipation in the deeper water at the offshore edge of the flats, whereas bottom friction dominates the dissipation in water depths less than about 250 cm (not shown). Comparisons of the frequency-dependent source and sink terms with the frequency-dependent energy flux gradients show good agreement, suggesting that nonlinear transfers are small at frequencies less than 0.7 Hz (not shown).

Bottom drag owing to waves is being compared with estimates of the bottom drag owing to the mean flows. During the 2009 study, near-bed currents estimated at 24 locations show significant divergences during all stages of the tide (Figure 5). In particular, onshore flows during the flood (blue arrows in Figure 5) are northwestward and northeastward at the northwest (near the river mouth) and southeast sides of the array, respectively. At high tide (green arrows), north to northwest flows increase in strength towards the northwest. Residual flows averaged over a tidal cycle (not shown) are westward, consistent with model predictions showing strong ebb flows westward through Deception Pass, with weaker eastward flood flows.

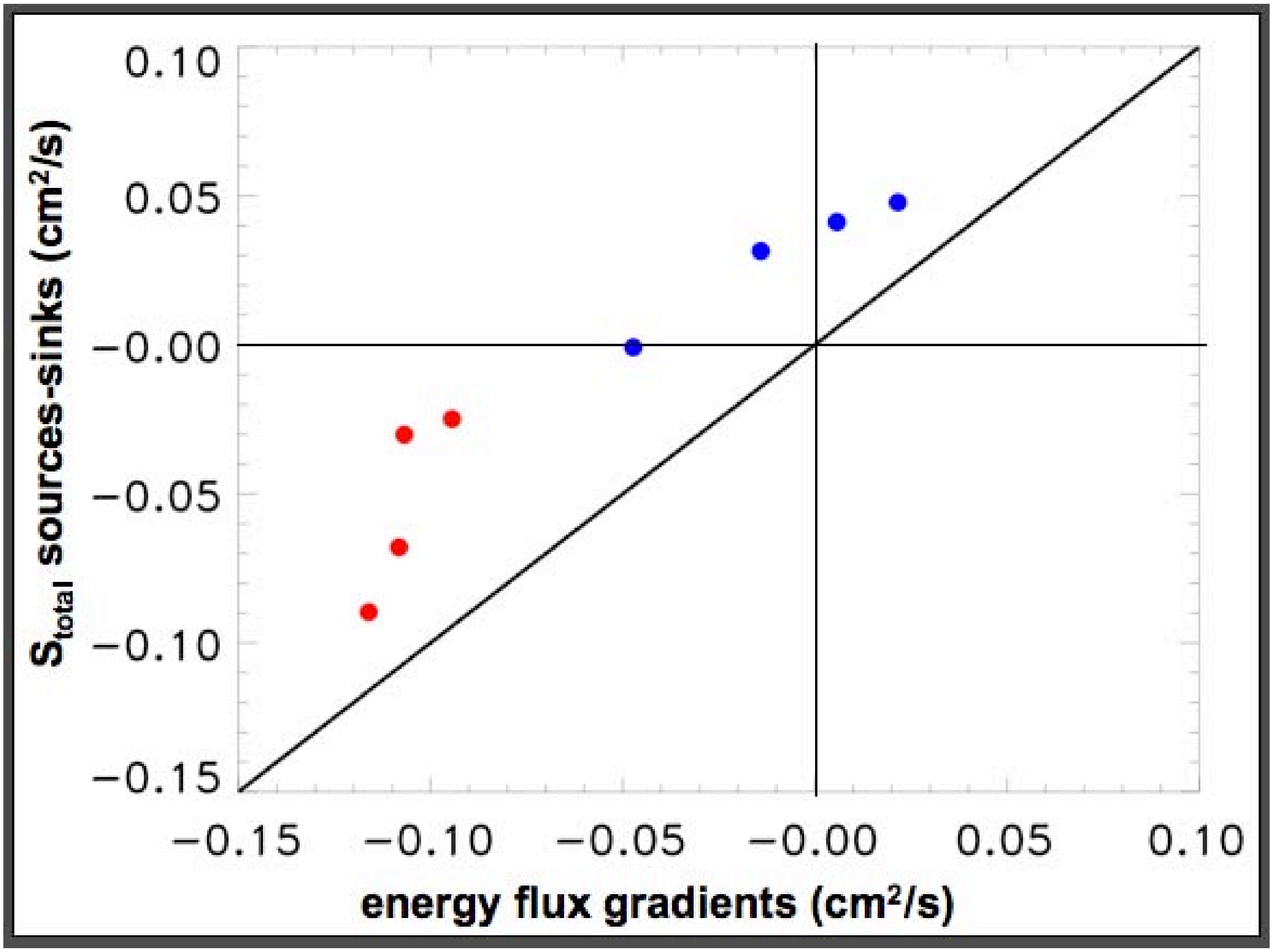

Figure 4: Total energy input S_{total} (sources minus sinks) estimated from formulas commonly used in SWAN versus wave energy flux gradients estimated from observations for the alongshore (red symbols) and onshore (blue symbols) wind events. Good agreement is shown by the proximity of the symbols to the diagonal black line representing perfect agreement.

Preliminary analysis of the observations suggests that flows are near vertically uniform throughout most of the tidal cycle (Figure 6). However, as the flows switch from the weak ebb to weak flood (left red arrow in Figure 6), and near the end of the strong ebb (right red arrow), strong surface jets may occur. These jets may be important to the momentum balances, and also may result in increased or decreased stratification via tidal straining, which can hinder or enhance turbulence and sediment transport. Observations from colocated current profilers and vertical stacks of conductivity-temperature sensors will be used to examine the spatial and temporal structure of the three-dimensional flows and densities.

The current profiler data also are being used to estimate temporal and spatial variations of the bed stress, which may be affected by near bed stratification owing to suspended sediments or river discharge, biological activity, and bedforms. These estimates will be compared with estimates of the drag coefficient based on the tidal momentum balances (between pressure gradients and bottom stress).

