Development of the Full Bay ROMS Hydrodynamic-Dye Transport Model for the Providence River: Comparisons with Data from Spring 2010 Tilt Current Meter Network

Final Report Prepared by Kincaid Consulting
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1.0 Executive Summary

This report summarizes the completion of work on Tasks 8, 9 and 10 for project 08A-114-01-00 towards the development of a high resolution, 3D hydrodynamic and chemical transport model for upper Narragansett Bay using the public domain Regional Ocean Modeling System (ROMS) computer code. A goal of this section of the project is to transition from an older coarse-grid model for Providence River (developed by D. Bergondo, 2004) (Figures 1, 2, 3a) which had the capability of tagging and tracking multiple dye sources (one for each river and waste-water treatment facility -WWTF) within the model (LaSota, 2010) (Figures 4-8) to a newer, higher resolution version of the ROMS. The newer model is referred to as the NBC Full Bay ROMS Model (NBC Report by Kincaid and Rogers, 2009). A second goal is to test how the Full Bay Model does at representing flow, specifically residual flow processes, in the Providence River. The basic character of flow in this estuary has been mapped in NBC-sponsored underway acoustic Doppler current meter (ADCP) surveys (Figures 9-11). The Full Bay ROMS model has been shown to do an excellent job of representing instantaneous or tidal currents (Rogers, 2008; Kremer et al, 2010) (Figure 3). However, residual or sub-tidal circulation patterns are often more challenging for such models to simulate than instantaneous or tidal records (Tables 1-3). Because residual flows are so crucial to the proper simulation of long-term chemical transport and flushing processes / residence times within the estuary, a two-step process has been undertaken for the development of the Full Bay ROMS model prior to conducting extensive dye transport simulations for the estuary. These steps are described in Tasks 8 - 10 in Amendment 1 of Project 08A-114-01-00, and summarized here.

Task 8: Deployment, analysis and reporting of a tilt current meter (TCM) study of Providence River circulation during March-May, 2010 (Figures 12-13, Tables 4-5).

Task 9: Modification of the Full Bay ROMS model to a) provide model output in the TCM locations (Figure 13), b) develop ROMS environmental forcing files for the period when TCMs were deployed (Figures 14-18), c) run ROMS simulations for the Spring 2010 period and perform statistical data-model comparisons for checking the accuracy of the model's ability to simulate residual currents (Table 6) and d) development of the dye release and transport capabilities from the coarse ROMS model (LaSota, 2010) into the higher resolution Full Bay Model.

Task 10: Development of presentations for and attendance at meetings held by the Narragansett Bay Commission.

This report summarizes the work that now has been fully completed for tasks 8-10 of Amendment 1, including a) analyzing results from the TCM deployment during Spring 2010 (Figures 19-30) and b) developing model simulations using the Full Bay ROMS during the period when the TCMs were deployed (Figures 32-34). As part of this the TCM station output on currents has been qualitatively and quantitatively compared with ROMS output in the same locations and over the same time window (Figures 35-40; Table 6). Results show excellent agreement between observations and ROMS output. The last aspect of the preparation needed to use the new Full Bay ROMS model for a wide array of dye dispersion simulations has been to add the logic from the Bergondo-LaSota upper Bay ROMS (or PR-ROMS) model (Figure 4) into the newer high resolution ROMS. This work is also complete such that the Full Bay ROMS has the capacity for tracking distinct chemical dyes released within all major river sources including the Blackstone, Moshassuck, Woonasquatucket, Pawtuxet, Taunton and Palmer Rivers. It also has the ability to track distinct dyes released within the WWTF inputs from Fields Pt., Bucklin Pt. and East Providence. Now that the Full Bay ROMS has been validated for residual flows against very detailed current meter data in our area of interest and includes the full range of chemical dye sources, the next stage of the project (outlined in Tasks 11 and 12 of Amendment 2) involving mapping individual dye transport form all key sources for a wide range in environmental conditions can commence.

2.0 Previous Work

The Narragansett Bay Commission (NBC) has supported the development of three generations of hydrodynamic models for simulation 3D water circulation and thermal-chemical transport within Narragansett Bay. Figure 1 shows the spatial extent of these three progressions in computational domains. The first is a coarse grid ROMS model focused on the upper Bay, from the Ohio Ledge region in the south to the Seekonk River in the north (referred to as the PR-ROMS model; Bergondo, 2004). A limitation of this model, pointed out by NBC outside consultants, is the close proximity of the southern ocean boundary to the region of interest in the Providence River. Another limitation is the relatively coarse grid resolution this version has for representing processes in the Providence River (Figure 2). The second generation of ROMS models, referred to as the RIS-NB ROMS, solved the southern boundary proximity issue by extending this model interface as far south as Rhode Island Sound (Figure 1) (Rogers, 2008). Even though both of these models employ relatively coarsely spaced grid boxes within upper Narragansett Bay (Figure 2), they have both been shown to compare well with instantaneous currents and hydrographic records at instantaneous or tidal time scales (Figure 3; Table 1-3). Instantaneous records do not have the currents due to oscillatory, semi-diurnal tides filtered out.

A hydrodynamic computer model such as ROMS that has been shown to successfully match observational data can subsequently serve as a powerful tool for simulating a range of processes, such as flushing dynamics and biological-chemical transport. This was done by N. LaSota (URI-GSO MS student) who used the PR-ROMS Model (LaSota, 2010) to study chemical transport in the Providence River. All rivers and WWTFs were tagged with a distinct dye within a series of model simulations to quantify which sources contributed most significantly to overall chemical concentrations within specific regions of the Providence River (Figure 4). When results are scaled such that dye concentrations represent nutrient loadings specific to each source, models such as the one shown in Figure 5 indicate the Blackstone River, Fields Pt. WWTF and the Pawtuxet River are typically the largest contributors to overall nutrient levels on the Edgewood Shoals. LaSota (2007; 2010) used the PR-ROMS to test how each chemical source was flushed from or held within the estuary for different wind conditions (Figure 5).

While the LaSota (2010) results are interesting, it is important to consider how well the underlying hydrodynamics of any chemical transport model perform in simulating the sub-tidal, or residual currents. This is because the sub-tidal flows are important in longer-term chemical transport through the Bay. Unfortunately, the first and second generation versions of ROMS have difficulty simulating residual, or sub-tidal, flows and hydrographic properties (salinity and temperature) in upper Narragansett Bay (Table 3). Rogers [2008] did a careful comparison between residual flows predicted in the RIS-NB ROMS model versus ADCP records in the northern West Passage. Rogers (2008) found that Wilmont Skill values, which are a statistical measure of how well models simulate data records, were in the 0.5-0.6 range, well below skill values of 0.75-0.85, which are generally considered to indicate a well calibrated model (Table 3) (Warner et al., 2005). A Wilmont Skill of 1 would indicate a perfect match.

A closer look at the coarse-grid PR-ROMS models actually shows the model does not match either instantaneous or residual flow patterns observed for the Edgewood Shoals region of the Providence River (Kincaid, 2001a-c). For example, Figures 7 and 8 show vertically averaged flow vectors for a representative flood and ebb stage of the tidal cycle from the LaSota (2010) PR-ROMS models. The simulations predict the Edgewood Shoals is strongly flushed by an outflow during ebb and by an inflow during flood. The models predict that flows on the shoal are similar in both magnitude and direction as those in the neighboring channel over all tidal stages (e.g., Figure 9b). This basic pattern is in contrast to results observed in NBC-sponsored underway ADCP surveys (Kincaid, 2001a-c; 2002). A series of east-west oriented ADCP transects from Edgewood Shoals to the shipping channel show that both instantaneous and residual flows on the shoals are typically not of the same magnitude or in the same direction as currents in the channel. Figures 9-11 show a very typical pattern of prevailing outflow during the ebb and the flood (Figure 11) involving a focused outflow along the western side of the channel coincident in time with a weak northward flow on the shoals. The underway ADCP data, while limited in time, consistently indicate the presence of a clockwise gyre on the Edgewood Shoals, which is not simulated in the PR-ROMS model simulations.

3.0 Methods

Because the PR-ROMS model could not simulate the style of flow that was been observed between the shipping channel and the Edgewood Shoals, and because this style of flow is so vital in determining overall chemical transport, Tasks 8-10 of this project were designed to a) better understand spatial and temporal patterns in currents in this area through observations and b) to combine these measurements with ROMS simulations over the same time period in order to quantitatively test the accuracy of the ROMS Full Bay model.

3.1 Tilt Current Meters:

Velocity measurements were made using SeaHorse Tilt Current Meters (TCM's) (Manning and Sheremet, 2008) (Figure 12). A TCM instrument consists of a heavy base that is connected to a buoyant PVC pipe by a soft membrane. When the instrument is located on the bottom of the sea floor (Figure 12b), it tilts on the membrane as a result of the current that flows across the length of the pipe. An accelerometer sensor, situated at the top of the PVC pipe, records the tilt angle and direction of the instrument at five minute intervals. Tilt current meters are tested in a flow tank to provide necessary coefficients for converting tilt angle and direction into north-south and east-west water velocities (V. Sheremet, pers. communication). A network of 21 TCM instruments were deployed in the Providence River (Figure 13) on March 8, 2010. Data on near-bottom currents where collected for 52 days, or through April 30, 2010. The PVC pipes of the instruments were 1 m in length and thus recorded current velocity information of a column of water between roughly 12 cm and 1.12 m above the bottom. The majority of TCMs where deployed on the Edgewood Shoals in depths of 3-4 meters. In these cases, TCMs measured the lower 3rd to lower half of the water column. TCMs 12 and 15 were in slightly deeper water in the Port Edgewood channel (~5m of water). TCMs 17 and 18 were in the shipping channel.

NBC sponsored the deployment of 6 of these TCMs (3, 5, 7, 19, 10, 14) in locations that strategically added to an ongoing study. Stations 3, 5 and 7 were located on the eastern side of the Edgewood Shoals, near the shipping channel. TCM 19 was along the same shoal-channel interface, but further south. TCM 10 was located mid-way across the Edgewood Shoals and TCM 14 was located at the western side of the shoals (Figure 13). The environmental conditions for water temperature, tide height, wind and runoff that occurred during this deployment are shown in Figures 14-18. Water temperatures rose sharply during the period decimal day 90 to 98 reaching ~15°C, before dropping back to an average value of 10°C. The largest, or Spring Tide, occurred near decimal day 88. The most notable feature of these records was the large flooding event that occurred near decimal day 88, at the end of March, 2010.

3.2 Full Bay Regional Ocean Modeling System (ROMS)

The modeling tool used in this study is the Regional Ocean Modeling System (ROMS) 3D hydrodynamic-transport model developed by the coastal modeling group at Rutgers University (http://www.myroms.org/index.php) (Haidvogel et al. 2008; Wilkin et al, 2005). ROMS was and has been widely used as a 3-dimensional hydrodynamic model in studies of many different coastal embayments (e.g. Chesapeake Bay, Li et al. 2005; Hudson River, Warner et al. 2005; Columbia River, MacCready et al. 2009). A version of ROMS has been modified at URI's Graduate School of Oceanography for specific application to Narragansett Bay (Figure 1) (Bergondo, 2004; Rosenberger, 2001; Rogers, 2008). The model is used to simulate three-dimensional (3D) water circulation within Narragansett Bay as well as related transport of temperature, salinity and a number of chemical tracer fields. ROMS is described as a free-surface coastal model that solves the set of hydrodynamic equations for mass, momentum, salt and energy conservation using certain simplifying assumptions. The details of these may be found in Shchepetkin and McWilliams (2003), but include what are termed the hydrostatic and Boussinesq assumptions. These assumptions allow ROMS to more easily compute vertical, or rising/sinking flows. The set of hydrodynamic equations are solved separately for total momentum and vertically integrated momentum and then these solutions are coupled together. A key step in the process of solving coupled mathematical equations is breaking the volume of the domain (in this case Narragansett Bay) into an array of small scale 3-D volume elements, called grid boxes, where each grid box is bounded by 8 grid nodes (or corner points). Once the domain is defined as discrete points/boxes, the system of equations are solved using a step in which mathematical equations are converted in simplified algebraic expressions, describing the exchange of water, energy and chemical species between neighboring grid boxes.

