DARLA: Data Assimilation and Remote Sensing for Littoral Applications

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LONG-TERM GOALS

Our long-term goal is 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 will improve environmental parameter estimation via remote sensing fusion, determine the success of using remote sensing data to drive DA models, and produce a dynamically consistent representation of the wave, circulation, and bathymetry fields in complex environments.

OBJECTIVES

The objectives are 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.

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APPROACH

Our overall approach is 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 are establishing a test bed location at Duck, NC, using tower-based remote sensing (EO, radar, IR) and current versions of the DA modeling system. We will participate in the field experiment scheduled for May 2012 at New River Inlet near Camp LeJeune, NC under the ONR-sponsored Inlets and Rivers Mouth Dynamics Departmental Research Initiative (RIVET). This approach will benefit both the remote sensing research (by leveraging the RIVET in situ measurements) and the RIVET itself via our integrated remote sensing and DA modeling system. The combined capabilities provide an innovative solution that couples spatially dense sampling with data assimilation methods to study the complicated dynamics of interacting wave, bathymetry, and current fields. The key to this project is an interactive process that blends sophisticated remote sensing, in-situ sensing, and data assimilation modeling. Our approach will be 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.

WORK COMPLETED and RESULTS

During the first year, we carried out a pilot experiment at Duck, NC during the Surf Zone Optics DRI Experiment in September, 2010 and participated in planning of the upcoming RIVET DRI experiment at New River Inlet, NC. We also worked on analysis and assimilation of the data from the Duck pilot experiment and on coupled wave-circulation models.

Due to the number of investigators involved and the complexity of the project, we have chosen to provide a section for each team which combines their Work Completed and Results contributions. The lettered sections correspond to the following teams:

A. Infrared Remote Sensing – UW: Chickadel and Jessup
B. Electro-Optical Remote Sensing – OSU: Holman
C. Microwave Remote Sensing – UW: Farquharson
D. Microwave Remote Sensing – OSU: Haller
E. In situ Measurements – UW: Thomson
F. In situ Measurements – WHOI: Elgar and Raubenheimer
G. Data Assimiliative Modeling – OSU: Ozkan-Haller and Kurapov

A. Infrared Remote Sensing – UW

In the nearshore and surfzone, significant progress has been made in understanding visual and radar signatures, but infrared remote sensing remains unused and untested. However, the sea surface in the nearshore is rich in observable natural temperature variation directly related to dominant physical processes including waves, wave breaking, and currents. In preparation for the upcoming field experiment at New River Inlet in conjunction with the RIVET DRI in May 2012, we conducted a weeklong pilot deployment of thermal infrared (IR) cameras at the Field Research facility in Duck NC. In alignment with the MURI-wide goals, this data will help us to address our specific objective in sampling the nearshore and surfzone with thermal imaging, which include:

1. Estimating geophysical parameters from surface IR signatures including currents, wave parameters, and wave breaking,
2. Validation of remotely-sensed waves and currents with in situ data, and
3. Providing data with confidence limits for inclusion into data assimilation.

For this pilot, a cooled long wave (8.5-10 μm sensitivity) camera was mounted on the FRF coastal imaging tower, and the Lighter-Than-Air Infrared System (LTAIRS), a tethered helium balloon platform, was deployed from the FRF pier.The tower camera had a fixed view of the surfzone and data was recorded continuously for 6 days.

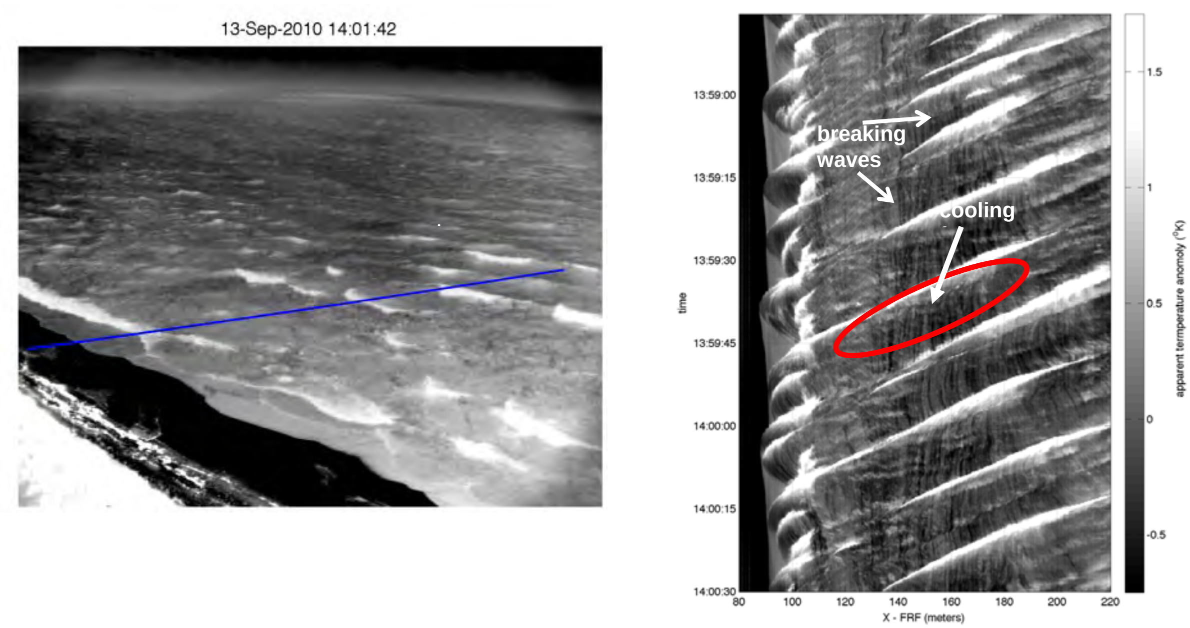

Figure A1. (left) IR image from of the beach and surfzone at the USACE Field Research Facility in Duck NC, looking NNE. The camera tilt was ~15° below horizontal (75° incidence). Bright regions in the image indicate breaking wave crests which appear warmer than quiescent water and the much cooler region of the beach (lower left). (right) Space-time plot (timestack) of IR apparent temperature anomaly (mean removed) along the blue transect at left. Wave crests approach the beach from right to left and the bright fronts of breaking waves are visible near the beach and over a submerged bar (at X = 180m). Near vertical traces of cooler (darker) residual foam appear almost instantaneously after individual breaking events.