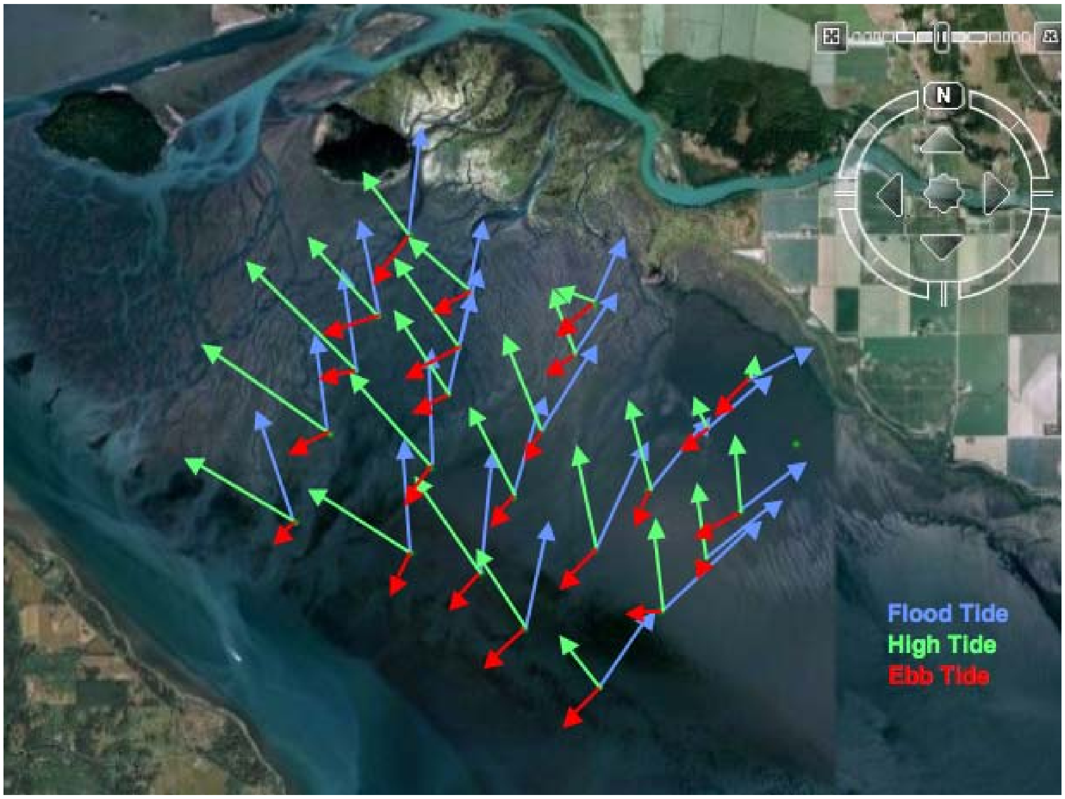

Figure 5: Near-bed flows (1-hr means) measured during the flood tide (blue arrows), high tide (green arrows), and ebb tide (red arrows) shown on a Google Earth image. The longest arrow represents flows of about 25 cm/s. Flow speeds and directions vary across the array.

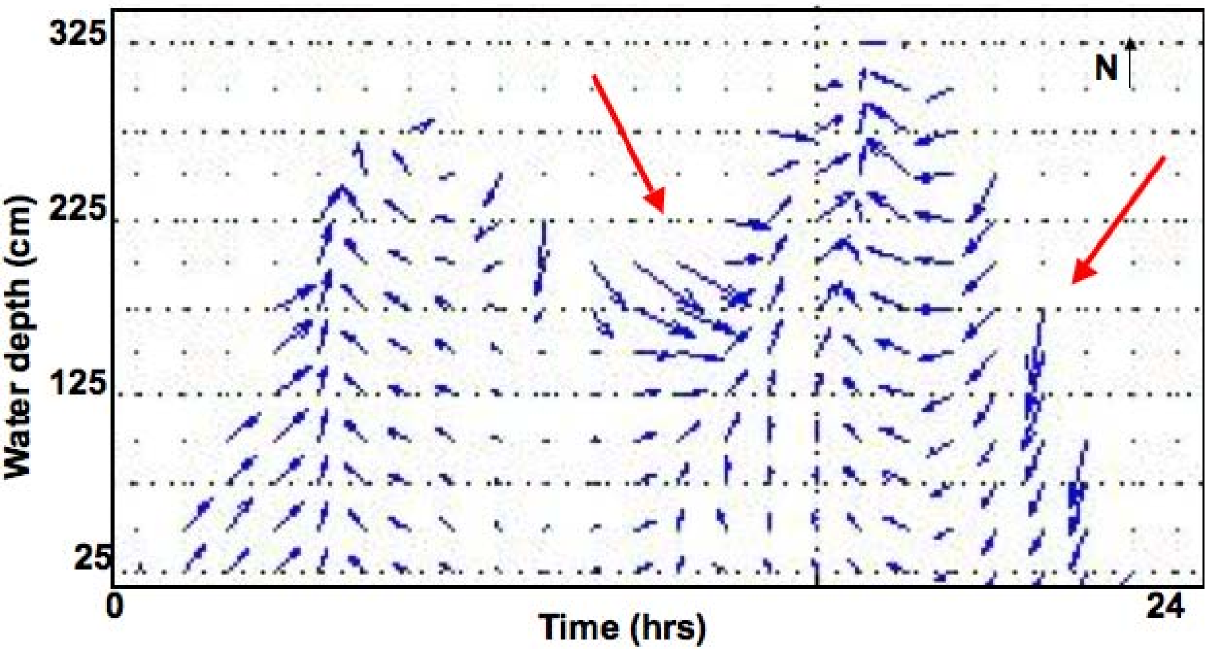

Figure 6: Flows (blue arrows, 1-hr means) as a function of water depth and time measured near the offshore end of the flats. Northward and eastward flows are toward the top and right of the page, respectively. The longest arrow is 57 cm/s. Surface jets are identified by the red arrows.

IMPACT/APPLICATIONS

Although the results from this study are preliminary, it appears that the local wind-wave generation on the shallow tidal flats can be predicted with existing formulations and models. These predictions will be useful to estimate the importance of wave-induced bottom stresses to morphological evolution on the flats. Additionally, preliminary observations suggest that the vertical and horizontal structure of flows on the flats are significant and may be important to the bathymetric evolution.

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 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. For example, in 2009 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, and WORMSEX 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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HONORS/AWARDS/PRIZES

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