ROMS is able to model irregular shaped grid boxes by making use of a terrain-following vertical coordinate and non-rectangular volume shapes in the horizontal, or mapview, orientation. These attributes allow for representing variable bottom topography and highly varying coastlines in the model simulations (Shchepetkin and McWilliams, 2003; 2005). In any coastal modeling effort two fundamental strategies are: 1) to have as finely spaced computational grid boxes as your computer resources will allow and 2) to keep the model boundaries as far removed from your region of interest as possible.

On this project we further develop and test the accuracy of a Full Bay ROMS model that includes increased grid box resolution in the Providence River (Figure 31). A strategy used in the Full Bay ROMS development has been to use the larger RIS-NB ROMS developed by Rogers (2008) (shown in blue in Figure 1) to provide information on circulation and hydrographic conditions at the mouth of Narragansett Bay. The finer grid Full Bay model (Figure 1; Figure 31) then makes use of this information to simulate detailed processes operating within Narragansett Bay, extending from the mouth of the Bay to the Seekonk River in the north. This high-resolution ROMS model grid has 15 vertical levels, meaning the resolution of the model in the vertical dimension is the water depth divided by 15. Figure 31 shows in mapview how tapering of the grid towards the north is used to focus grid resolution in the upper Bay and the Providence River (e.g., ~ 40 meter wide boxes within the Providence River).

ROMS simulations must be driven by environmental forcing conditions, which are typically either close approximations to actual data or applied as a series of idealized conditions. Various forcing parameters include tidal (water level) oscillations, wind stresses applied on the water surface and water density differences, driven in turn by surface heating/cooling events, rainfall, river runoff and ocean water intrusions. In all the Narragansett Bay ROMS models the flow through the interface between the Bay and RIS is driven by sea-level height variations, and associated velocity variations, calculated from an Atlantic Ocean –scale model, called ADCIRC (http://www.adcirc.org/). ADCIRC outputs tidal information for use in driving the RIS-NB model (Figure 1). The output includes seven tidal harmonics (M2, N2, S2, K2, O1, M4, M6) which are applied at each of the RIS-NB ROMS open ocean grid nodes. The RIS-NB model then outputs information on water elevation, currents, salinity and temperature at the mouth of Narrgansett Bay, which is converted into a forcing file for driving the Full Bay ROMS models. The simulations reported on here are also forced by the 2010 environmental forcing data for temperature, wind and runoff shown in Figures 14-18.

An important step in developing and validating a model like ROMS for a specific area of the Bay, is to define output stations within the computational model that coincide with geographic locations where observational data is available. In the work reported here, data stations have been added to the ROMS model for outputting information on flow, temperature, and salinity at all of the TCM locations (Figure 13) and within key regions of the upper Bay. Work on this project has also been to develop the capacity for releasing and tracking distinct chemical dyes for the Blackstone, Taunton, Pawtuxet, Moshassuck, Woonasquatucket and Palmer river sources and the East Providence, Bucklin Point and Fields Point wastewater treatment facilities. ROMS then simulates the longer term motion and dispersion of each of these conservative chemical dye fields within the model domain. The logic for these dye fields that has been developed for this section of the project will be used in a subsequent NBC-sponsored study of chemical transport for each major nutrient source within the Providence River and upper Narragansett Bay.

3.0 Results:

Tilt Current Meter Findings

Results are presented on two aspects of Tasks outlined in Appendix 1 for this project, the TCM findings and the subsequent validation step for ROMS predicted flow fields at the TCM locations. Figure 19 shows a mapview summary of the deployment averaged (e.g. time averaged over the entire record) current vectors from TCM stations. The flow magnitudes (cm/s) are given numerically beside each arrow. The time-averaged data (also summarized in Table 4) clearly show the residual clockwise gyre on the Edgewood Shoals that is not seen in the coarse-grid versions of ROMS (PR-ROMS-Bergondo; RIS-NB ROMS-Rogers). Flows on the shoals are not of the same magnitude, and in the same direction as in the channel, as is predicted by PR-ROMS (Figure 7-8). These results are consistent with previous NBC ADCP data (Figure 9-11).

The time variations in residual (or sub-tidal) flow recorded by the NBC supported TCM stations are shown in Figures 20-24. Variances (a measure of the energy of time variations) are summarized in Table 5. These data show how the system responds to various environmental forcing factors. For the stations near the northeastern corner of the Edgewood Shoal, near the intersection with the shipping channel, the records show three clear regimes. The first period is before the flood (days 68-88). During this time TCMs record the average outflow of water at 5-10 cm/s. The onset of the flood is clearer seen in these records, where residual outflow increases to 20-25 cm/s. The peak in outflow occurs roughly 2-3 days after the peak in the runoff data (Figure 18). The signal from the flood is seen to decay monotonically over the period from roughly day 90 to 102. The final period of the record begins after day 103, when there is again a residual outflow of 5-10 cm/s though this region along the eastern side of the shoal and western side of the channel. TCM station 19, which is at this same bathymetric transition, but further south, shows a similar basic flow pattern (Figure 24), though the flood signal seems to decay faster here. This is likely due to a narrowing of the stronger outflow feature seen at TCMs 3, 5 and 7 such that it bypasses this southern location. The mid-shoal also has a muted flood response (Figure 23A). Interestingly, the western side of the shoal does not feel the flood in terms of residual flow (Figure 23B). At TCM 14, there is a persistent northward flow of water that is larger (2-8 cm/s) during the first half of the record, and smaller during the latter half of the record (0-4 cm/s). There are a few short-lived periods when the northward flow increases and a few when the clockwise gyre seems to stall or even reverse (e.g., days 85, 99, 112).

A measure of the clockwise flow of this gyre feature can be seen by taking the difference in north-south residual flow rates at stations on either side of the shoal (Figure 25). This measure of gyre rotation shows that there is net clockwise flow during the entire deployment period and that it clearly divides into pre-flood, flood and post-flood increments. While the runoff event at the end of March 2010 dominates this signal, the wind is also seen to influence the dynamics of this feature. Figures 26-30 summarize in mapview how the flow vectors on the western shoal are unaffected by the flood and tend to correlate with different wind conditions during non-flood periods. In general, winds that blow with a westward component (Figures 29,30) tend to drive stronger northward flow along the western shoals.

Data-Model Comparisons: ROMS vs TCMs

The Narragansett Bay ROMS model has been modified based on suggestions from NBC outside consultants. Two important improvements over the PR-ROMS model (Bergondo, 2004) were to increase grid resolution in the Providence River, specifically in the vicinity of Fields Point (Figure 31), and to push the southern ocean boundary further south, to the mouth of the Bay. The effect of adding resolution to the model in the Providence River is shown in Figure 32. Whereas the PR-ROMS model predicts no distinction between channel and shoal flow vectors (Figure 32A), the Full Bay ROMS readily simulates the basic characteristics of the Edgewood Shoals gyre (Figure 32B). Vertically averaged flow vectors show a prevailing counterclockwise flow on the shoals in both the instantaneous records (Figures 32B, 33B, 34) and the residual flow patterns. Figure 33 highlights how closely, in a qualitative sense, the ROMS simulated flows match with characteristics of the underway ADCP records.

Traditionally, a parameter called model skill (Warner et al., 2005) is used to provide a quantitative, statistical measure of how well model values agree with observed values. A model skill of 1.0 represents a perfect match between observations and ROMS predictions. Whereas prior versions of ROMS developed for Narragansett Bay have done well at simulating instantaneous records (Rogers, 2008; Kremer et al., 2010), the lack of good skill values for residual flows (Table 3) have meant that chemical transport models were less reliable. A quantitative assessment of how the Full Bay Model does at representing the residual flows recorded by the spatially-temporally detailed TCM network from 2010 has been completed. Figure 35 shows that at TCM station 3 near the channel edge at the northeastern corner of the shoal, the ROMS residual flow is very close to the observed values. ROMS recreates the three stage aspect of the flow, with slower net southward flows before and after the flood. ROMS also captures the magnitude and onset timing of the flood. The decay in flood signal is faster in

ROMS, which is likely due to the slight offset of the outflow core, a process revealed in the TCM 19 data. ROMS predictions at other TCM stations along the shoal-channel interface are also quite good (Figures 36-38), capturing the pre-flood character of the outflow and primary aspects of the flood event. ROMS also does a remarkable job of simulating the spring 2010 residual flows on the mid and inner (western) sections of the shoal (Figures 39, 40). At TCM 14, ROMS predicts the average northward flow of the clockwise gyre and the much of the time variation of this feature. Such strong quantitative comparisons between TCM data and ROMS, with skill values of >0.8 (see Table 6).

4.0 Conclusions:

This report summarizes the completion of work on Tasks 8, 9 and 10 for project 08A-114-01-00 towards the development of a high resolution, 3D hydrodynamic and chemical transport model for upper Narragansett Bay using the public domain Regional Ocean Modeling System (ROMS) computer code. This Full Bay version of the ROMS model has been developed for NBC for use in simulating and characterizing the transport and flushing (or retention) of distinct dye fields from each major river source and WWTF. The goal is to build a useful tool for simulating how various environmental forcing conditions and policy scenarios may influence the total concentration of dye, which can be scaled to represent nutrient fields, within various sub-regions of the upper Bay, particularly those suffering from chronic water quality problems. This modeling tool will allow for the identification of which nutrient sources bypass versus accumulate within specific regions of the Providence River and upper Bay for all wind, tide and runoff conditions experienced within the Bay.

A number of important steps have been completed in the process of developing the ROMS modeling tool. The Full Bay version of the model has been developed to keep the southern boundary removed from the area of interest, while also maintaining fine packing of computational grid boxes in the key regions, such as the Fields Pt. section of the Providence River. A spatially-temporally detailed current meter program, using TCMs, has been completed and analyzed that reveals important features of the flows in the Field Pt. region. Data show a strong residual clockwise gyre that exists under all conditions of the deployment and how this feature varies with different forcing conditions. Forcing conditions for the period when the TCMs were out in 2010 have been developed into files for the Full Bay ROMS model. Model runs using the Full Bay ROMS and these Spring 2010 forcing conditions have been completed and show that ROMS does remarkably well at simulating the observed flow fields. Most notably, the Full Bay model does exceptionally well at simulating the residual flows, which are so crucial to the movement of chemical and biological species within the estuary. All dye logic from the coarse grid PR-ROMS model developed by LaSota (2010) have been added to the well calibrated Full Bay ROMS, which is ready for running detailed dye dispersion experiments. Because the Full Bay ROMS does so well at reproducing residual flow patterns south of Fields Pt., the models ability to accurately represent chemical transport is greatly enhanced over prior coarse grid Narragansett Bay ROMS models (e.g., PR-ROMS; RIS-NB ROMS).

5.0 References.

Bergondo, D., 2004. Water column variability in Narragansett Bay, Ph.D. thesis, University of Rhode Island, Narragansett, Rhode Island.

Haidvogel, D.B., H. Arango, W.P. Budgell, B.D. Cornuelle, E. Curchitser, E. Di Lorenzo, K. Fennel, W.R. Geyer, A.J. Hermann, L. Lanerolle, J. Levin, J.C. McWilliams, A.J. Miller, A.M. Moore, T.M. Powell, A.F. Shchepetkin, C.R. Sherwood, R.P. Signell, J.C. Warner, J. Wilkin, 2008, Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. *Journal of Computational Physics.* 227:3595–3624

Holt , J., J. Icarus-Allen , R. Proctor, F. Gilbert, Error quantification of a high-resolution coupled hydrodynamic–ecosystem coastal–ocean model: Part 1 model overview and assessment of the hydrodynamics, Journal of Marine Systems 57 , 167 – 188 , 2005.