Waves and Breaking

Waves and breaking are readily apparent in the thermal imagery. Figure A1 shows a tower image from the early morning when local sea and swell waves were present. The time stack from a cross-shore array of pixels, in Figure A1, demonstrates the repeated breaking of waves over a sandbar-terrace and again at the shore. Breaking waves are visible in the surfzone as brighter (warmer) regions, due to the higher emissivity of sea foam compared with the surrounding undisturbed water. This thermal imaging mechanism for wave breaking is in contrast to the visual enhancement of aerated water, which appears white in RGB images due to its highly diffuse reflection. Between the wave crests, however, the thermal imagery shows patterns of cooler patches associated with residual foam, where visually this foam is bright. This finding confirms observations from open-ocean thermal imaging of white capping, where cooling foam was first seen. The thermal imaging properties of cooling foam in the surfzone can be exploited to isolate active breaking (wave rollers) from the dynamically unimportant residual foam, and as discussed below, can be used to infer large scale circulation.

Unbroken waves are also thermally observable, due to the modification of sensor incidence angle at the surface due to passing waves. Emissivity of the sea surface is a strong function of incidence angle. From nadir (zero incidence angle) to about 60° incidence, the emissivity is very close to unity and reflection effects are negligible. In the rapid transition zone near grazing where reflection begins to dominate, relatively small modulations of local incidence angle by surface waves lead to significant observable modulation of the emissivity (reflectivity), which make waves visible in IR and exploitable for estimating their characteristics (wavelength, speed, and direction). This is evident in the offshore portions of the image in Figure A1 and in the accompanying timestack. One important note is that shorter waves which have the highest slopes will be a more dominant part of this reflection-based signal, and is noticable in timestack example. We plan to use this phenomenon to duplicate the techniques developed for Argus visual images to measure wavelengths, period, and directions remotely.

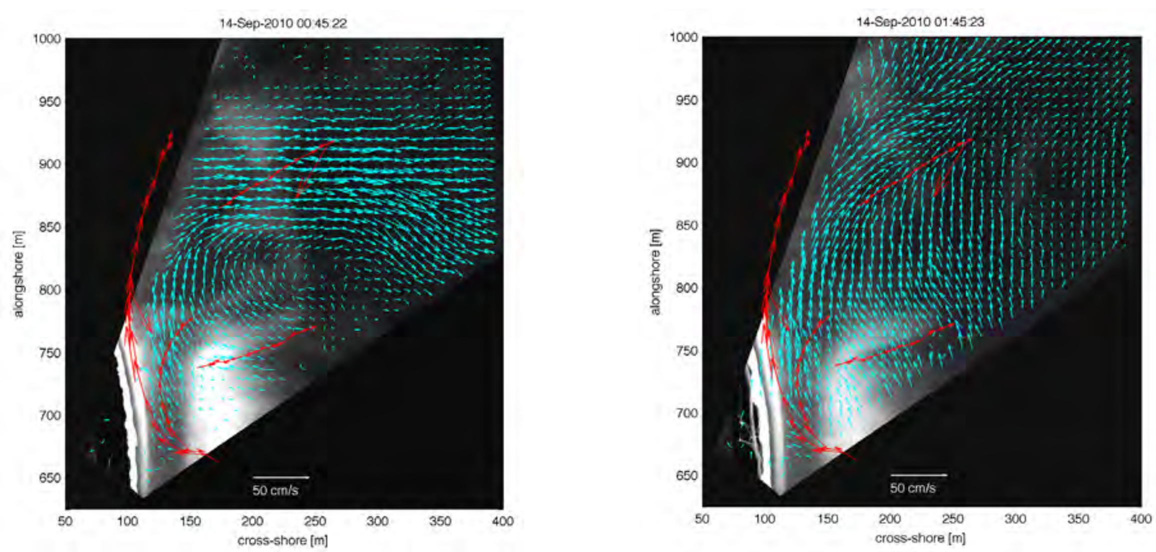

Figure A2. (left) 15-minute averaged, IR-based PIV surface velocity map (blue vectors) revealing a significant rip current centered between 850-900m in the alongshore position. The red vectors indicate SWIFT drifter velocities taken several hours later. The underlying image is the rectified view of the standard deviation of the IR intensity at the time of the velocity estimation. (right) Identical to the left velocity map, but taken one hour later when the rip current has swung 45 degrees up-coast

Currents

Nearshore and surfzone flows are a mix of currents, wave motions, and turbulence, and measurements of all three are important to understanding nearshore hydrodynamics and testing models.Using the pilot data, we have developed a novel particle image velocimetry (PIV) -based technique to estimate 2-D surfzone circulation. Our technique is based on the infrared-PIV method by Chickadel et al. (2011), but incorporates pre-processing that removes the wave signatures from the thermal images. We first calculate the darkest pixel over short, consecutive image series (here 10s videos are used), which preserves the cooling foam signature and eliminates the apparently warmer breaking waves. We can then track the shifting patterns in the darkest images over time with our PIV technique with less contamination of wave orbital velocities. We assume that cool foam and other temperature variability are passive tracers of the ambient currents thus the PIV velocity maps represents real velocity patterns in the absence of waves. Two examples of 15-mintue average velocity maps from the Duck pilot are shown in Figure A2, and are plotted with SWIFT-derived drifter velocities which were taken later in that day. Both velocity maps reveal the presence of a significant rip current meandering over time, and the validity of the PIV fields are generally confirmed by the drifter tracks. It is clear that this IR based velocimetry technique will be a crucial contribution to the study of nearshore currents, and represents an important source of model validation and data source for assimilation – a focus of the MURI efforts.

B. Electro-Optical Remote Sensing – OSU

The goal of EO sampling in the DARLA MURI is to provide measurements of optically-derived geophysical variables, along with error estimates, for both direct characterization of the surf zone and very shallow water domains and as input to numerical models through data assimilative formalism. During the first year, we have focused on bathymetry, wave dissipation and longshore currents.

