Prediction of Hydrodynamics for Unidirectional Flow

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LONG-TERM GOALS

Our long term goal is to gain a thorough understanding of the flows in the regions of the ocean ranging from the inner shelf through the surf zone to the upper reaches of rivers. We aim to develop integrated observation and modeling systems that are able to observe and predict them.

OBJECTIVES

Over the course of this project our aim is to transition from the study of nearshore currents to the study of river current. Our approach is to apply methods used in nearshore circulation (in particular longshore current predictions) to the prediction of flow in riverine environments. Specific objectives are:

1. Complete work on publications related to circulation in the nearshore zone currently under preparation.

2. Carry out a focused study for the application of variational data assimilation (DA) methods to steady state river problems using simple dynamical models for the flow field. The work will be geared towards obtaining estimates of upstream conditions, frictional parameters and channel topography given observations of stream velocities at several locations. This work will be carried out in two phases

   - Assess the utility of a shelf/surf zone circulation model (e.g. ROMS) in determining the 2D flow field in a river setting.

   - Implement variational DA into a simple 1D river flow model (assuming a straight channel and no cross-stream flow).

   - Use a simple 2DH formulation for flow in a meandering stream and apply variational DA methodology in this more realistic 2D setting.

APPROACH

This project involves a transition from studying the dynamics of nearshore flows to the study of riverine environments. First we finalize two publications. The first involves a look at the response of the wave-induced circulation field to forcing by a sequence of wave groups of varying strengths and scales. There has been some disagreement in previous literature on this subject, and our results show that the circulation field responds in a forced and coupled manner to the wave group forcing. The

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second manuscript involves simulations of the NCEX field experiment during the entire month of October 2003. Our results show the controls on rip current generation, location, persistence and decay and involve comparisons to video and in-situ observations.

The remainder of the work involves a shift to river environments. We focus our attention on steady state conditions and time scales over which the channel topography does not change appreciably (O(hours)). The work is carried out with an eye towards inverting the dependency of the flow on channel geometry, upstream boundary conditions, and frictional characteristics. There are many parallels between river flows in a channel and longshore currents in the nearshore (especially in situations where the beach is barred and strong alongshore pressure gradients exist), so lessons we have learned during longshore current simulations should transfer to this new area. Our focus is on establishing whether or not DA methods are useful for the problem of flow through a realistic river channel.

WORK COMPLETED

We have completed our work on surf zone vortices and are in the process of submitting the last publication on NCEX-related work. In parallel, we have pursued simulations in riverine environments using ROMS for idealized situations involving bars/pools and river bends as well as realistic river conditions. Finally, we have begun to interface with the ONR MURI group on Coherent Structures (COHSTREX) and have participated in their pilot experiment on the Snohomish river in September 2008.

RESULTS

Application of ocean models to rivers

We have applied ROMS to a number of idealized river problems, ranging from flow in a trapezoidal channel with bars and pools to flow in an idealized river bend. So far we have found that ROMS reproduces qualitatively characteristics of the expected flows in these situations. For example, ROMS successfully predicts that flow velocities should be largest near the deepest section of a straight channel, and the across-stream position of this extremum varies along-stream with alongstream variations in the channel geometry. Also, increased velocities on the inner bank of a river bend are reproduced.