Kincaid, C., The exchange of water through multiple entrances to the Mt. Hope Bay Estuary, Northeast Naturalist, 13(Special Issue 4): 117-144, 2006.

Kincaid, C., R. Pockalny, and L. Huzzey, 2003. Spatial and temporal variability in flow at the mouth of Narragansett Bay, Journal Geophysical Research, doi:10/1029/2002JC001395.

Kincaid, C., D. Bergondo, and K. Rosenburger, 2008. Water exchange between Narragansett Bay and Rhode Island Sound, in Science for Ecosystem-based Management, edited by A. Desbonnet and B. A. Costa-Pierce, chap. 10, Springer, 2008.

Kincaid, C., 2001a. Results of Hydrographic Surveys on the Providence and Seekonk Rivers: Summer Period, Report submitted to the Narragansett Bay Commission, Prov., R.I., 45 pp..

Kincaid, C., 2001b. Results of Hydrographic Surveys on the Providence and Seekonk Rivers: Fall Period, Report submitted to the Narragansett Bay Commission, Prov., R.I., 35 pp.

Kincaid, C., 2001c. Results of Hydrographic Surveys on the Providence and Seekonk Rivers: Winter Period, Report submitted to the Narragansett Bay Commission, Prov., R.I., 27 pp.

Kincaid, C., D. Bergondo, and K. Rosenburger, Water exchange between Narragansett Bay and Rhode Island Sound, in Science for Ecosystem-based Management, edited by A. Desbonnet and B. A. Costa- Pierce, chap. 10, Springer, 2008

Kremer, J. N., J. M. P. Vaudrey, D. S. Ullman, D. L. Bergondo, N. LaSota, C. Kincaid, D. L. Codiga, and M. J. Brush. Simulating property exchange in estuarine ecosystem models at ecologically appropriate scales, Ecological Modelling, 221: 1080-1088, 2010

LaSota, N., 2010. Observational and numerical experiments on the flushing of nutrients in the Providence River estuary, University of Rhode Island, Master Thesis, Kingston, RI, 186 pages, defended 2010.

LaSota, N., D. Bergondo, and C. Kincaid. 2007. Observational and numerical experiments on the flushing of nutrients in the Providence River estuary. Abstract, *ERF* Annual Meeting, Providence, Rhode Island.

Li, M., L. Zhong, and W. Boicourt. 2005. Simulations of Chesapeake Bay estuary: sensitivity to turbulence mixing parameterizations and comparison with observations. *J. Geophys. Res.* **110**:C12004

MacCready, P., N.S. Banas, B.M. Hickey, E.P. Dever, and Y. Liu. 2009. A model study of tide- and wind-induced mixing in the Columbia River estuary and plume. *Continental Shelf Research,* 29:278-291.

Manning J. and V. Sheremet. 2008: Building a Low-Cost Observing System with Help from Lobstermen. MABPOM 2008 Meeting.

Rogers, J., 2008. Circulation and transport in upper Narragansett Bay , University of Rhode Island, Master Thesis, Kingston, RI, 107 pages.

Rosenberger, K., 2001. Circulation patterns in Rhode Island Sound: Constraints from a bottom mounted acoustic Doppler current profiler, M.S. Thesis in Oceanography, University of Rhode Island, Narragansett, RI, 226pp.

Shchepetkin, A.F. and J.C. McWilliams, 2003: A Method for Computing Horizontal Pressure-Gradient Force in an Oceanic Model with a Non-Aligned Vertical Coordinate, *Journal of Geophysical Research,* 108,1-34.

Shchepetkin, A.F. and J.C. McWilliams, 2005: The Regional Ocean Modeling System: A split-explicit, free-surface, topography-following coordinates ocean model. *Ocean Modeling*, 9:347-404.

Warner, J. C., C. R. Sherwood, H. G. Arango, and R. P. Signell. 2005. Performance of four turbulence closure models implemented using a generic length scale method, *Ocean Modelling,* 8:81-113.

Wilkin, J., H. G. Arango, D. B. Haidvogel, C. Sage Lichtenwalner, S. Glenn, and K. Hedstrom, A regional ocean modeling system for the Long-term Ecosystem Observatory, J. Geophys. Res., Vol. 110, C06S91, doi:10.1029/2003JC002218, 2005

Table 1: Model skill parameters and statistical root-mean-square (RMS) values for station locations within the Providence River and at Conimicut Pt. (Rogers, 2008) (using NOAA tide gauges). Model and data values are instantaneous (tidal time scale) records for 2006. Comparisons based on a 9 month ROMS simulation (Rogers, 2008). Skills of 0.8 and higher are considered very strong. A skill of 1 is a perfect match.

	Skill	RMS Diff (cm)
Newport	0.98	9.8
Quonset	0.98	11.3
Conimicut	0.97	14.7
Providence	0.96	17.7
CN-NP Slope	0.82	1.2

Table 2: Temperature skill values and statistical root-mean-square (RMS) differences between ROMS output and data for buoy locations at Conimicut Pt., Mount View and Poppasquash Pt. Values are comparing instantaneous or unfiltered records. Because records are unfiltered they are referred to as tidal.

Buoy	Skill	RMS (°C)
Conimicut Top	0.98	0.78
Bottom	0.95	0.86
Mount View Top	0.97	1.11
Bottom	0.96	1.13
Poppasquash Top	0.98	0.88
Bottom	0.81	2.19

Table 3: Observed instantaneous velocity fields also compare well ROMS output. Here comparisons are between ADCP records in the West Passage from 2006 (Rogers, 2008). RMS units are m/s. Values from comparisons of instantaneous records are in the top two rows. Data-model comparisons of sub-tidal or residual velocity fields are shown in the bottom two rows. Skill values are not high for the sub-tidal flow, which is an important component for chemical transport.

	WP Skill	WP RMS
Surface	0.86	0.15
Bottom	0.83	0.14
Surface Residual	0.56	0.03
Bottom Residual	0.62	0.05

Table 4. Summary of flow energy in terms of variance about a mean for 2010 TCMs in the Providence River. Deployment-long velocity averages are in cm/s. Std. Dev.=Standard deviation. Abs. Max. = maximum velocity value recorded in the absolute value of the record.

TCM Station	E-W Vel. Avg.	E-W Std. Dev.	E-W Abs. Max.	N-S Vel. Avg.	N-S Std. Dev.	N-S Abs. Max.
3	-0.53	4.87	30.04	-5.78	10.58	37.25
5	1.00	5.43	30.08	-6.00	9.89	39.56
7	1.00	5.22	30.78	-7.30	10.82	36.80
10	-.37	5.02	27.22	-5.00	8.88	32.84
14	0.67	2.27	19.48	1.57	5.11	27.68
19	1.06	4.01	33.39	-4.36	8.49	63.06
20	-0.84	2.95	21.13	1.28	8.58	28.73

Table 5. Summary of flow energy in terms of variance about a mean for 2010 TCMs in the Providence River.

TCM Station	East Velocity Variance$(cm/s)^2$	North Velocity Variance $(cm/s)^2$
3	20.51	106.14
5	27.37	92.77
7	25.19	110.56
10	23.87	75.10
14	4.73	25.06
19	14.92	69.09

Table 6. Statistical data-model comparison for sub-tidal or residual flow fields for NBC - supported TCM stations.

ROMS Station	**TCM Station**	Wilmont Skiill	RMS (cm/s))
18	**3**	0.78	4.2
16	**5**	0.88	3.7
14	**7**	0.82	5.2
12	**10**	0.89	2.3
8	**14**	0.82	1.3
3	**19**	0.8	3.6

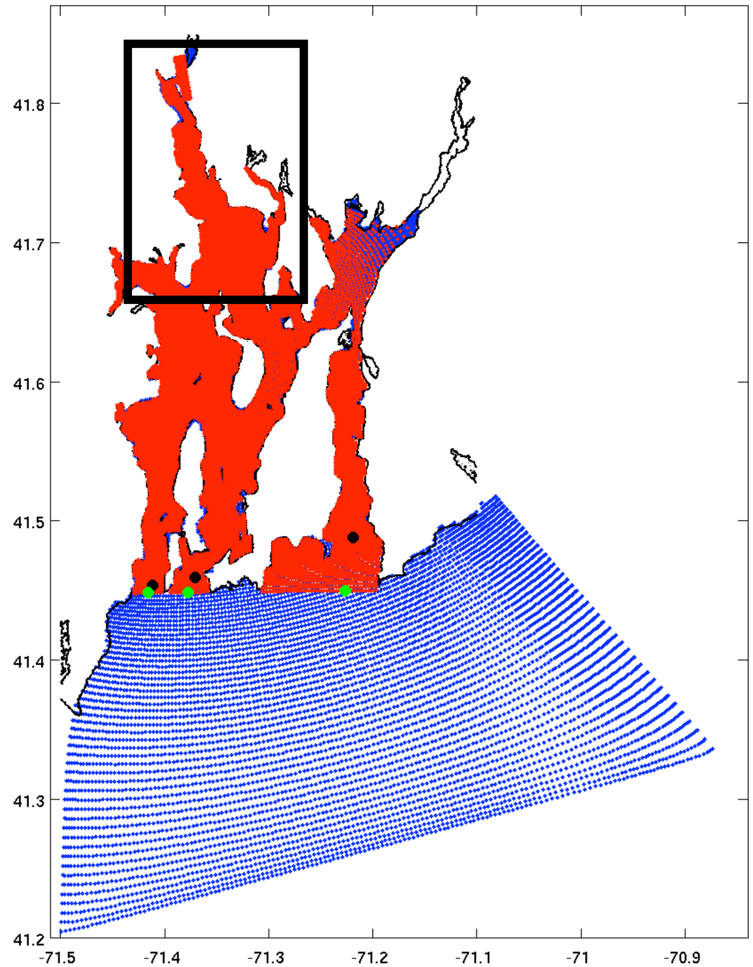


Figure 1. The Narragansett Bay Regional Ocean Modeling System (or ROMS) hydrodynamic-transport model has been developed for the Narragansett Bay and Rhode Island Sound (RIS) (Bergondo, 2003, Rogers, 2008). Bergondo (2003) used a relatively coarse grid version to focus on upper Bay processes (black box) (referred to as the PR-ROMS model). Rogers (2008) developed a wider extend ROMS extending from RIS up through the Seekonk River (blue grid), referred to here as the RIS-NB ROMS model. Both of these model grids have relatively coarsely spaced grid boxes in the Providence River (>150 m horizontal spacing). A Full-Bay ROMS model (red region) has been developed with finer grid box spacing in the Providence River (<50 m).