Bathymetry is estimated using the cBathy algorithm, an extension from the BeachWizard program that reflects maturing statistical approaches for improving signal to noise and for properly tracking uncertainty. cBathy is based on model fits to the cross-spectral matrix, exploiting good temporal sampling while significantly reducing sample domain size requirements of previous Fourier methods. Approximately 18 monthly surveys from Duck and one survey from Agate Beach, Oregon, are being used for ground truth testing. Focus is on understanding resolution over short features (bars and rips), adequacy of error bars and environmental dependencies for Kalman filtering.

Dissipation, a key dynamical variable for both energy and momentum balances and for driving circulation, is being investigated by comparing EO signatures with Lagrangian (SWIFT floats) and fixed in-situ dissipation measurements from the Surf Zone Optics (SZO) experiment in September, 2011. Since optical reflectance saturates for surf zone bubble depths greater than about ten bubble diameters, our hypothesis, based on the Battjes and Janssen (1978), is that dissipation can be adequately modeled in terms of a depth-dependent magnitude times the spatially-variable fraction of breaking, Q_b.

The May, 2012 New River Inlet experiment will place new challenges on sampling and modeling due to the complex bathymetry, wave and current patterns of the active tidal inlet. To gain experience in this domain type and to test sampling methods, collections were begun at Teignmouth, England, a similar tidal inlet environment.

Since access to EO data is key to many investigators, methods have been developed to automatically provide simple, MATLAB-compatible accessibility to all Argus image and time series data.

The primary accomplishment of our first year has been successful participation in the Surf Zone Optics experiment in Duck, NC last September. EO data were collected for cBathy, dissipation and longshore current purposes and have been made easily accessible on ftp using simple MATLAB formats.

Standard collections have also been set up and continue to execute for the test bed phase of Duck data collections, designed to provide ongoing remote sensing input data for testing model and data assimilation methods.

C. Microwave Remote Sensing – UW

Our primary goal is to measure surface flow over the domain of the New River mouth (river, inlet, and nearshore). Our sensors will also provide information (imagery) of alongshore variations in the incident wave field and the spatial distribution of wave breaking. We will use two sensors to make these measurements: an airborne dual-beam along-track interferometric (ATI) synthetic aperture radar (SAR), and the ground-based APL-UW Coherent Real-aperture Radar (CORAR) system.

Dual-beam ATI micro SAR
We are in the final stages of assembling the dual-beam ATI micro SAR, and we anticipate conducting local test flights in October, 2011. The major subsystems of the sensor are the radar transceiver and data acquisition electronics, an inertial navigation system (INS), and the antennas and mounting hardware.

Transceiver: The dual-beam ATI micro SAR, uses two Artemis, Inc.microASARs(Edwards et al., 2008). These units consist of a transmitter, a dual-channel receiver, and a data acquisition and storage subsystem. Artemis has customized the microASAR units to operate at the same time in non-overlapping frequency bands to enable us to implement the fore- and aft-squinted ATI SARs in the dual-beam system. We have purchased one of the microASAR units, and the second is on loan to us from Artemis for use during the DARLA field experiments. The microASAR units are currently being upgraded with the latest firmware improvements developed for the Artemis SlimSAR system. These include the ability to configure the operating setting of the microASAR and record data over an Ethernet connection.

Antennas: Flat-panel antennas, designed specifically for the dual-beam ATI micro SAR, are in the final stages of fabrication.The requirements(gain, beamwidth, sidelobes, mechanical mounting) for these antennas were derived from an analysis of the desired ATI SAR performance. These antennas have a higher gain (18 dBi) than the standard microASAR antennas (9 dBi) in order to increase the sensitivity of the system to measure ocean scattering, and good sidelobesuppression (greater than 20~dB one-way) to minimize azimuth and elevation aliasing. The antennas will mount to a frame under the belly of the aircraft (Figure C1). Mounting brackets attach the antennas to the frame, and accurately set the squint and incidence angles.The antennas are currently undergoing final fabrication. Once fabricated, the vendor will use a custom rig to validate antenna performance in the desired configuration for the aircraft.

Inertial Navigation System: Accurate measurement of aircraft attitude and velocity are critical for removing aircraft motion from the Doppler velocity measurements. We have purchased a Novatel ProPak V3 GPS receiver with an iMAR FSAS inertial measurement unit to provide sensor attitude measurements. This INS interfaces directly with the microASAR units so that platform attitude, position, and velocity are recorded directly with the SAR data. We have tested the INS in the lab and a car.

Predicted System Performance: A detailed analysis of the system was done to verify the design.Since the primary goal for the sensor is a surface velocity measurement, we characterize the system performance in terms of velocity uncertainty.The predicted rms velocity for the dual beam ATI micro SAR, with typical operating parameters, is shown in Figure C2. The range resolution is 1.87 m and the cross-track swath extends from 300 m to 2100 m. Over most of the swath, the velocity standard deviation for a single pixel is around 12 cm s^{-1}. The azimuthal size of a resolution cell is 6~m (limited by the coherence time of the scatterers), and the range resolution is 1.87~m. Averaging over 3 pixels in range to create 5.6 m × 6 m pixels, the standard deviation in the velocity measurement reduces to around 7 cm s^{-1}, which is comparable to the error reported for in situ current meters (Feddersen and Guza, 2003). A further reduction in velocity uncertainty can be obtained by spatially averaging more pixels.

