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DARLA: Data Assimilation and Remote Sensing for Littoral Applications
Final Report
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Andrew T. Jessup
Chris Chickadel, Gordon Farquharson, Jim Thomson
Applied Physics Laboratory, University of Washington
Seattle, WA 98105
phone: ((206) 685-2609 fax: (206) 543-6785 email: jessup@apl.washington.edu

Robert A. Holman
Merrick Haller, Alexander Kuropov, Tuba Ozkan-Haller
Oregon State University
Corvallis, OR 97331
phone: (541) 737-2914 fax: (541) 737-2064 email: holman@coas.oregonstate.edu

Steve Elgar
Britt Raubenheimer
Woods Hole Oceanographic Institution, MS11
Woods Hole, MA 02543
phone: (508) 289-3614 fax: (508) 457-2194 email: elgar@whoi.edu

LONG-TERM GOALS

Our long-term goal was to use remote sensing observations to constrain a data assimilation model of wave and circulation dynamics in an area characterized by a river mouth or tidal inlet and surrounding beaches. As a result of this activity, we have improved environmental parameter estimation via remote sensing fusion, determined the success of using remote sensing data to drive DA models, and produced a dynamically consistent representation of the wave, circulation, and bathymetry fields in complex environments.

OBJECTIVES

The objectives were to test the following three hypotheses:

1. Environmental parameter estimation using remote sensing techniques can be significantly improved by fusion of multiple sensor products.
2. Data assimilation models can be adequately constrained (i.e., forced or guided) with environmental parameters derived from remote sensing measurements.
3. Bathymetry on open beaches, river mouths, and at tidal inlets can be inferred from a combination of remotely-sensed parameters and data assimilation models.

APPROACH

Our overall approach was to conduct a series of field experiments combining remote sensing and in situ measurements to investigate signature physics and to gather data for developing and testing DA models. To ensure early and ongoing testing, we performed a pilot experiment at Duck, NC, using tower-based remote sensing (EO, radar, IR) and current versions of the DA modeling system. We participated in the field experiments in May 2012 at New River Inlet near Camp LeJeune, NC and in May and June of 2013 at the mouth of the Columbia River near Astoria, OR under the ONR-sponsored Inlets and Rivers Mouth Dynamics Departmental Research Initiative (RIVET I and II). During this campaign, APL-UW scientist Craig McNeil and Andrea Shcherbina deployed a REMUS UUV to provide subsurface measurements in conjunction with the airborne measurements. We also conducted airborne measurements and in situ measurements at the mouth of the Columbia River for one to two weeks each during July and September 2013.

Our approach benefited both the remote sensing research (by leveraging the RIVET in situ measurements) and RIVET itself via our integrated remote sensing and DA modeling system. The combined capabilities provided an innovative solution that coupled spatially dense sampling with data assimilation methods to study the complicated dynamics of interacting wave, bathymetry, and current fields. The key to this project was an interactive process that blended sophisticated remote sensing, in-situ sensing, and data assimilation modeling. Our approach was to conduct closely coupled field and numerical model experiments to test the hypotheses listed above. Work on each facet informs the work on the others, and conflicts in results or interpretations are resolved by testing the hypotheses and the sensitivity of the results to a range of parameter variations.

The project resulted in a total of 26 publications in peer-reviewed journals, listed below first as the reference only followed by a list of each reference with its abstract.

Publications

1. Akan, C., J. McWilliams, S. Moghimi, and H. T. ozkan-Haller (2017a), Frontal Dynamics at the Mouth of the Columbia River, *Geophysical Research Letters, submitted*.
2. Akan, C., S. Moghimi, H. T. Ozkan-Haller, J. Osborne, and A. L. Kurapov (2017b), On the dynamics of the Mouth of Columbia River: Results from a three-dimensional fully coupled wave-current interaction model, *J. Geophys. Res.*, *in review*.
3. Carini, R. J., C. C. Chickadel, A. T. Jessup, and J. Thomson (2015), Estimating wave energy dissipation in the surf zone using thermal infrared imagery, *Journal of Geophysical Research-Oceans*, *120*(6), 3937-3957.
4. Goncharenko, Y. V., G. Farquharson, F. Y. Shi, B. Raubenheimer, and S. Elgar (2015), Estimation of Shallow-Water Breaking-Wave Height From Synthetic Aperture Radar, *Ieee Geoscience and Remote Sensing Letters*, *12*(10), 2061-2065.
5. H, D., G. Farquharson, Y. Goncharenko, and J. Mower (2017), Phase Calibration of an Along-track Interferometric FMCW SAR, *IEEE Transactions of Geoscience and Remote Sensing., in revision*.

6. Haller, M. C., D. A. Honegger, and P. A. Catalan (2014), Rip current observations via marine radar, *J. Waterway, Port, Coastal, and Ocean Engineering*, *140*(2), 115-124.

7. Holman, R., N. Plant, and T. Holland (2013), cBathy: A robust algorithm for estimating nearshore bathymetry, *Journal of Geophysical Research-Oceans*, *118*(5), 2595-2609.