Next we applied ROMS to the classic data set of Dietrich and Smith (1983) who gathered information about the river depth and the 3D velocity field over a 40m-reach of Muddy Creek, WY. The river geometry is characterized by very pronounced bends and the presence of large shoals and pools (see Figure 1).
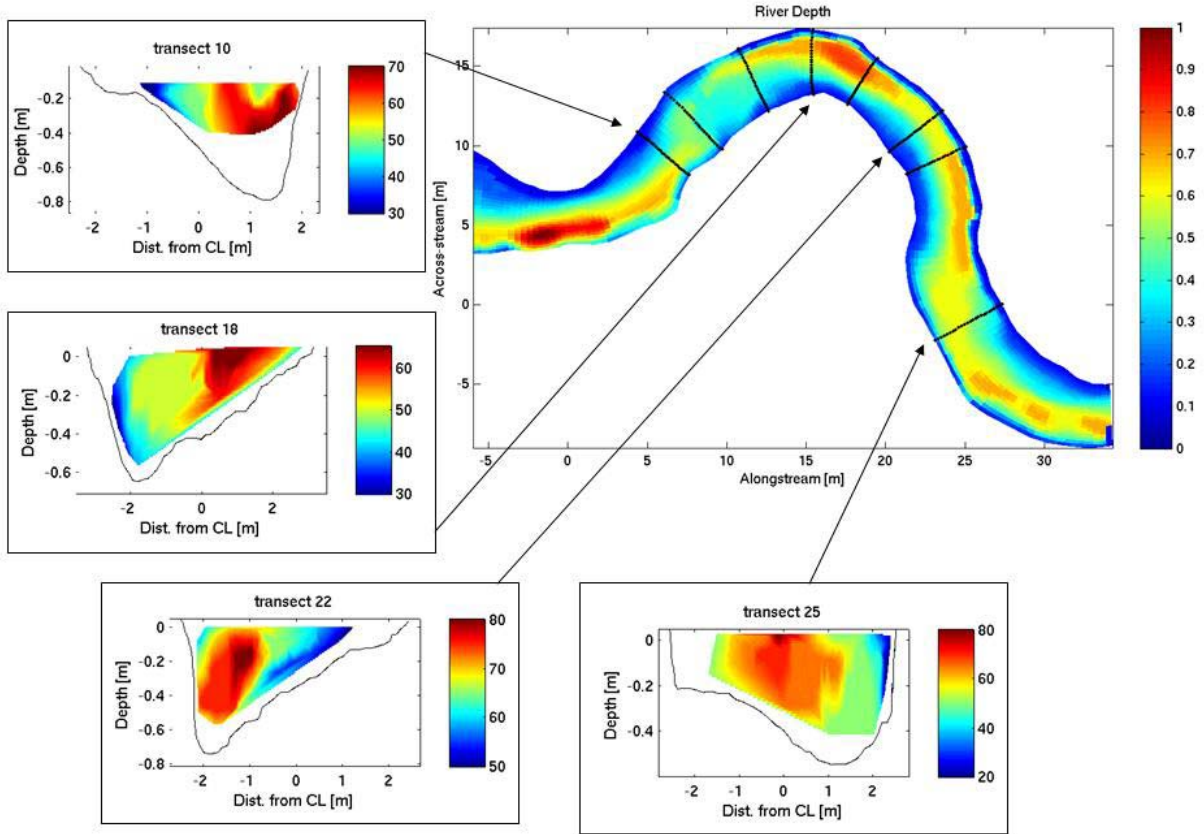
Figure 1: Observations at Muddy Creek, WY by Dietrich and Smith (1983). River depth (large panel) and along-stream velocities at across-stream transects 10, 18, 22, and 25 (small panels from left to right).The pools in the river depth are indicated with hotter colors.

The observations of flow velocities indicate that the maximum velocities occur near the deepest point in the channel at location where the river is relatively straight (e.g. transect 10 in Figure 1). However, where the curvature is large (e.g. transect 18), the maximum velocities are over the shoals despite the fact that it is significantly shallower in these areas. This is due to centripetal forces that set up an across-stream pressure gradient – the water surface at the outer bank is relatively high compared to the elevation near the inside bank. This modifies the local downstream pressure gradients, reducing it at the outer bank and increasing it at the inside bank. Since velocities are driven by local downstream pressure gradients, they are then stronger on the inside bend than on the outside. This effect is proportional to the centripetal forces which depend on the stream curvature. The Muddy Creek observations also show that the flow maximum moves back to the deepest part of the channel soon after the bend (transect 22) but then begins to move onto the next shoal near the inner bank as the next bend is approached (transect 25).