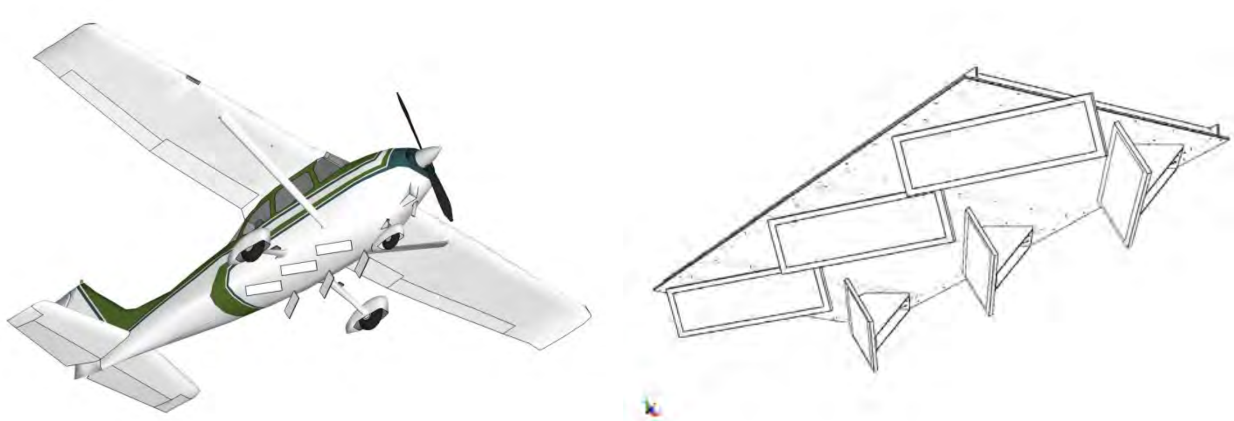

Figure C1: (Left) Concept drawing of the antennas under the belly of a Cessna 172 aircraft. The mounting hardware is not shown in this drawing.(Right) Engineering drawing of the frame to which the antennas mount. The three forward-squinted antennas and three aft-squinted antennas are visible. Mounting brackets accurately set the incidence and squint angles of the antenna panels.

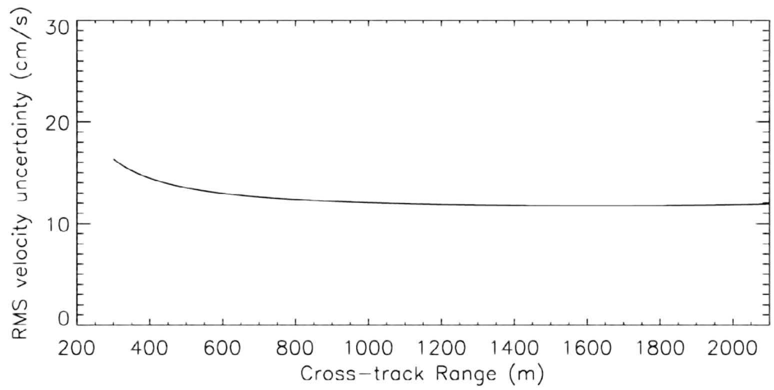

Figure C1: Predicted rms velocity uncertainty for the microASAR operating at an altitude of 600 m, a nominal incidence angle of 60°, and a squint angle of 30°. The cross-track swath extends from 300 to 2100 m. The normalized radar cross section is computed from the CMOD5n model function (CMOD5 for neutral winds) for a wind speed of 2 m s−1 with the radar looking nominally upwind.

CORAR

We have completed several upgrades to CORAR to improve the performance and ease of use. CORAR has been upgraded with a reconfigurable digital timing subsystem. This timing system allows us to easily tune the operating mode of the radar to suit the measurement. We are integrating a pan-tilt pedestal in CORAR that will allow us to perform sector scans (as well as 360° scans) to optimally sample the measurement domain, and to accurately adjust and maintain the incidence angle to the antennas. Test data of boats on Lake Union, Seattle is shown in Figure C3. These data was collected and processed by Thomas Stone, a UW undergraduate Physics student.

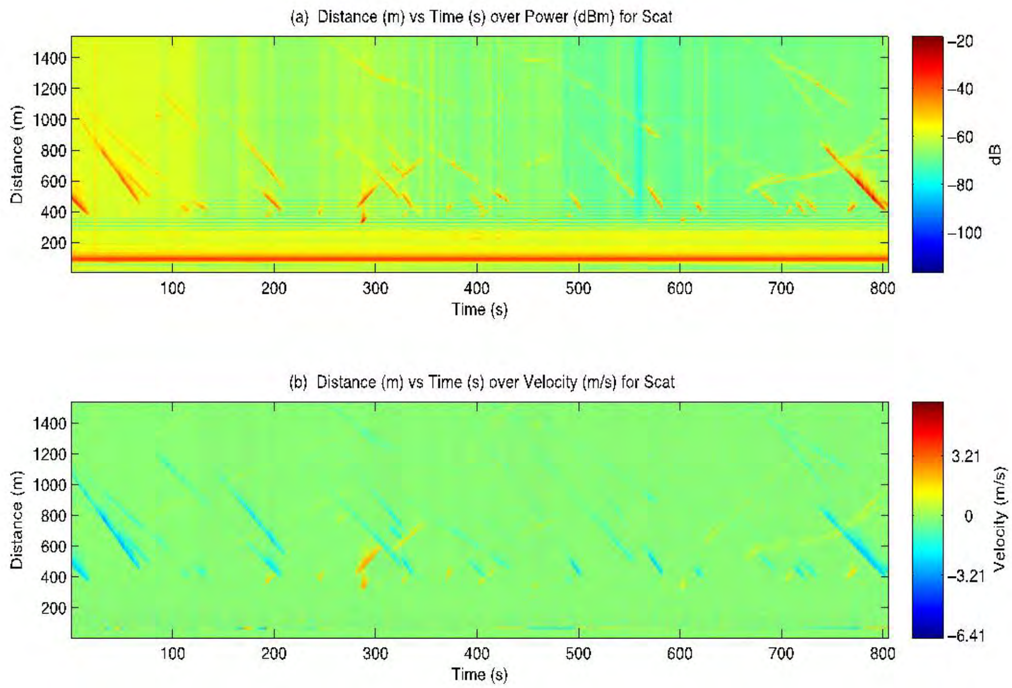

Figure C2: Backscattered power (top panel) and Doppler velocity (bottom panel) plotted on a range (y-axis) versus time (x-axis) plot. These data were collected during testing of CORAR on the roof of the Benjamin Hall Interdisciplinary Building. The antennas were held at a constant angle for the period of the measurement. The streaks are boats on Lake Union. This image was created by Thomas Stone, an undergraduate Physics student.