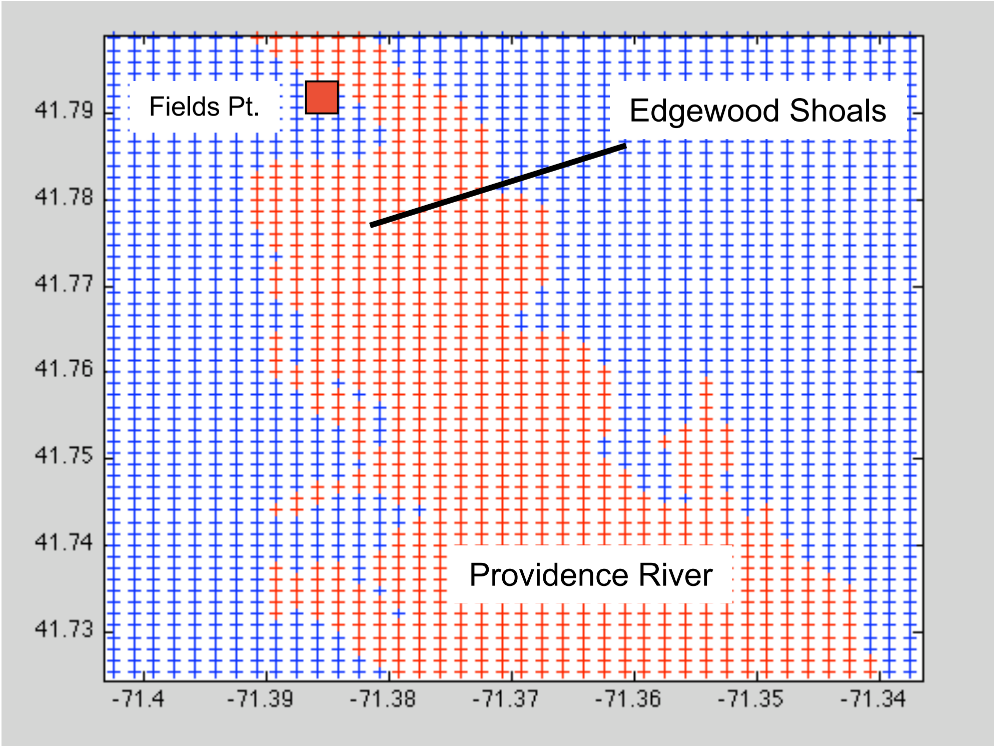
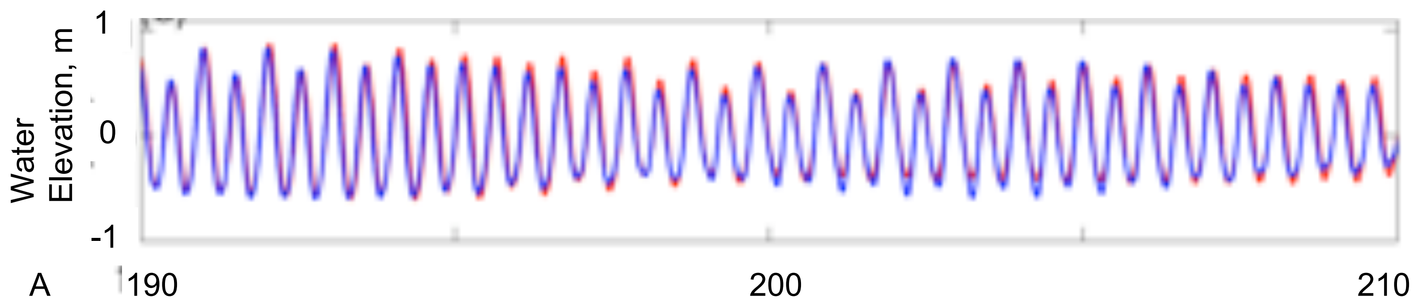


Figure 2. Mapview plot of the coarser grid resolution for the PR-ROMS (similar in scale to the RIS-NB model of Rogers, 2008). Blue crosses mark land grid boxes and red crosses indicate water grid boxes. A total of 12 grid boxes span the east-west extent of the Edgewood Shoals in this model for an east-west grid spacing of ~140m.

A



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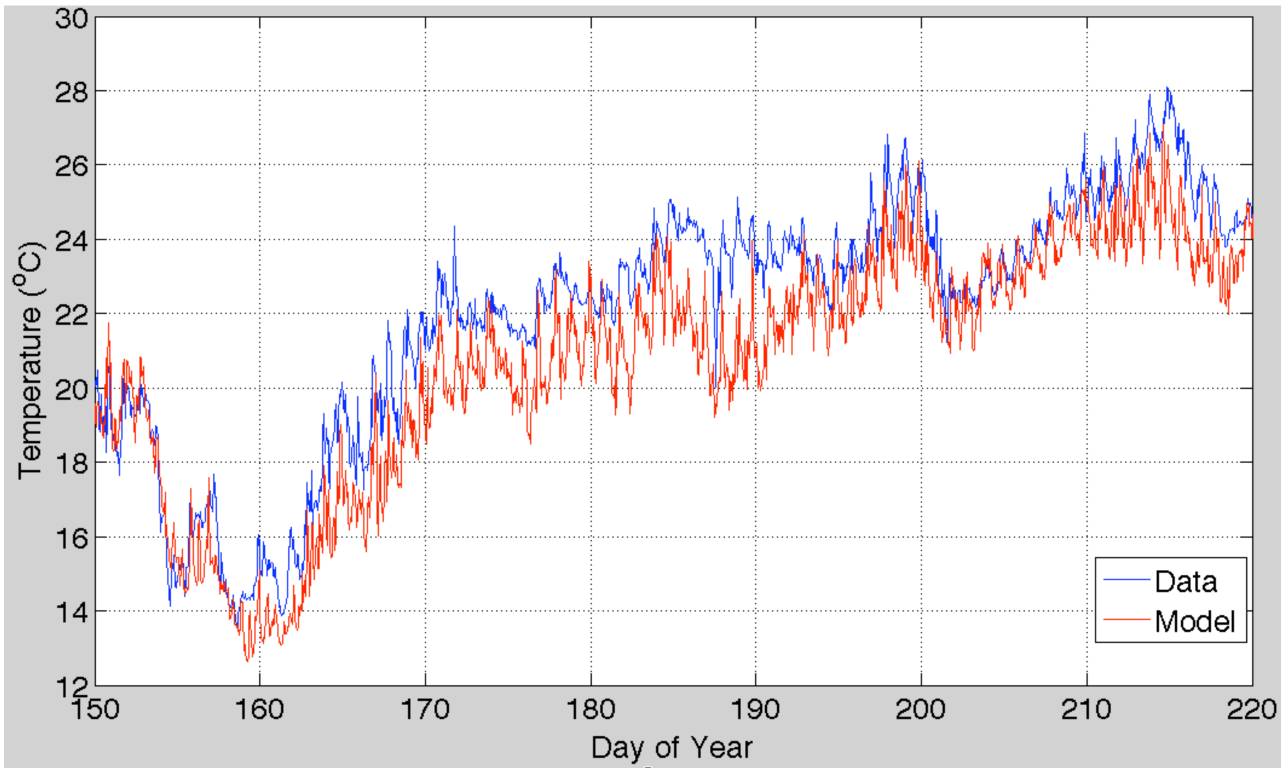


Figure 3. Output from the coarse grid PR and RIS-NB ROMS models (Rogers, 2008) in selected regions where observational data exist, show that ROMS does a very good job of matching observed instantaneous, or tidal records.   A. Water elevation for a 2006 NB-RIS ROMS run (red line) plotted versus time (decimal day for 2006) at the location of the Newport tide station (blue). Data and model tide heights match exceptionally well.   B. Similar strong match for data-model comparison of surface water temperature recorded at Conimicut Pt. buoy.

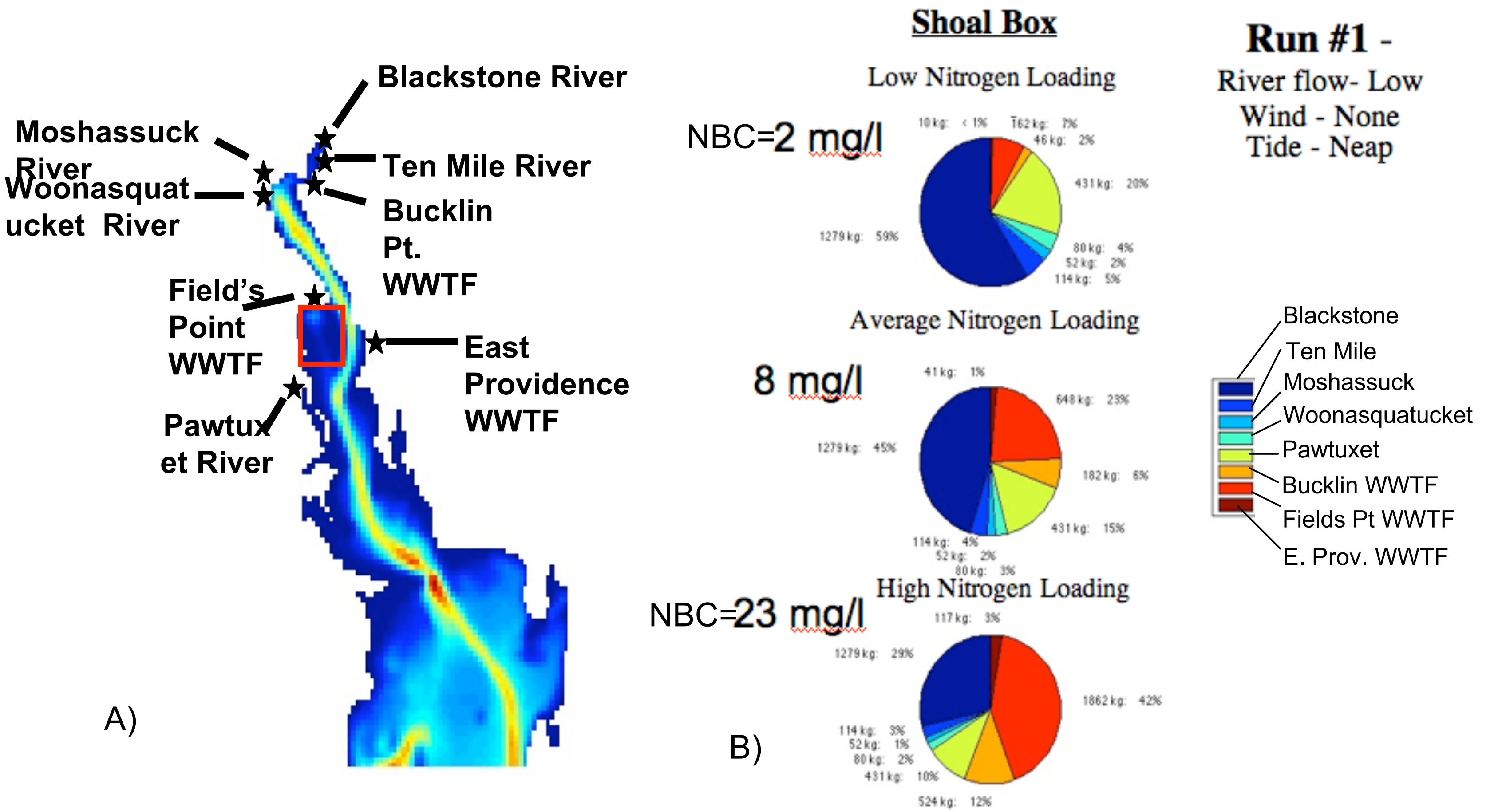


Figure 4. A) URI MS student N. LaSota added compositional dye fields into the PR-ROMS model for the purpose of the tracking the transport (accumulation) of individual dye (chemical) sources within key regions of the Providence River. B) LaSota used the PR-ROMS model to calculate relative contributions of individual dyes representing total nitrogen fields accumulating on Edgewood Shoals. Distributions are shown using pie diagrams for one of her cases with low river runoff, no winds and a neap tide period. LaSota varied the concentration levels from the NBC Fields Pt. Plant from 2 ml.l to 23 mg/l to show the relative changes in shoal dye from the Blackstone versus Fields Pt. Results show relatively minor dye input from the Pawtuxet River. Long term chemical transport relies strongly on the sub-tidal flows, as well as the tidal scale flow processes that have been shown to match well with data (Figure 2; Rogers, 2008).