ROMS reproduces the general behavior captured by the observations (see Figure 2). These simulations are driven by the observed total volume flux at the upstream boundary (on the left hand side of the domain) and utilize the measured stream depth. The simulation is initiated with an initial guess for the water surface elevation and the integration is carried out until a steady state is reached. Because of the

way the flow is initiated at the upstream boundary some start-up transients occur near that boundary. Idealized cases confirm that these transients are localized and do not affect the flow past distances corresponding to a few channel widths.

The simulation results (Figure 2) show that ROMS indeed produces across-stream pressure gradients at the bends that are similar in size to the overall downstream pressure gradients. The overall effect is a slowing of the flow on the outside bank at the bends. Smaller scale variations in the surface elevation also exist and are mostly a function of variations in the bottom at those length scales.
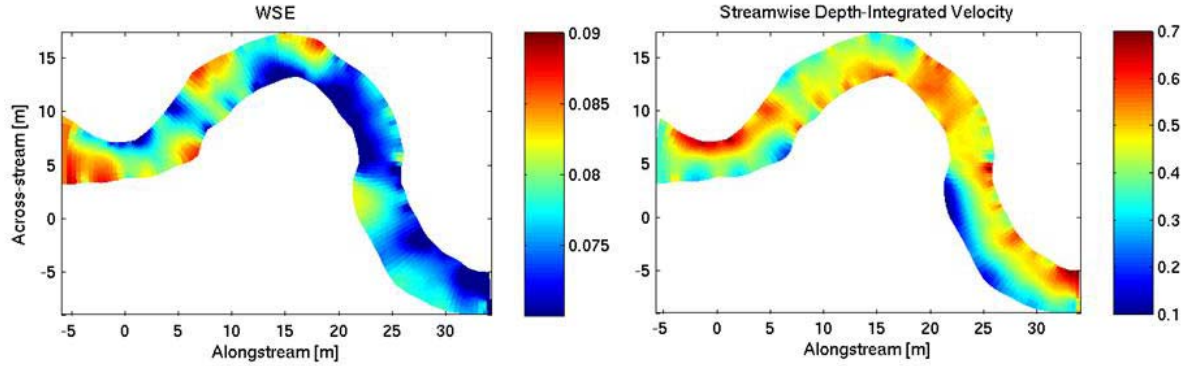

Figure 2: ROMS simulation results for Muddy Creek, WY: Water surface elevation (left panel) and streamwise depth-integrated velocity (right panel). Flow is from left to right.