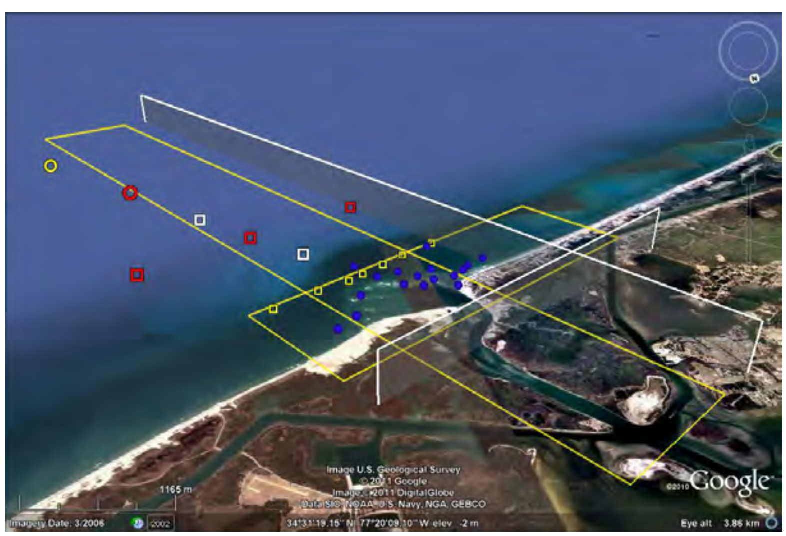

Figure C3: New River Inlet, NC. The white lines represent along-shore and cross-shore flight tracks at 600 m altitude. The along-shore track is 5 km in length, and would take approximately two minutes to fly. The cross-shore track is 13.5 km, and would take five and a half minutes to fly. The yellow rectangles at ground level mark the area imaged by the dual-beam ATI micro SAR. The positions of in situ sensors are marked by yellow and white squares, and red dots. The sensor provides measurements over most of the domain in a single flight pass.

Experiment Design

We have conducted a field site analysis and prepared an experiment design for the New River Inlet in North Carolina. In Figure C4, the white lines are the planned along-shore and cross-shore flight tracks for the SAR, andthe yellow boxes are the measurement footprint for each track.

D. Microwave Remote Sensing – OSU

- Conducted pilot field experiment (September, 2010; Duck, NC), collected marine radar incoherent images plus newly-developed coherent-on-receive data. Coherent-on-receive has not yet been analyzed (still in proof-of-concept stage).

- Revised, resubmitted and published: Catalán, P.A., M.C. Haller, R.A. Holman, and W.J. Plant, Optical and microwave detection of wave breaking in the surf zone, *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 6, pp. 1879—1893, Jun. 2011.

- Submitted: Catalán, P.A., M.C. Haller, and W.J. Plant, Microwave backscattering from surf zone waves, *J. Geophys. Res*., 2011.

- Sole source paperwork approved, purchase order submitted to Imaging Science Research for solid-state coherent X-band radar. To be delivered spring 2012.

- Performed hiring search for Postdoctoral position. Interview stage complete, offer letter being sent to top candidate.

- Work presented at: Sensing the Ocean with Marine Radars (SoMaR-1), NURC, Lerici, Italy, May 2-4, 2011; Argus Workshop, Corvallis, OR, July 27, 2011.

Marine radar data from the Duck pilot experiment demonstrates the presence of morphologic rip currents. These images represent ~12 minutes averaged, incoherent radar returns from our shore-based marine radar. Examples are shown in Figures D1 & D2 where they are also compared to other data sources. In Figure D1 (right panel) SWIFT drifter tracks provided by Jim Thompson (UW-APL) that are coincident with the marine radar collection are overlaid the marine radar image. The tracks drift offshore near the rip in accordance with the radar identification of rip location.

In Figure D2 we compare the mean intensity image to model current output from ShoreCirc courtesy of Greg Wilson (OSU-COAS). The depth-averaged current vectors indicate surf zone recirculation patterns consistent with rip currents near y=800 m and 500 m (under the FRF pier). These results also corroborate our finding that rip currents were well-imaged by the marine radar.

Additional analysis has shown that one-minute running average image sequences effective average out the wave-by-wave signal and suggest the presence of coherent vertical structures in the data. We are presently researching PIV-type analysis that would help us to quantify the speeds and trajectories of these structures.

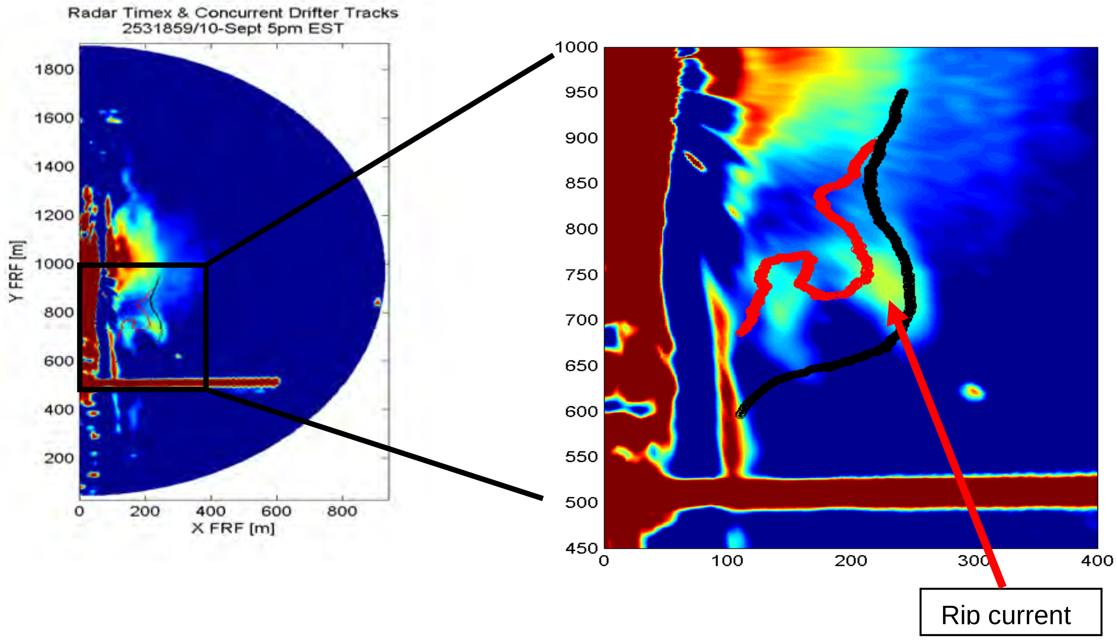

Figure D1: (image) Mean radar intensity in FRF coordinate system, 1700EST Sept. 10, 2011 (overlay) SWIFT drifter tracks, courtesy of Jim Thompson UW-APL. Horizontal red feature is FRF pier. Drifter tracks corroborate radar evidence of rip current.