8. Holman, R., M. Haller, T. Lippmann, T. Holland, and B. Jaffe (2015), Advances in nearshore processes research: four decades of progress, *Shore and Beach*, *83*(1), 39-54.

9. Holman, R. A., and M. C. Haller (2012), Remote Sensing of the Nearshore, *Remote Sensing of the Nearshore*(5), 95-113.

10. Honegger, D. A., M. C. Haller, W. R. Geyer, and G. Farquharson (2017), Oblique internal hydraulic jumps at a stratified estuary mouth, *J. Phys. Ocean.*, *47*, 85-100.

11. Hopkins, J., S. Elgar, and B. Raubenheimer (2016), Observations and model simulations of wave-current interaction on the inner shelf, *Journal of Geophysical Research-Oceans*, *121*(1), 198-208.

12. Hopkins, J., S. Elgar, and B. Raubenheimer (2017), Flow separation effects on shoreline evolution, *Coastal Engineering*, *in review*.

13. Kurapov, A. L., and H. T. Ozkan-Haller (2013), Bathymetry correction using an adjoint component of a coupled nearshore wave-circulation model: Tests with synthetic velocity data, *Journal of Geophysical Research-Oceans*, *118*(9), 4673-4688.

14. Mendez, G. M. D., M. C. Haller, B. Raubenheimer, S. Elgar, and D. A. Honegger (2015), Radar Remote Sensing Estimates of Waves and Wave Forcing at a Tidal Inlet, *Journal of Atmospheric and Oceanic Technology*, *32*(4), 842-854.

15. Moghimi, S., J. Thomson, T. Ozkan-Haller, L. Umlauf, and S. Zippel (2016), On the modeling of wave-enhanced turbulence nearshore, *Ocean Modelling*, *103*, 118-132.

16. Moghimi, S., H. T. Ozkan-Haller, G. W. Wilson, and A. L. Kurapov (2017), Data assimilation for bathymetry estimation at a tidal inlet, *J. Atmos. Ocean. Tech.*, *in press*.

17. Orescanin, M., S. Elgar, and B. Raubenheimer (2017), Effects of a shallow flood shoal and friction on hydrodynamics of a multiple-inlet system, *J. Geophys. Res.*, *in review*.

18. Orescanin, M. M., S. Elgar, and B. Raubenheimer (2016), Changes in bay circulation in an evolving multiple inlet system, *Continental Shelf Research*, *124*, 13-22.

19. Pianca, C., R. Holman, and E. Siegle (2015), Shoreline variability from days to decades: Results of long-term video imaging, *Journal of Geophysical Research-Oceans*, *120*(3), 2159-2178.

20. Radermacher, M., M. Wengrove, J. V. de Vries, and R. Holman (2014), Applicability of video-derived bathymetry estimates to nearshore current model predictions, *Journal of Coastal Research*, 290-295.

21. Shi, F. Y., C. C. Chickadel, T. J. Hsu, J. T. Kirby, G. Farquharson, and G. F. Ma (2017), High-Resolution Non-Hydrostatic Modeling of Frontal Features in the Mouth of the Columbia River, *Estuaries and Coasts*, *40*(1), 296-309.

22. Thomson, J. (2012), Wave Breaking Dissipation Observed with "SWIFT" Drifters, *Journal of Atmospheric and Oceanic Technology*, *29*(12), 1866-1882.

23. Thomson, J., A. R. Horner-Devine, S. Zippel, C. Rusch, and W. Geyer (2014), Wave breaking turbulence at the offshore front of the Columbia River Plume, *Geophysical Research Letters*, *41*(24), 8987-8993.

24. Wilson, G. W., H. T. Ozkan-Haller, and R. A. Holman (2013), Quantifying the length-scale dependence of surf zone advection, *Journal of Geophysical Research-Oceans*, *118*(5), 2393-2407.

25. Wilson, G. W., H. T. Ozkan-Haller, R. A. Holman, M. C. Haller, D. A. Honegger, and C. C. Chickadel (2014), Surf zone bathymetry and circulation predictions via data assimilation of remote sensing observations, *Journal of Geophysical Research-Oceans*, *119*(3), 1993-2016.

26. Zippel, S., and J. Thomson (2015), Wave breaking and turbulence at a tidal inlet, *Journal of Geophysical Research-Oceans*, *120*(2), 1016-1031.

27. Zippel, S., and J. Thomson (2017), Surface wave breaking over sheared currents: observations from the Mouth of the Columbia River, *J. Geophys. Res., in revision*.

Publications with Abstracts

1. Akan, C., J. McWilliams, S. Moghimi, and H. T. Ozkan-Haller (2017a), Frontal Dynamics at the Mouth of the Columbia River, *Geophysical Research Letters, submitted*.

Abstract: In the tidal ebb cycle at the Mouth of the Columbia River, strong density and velocity fronts form at both sides of the near-shore freshwater plume perpendicular to the coast. We present simulation results to investigate the mechanisms behind this frontogenesis. Tidal velocities on average range between 1 m/s in flood to 2 m/s in ebb. The tidal fronts exhibit strong horizontal velocity and density gradients on a scale ~100 m in width with normalized relative vorticity values reaching up to 50. We specifically focus on the front on the north edge of the plume and examine the evolution in plume characteristics such as spatial variability of the stratification, vertical velocity, and turbulent vertical mixing along these fronts, and frontogenetic sharpening. Because of the large negative vorticity, centrifugal instability develops along the front, but only after the turn of the tide do frontal fragmentation and decay set in. Surface gravity wave Stokes drift vortex forces and material advection are included in the model but do not play a dominant role in the frontal evolution.

