# Tidal Flats, Muddy Seafloors, Sandy Coasts, and Inlets

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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 FY11 were 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 were to investigate the relative importance of riverine and tidal flows to the circulation and density stratification.

Additional goals in FY11 included developing models for mud-induced dissipation of waves, analyzing waves, currents, and morphological change on sandy beaches, providing ground truth for remote sensing of littoral areas, and planning a study of waves and circulation in the vicinity of a strong, narrow jet of water at an inlet.

## APPROACH

Our approach is to collect field observations to test existing hypotheses, to discover new phenomena, to provide ground truth for remote sensing studies, to initialize and test data assimilative models that invert for bathymetry, 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*
Comparisons of measurements collected near the seabed in a small channel and on the nearby tidal flat showed that flows were about 30% smaller and 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 2010a,b).

Correlations between wind speeds and directions observed along the flats decrease exponentially with separation distance (Raubenheimer *et al.* 2010). The statistics of wind speeds and directions are predicted reasonably well by a triple-nested Weather Research and Forecast model. Simulations suggest that decorrelation distances increase significantly during fall and early winter, as the diurnal winds weaken and passage of strong (larger-scale) frontal systems becomes more common (Raubenheimer *et al*. 2011).

*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.* 2010a,b).

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) Surf and swash on sandy coasts*
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.* 2011). Consistent with observations, Delft3D numerical-model-simulations (driven with SWAN predicted waves) suggest flows were driven primarily by obliquely incident waves on some occasions, and by alongshore set-up gradients at other times (van der Linde 2010).

Estimates of sediment transport owing to waves and currents in the inner surfzone roughly were consistent with the observed (rapid) filling of large (10-m diameter, 2-m deep) man-made holes (Moulton *et al.* 2010). Estimates of the depth of the holes based on signal strength measured with an acoustic current profiler agreed well with measurements made by SCUBA divers with tape measures and with GPS survey systems (Kilgallin *et al.* 2011).

Water oscillations observed in a 10-m diameter, 2-m deep hole excavated on the foreshore just above the low-tide line on an ocean beach are consistent with theory, with oscillations changing in frequency as the hole filled with sand and evolved from circular to semi-circular (Elgar *et al.* 2011).

Lidar-based observations of sand and water levels, and comparisons of the run-up edge with ballistic-model-predictions, suggest the Lidar may be a useful instrument for studying overwash and beach evolution in the swash zone (List *et al.* 2010).

Bacterial levels in 1-m long sand cores collected across the beach face in Kitty Hawk, NC before, during, and after large waves from an offshore hurricane indicate that ocean beach sands with persisting enterococci signals could be exposed and redistributed when wind, waves, and currents cause beach erosion or accretion (Gast *et al.* 2011).

*iv) Inlets*

We provided the Surf Zone Optics and MURI teams with observations of waves and currents made along a cross-shore transect extending from the surfzone to approximately 4-m water depth at the Field Research Facility, Duck, NC (funded by a National Security Science and Engineering Faculty Fellowship, Office the Secretary of Defense). We also provided a Lidar to observe the sea surface near the breaking region. MURI and Surf Zone Optics investigators will use the observations for background environmental information for their nearshore and inlet studies, for ground truth for remote sensing observations, and to initialize and evaluate numerical model predictions of waves, currents, and the underlying bathymetry.

We also worked with colleagues from the MURI and ONR Rivers and Inlet Mouths DRI teams to design an *in situ* sensor array to be deployed at New River Inlet in spring 2012 (Figure 1). In collaboration with ONR CODE 30 we have been planning and scheduling the field project.