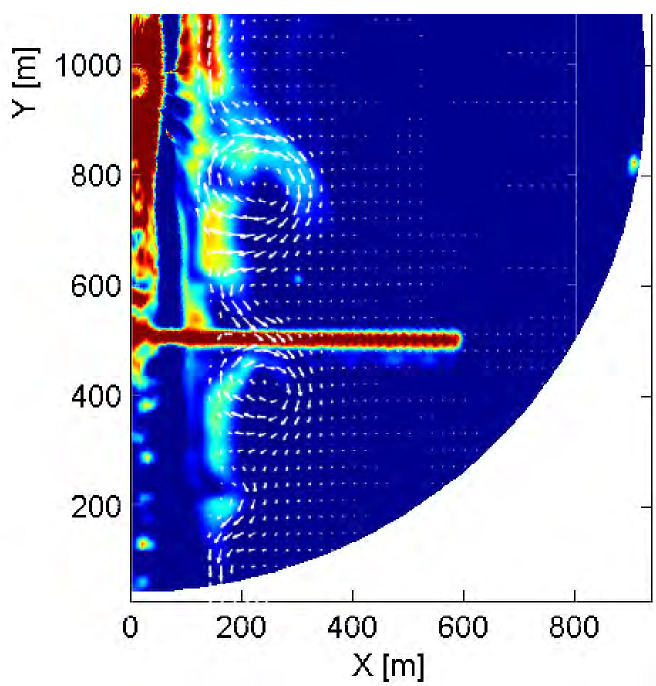

Figure D2: (image) Mean radar intensity in FRF coordinate system, 1700EST Sept. 13 2010 (overlay) model output currents courtesy of Greg Wilson OSU-COAS. Horizontal red feature is FRF pier. Model outputs corroborate radar evidence of rip current.

In summary, the clear and extended (over several weeks) evidence of rip currents imaged in incoherent marine radar data is a new result. We are not aware of the previous existence of such high-quality data and the other sources of ground-truth clearly make this a unique data set. In addition, the new data product (one-minute running average) really shows a lot of promise for quantifying the presence of vortical structures. Our future plans include quantifying the influence of shelf currents and wind direction on the obliqueness of the rip current flow, quantifying the imaging mechanism of these small to mid-scale rips, and investigating the presence of coherent Lagrangian structures in the running averaged data.

E. In Situ Measurements – UW

A new platform and methodology have been developed for obtaining in situ measurements of surface waves, currents, and turbulence. In contrast to conventional in situ measurements, the new method tracks the surface and thus provides improved groundtruth information for remote sensing products. The drifting platform, termed a Surface Wave Instrument Float With Tracking, or ‘SWIFT’, was tested during the Surf Zone Optics experiment at the Duck FRF in the fall of 2010, and refined during additional testing on Lake Washington in the winter of 2010/2011. The production version of the SWIFT is shown in Figure E1, and six units have now been assembled.

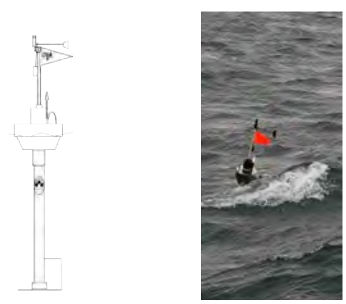

Figure E1. Surface Wave Instrument Float with Tracking (SWIFT).

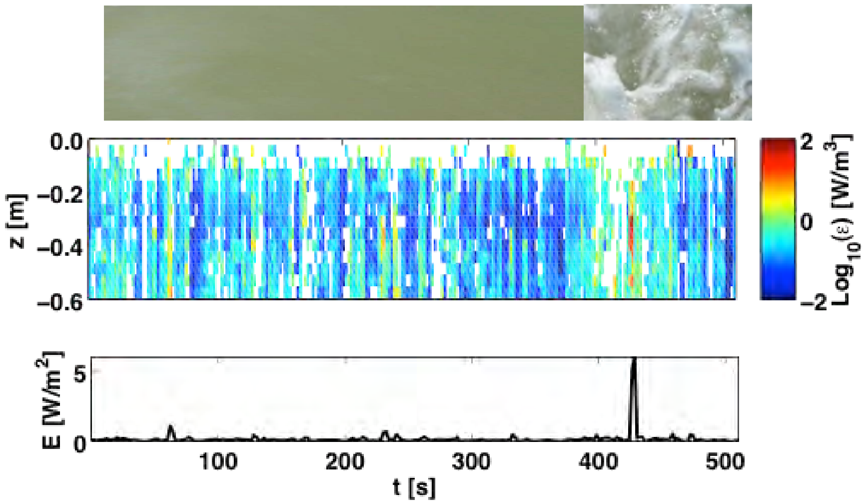

Figure E2. Example of breaking wave observed via SWIFT using onboard surface video (upper panel), turbulent dissipation profiles (middle panel, z=0 is surface), and integrated turbulent dissipation rate (lower panel).

An example of SWIFT data is shown in Figure E2, where a breaking wave is observed visually at t = 420 s, and the estimated turbulent dissipation rate *E* increases 100 fold. The dissipation rate is a key dynamic quantity for accurate modeling of the nearshore region. In addition to turbulence, the SWIFTs measure wave directional spectra (via orbital motion) and nearshore circulation (via GPS tracking). The combined observations (waves, currents, turbulence) can now be assimilated into numerical models and used to groundtruth remote sensing observations.

Ongoing processing of the test data from Duck indicates that the SWIFT method successfully measures waves, currents, and turbulence in the nearshore region. Wave and currents estimates have been validated against fixed in situ observations provided by the FRF and WHOI arrays. Turbulence dissipation has be compared, favorably, against the incoming energy flux of incident swell and spatial patterns of breaking, as shown in Figure E3, where the composite of all SWIFT dissipation values has a peak over the bar at the Duck FRF. These results are now being compared with remote sensing observations (video, IR, and radar).