2. Akan, C., S. Moghimi, H. T. Ozkan-Haller, J. Osborne, and A. L. Kurapov (2017b), On the dynamics of the Mouth of Columbia River: Results from a three-dimensional fully coupled wave-current interaction model, *J. Geophys. Res., in review*.

Abstract: Numerical simulations were performed 4 using a 3D ocean circulation model (ROMS) two-way coupled to a phase-averaged wave propagation model (SWAN) in order to expand our understanding of the dynamics of wave-current interactions at the Mouth of the Columbia River (MCR). First, model results are compared with water elevations, currents, temperature, salinity

and wave measurements obtained by the U.S. Army Corp of Engineers during the Mega-Transect Experiment in 2005. We then discuss the effects of the currents on the waves and vice versa. Results show that significant wave heights are intensified notably at the entrance of the mouth in the presence of the tidal currents, especially in ebb flows. Next, we analyze the wave-plume interactions and show implications of wave effects on the plume specifically at the plume front.

3. Carini, R. J., C. C. Chickadel, A. T. Jessup, and J. Thomson (2015), Estimating wave energy dissipation in the surf zone using thermal infrared imagery, *Journal of Geophysical Research-Oceans*, *120*(6), 3937-3957.

Abstract: Thermal infrared (IR) imagery is used to quantify the high spatial and temporal variability of dissipation due to wave breaking in the surf zone. The foam produced in an actively breaking crest, or wave roller, has a distinct signature in IR imagery. A retrieval algorithm is developed to detect breaking waves and extract wave roller length using measurements taken during the Surf Zone Optics 2010 experiment at Duck, NC. The remotely derived roller length and an in situ estimate of wave slope are used to estimate dissipation due to wave breaking by means of the wave-resolving model by Duncan (1981). The wave energy dissipation rate estimates show a pattern of increased breaking during low tide over a sand bar, consistent with in situ turbulent kinetic energy dissipation rate estimates from fixed and drifting instruments over the bar. When integrated over the surf zone width, these dissipation rate estimates account for 40-69% of the incoming wave energy flux. The Duncan (1981) estimates agree with those from a dissipation parameterization by Janssen and Battjes (2007), a wave energy dissipation model commonly applied within nearshore circulation models.

4. Goncharenko, Y. V., G. Farquharson, F. Y. Shi, B. Raubenheimer, and S. Elgar (2015), Estimation of Shallow-Water Breaking-Wave Height From Synthetic Aperture Radar, *Ieee Geoscience and Remote Sensing Letters*, *12*(10), 2061-2065.

Abstract: The relationship between synthetic aperture radar (SAR) signatures of depth-limited breaking waves and wave height is studied. Wave height is estimated from SAR images using an empirically derived relationship that exploits the azimuthal shift in SAR images associated with moving scatterers. This relationship is derived from in situ measurements rather than from an idealized model of breaking waves as was done in a previous study. We find that the lengths of the SAR signatures are correlated with the observed significant wave height (the correlation coefficient is 0.78) for a range of wave conditions. The relationship between the wave heights and velocity bandwidths from the field data is similar to that between simulated (with a Boussinesq surface wave model) wave heights and velocity ranges (correlation coefficient = 0.82).

5. H, D., G. Farquharson, Y. Goncharenko, and J. Mower (2017), Phase Calibration of an Along-track Interferometric FMCW SAR, *IEEE Transactions of Geoscience and Remote Sensing.*, *in revision*.

Abstract: We introduce a phase calibration scheme for an interferometric frequency-modulated continuous wave (FMCW) synthetic aperture radar (SAR) to correct range-dependent phase errors in FMCW SAR interferograms. We demonstrate that the receiver filters operating on the FMCW beat frequency signal account for most of the phase mismatch between the different receiver

channels. The scheme presented estimates the phase error in each channel. We present results of the scheme for three estimation approaches (curve fitting, joint least squares, and maximum likelihood) for two different phase models. The results are quantified by computing the reduction in spectral energy associated with the phase mismatch. We find that phase error can be reduced by 14 dB using the approach.

6. Haller, M. C., D. A. Honegger, and P. A. Catalan (2014), Rip current observations via marine radar, *J. Waterway, Port, Coastal, and Ocean Engineering*, *140*(2), 115-124.