***Figure 1. Array of in situ sensors planned for New River Inlet, spring 2012. Solid red circles are colocated pressure sensors and acoustic Doppler velocimeters. Black and red circles are colocated pressure gages and acoustic Doppler profiling current meters. CTDs will be colocated with some of the sensors. Bathymetry will be surveyed pre and post deployment, and weekly during the experiment [Instruments are located across the ebb shoal and about 2 km up the river].***

## RESULTS

Stratification of the shallow waters on tidal flats is important because it affects turbulence, mixing, bottom stress, circulation, and sediment transport. The observations of density, currents, and sea levels collected in 2008 and 2009 on the shallow, broad, periodically inundated tidal flats (shoals) that lie between the mouths of the north and south forks of the Skagit River are being used to investigate the processes driving the temporal and spatial variations of stratification. The majority of the discharge from the north and south forks (about 120 $m^3/s$ and 80 $m^3/s$, respectively, during our study) flows onto the flats about 2.5 km northeast and 4.5 km southwest of the study area. In addition, numerous small channels [depth $O(10\ \text{cm})$] split off from the north fork and extend across the marshes onto the tidal flats near the measurement locations (Elgar and Raubenheimer 2010).

The stratification is quantified using the potential energy anomaly ($\Phi$), the amount of energy per unit volume required to homogenize the water column (Simpson 1990, Burchard and Hofmeister 2008). The temporal variations of $\partial\Phi/\partial t$ (where *t* is time) at a mid-flat location (figure 2) are shown to result primarily from three processes: (1) advection of the density front, (2) tidal straining (owing to the vertically sheared velocity profile acting on the horizontal density gradient), and (3) mixing. The good agreement between direct calculation of the stratification (black curve, based on observed density profiles) and the process-based estimates (dashed purple curve, based on process theory driven with observations of currents and density) suggests that other terms are not large. The stratification has similarities to (and differences from) estuaries with complex bathymetry and coastal plumes (regions of freshwater influence, ROFIs) in which alongshore (lateral) processes are important, and to narrow, shallow strongly forced salt-wedge estuaries and tidal flat channels in which along-channel processes dominate.

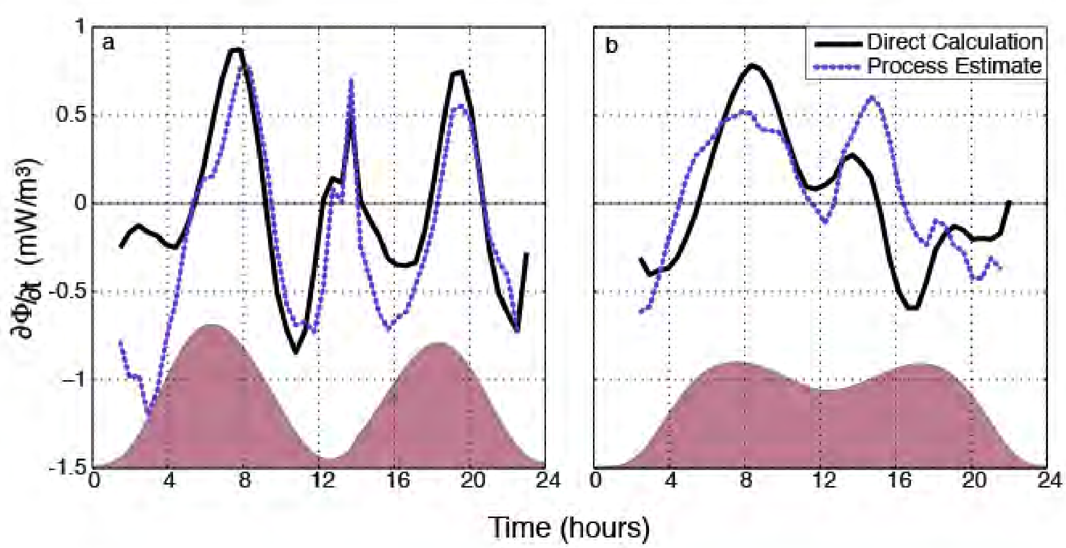


***Figure 2: Phase-averaged $\partial\Phi/\partial t$ based on the observed density profiles (solid black curves) and on estimations of stratification-related processes (dotted purple curves) versus time for (a) nearly semi-diurnal (type 1) and (b) nearly diurnal (type 2) tides, respectively. Squared correlations between the direct and process estimates are about 0.7. The shaded area shows the relative water depth over the tidal cycle.***

The fresh water draining off the flats during the strong ebbs remains partly stratified, and thus the initial tongue of water crossing the flats on strong floods often is partly stratified. However, the water becomes increasingly well mixed (e.g., $\partial\Phi/\partial t < 0$) owing to negative advection, depth-mean straining, and mixing (figure 3, solid blue, dashed purple, and dashed green curves, respectively) as better-mixed and more saline offshore water is carried onshore.