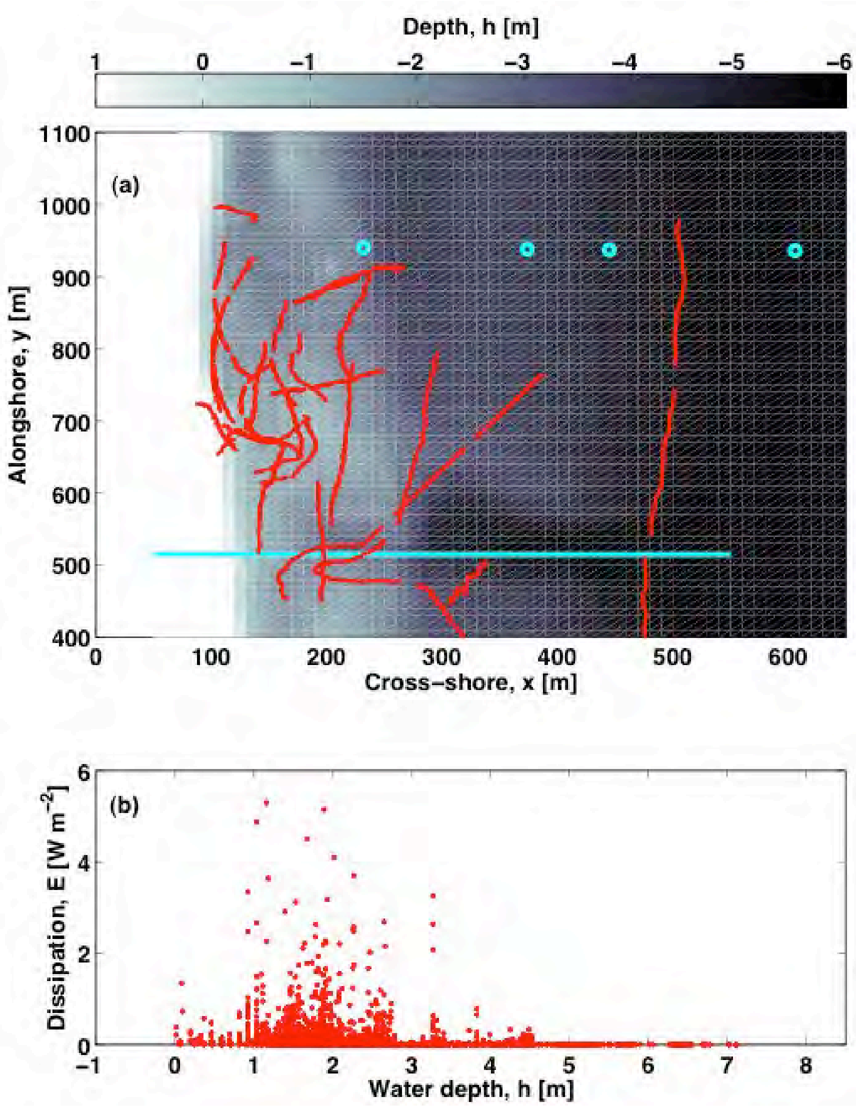

Figure E3. Composite of all SWIFT tracks from Duck FRF (upper panel) and turbulent dissipation versus depth (lower panel). Dissipation has a maxima collocated with strong wave breaking over the nearshore bar at x ~ 200 m. The cyan line shows the FRF pier and the cyan symbols are the FRF in situ array.

F. In Situ Measurements – WHOI

We provided the Surf Zone Optics and MURI teams with observations of waves and currents made along a cross-shore transect extending from the surf zone 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 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 F1). In collaboration with ONR CODE 30 we have been planning and scheduling the field project.

Figure F1. 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.

G. Data Assimilative Modeling

Over the past year, our efforts have been focused on three approaches. On one hand, we have been working with observations from the Fall 2010 field study at Duck, NC. As part of this effort, we have been building on our work assimilating in situ observations from the SandyDuck experiment to assess bathymetry (Wilson et al, 2010) using a statistical maximum likelihood estimator to determine the bathymetry (posterior estimate) given an initial guess (prior estimate). To determine the necessary covariances, model simulations of the wave and circulation field for a large number of ensemble members are utilized. We have now applied this methodology to the assimilation of remotely sensed estimates of alongshore current velocities and phase speed information. Second, we have started work on the tangent linear and adjoint components of a coupled wave-circulation model that would enable implementation of the variational method. To help us figure out details of how variational assimilation can proceed with the coupled system, we start this work with a somewhat idealized model, which still be applied with realistic data. The circulation model is based on shallow water equations, with forcing provided in form of the radiation stress divergence (Kurapov et al., 2007). The wave model is based on Slinn et al. (2000), formulated for narrow-banded sea state. Finally, we have been working on applying coupled wave and circulation models (in particular, SWAN+ROMS) to our next field site at New River Inlet. Of particular interest has been the potential inclusion of wetting/drying effects, large scale pressure gradients and upstream boundary conditions.

The ensemble-based bathymetry estimation method has been applied to remotely sensed observations from the Sept 2010 field experiment at Duck, NC. The experimental period encompassed a period of time when a pronounced rip current existed ~300m north of the FRF pier. Herein, we have initially utilized video-based observations of alongshore currents as well as phase speed information. Given our previous experience applying this method with in situ observations in the surf zone as well as in a river setting, we have also considered the effect of including iterative steps in the bathymetry estimate. In particular, we update our prior estimate using the posterior at the end an assimilation step and re-compute the necessary covariances using model simulations for ensembles centered around this new prior guess. This iterative step proves especially useful in situations where the initial prior estimate is far from the actual state of the bathymetry.

For the case involving the assimilation of video-based alongshore velocities (using the algorithm of Chickadel et al., 2003), results are shown in Figure G1. For this simulation, we utilize a prior bathymetry estimate based on a survey carried out in July 2010, months before the experimental period. Further, we assemble ~250 ensemble members that correspond to perturbations around the prior state. An iteration is carried out updating the prior as well as the ensemble set once a posterior estimate is obtained. The resulting posterior velocity field (see Figure G1) reproduces the presence of a observed circulation gyre north of the FRF pier. The resulting bathymetry qualitatively indicates the presence of an alongshore varying bar system seen in the corresponding ground-truth bathymetry survey. Consistent with our previous findings, our initial results assimilating phase speed information (not shown) indicate that assimilating different measurement types (e.g. remotely sensed surface currents and phase speed estimates) results in more useful information than a single observation type alone.