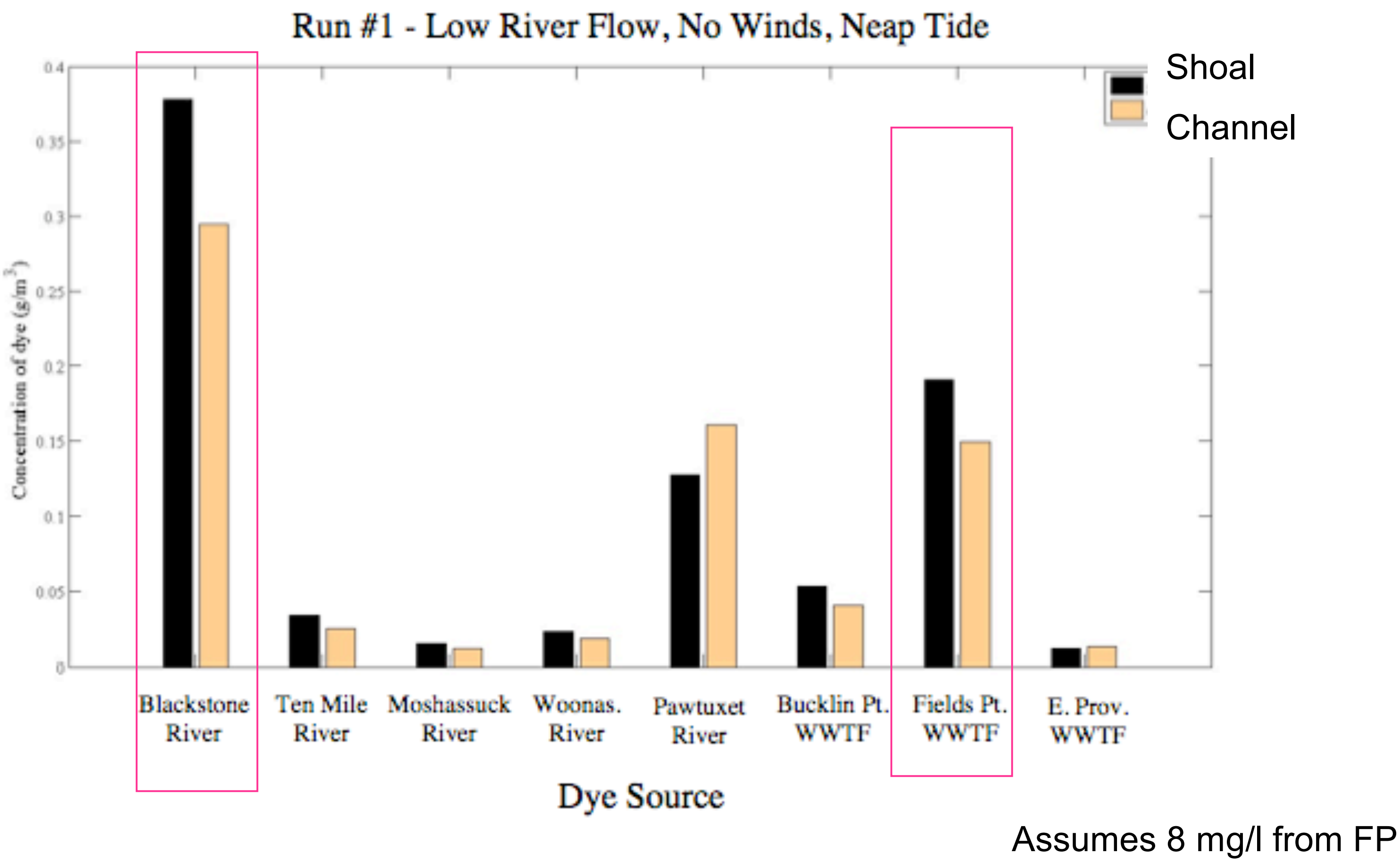


Figure 5. Plots of dye concentrations recorded in the Providence River, south of Fields Pt, from ROMS simulations by N. LaSota using the coarse-grid PR-ROMS. The values are shown for accumulated dye (mg/l) for individual dye sources coming each river and WWTF as recorded both on the Edgewood Shoal and in the channel near Edgewood Shoals. Conditions are listed, and include no applied winds, low steady river flow and neap tides. Using an applied output concentration of 8 mg/l from Fields Pt. WWTF, the results suggest the Blackstone River and Fields Pt. WWTF are the largest contributers to dye on the shoals.

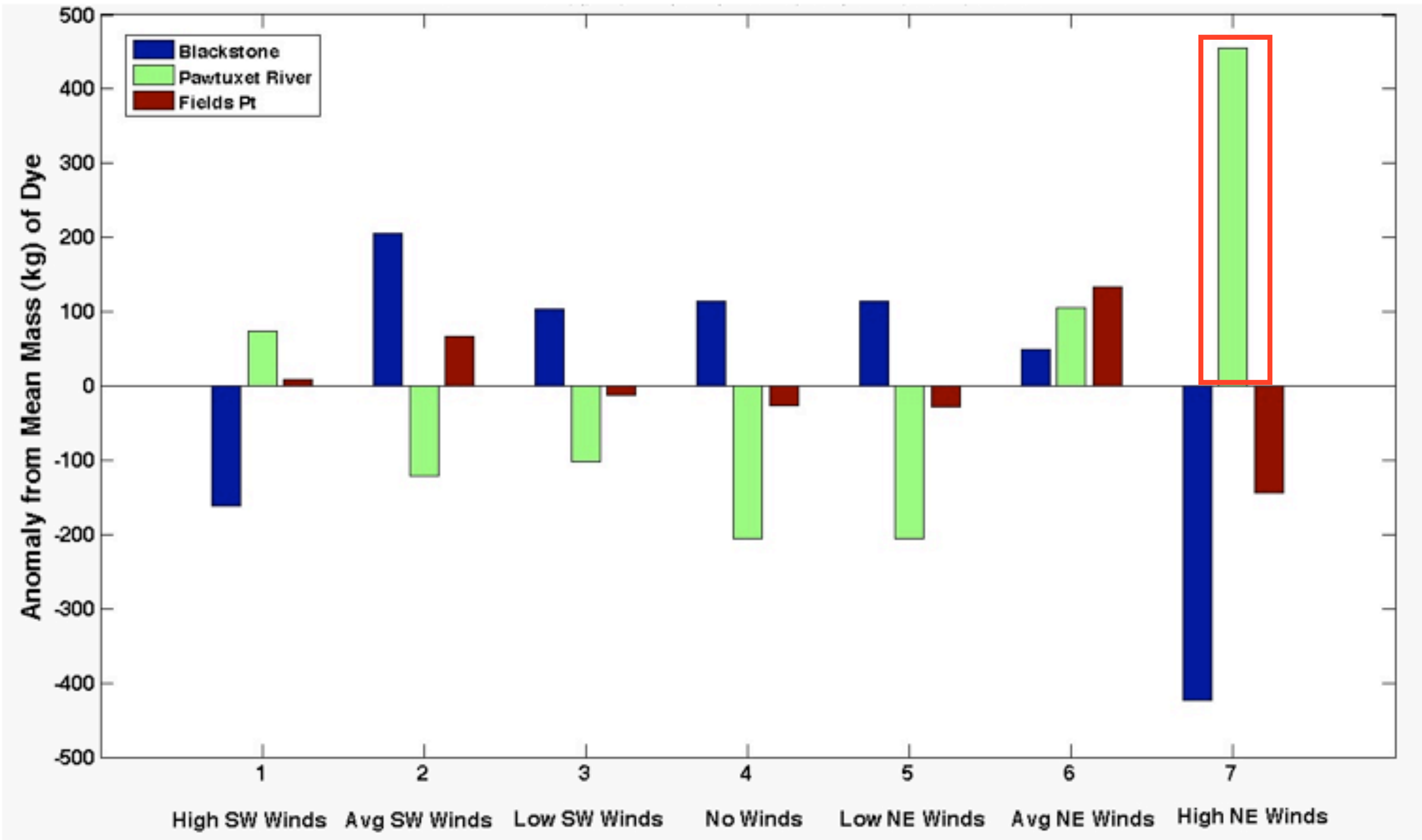


Figure 6. Plots showing how dye mass concentrations (kg of dye) recorded on the Edgewood Shoals using PR-ROMS (N. LaSota, unpublished data), vary from the reference state in Figure 5 given different wind conditions. These PR-ROMS models predict that only northward blowing winds cause the dye coming from the Pawtuxet River to dominate the Edgewood Shoals total dye mass distribution.

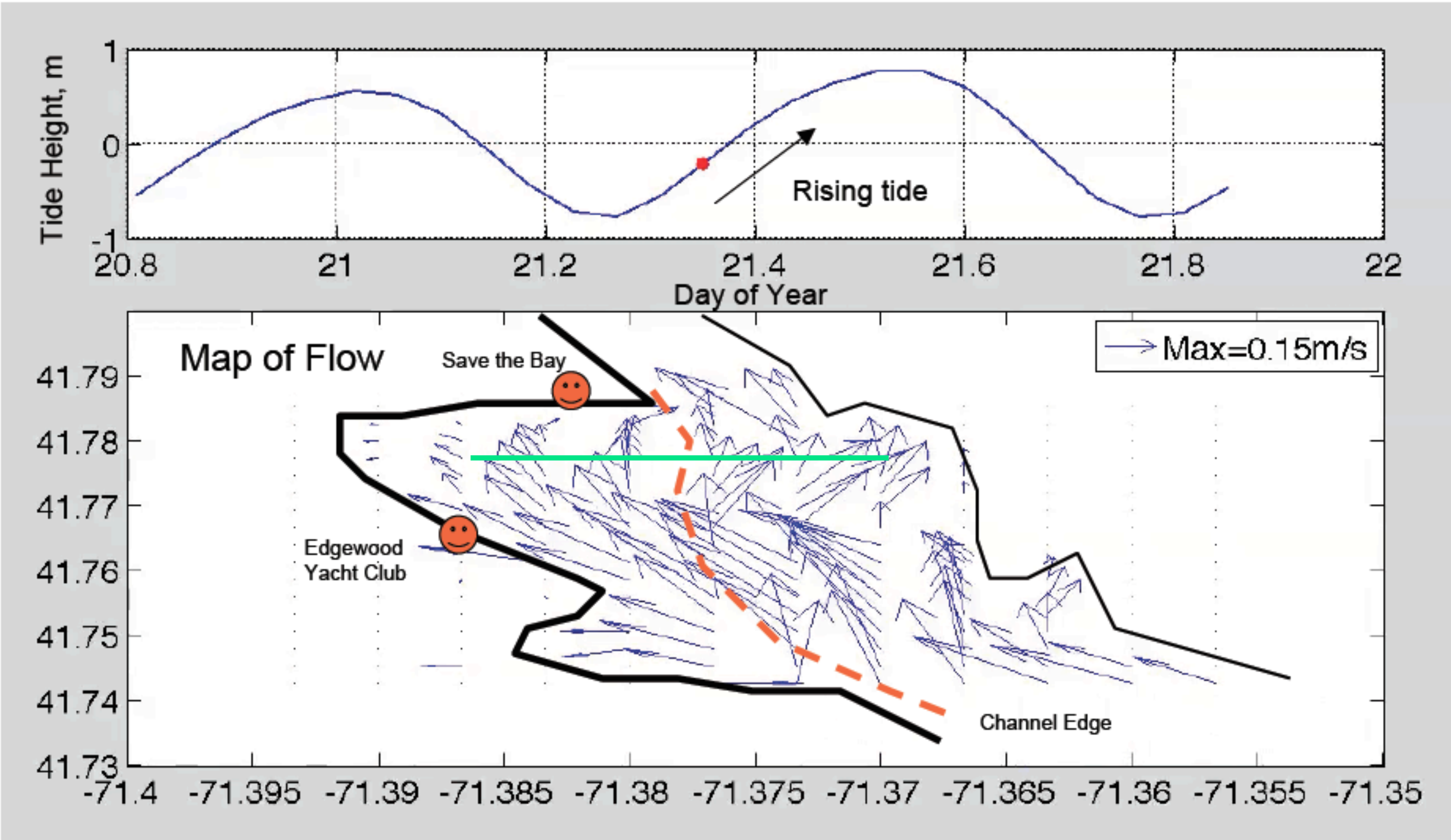


Figure 7. Plot of tide height variation used to force coarse grid ROMS simulation by N. LaSota (unpublished data) (top frame). Bottom frame shows mapview of vertically averaged flow vectors for PR-ROMS model simulation. Edge of the shipping channel is marked with dashed red line. The stage of the tide for this vector map is shown with a red circle, and corresponds to a mid-flood period. Vectors show that flow is uniformly in across the entire section south of Fields Pt.. The location of 2001-2002 NBC-sponsored ADCP transects is shown with the green line.