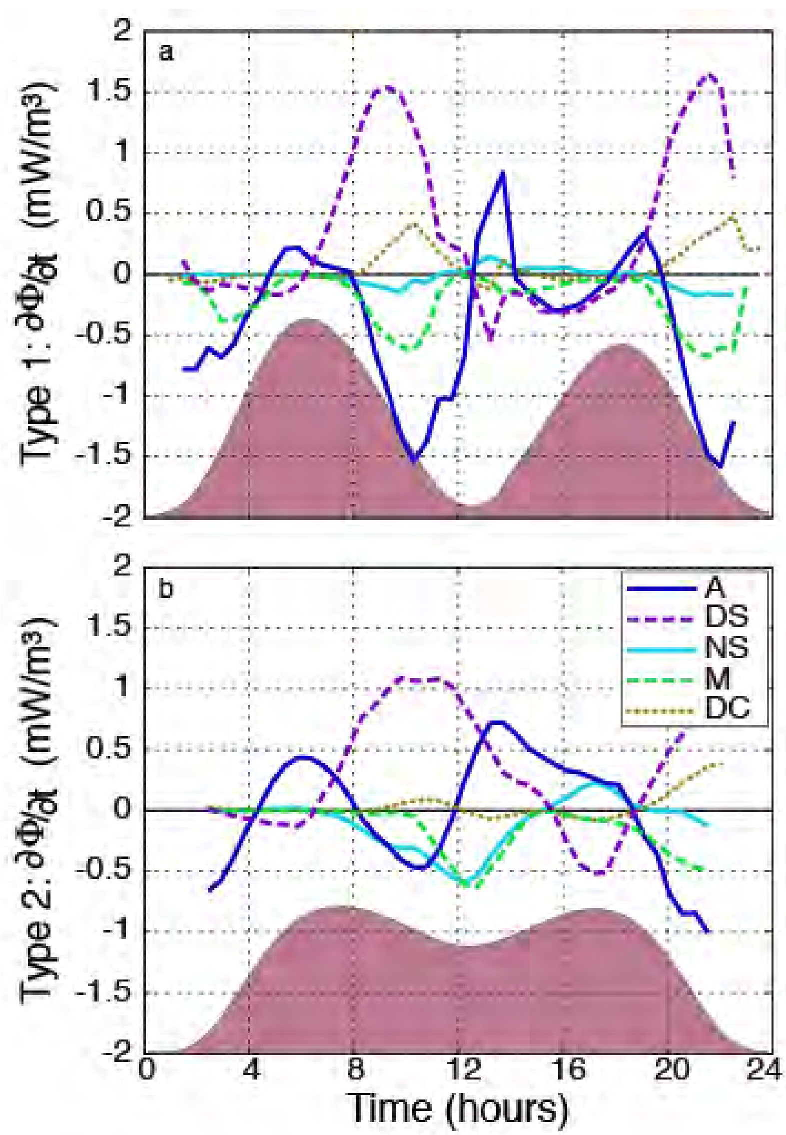


***Figure 3: Phase-averaged estimates of processes for (a) type 1 and (b) type 2 tides. The shaded area shows the relative water depth over a tidal cycle. The colored curves are advection (A, solid dark blue), depth-mean straining (DS, dashed purple), non-mean straining (NS, solid light blue), mixing (M, dashed green), and depth change (DC, dashed olive).***

Changes in stratification observed during nearly semi-diurnal (type 1) tides are similar to observations in salt-wedge estuaries (Ralston *et al.* 2010, Giddings *et al.* 2011). For example, during the flood following the smaller low tide (when the flat does not go dry), the stratification increases sharply (e.g., figure 2a time about 12 to 14 hrs) as the density front is transported onshore. Advection (blue curve, figure 3a) usually opposes the positive depth-mean straining (dashed-purple curve, figure 3a) on the ebb, indicating that the fresh water that is trapped near the shore at high tide is less stratified than the offshore water. Maximum stratification (where $\partial\Phi/\partial t$ changes from positive to negative) occurs at about mid ebb tide. Although cross- and alongshore flows have roughly equal magnitudes (figure 4a and c), the changes in stratification result primarily from cross-shore processes (not shown), because the cross-shore density gradients are much larger than those in the alongshore.