Quantitative comparison of the depth-averaged velocities with the observations shows that the general trends are captured, yet the exact values are not reproduced (Figure 3). One reason for this may be inaccuracies in the specification of the boundary and initial conditions such as the total flow rate or the bathymetry. However, it is also likely that some parameterizations may be inappropriate. One example is the horizontal diffusion parameterization. Currently, ROMS incorporates detailed parameterizations for vertical momentum diffusion, yet only uses a simple eddy viscosity formulation for the horizontal diffusion. Modification to this scheme would be a natural first extension. Parameterizations used in current river flow models will serve as a guide.
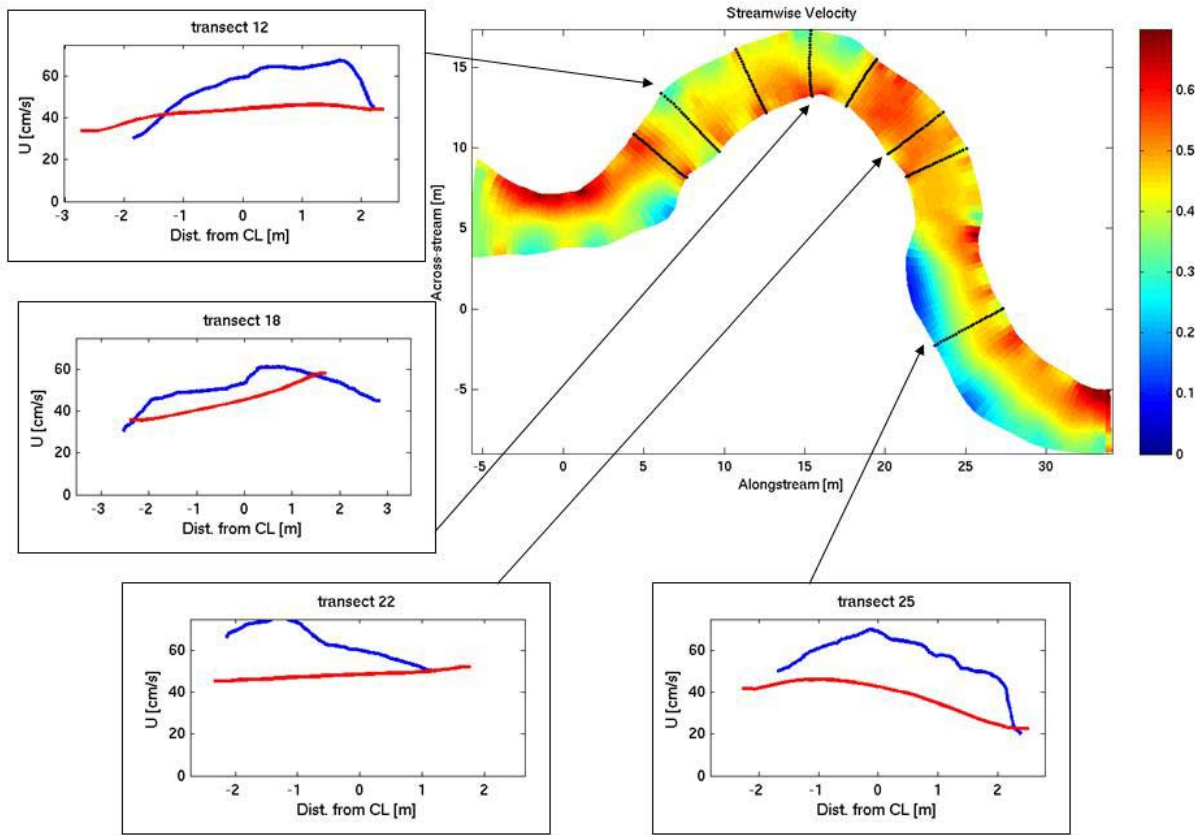
Figure 3: ROMS simulation results for Muddy Creek, WY: Predicted depth-averaged along-stream velocity over the analyzed domain (large panel) and at across-stream transects 12, 18, 22, and 25 (small panels from left to right). Shown are both data (blue) and model (red).

Use of DA methods for depth estimation

Some of our recent forays into DA methods for surf zone applications indicate that the depth-inversion problem for rivers may be tractable. This recent work (primarily carried out by Greg Wilson) involves a situation (corresponding to Oct 20 during the Sandyduck field experiment) where a mean alongshore current exists, although some secondary currents are also present due to alongshore variations in the bathymetry. Bathymetry observations on this day were sparse, so the model bathymetry was produced using a combination of the most recent surveys, even if some of these surveys were carried out days before or after the time of interest here. Velocity estimates on this day were available from about two dozen current meters distributed over an approximately 200m×200m area. Model-data comparisons using our best-estimate bathymetry suggest that the general flow features are predicted, but that even the flow direction very close to shore is not reproduced. This is likely due to the misplacement of the computed gyres near this location which are very sensitive to alongshore variations in the bathymetry. This situation is analogous to a river flow of moderate strength that can also be modulated downstream due to depth variability in the form of bars and pools.

We utilized an ensemble Kalman filter approach to the depth inversion. This treatment involves generating many realizations of the bathymetry. In this case, we generated 150 ensemble members by computing the empirical orthogonal functions (EOF's) associated with the bathymetry at this site

(utilizing all available bathymetry observations) and then perturbing each EOF with noise of a magnitude that was consistent with the noise level associated with the bathymetric observations.