Abstract: New remote sensing observations that demonstrate the presence of rip current plumes in X-band radar images are presented. The observations collected on the Outer Banks (Duck, North Carolina) show a regular sequence of low-tide, low-energy, morphologically driven rip currents over a 10-day period. The remote sensing data were corroborated by in situ current measurements that showed depth-averaged rip current velocities were 20e40 cm=s whereas significant wave heights were Hs 50:5e1m. Somewhat surprisingly, these low-energy rips have a surface signature that sometimes extends several surf zone widths from shore and persists for periods of several hours, which is in contrast with recent rip current observations obtained with Lagrangian drifters. These remote sensing observations provide a more synoptic picture of the rip current flow field and allow the identification of several rip events that were not captured by the in situ sensors and times of alongshore deflection of the rip flow outside the surf zone. These data also contain a rip outbreak event where four separate ripswere imaged over a 1-kmstretch of coast. For potential comparisons of the rip current signature across other radar platforms, an example of a simply calibrated radar image is also given. Finally, in situ observations of the vertical structure of the rip current flow are given, and a threshold offshore wind stress (.0:02m=s2) is found to preclude the rip current imaging.

7. Holman, R., N. Plant, and T. Holland (2013), cBathy: A robust algorithm for estimating nearshore bathymetry, *Journal of Geophysical Research-Oceans*, *118*(5), 2595-2609.

Abstract: A three-part algorithm is described and tested to provide robust bathymetry maps based solely on long time series observations of surface wave motions. The first phase consists of frequency-dependent characterization of the wave field in which dominant frequencies are estimated by Fourier transform while corresponding wave numbers are derived from spatial gradients in cross-spectral phase over analysis tiles that can be small, allowing high-spatial resolution. Coherent spatial structures at each frequency are extracted by frequency-dependent empirical orthogonal function (EOF). In phase two, depths are found that best fit weighted sets of frequency-wave number pairs. These are subsequently smoothed in time in phase 3 using a Kalman filter that fills gaps in coverage and objectively averages new estimates of variable quality with prior estimates. Objective confidence intervals are returned. Tests at Duck, NC, using 16 surveys collected over 2 years showed a bias and root-mean-square (RMS) error of 0.19 and 0.51 m, respectively but were largest near the offshore limits of analysis (roughly 500m from the camera) and near the steep shoreline where analysis tiles mix information from waves, swash and static dry sand. Performance was excellent for small waves but degraded somewhat with increasing wave height. Sand bars and their small-scale alongshore variability were well resolved. A single ground truth survey from a dissipative, low-sloping beach (Agate Beach, OR) showed similar errors over a region that extended several kilometers from the camera and reached depths of 14 m. Vector wave number estimates can also be incorporated into data assimilation models of nearshore dynamics.

8. Holman, R., M. Haller, T. Lippmann, T. Holland, and B. Jaffe (2015), Advances in nearshore processes research: four decades of progress, *Shore and Beach*, *83*(1), 39-54.

Abstract: The purpose of this paper is to summarize four decades of progress in nearshore research, the duration of the science career of Dr. Abby Sallenger. This paper is a retrospective foundation and jumping-off point for a companion paper that discusses the priority directions for future research as developed in a recent community meeting and from subsequent discussions. Our review starts with a short discussion of the nature of the nearshore problem, then is divided into four periods, pre-1974, 1974-1989, 1989-2000 and finally 2000-the present. Each section covers the research highlights for fluid and sedimentary processes, key facilitators of progress including instrumentation development and large experiments, and community assessments of priority unsolved problems at the end of each period.

9. Holman, R. A., and M. C. Haller (2012), Remote Sensing of the Nearshore, *Remote Sensing of the Nearshore*(5), 95-113.

Abstract: The shallow waters of the nearshore ocean are popular, dynamic, and often hostile. Prediction in this domain is usually limited less by our understanding of the physics or by the power of our models than by the availability of input data, such as bathymetry and wave conditions. It is a challenge for traditional in situ instruments to provide these inputs with the appropriate temporal or spatial density or at reasonable logistical or financial costs. Remote sensing provides an attractive alternative. We discuss the range of different sensors that are available and the differing physical manifestations of their interactions with the ocean surface. We then present existing algorithms by which the most important geophysical variables can be estimated from remote sensing measurements. Future directions and opportunities will depend on expected developments in sensors and platforms and on improving processing algorithms, including data assimilation formalisms.

10. Honegger, D. A., M. C. Haller, W. R. Geyer, and G. Farquharson (2017), Oblique internal hydraulic jumps at a stratified estuary mouth, *J. Phys. Ocean.*, *47*, 85-100.

Abstract: Observations and analyses of two tidally recurring, oblique, internal hydraulic jumps at a stratified estuary mouth (Columbia River, Oregon/Washington) are presented. These hydraulic features have not previously been studied due to the challenges of both horizontally resolving the sharp gradients and temporally resolving their evolution in numerical models and traditional observation platforms. The jumps, both of which recurred during ebb, formed adjacent to two engineered lateral channel constrictions and were identified in marine radar image time series. Jump occurrence was corroborated by (i) a collocated sharp gradient in the surface currents measured via airborne along-track interferometric synthetic aperture radar and (ii) the transition from supercritical to subcritical flow in the cross-jump direction via shipborne velocity and density measurements. Using a two-layer approximation, observed jump angles at both lateral constrictions are shown to lie within the theoretical bounds given by the critical internal long-wave (Froude) angle and the arrested maximum-amplitude internal bore angle, respectively. Also,

intratidal and intertidal variability of the jump angles are shown to be consistent with that expected from the two-layer model, applied to varying stratification and current speed over a range of tidal and river discharge conditions. Intratidal variability of the upchannel jump angle is similar under all observed conditions, whereas the downchannel jump angle shows an additional association with stratification and ebb velocity during the low discharge periods. The observations additionally indicate that the upchannel jump achieves a stable position that is collocated with a similarly oblique bathymetric slope.