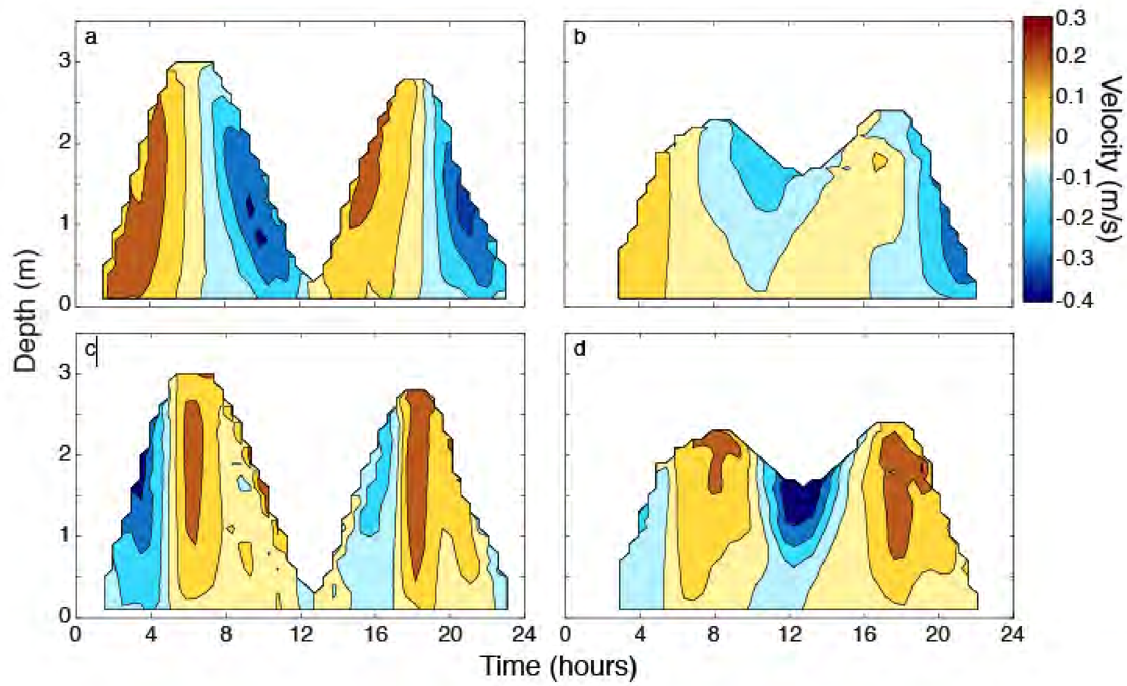


***Figure 4: Phase-averaged cross-shore (a and b) and alongshore (c and d) velocity profiles (colors) and water depth (black curve) for type 1 (a and c) and type 2 (b and d) tides, respectively.***

Consistent with both salt-wedge estuaries and ROFIs, stratification is stronger during neap (type 2) tides with a relatively small low tide than during nearly semi-diurnal (type 1) tides. However, the processes controlling the increased stratification during the weak ebb and the beginning of the weak flood ($\partial\Phi/\partial t > 0$ for time=8 to 15 hrs in figure 2b) are more similar to ROFIs than to salt-wedge estuaries. In particular, alongshore flows are stronger than cross-shore flows (compare figure 4d with figure 4b), and the increased stratification is partly owing to alongshore advection. Specifically, the stratification at the mid-flat location increases during the small low and early weak-flood owing to strong southwesterly alongshore flows (figure 4d) transporting stratified water from the north fork of the Skagit River towards the instrument location (not shown), as well as to strongly sheared cross-shore flows (figure 4b) that remain offshore-directed at the surface until mid-weak-flood. The stratification decreases from about mid-weak-flood through the second high tide and the following strong ebb ($\partial\Phi/\partial t < 0$ for time=15 to 22 hrs in figure 2b), and maximum stratification occurs mid-weak-flood (time = 15 hrs in figure 2b).