We then perform a circulation model simulation for each ensemble bathymetry member, generating an ensemble of flow estimates. The ensemble Kalman filter (see Evensen, 2006) then enables us to find the circulation prediction (and bathymetry) out of the ensemble of 150 members that best reproduces the observed velocity field by minimizing a cost function that relates to the data-model misfit.

The resulting circulation prediction (see Figure 4) is much improved (rms-errors have been reduced by 50%). The corresponding bathymetry is different from the initial model bathymetry by as much as ±0.5m, and the spatial distribution of the difference suggests that the bar should be steeper and somewhat further offshore than the coarse bathymetry suggested (Figure 4). Differences of this magnitude are not surprising given the bathymetry we used was not gathered simultaneously with the velocity observations, and changes of ±0.5m of the kind predicted herein are certainly possible over a few hours. Further, and perhaps more importantly, independent (un-assimilated) sonar altimeter observations of the bathymetry confirm the Kalman filter prediction (Figure 5) and show a deeper trough and more pronounced bar. Similar simulations for other days during the experiment were also carried out and show similar skills.
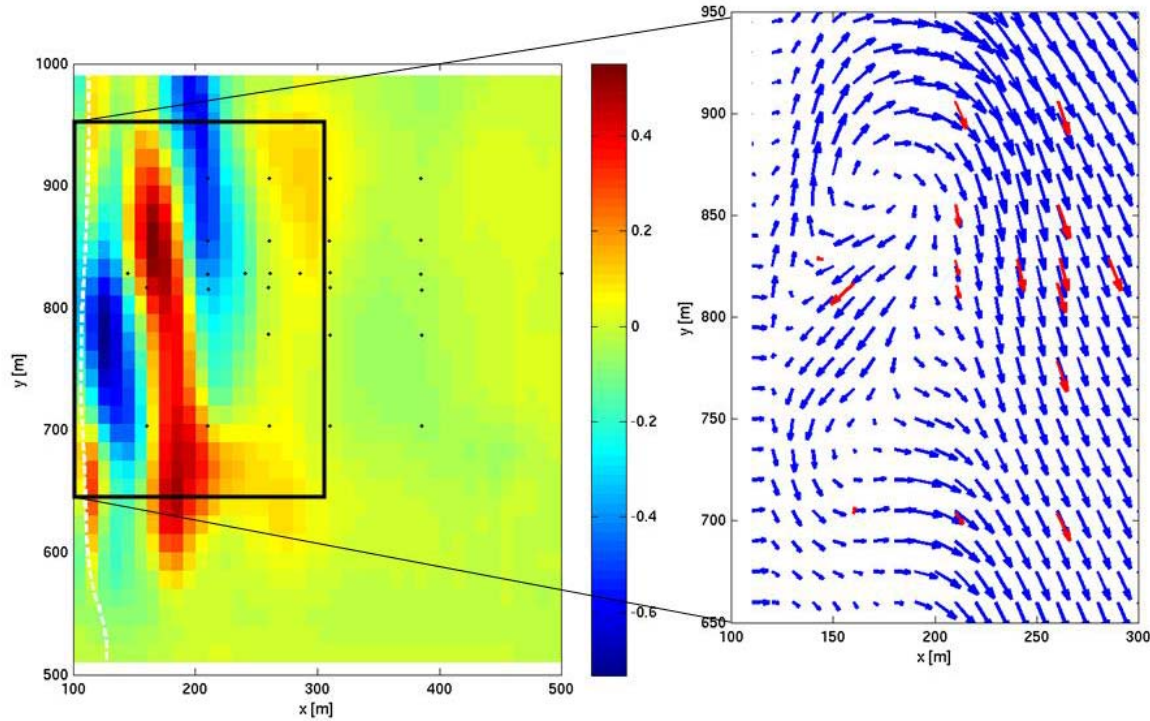

Figure 4: Analyzed flow field after application of the Kalman filter (right panel), and difference between the initial bathymetry and the analyzed bathymetry result from the Kalman filter (left panel).Maximum flow velocities are under 1m/s.