11. Hopkins, J., S. Elgar, and B. Raubenheimer (2016), Observations and model simulations of wave-current interaction on the inner shelf, *Journal of Geophysical Research-Oceans*, *121*(1), 198-208.

Abstract: Wave directions and mean currents observed for two 1 month long periods in 7 and 2 m water depths along 11 km of the southern shoreline of Martha's Vineyard, MA, have strong tidal modulations. Wave directions are modulated by as much as 70 degrees over a tidal cycle. The magnitude of the tidal modulations in the wavefield decreases alongshore to the west, consistent with the observed decrease in tidal currents from 2.1 to 0.2 m/s along the shoreline. A numerical model (SWAN and Deflt3D-FLOW) simulating waves and currents reproduces the observations accurately. Model simulations with and without wave-current interaction and tidal depth changes demonstrate that the observed tidal modulations of the wavefield primarily are caused by wave-current interaction and not by tidal changes to water depths over the nearby complex shoals.

12. Hopkins, J., S. Elgar, and B. Raubenheimer (2017), Flow separation effects on shoreline evolution, *Coastal Engineering, in review*.

Abstract: Field-tested numerical model simulations are used to estimate the effects of an inlet, ebb shoal, wave height, wave direction, and shoreline geometry on the variability of bathymetric change on a curved coast with a migrating inlet and strong nearshore currents. The model uses bathymetry measured along the southern shoreline of Martha’s Vineyard, MA, and was validated with waves and currents observed from the shoreline to ~10-m water depth. Between 2007 and 2014, the inlet was open and the shoreline along the southeast corner of the island eroded ~200 m and became sharper. Between 2014 and 2015, the corner accreted and became smoother as the inlet closed. Numerical simulations indicate that variability of sediment transport near the corner shoreline depends more strongly on its radius of curvature (a proxy for the separation of tidal flows from the coast) than on the presence of the inlet, the ebb shoal, or wave height and direction. As the radius of curvature decreases (as the corner sharpens), tidal asymmetry of nearshore currents is enhanced, leading to more sediment transport near the shoreline over several tidal cycles. The results suggest that feedbacks between shoreline geometry and inner-shelf flows can be important to coastal erosion and accretion in the vicinity of an inlet.

13. Kurapov, A. L., and H. T. Ozkan-Haller (2013), Bathymetry correction using an adjoint component of a coupled nearshore wave-circulation model: Tests with synthetic velocity data, *Journal of Geophysical Research-Oceans*, *118*(9), 4673-4688.

Abstract: The impact of assimilation of wave-averaged flow velocities on the bathymetric correction is studied in tests with synthetic (model-generated) data using tangent-linear and adjoint

components of a one-way coupled nearshore wave-circulation model. Weakly and strongly nonlinear regimes are considered, featuring energetic unsteady along-beach flows responding to time-independent wave-averaged forcing due to breaking waves. It is found that assimilation of time-averaged velocities on a regular grid (mimicking an array of remotely sensed data) provides sensible corrections to bathymetry. Even though the wave data are not assimilated, flow velocity assimilation utilizes adjoint components of both the circulation and wave models. The representer formalism allows separating contributions of these two components to the bathymetric correction. In a test case considered, involving a beach with an alongshore varying bar, the adjoint wave model contribution was mainly to determine the cross-shore position of the bar crest. The adjoint circulation model provided an additional contribution, mostly adding to alongshore variability in the shape of the bar. The array mode analysis reveals that there are very few modes that can be effectively corrected, given the assumed data error level. Bathymetry perturbations associated with these modes are a mixture of near-coast intensified modes as well as modes extending their influence to deep water (along the background wave characteristics). Additional tests show the utility of different observational arrays in providing the bathymetric correction.

14. Mendez, G. M. D., M. C. Haller, B. Raubenheimer, S. Elgar, and D. A. Honegger (2015), Radar Remote Sensing Estimates of Waves and Wave Forcing at a Tidal Inlet, *Journal of Atmospheric and Oceanic Technology*, *32*(4), 842-854.

Abstract: The time and space variability of wave transformation through a tidal inlet is investigated with radar remote sensing. The frequency of wave breaking and the net wave breaking dissipation at high spatial resolution is estimated using image sequences acquired with a land-based X-band marine radar. Using the radar intensity data, transformed to normalized radar cross section sigma(0), the temporal and spatial distributions of wave breaking are identified using a threshold developed via the data probability density function. In addition, the inlet bathymetry is determined via depth inversion of the radar-derived frequencies and wavenumbers of the surface waves using a preexisting algorithm (cBathy). Wave height transformation is calculated through the 1D cross-shore energy flux equation incorporating the radar-estimated breaking distribution and bathymetry. The accuracy of the methodology is tested by comparison with in situ wave height observations over a 9-day period, obtaining correlation values R = 0.68 to 0.96, and root-mean-square errors from 0.05 to 0.19 m. Predicted wave forcing, computed as the along-inlet gradient of the cross-shore radiation stress partial derivative S-xx/partial derivative x was onshore during high-wave conditions, in good agreement (R = 0.95) with observations.