Although the ensemble-based method is simple, useful and model-independent, it has several limitations. For example, there exists an implicit linearization about the prior estimate of bathymetry that we have attempted to overcome through the use of an iterative scheme. Although this approach is promising, it nonetheless adds significant coast in terms of computational needs. Also, results can be sensitive to whether or not the ensemble characterizes the variability in the system, and dependencies on multiple parameters may result in large ensembles. An elegant way to overcome these shortcomings involves the use of tangent linear and adjoint components of the coupled wave-circulation modeling system. In our earlier study of this problem (Kurapov et al., 2007), the tangent linear and adjoint components of the circulation model only allowed for the correction of initial conditions and forcing. During this report period, we have modified this code to allow sensitivity to bathymetry. The tangent linear and adjoint codes, modified in this part, have passed rigorous symmetry checks. Our current efforts are focused on development of the tangent linear component of the wave model and its adjoint counterpart.

Our immediate future plans will include completion of the tangent linear and adjoint wave system. Then, we can compute directly the time- and space-evolving model error covariance structures in both circulation and wave models. Adjoint sensitivity of the bathymetry will be obtained as a sum of contributions from the circulation and wave models. We will assess the relative magnitudes of the sensitivities contributed by each model, and compare their structures. Model-state/bathymetry covariances will be compared to those computed with the ensemble method. The variational system will be tested using synthetic and actual observations, initially for the beach case and continuing on to the inlet case.

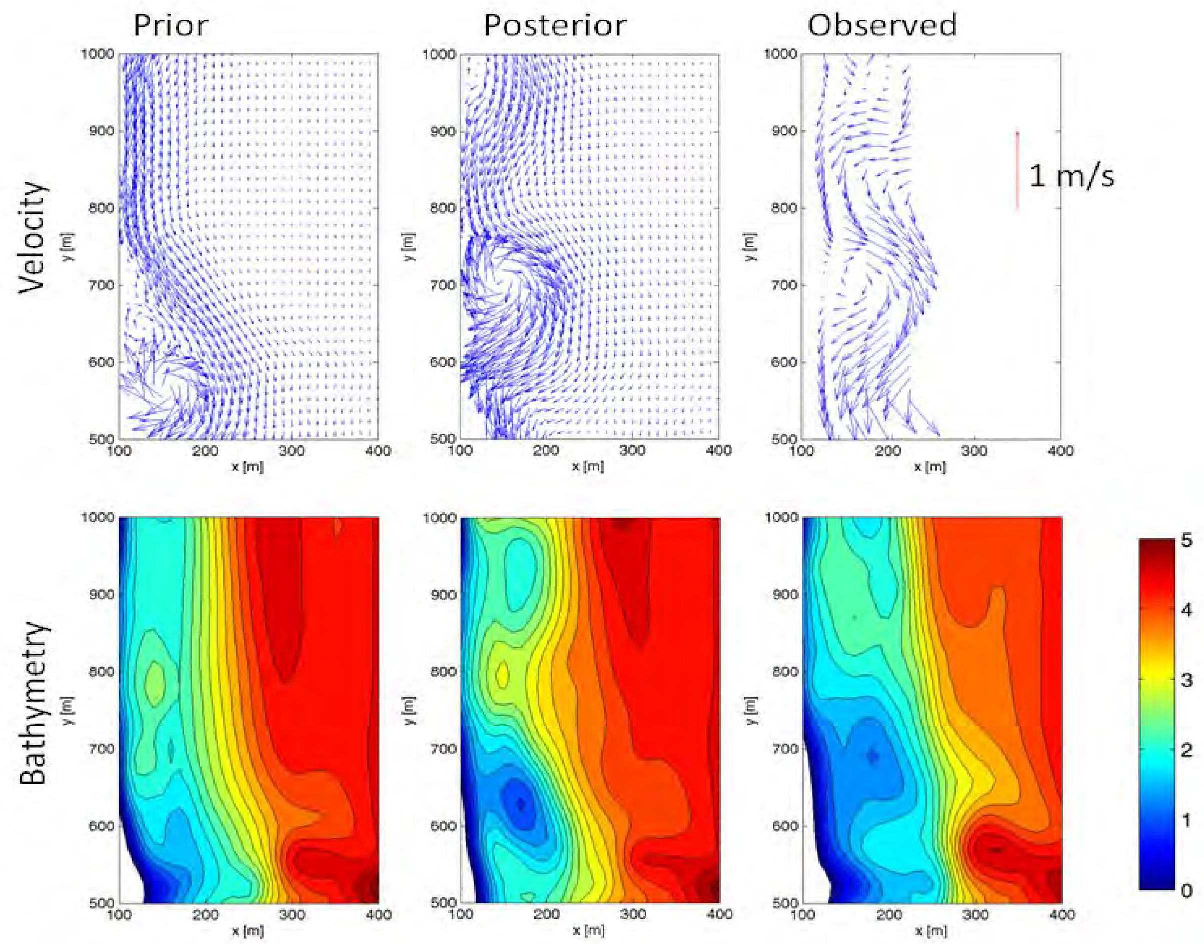

Figure G1: Results for circulation (upper panels) and bathymetry (lower panels) from the ensemble-based bathymetry estimation for Duck, NC on Sep 13, 2010 0800EST. The prior estimates (left panels) are based on a bathymetry survey carried out in July 2010 and the predicted circulation given wave conditions on Sep 13. The posterior estimates (middle panels) indicate the presence of an alongshore-variable bar system and associated gyre/rip current features that are also present in the observed bathymetry and circulation (right panels). Note that the observed circulation is based on video-based alongshore current observations. For esthetic reasons, the principle of continuity is used to estimate cross-shore current magnitudes. However, only the measured alongshore currents are assimilated.

Finally, we have been utilizing a coupled modeling framework (SWAN+ROMS) for the conditions expected during the RIVET experiment at the New River Inlet in NC. Of particular concern have been the utilization of wetting/drying effects in the estuary, the inclusion of coastal circulation features (e.g. forced by large scale pressure gradients) and the specification of the upstream boundary conditions. For the latter issue, we have been interacting with the group led by R. Luettich at UNC and are exploring the possibility of nesting our modeling domain into a larger scale ADCIRC simulations.

RELATED PROJECTS

None