These results indicate that bathymetry inversion using current observations may be tractable for river flows as well, even with a simple sequential (and computationally efficient) method such as the Kalman filter. We are getting ready to test this method using observations from the Snohomish River collected as part of the COHSTREX MURI project. However, more sophisticated adjoint data assimilation methods exist and can also be exploited for depth inversion.
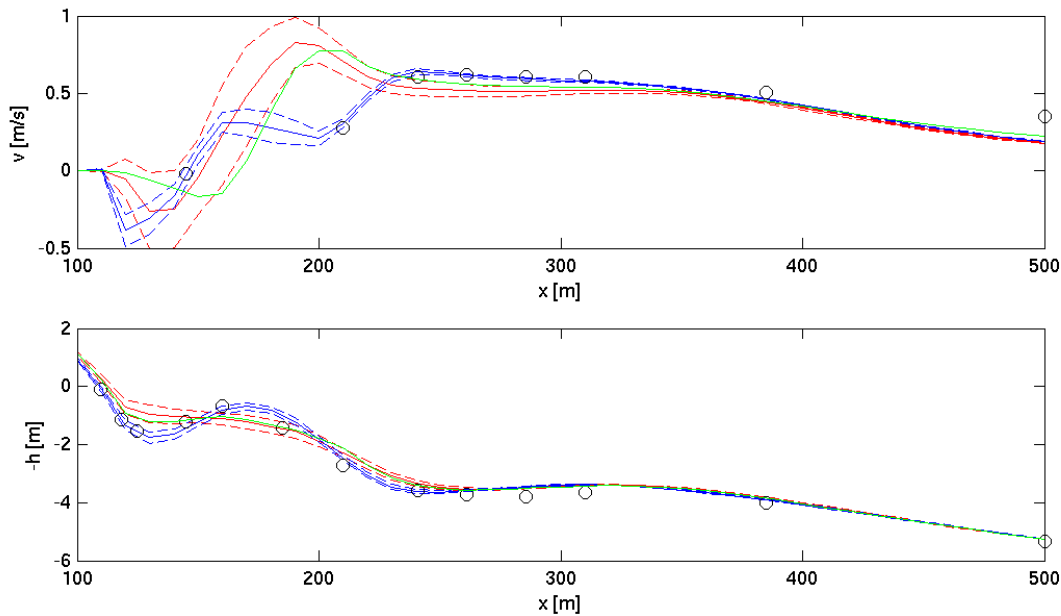
Figure 5: Mean and Mean±standard deviation of ensemble alongshore velocity v (top panel) and water depth h (bottom panel). Initial values(red) and analyzed values after the application of the Kalman filter (blue) are shown along with observation (circles) from assimilated current meters (top) and independent (un-assimilated) sonar altimeter observations (bottom). Green lines indicate one particular ensemble member corresponding to the flow shown in Figure 4. All plots are for a transect at y=900m.

IMPACT/APPLICATIONS

As part of this study we are developing methods to estimate the depth of river channels given information about the flow velocities in the river. The potential application of this work is primarily related to problems related to navigation up river channels.

RELATED PROJECTS

The Coherent Structures Experiment (COHSTEX) MURI lead by Andrew Jessup of U. of Washington is closely related to this work. The data that the COHSTREX group will obtain on the Snohomish river over the next year will be utilized here to validate the numerical model and aid in the assessment of depth inversion techniques.

PUBLICATIONS

Long, J.W., and H.T.Özkan-Haller, Temporal response of wave group forced vortices, Journal of Geophysical Research, in review, 2008.

Long, J.W., and H.T.Özkan-Haller, The persistance and reoccurance of rip currents in So. California, Jpirnal of Geophysical Research, in preparation, 2008.