15. Moghimi, S., J. Thomson, T. Ozkan-Haller, L. Umlauf, and S. Zippel (2016), On the modeling of wave-enhanced turbulence nearshore, *Ocean Modelling*, *103*, 118-132.

Abstract: A high resolution k-omega two-equation turbulence closure model, including surface wave forcing was employed to fully resolve turbulence dissipation rate profiles close to the ocean surface. Model results were compared with observations from Surface Wave Instrument Floats with Tracking (SWIFTs) in the nearshore region at New River Inlet, North Carolina USA, in June 2012. A sensitivity analysis for different physical parameters and wave and turbulence formulations was performed. The flux of turbulent kinetic energy (TKE) prescribed by wave dissipation from a numerical wave model was compared with the conventional prescription using the wind friction velocity. A surface roughness length of 0.6 times the significant wave height was proposed, and the flux of TKE was applied at a distance below the mean sea surface that is half of this roughness length. The wave enhanced layer had a total depth that is almost three times the significant wave height. In this layer the non-dimensionalized Terray scaling with power of -1.8 (instead of -2) was applicable.

16. Moghimi, S., H. T. Ozkan-Haller, G. W. Wilson, and A. L. Kurapov (2017), Data assimilation for bathymetry estimation at a tidal inlet, *J. Atmos. Ocean. Tech.*, *in press*.

Abstract: Here we developed and tested a data assimilation framework which accommodates different types of geophysical ocean data (i.e. surface velocity and waves information) and provides an estimation of the bathymetry of a mixed-energy tidal inlet. We successfully applied this framework to a highly variable tidal environment using synthetic data (twin test). The synthetic data consisted of surface velocity components associated with the tidal circulation and wavenumber-frequency pairs of incoming surface gravity waves which mimic data that could be derived from an airborne Synthetic Aperture Radar system and a tower-mounted X-band radar system, respectively. The present ensemble-based assimilation framework has previously been applied in both wave-dominated (coastal) and current-dominated (riverine) environments. In contrast, the inlet environment is neither wave- or current-dominated. Indeed, assimilation of both wave and current data together was most useful to obtain skillful estimate of the spatial map of bathymetry.

17. Orescanin, M., S. Elgar, and B. Raubenheimer (2017), Effects of a shallow flood shoal and friction on hydrodynamics of a multiple-inlet system, *J. Geophys. Res.*, *in review*.

Abstract: Prior studies have shown that frictional changes owing to evolving geometry of an inlet in a multiple inlet-bay system can affect tidally driven circulation. Here, a step between a relatively deep inlet and a shallow bay also is shown to affect tidal sea-level fluctuations in a bay connected to multiple inlets. To examine the relative importance of friction and a step, a lumped element (parameter) model is used that includes tidal reflection from the step. The model is applied to the two-inlet system of Katama Inlet (which connects Katama Bay on Martha's Vineyard, MA to the Atlantic Ocean) and Edgartown Channel (which connects the bay to Vineyard Sound). Consistent with observations and previous numerical simulations, the lumped element model suggests that the presence of a shallow flood shoal limits the influence of an inlet. In addition, the model suggests an increasing importance of friction relative to the importance of the step as an inlet shallows, narrows, and lengthens, as observed at Katama Inlet from 2011 to 2014.

18. Orescanin, M. M., S. Elgar, and B. Raubenheimer (2016), Changes in bay circulation in an evolving multiple inlet system, *Continental Shelf Research*, *124*, 13-22.

Abstract: Observations and numerical model (ADCIRC) simulations are used to quantify the changes in circulation within the evolving, shallow, two-inlet tidal Katama system, Martha's Vineyard, MA. From 2011 to 2013, Katama Inlet, connecting Katama Bay to the Atlantic, became 5 times longer, 1/3 as wide, and 1/3 as deep as the inlet migrated and rotated. This morphological evolution caused a significant loss of energy throughout Katama Bay and Edgartown Channel, which connects the bay to Vineyard Sound. The decrease in energy as the inlet evolved between 2011 and 2013 was not monotonic. Model simulations suggest bathymetric changes caused by

Hurricane Irene (August 2011) resulted in a temporary increase in circulation energy throughout the inlets and bay. Changes in the M4 and M6 tidal constituents, harmonics of the primary M2 tidal forcing, suggest the changes in the observed circulation patterns primarily were owing to changes in friction, and not to changes in advection resulting from the evolving inlet location, orientation, or geometry, consistent with previous results.

19. Pianca, C., R. Holman, and E. Siegle (2015), Shoreline variability from days to decades: Results of long-term video imaging, *Journal of Geophysical Research-Oceans*, *120*(3), 2159-2178.