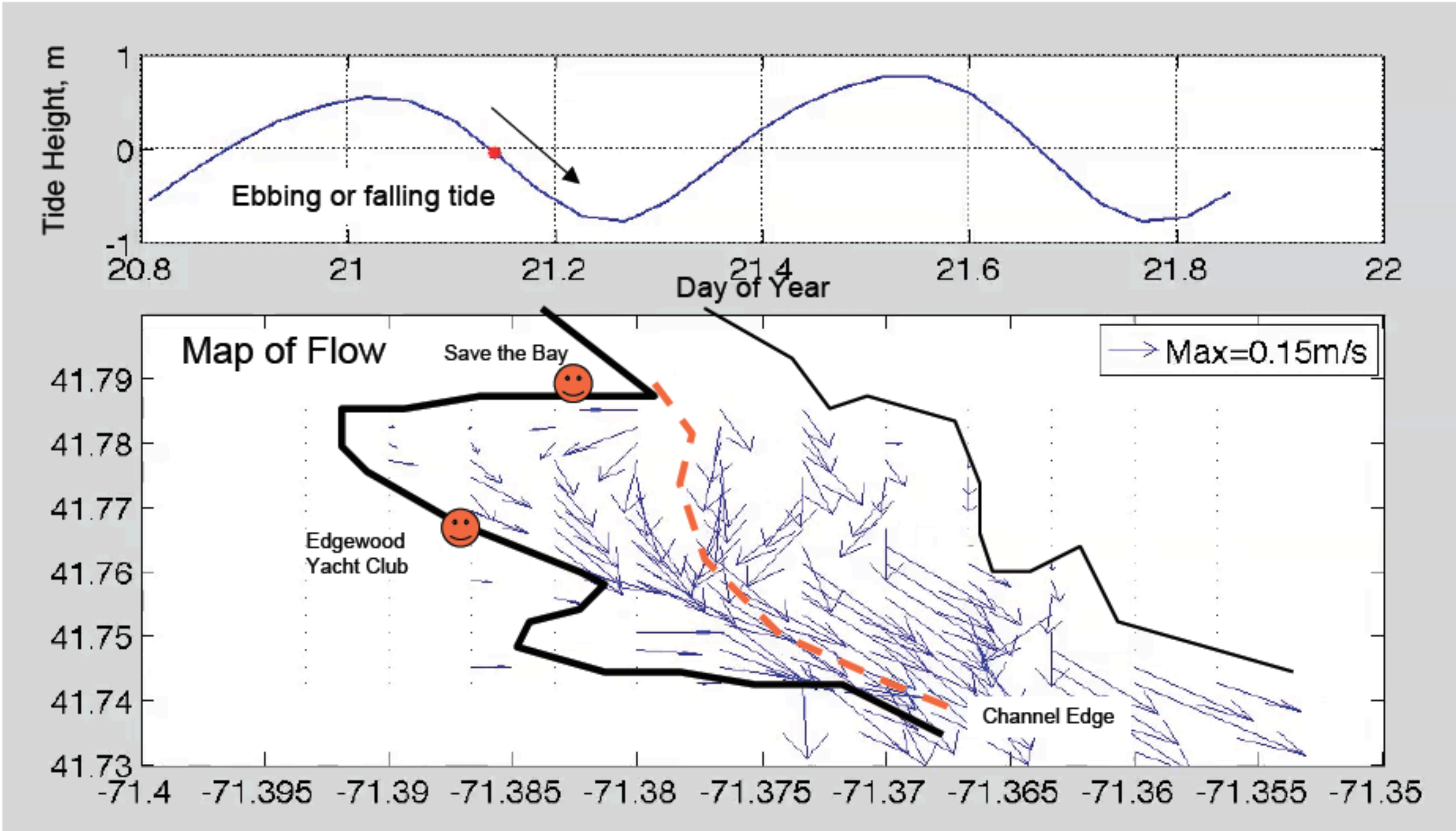
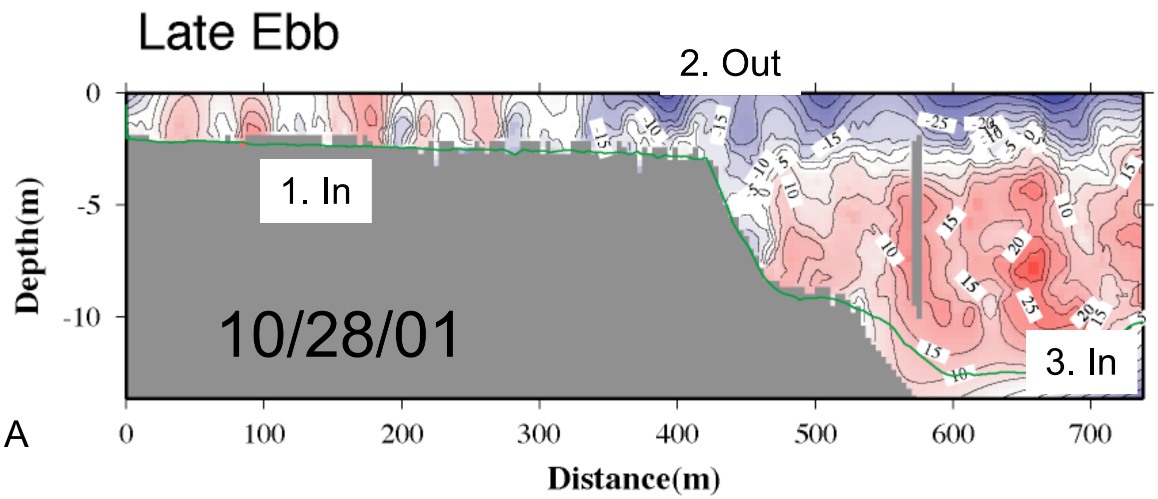


Figure 8. Plot of tide height variation used to force coarse grid ROMS simulation by N. LaSota (unpublished data) (top frame).   Bottom frame shows mapview of vertically averaged flow vectors for PR-ROMS model simulation. The stage of the tide for this vector map is shown with a red circle, and corresponds to a mid-ebb conditions.   As in Figure 7 for flood conditions, here again vectors show that flow is uniformly outward across the entire section south of Fields Pt.. The location of 2001-2002 NBC-sponsored ADCP transects is shown with the green line.

A



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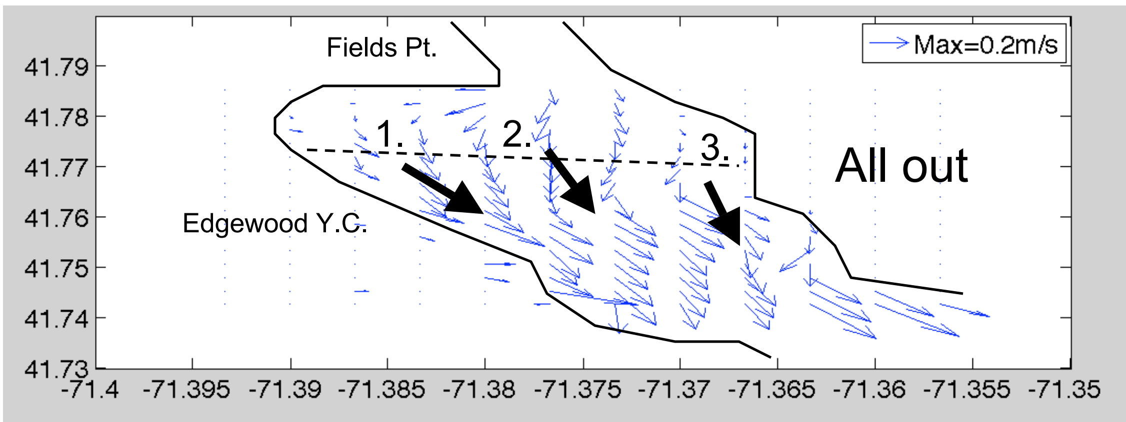


Figure 9. A. Underway ADCP data from the Edgewood Shoals region of the Providence River collected for NBC during 2001. Data highlight three characteristic, repeatable flow regimes within this section of Edgewood Shoals. Underway and moored ADCP data consistently show a pattern of surface outflow (2) and deep inflow (3) within the shipping channel, and a broad northward recirculation zone (1) on the western shoals (or shallows). B. Neither of the coarser grid models (PR-ROMS; NB-RIS ROMS) capture the level of flow heterogeneity seen in the ADCP data (A). Coarse models predict a sweeping outflow across the shoals. Such a discrepancy between models and data needed to be resolved to improve chemical transport studies (e.g., Figures 4-6),