Mixing (figure 3, green dashed curve), which always is negative (reducing stratification), is largest when internal or bottom shear is large and when the water is not well mixed already. During type 1 tides, mixing is strongest during the ebbs (figure 3a, time=10 and 22 hrs), consistent with the combined interfacial- and bottom-generated mixing observed in strongly forced salt-wedge estuaries (Ralston *et al.* 2010, Wang *et al.* 2011). Mixing is weak during floods (figure3a, time=4 and 14 hrs) despite strong near-bed flows (figure 4 a and c) primarily because the water-column already is well mixed. During type 2 tides, mixing is estimated to be large during higher-low water (figure 3b, time=12 hrs). Near-bed flows are weak, while mid-water column shear is strong (figure 4b and d), suggesting the mixing on type 2 tides is owing primarily to internal shear. In contrast to many deeper or better-mixed estuaries and ROFIs, mixing is comparable in magnitude to advection and depth-mean straining.

The non-mean straining (figure 3a, light blue solid curve) is small during type 1 tides. However, in contrast with numerical simulations showing that non-mean straining typically is large only near the river or estuarine mouth (e.g., de Boer *et al.* 2008, Marques *et al.* 2010), here it is similar in magnitude to the other terms during type 2 tides (figure 3b), and it reduces both the increase in stratification during higher-low water (figure 2b, $\partial\Phi/\partial t > 0$) and the decrease in stratification during the latter half of the weak flood (figure 2b, $\partial\Phi/\partial t < 0$). The prior simulations suggest vertical advection may balance non-mean straining, and thus the discrepancies between the direct- and process-based estimates of $\partial\Phi/\partial t$ (figure 2b) during the high-low and weak flood at least partly may be owing to neglecting vertical advection.

Temporal changes in stratification are similar across and along the flats (not shown). However, stratification increases offshore and alongshore towards the north fork (the river mouth closest to the instruments).

## IMPACT/APPLICATIONS

In contrast to tidal flat channels, the tidal flat shoals between the river mouths are affected by alongshore processes, flows, and density gradients during nearly diurnal (type 2) tides.

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 to model 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 have provided 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 2011 more than 20 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. The field observations of nearshore processes on sandy beaches are funded primarily by an NSSEFF project to study morphological evolution.

**REFERENCES**

Burchard, H., and R. Hofmeister, 2008 A dynamic equation for the potential energy anomaly for analyzing mixing and stratification in estuaries and coastal seas, *Estuar. Coastal Shelf Sci*., **77**, 679–687.

de Boer, G.J., J.D. Pietrzak, and J.C. Winterwerp, 2008 Using the potential energy anomaly equation to investigate tidal straining and advection of stratification in a region of freshwater influence, *Ocean Modell*., **22**, 1-11.

Elgar, S., and B. Raubenheimer, 2010 Currents in a small sandy tidal channel, *Cont. Shelf. Res*., **31**, 9–14.

Elgar, S., B. Raubenheimer, J. Thomson, and M. Moulton, 2011 Resonances in an evolving hole in the swash zone, *J. Water. Ports Coastal Ocean Eng*., *submitted*.

Engelstad, A., T. Janssen, T. Herbers, S. Elgar, and B. Raubenheimer, Observations of wave-mud interaction across the Louisiana shelf, *EOS Trans. AGU*, **91**, PO25C-20, 2010a.

Engelstad, A., T.T. Janssen, G. van Vledder, T.H. Herbers, S. Elgar, and B. Raubenheimer, Wave damping across the Louisiana shelf, *Abstract OS51B-1287*, presented at 2010 Fall Meeting, AGU, 2010b.

Gast, R.J., L. Gorrell, B. Raubenheimer, and S. Elgar, 2011 Impact of erosion and accretion on the distribution of enterococci in beach sands, *Cont. Shelf Res*., **31**, 1457-1461.

Gorrell, L., B. Raubenheimer, S. Elgar, and R. Guza, SWAN Predictions of waves observed in shallow water onshore of complex bathymetry, *Coastal Eng*., **58**, 510-516, 2011.