Abstract: The present work characterizes the time-space scales of variability and forcing dependencies of a unique 26 year record of daily to hourly shoreline data from a steep beach at Duck, North Carolina. Shoreline positions over a 1500 m alongshore span were estimated using a new algorithm called ASLIM based on fitting the band of high light intensity in time exposure images to a local Gaussian fit, with a subsequent Kalman filter to reduce noise and uncertainty. Our findings revealed that the shoreline change at long times scales dominates seasonal variability, despite that wave forcing had only 2% variance at interannual frequencies. The shoreline response presented 66% of the variance at interannual scales. These results were not expected since from wave forcing it would have been expected that the shoreline response should similarly lack interannual variability, but we found it to be dominated by this scale. The alongshore-mean shoreline time series revealed no significant annual cycle. However, there are annual oscillations in the shoreline response that are coherent with wave forcing and deserves further explanations. The pier was found to have a significant influence on shoreline behavior since restricts the seasonal longshore transport between the sides, resulting in a seasonally reversing sediment accumulation. Thus, there is a significant annual peak in shoreline variability that is coherent with the annual forcing but becomes insignificant in the longshore-average.

20. Radermacher, M., M. Wengrove, J. V. de Vries, and R. Holman (2014), Applicability of video-derived bathymetry estimates to nearshore current model predictions, *Journal of Coastal Research*, 290-295.

Abstract: In the framework of swimmer safety, coastal managers desire accurate nearshore current predictions obtained from numerical models. To this end, detailed and up-to-date bathymetry is a necessity. Remote sensing techniques for bathymetry estimation are a promising solution. The focus of this paper is to assess the performance of wavenumber-based bathymetric inversion using Argus imagery (also known as the cBathy algorithm) as a feasible input bathymetry for numerical models to make reasonable nearshore current predictions. Numerical flow simulations on a cBathy bed are compared to simulations on an in-situ surveyed bathymetry. Results demonstrate that simulated nearshore currents on a cBathy bathymetry have a root-mean-square error in the order of 10 cm/s (magnitude) and 40 degrees (direction) when compared to simulated currents on a surveyed bathymetry. In the intertidal zone cBathy should be combined with a different method for bathymetry estimation in order to decrease these errors.

21. Shi, F. Y., C. C. Chickadel, T. J. Hsu, J. T. Kirby, G. Farquharson, and G. F. Ma (2017), High-Resolution Non-Hydrostatic Modeling of Frontal Features in the Mouth of the Columbia River, *Estuaries and Coasts*, *40*(1), 296-309.

Abstract: Airborne data measured during the recent RIVET II field experiment has revealed that horizontally distributed thermal fingers regularly occur at the Mouth of Columbia River (MCR) during strong ebb tidal flows. The high-resolution, non-hydrostatic coastal model, NHWAVE, predicts salinity anomalies on the water surface which are believed to be associated with the thermal fingers. Model results indicate that large amplitude recirculation are generated in the water column between an oblique internal hydraulic jump and the North Jetty. Simulation results indicate that the billows of higher density fluid have sufficiently large amplitudes to interrupt the water surface, causing the prominent features of stripes on the surface. The current field is modulated by the frontal structures, as indicated by the vorticity field calculated from both the numerical model and data measured by an interferometric synthetic aperture radar.

22. Thomson, J. (2012), Wave Breaking Dissipation Observed with "SWIFT" Drifters, *Journal of Atmospheric and Oceanic Technology*, *29*(12), 1866-1882.

Abstract: Energy dissipation rates during ocean wave breaking are estimated from high-resolution profiles of turbulent velocities collected within 1 m of the surface. The velocity profiles are obtained from a pulse-coherent acoustic Doppler sonar on a wave-following platform, termed a Surface Wave Instrument Float with Tracking (SWIFT), and the dissipation rates are estimated from the structure function of the velocity profiles. The purpose of the SWIFT is to maintain a constant range to the time-varying surface and thereby observe the turbulence in breaking crests (i.e., above the mean still water level). The Lagrangian quality is also useful to prefilter wave orbital motions and mean currents from the velocity measurements, which are limited in magnitude by phase wrapping in the coherent Doppler processing. Field testing and examples from both offshore whitecaps and nearshore surf breaking are presented. Dissipation rates are elevated (up to 10(-3) m(2) s(-3)) during strong breaking conditions, which are confirmed using surface videos recorded on board SWIFT. Although some velocity contamination is present from platform tilting and heaving, the structure of the velocity profiles is dominated by a turbulent cascade of eddies (i.e., the inertial subrange). The noise, or uncertainty, in the dissipation estimates is shown to be normally distributed and uncorrelated with platform motion. Aggregated SWIFT measurements are shown to be useful in mapping wave-breaking dissipation in space and time.

23. Thomson, J., A. R. Horner-Devine, S. Zippel, C. Rusch, and W. Geyer (2014), Wave breaking turbulence at the offshore front of the Columbia River Plume, *Geophysical Research Letters*, *41*(24), 8987-8993.