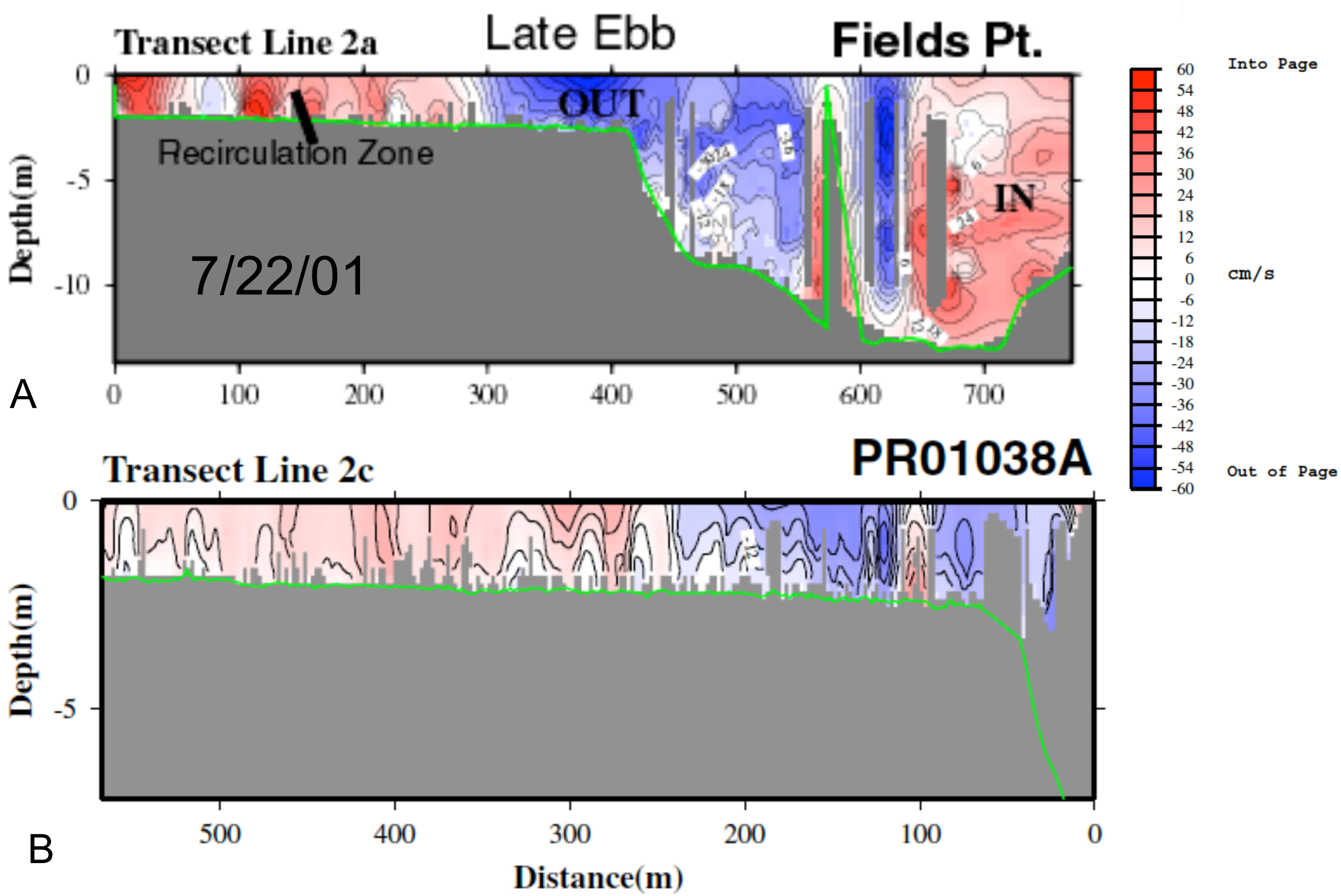


Figure 10. Cross sections showing northward velocity measured from NBC-sponsored underway ADCP surveys on 7/22/01. Orientation is viewed looking northward. Data are from Line 2, just south of Field Pt., running from the channel (on east or right) to Edgewood Shoals (on left or west). Red (blue) colors correspond to northward (southward) flow. A. Data from the whole line show common pattern of inflow in the deep channel and along western shoal, with outflow along western channel. B. Repeat survey across shoals reveals clear flow reversal (northward on west, southward on east side).

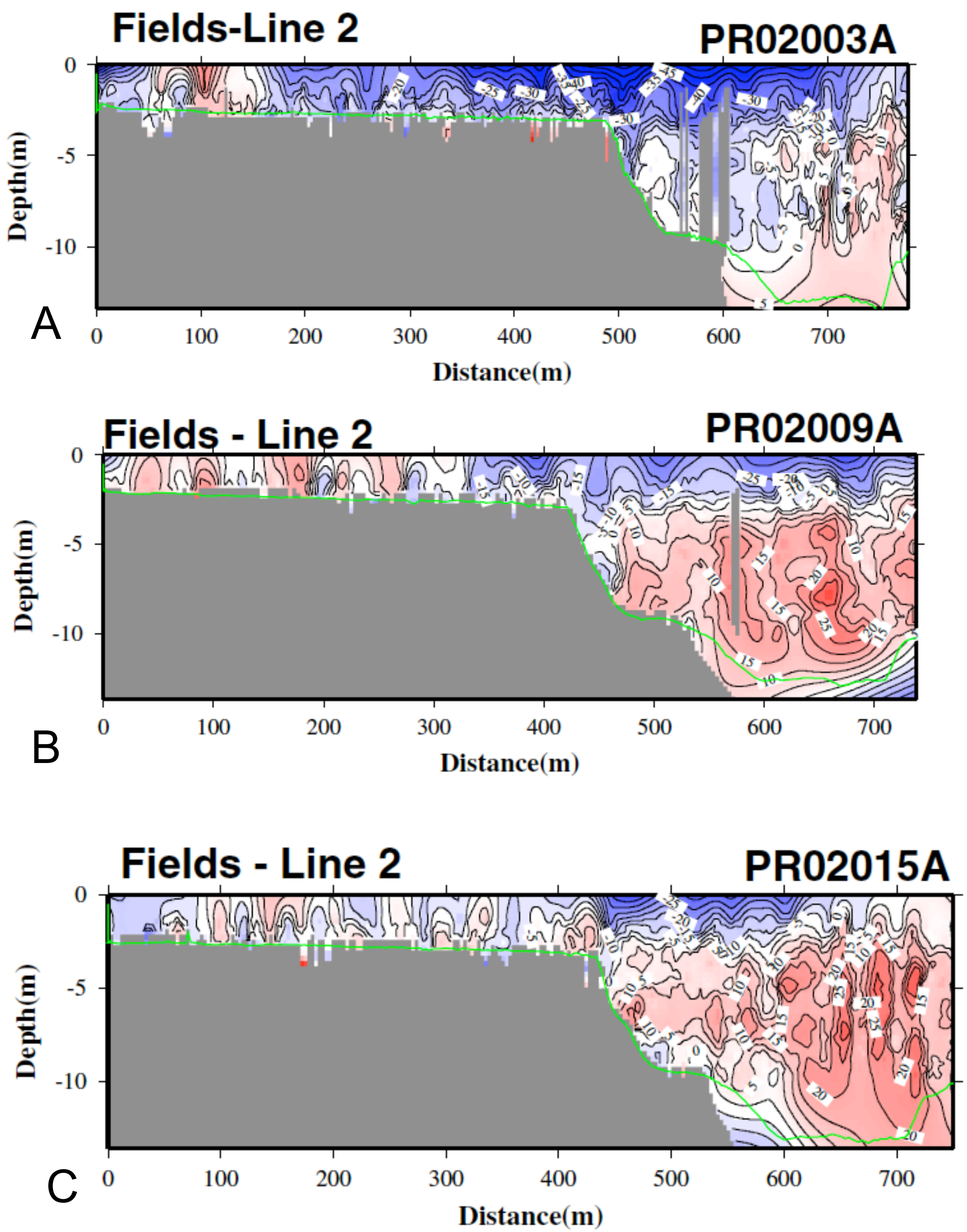


Figure 11. Similar cross sections to Figure 10 showing northward velocity measured from NBC-sponsored underway ADCP surveys on 10/28/01. Orientation is viewed looking northward. Data are from Line 2, just south of Field Pt.. View is northward. (Red=inflow, Blue=outflow, similar color scale as Figure 8). Data are from three stages of the tide: A. Ebb, B. Early Flood, C. Flood. Data show clear differences in flow direction between western shoal, eastern shoal and channel. Coarse grid ROMS does not capture this lateral variability in flow seen in ADCP records.

Figure 12. Images of the tilt current meter (TCM) model used in this study. These are designed and built by URI Marine Scientist V. Sheremet. The TCM is a 1m high buoyant cylinder that floats upright in the water column. Water currents cause the TCM to tilt in the direction of flow. The tilt angle is calibrated to flow speed. A total of 21 TCMs were deployed on Edgewood Shoals on March 8, 2010 and recorded usable data at 5 minute intervals through April 30, 2010 or for ~52 days. Data from TCM are omitted due to low signal to noise ratio.

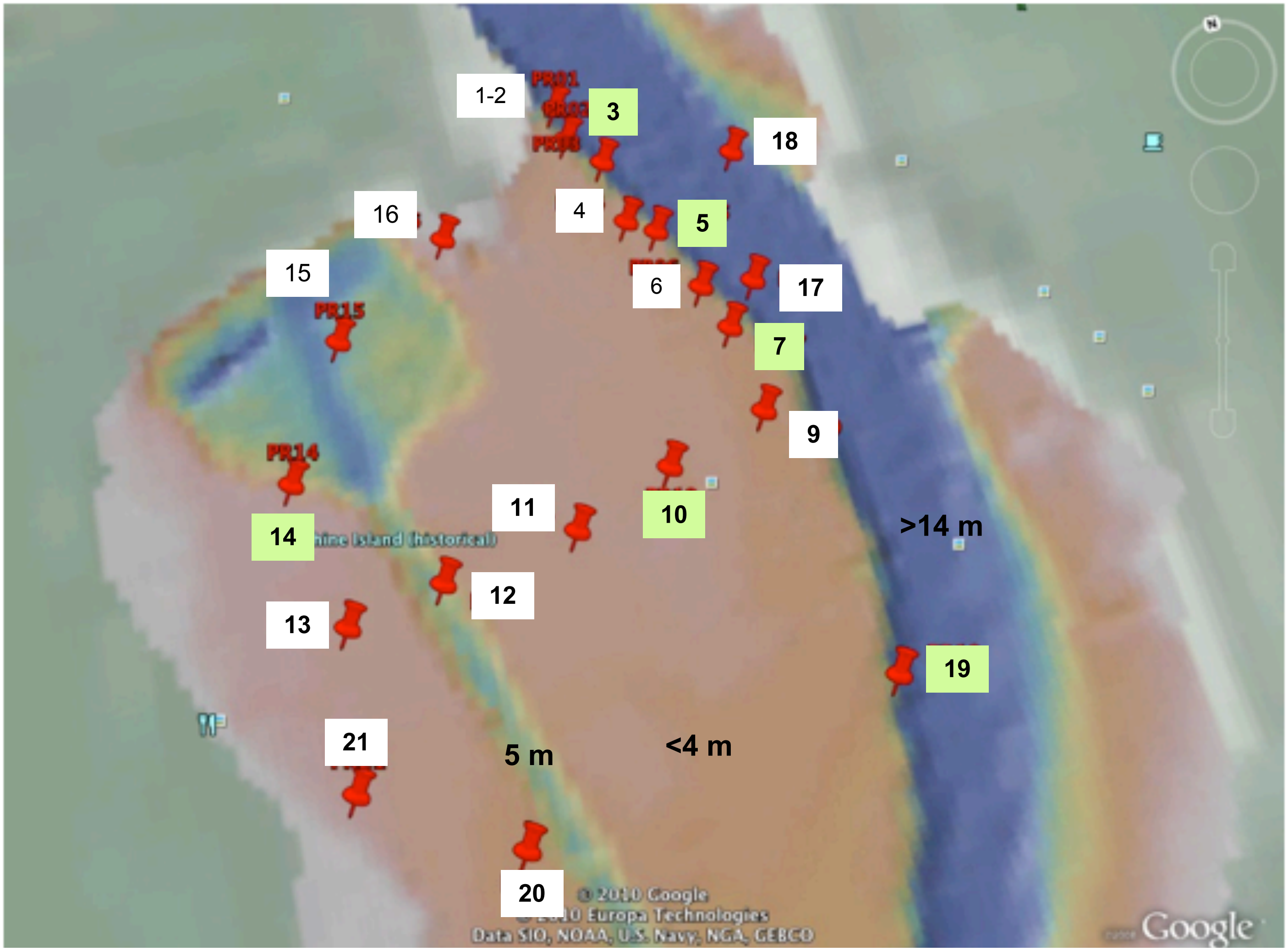


Figure 13.   Map showing locations of the tilt current meters (TCMs) deployed in the Providence River during March 8 -May 1, 2010.   TCMs at stations PR01-07 lie along the eastern edge of the Shoal, at the boundary with the shipping channel. Stations PR09-13 are distributed along a transect running from east to west across the Shoals.   Station P12 lies in the small Port Edgewood channel.   Stations PR14, 21 and 20 lie along the western side of the Shoals.   Station PR15 is in the dredged boat basin in the northwestern corner of Edgewood Shoals.   Station PR16 is at the Save the Bay dock.   Stations PR17 and 18 are on the western and eastern sides of the shipping channel.   Station PR19 is the southernmost TCM located at the shoal-channel interface.   The NBC-supported TCMs are shaded in green. These were used to fill in the array in key locations along the channel edge and on the Edgewood Shoals.