Giddings, S.N., D.A. Fong, and S.G. Monismith, 2011 Role of straining and advection in the intratidal evolution of stratification, vertical mixing, and longitudinal dispersion of a shallow, macrotidal, salt wedge estuary. *J. Geophys. Res*., **116**, doi:10.1029/2010JC006482.

Kilgallin, S., M. Moulton, S. Elgar, and B. Raubenheimer, 2011 Aquadopp measurements of circulation and accretion in man-made holes in the surfzone, *NorTek Symposium*.

List, K., B. Raubenheimer, and S. Elgar, 2010 Lidar observations of runup, *Abstract OS51B-1319*, presented at 2010 Fall Meeting, AGU.

Marques, W.C., E.H. Fernandes, and O.O. Möller, 2010 Straining and advection contributions to the mixing process of the Patos Lagoon coastal plume, Brazil. *J. Geophys. Res*., **115**, doi:10.1029/2009JC005653.

Moulton, M., S. Elgar, B. Raubenheimer, 2010 Big holes in the surfzone: Waves, Currents, and Sediment Transport in a Seafloor Perturbation Experiment, *Abstract OS51B-1299*, presented at 2010 Fall Meeting, AGU.

Pavel, V., B. Raubenheimer, S. Elgar, and D. Ralston, 2011 Processes affecting the stratification-induced potential energy anomaly on the Skagit River tidal flats, *Abstract OS34B-06*, presented at 2010 Fall Meeting, AGU.

Ralston, D.K., and M.T. Stacey, 2005 Stratification and turbulence in subtidal channels through intertidal mudflats, *J. Geophys. Res*., **110**, doi:10.1029/2004JC002650.

Ralston, D.K., W.R. Geyer, J.A. Lerczak, and M. Scully, 2010 Turbulent mixing in a strongly forced salt wedge estuary, *J. Geophys. Res*., **115.** C12024, doi:10.1029/2009JC006061.

Raubenheimer, B., D. Ralston, R. Signell, D. Giffen, and S. Elgar, 2010 Observations and predictions of winds on the Skagit River tidal flats, *Abstract OS31C-1429*, presented at 2010 Fall Meeting, AGU.

Raubenheimer, B., D. Ralston, S. Elgar, D. Giffen, and R. Signell, 2011 Winds on the Skagit tidal flats, *Cont. Shelf Res*., *submitted*.

Safak, I., A. Sheremet, S. Elgar, and B. Raubenheimer, 2010 Nonlinear wave propagation across a muddy seafloor, *EOS Trans. AGU*, **91**, PO14B-03.

Simpson, J.H., J. Brown, J. Matthews, and G. Allen, 1990 Tidal straining, density currents, and stirring in the control of estuarine stratification, *Estuaries*, **13**, 125-132.

Van der Linde, P., 2010 Modeling Nearshore currents driven by waves and set-up gradients, M.S. Thesis, Delft Univ. Tech.

Wang, B., O. B. Fringer, E. S. Gross, S. N. Giddings, D. A. Fong, and S. G. Monismith, 2011 Modeling and understanding turbulent vertical mixing in a macrotidal salt wedge estuary, *J. Geophys. Res*., **in press**.

## PUBLICATIONS

1. Elgar, S., and B. Raubenheimer, Currents in a small sandy tidal channel, *Cont. Shelf. Res*., **31**, 9–14 2010b. [published, refereed]

2. Elgar, S., B. Raubenheimer, J. Thomson, M. Moulton, Resonances in an evolving hole in the swash zone, *J. Water. Ports Coastal Ocean Eng*., submitted, 2011. [submitted, refereed].

3. Gast, R.J., L. Gorrell, B. Raubenheimer, S. Elgar, Impact of erosion and accretion on the distribution of enterococci in beach sands, *Cont. Shelf Res*., **31**, 1457-1461. [published, refereed].

4. Gorrell, L., B. Raubenheimer, S. Elgar, and R. Guza, SWAN Predictions of waves observed in shallow water onshore of complex bathymetry, *Coastal Eng*., **58**, 510-516, 2011. [published, refereed].

5. Raubenheimer, B., D. Ralston, S. Elgar, D. Giffen, R. Signell, Winds on the Skagit tidal flats, *Cont. Shelf Res*., submitted, 2011. [submitted, refereed].

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