Abstract: Observations at the Columbia River plume show that wave breaking is an important source of turbulence at the offshore front, which may contribute to plume mixing. The lateral gradient of current associated with the plume front is sufficient to block (and break) shorter waves. The intense whitecapping that then occurs at the front is a significant source of turbulence, which diffuses downward from the surface according to a scaling determined by the wave height and the gradient of wave energy flux. This process is distinct from the shear-driven mixing that occurs at the interface of river water and ocean water. Observations with and without short waves are examined, especially in two cases in which the background conditions (i.e., tidal flows and river discharge) are otherwise identical.

24. Wilson, G. W., H. T. Ozkan-Haller, and R. A. Holman (2013), Quantifying the length-scale dependence of surf zone advection, *Journal of Geophysical Research-Oceans*, *118*(5), 2393-2407.

Abstract: We investigate the momentum balance in the surf zone, in a setting which is weakly varying in the alongshore direction. Our focus is on the role of nonlinear advective terms. Using numerical experiments, we find that advection tends to counteract alongshore variations in momentum flux, resulting in more uniform kinematics. Additionally, advection causes a shifting of the kinematic response in the direction of flow. These effects are strongest at short alongshore length scales, and/or strong alongshore-mean velocity. The length-scale dependence is investigated using spectral analysis, where the effect of advective terms is treated as a transfer function applied to the solution to the linear (advection-free) equations of motion. The transfer function is then shown to be governed by a nondimensional parameter which quantifies the relative scales of advection and bottom stress, analogous to a Reynolds Number. Hence, this parameter can be used to quantify the length scales at which advective terms, and the resulting effects described above, are important. We also introduce an approximate functional form for the transfer function, which is valid asymptotically within a restricted range of length scales.

25. Wilson, G. W., H. T. Ozkan-Haller, R. A. Holman, M. C. Haller, D. A. Honegger, and C. C. Chickadel (2014), Surf zone bathymetry and circulation predictions via data assimilation of remote sensing observations, *Journal of Geophysical Research-Oceans*, *119*(3), 1993-2016.

Abstract: Bathymetry is a major factor in determining nearshore and surf zone wave transformation and currents, yet is often poorly known. This can lead to inaccuracy in numerical model predictions. Here bathymetry is estimated as an uncertain parameter in a data assimilation system, using the ensemble Kalman filter (EnKF). The system is tested by assimilating several remote sensing data products, which were collected in September 2010 as part of a field experiment at the U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck, NC. The results show that by assimilating remote sensing data alone, nearshore bathymetry can be estimated with good accuracy, and nearshore forecasts (e.g., the prediction of a rip current) can be improved. This suggests an application where a nearshore forecasting model could be implemented using only remote sensing data, without the explicit need for in situ data collection.

26. Zippel, S., and J. Thomson (2015), Wave breaking and turbulence at a tidal inlet, *Journal of Geophysical Research-Oceans*, *120*(2), 1016-1031.

Abstract: Field measurements collected with surface drifters at New River Inlet (NC, USA) are used to characterize wave breaking and turbulence in the presence of currents. Shoreward wave evolution is affected by currents, and breaking is observed in deeper water with opposing currents (ebb tides) relative to the following currents (flood tides). Wave dissipation models are evaluated with observed cross-shore gradients in wave energy flux. Wave dissipation models that include the effects of currents are better correlated with the observations than the depth-only models. Turbulent dissipation rates measured in the breaking regions are used to evaluate two existing scaling models for the vertical structure and magnitude of turbulent dissipation relative to wave

dissipation. Although both describe the rapid decay of turbulence beneath the surface, exponential vertical scaling by water depth is superior to power law vertical scaling by wave height.

27. Zippel, S., and J. Thomson (2017), Surface wave breaking over sheared currents: observations from the Mouth of the Columbia River, *J. Geophys. Res.*, *in revision*.

Abstract: Measurements of waves and currents from freely drifting buoys are used to evaluate wave breaking parameterizations at the Mouth of the Columbia River, where breaking occurs in intermediate depths and in the presence of vertically sheared currents. Breaking waves are identified using images collected with cameras onboard the buoys, and the breaking activity is well-correlated with wave steepness. Vertical shear in the currents produces a frequency-dependent effective current that modifies the linear dispersion relation. Accounting for these sheared currents in the wavenumber spectrum is essential in calculating the correct wave steepness; without this, wave steepness can be over (under) estimated on opposing (following) currents by up to 20%. The observed bulk steepness values suggest a limiting value of 0.4. The observed fraction of breaking waves is in good agreement with several existing models, each based on wave steepness. Further, a semi-spectral model designed for all depth regimes also compares favorably with measured breaking fractions. In this model, the majority of wave breaking is predicted to occur in the higher frequency bands (i.e., short waves). There is a residual dependence on directional spreading, in which wave breaking decreases with increasing directional spread.

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University of Washington – Applied Physics Laboratory
4333 Brooklyn Avenue NE
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14. ABSTRACT

Our long-term goal was to use remote sensing observations to constrain a data assimilation model of wave and circulation dynamics in an area characterized by a river mouth or tidal inlet and surrounding beaches. As a result of this activity, we have improved environmental parameter estimation via remote sensing fusion, determined the success of using remote sensing data to drive DA models, and produced a dynamically consistent representation of the wave, circulation, and bathymetry fields in complex environments.

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