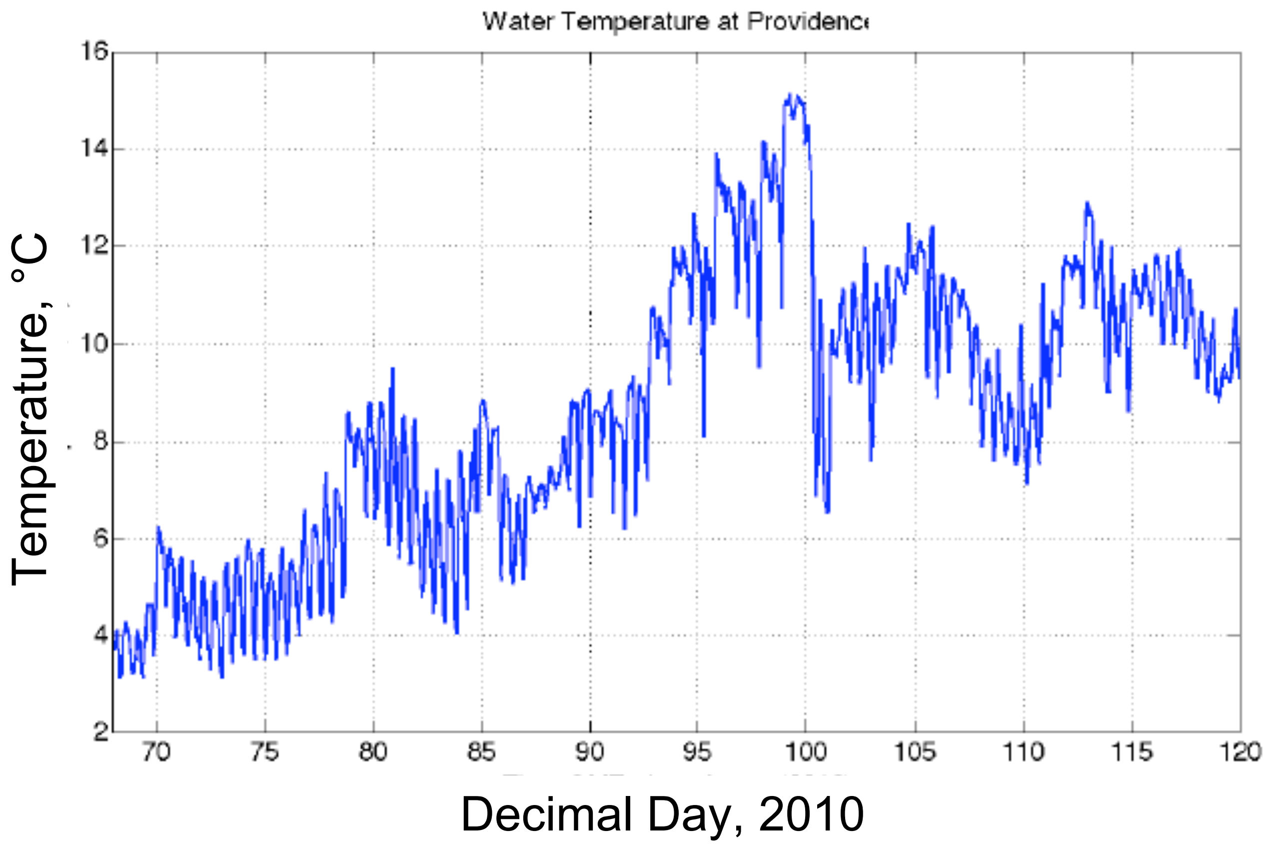


Figure 14. Plot of water temperature measured in Providence Harbor for the TCM deployment period in 2010.

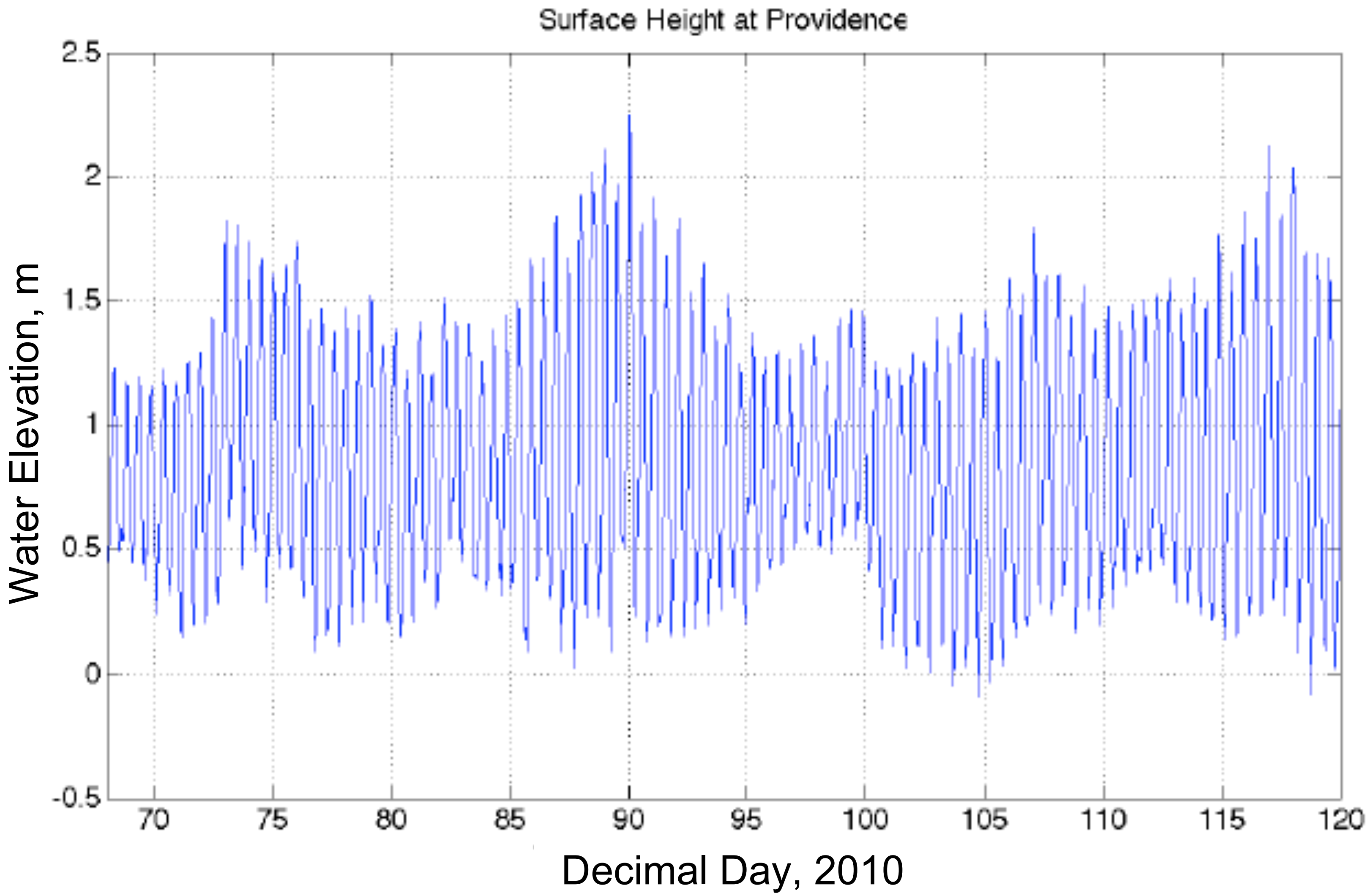


Figure 15. Plot of water elevation measured in Providence Harbor for the TCM deployment period in 2010. Plots show the semi-diurnal oscillation in the tides (or water elevation) and the longer period variations through spring-neap cycles.

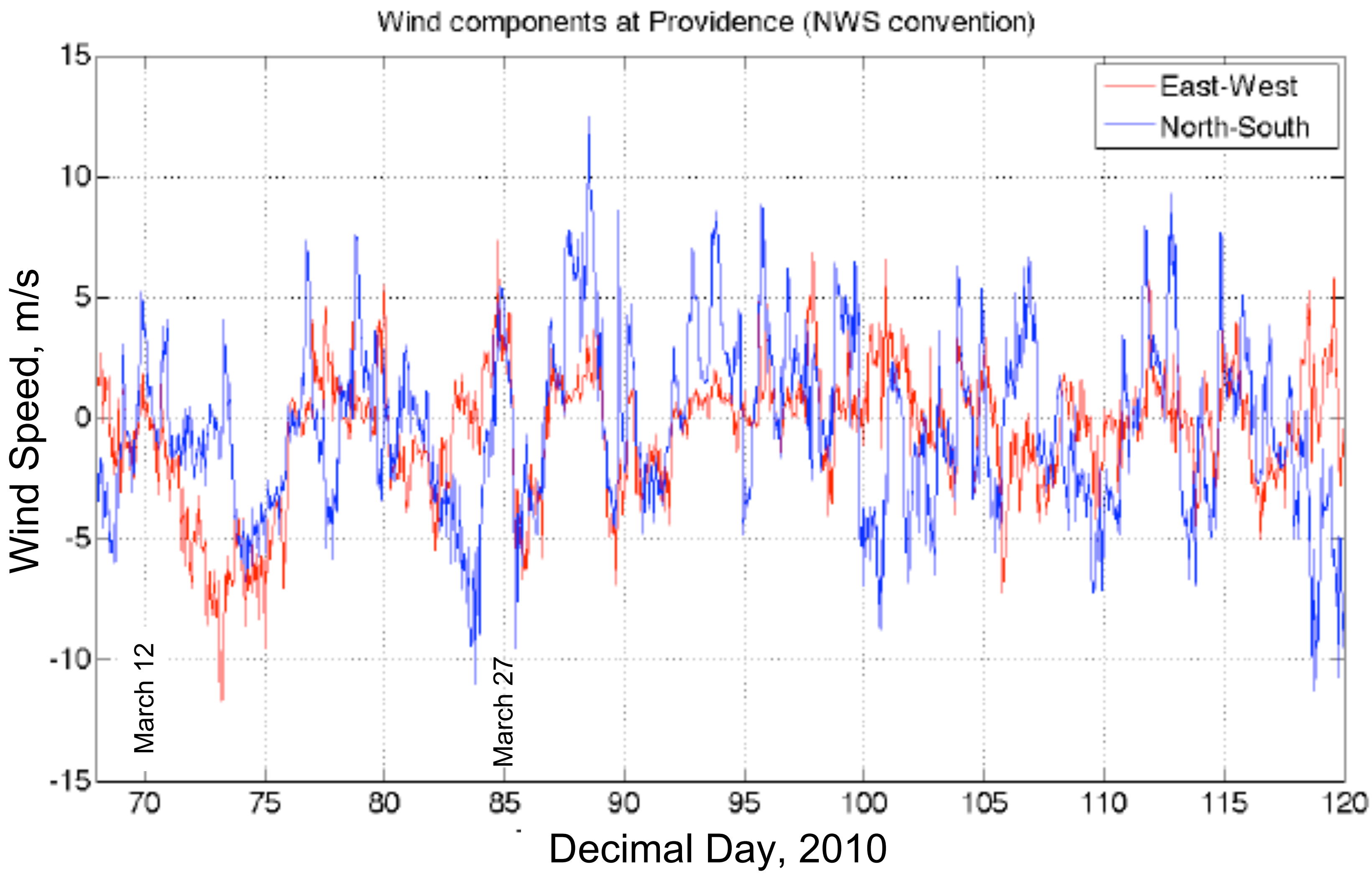


Figure 16. Plot of northward blowing (positive) and eastward blowing (positive) components of the wind vector measured in Providence for the TCM deployment period in 2010. Plots show the semi-diurnal oscillation in the tides (or water elevation) and the longer period variations through spring-neap cycles. Records shows oscillations on a 5-10 cycle between southward and northward blowing wind events.

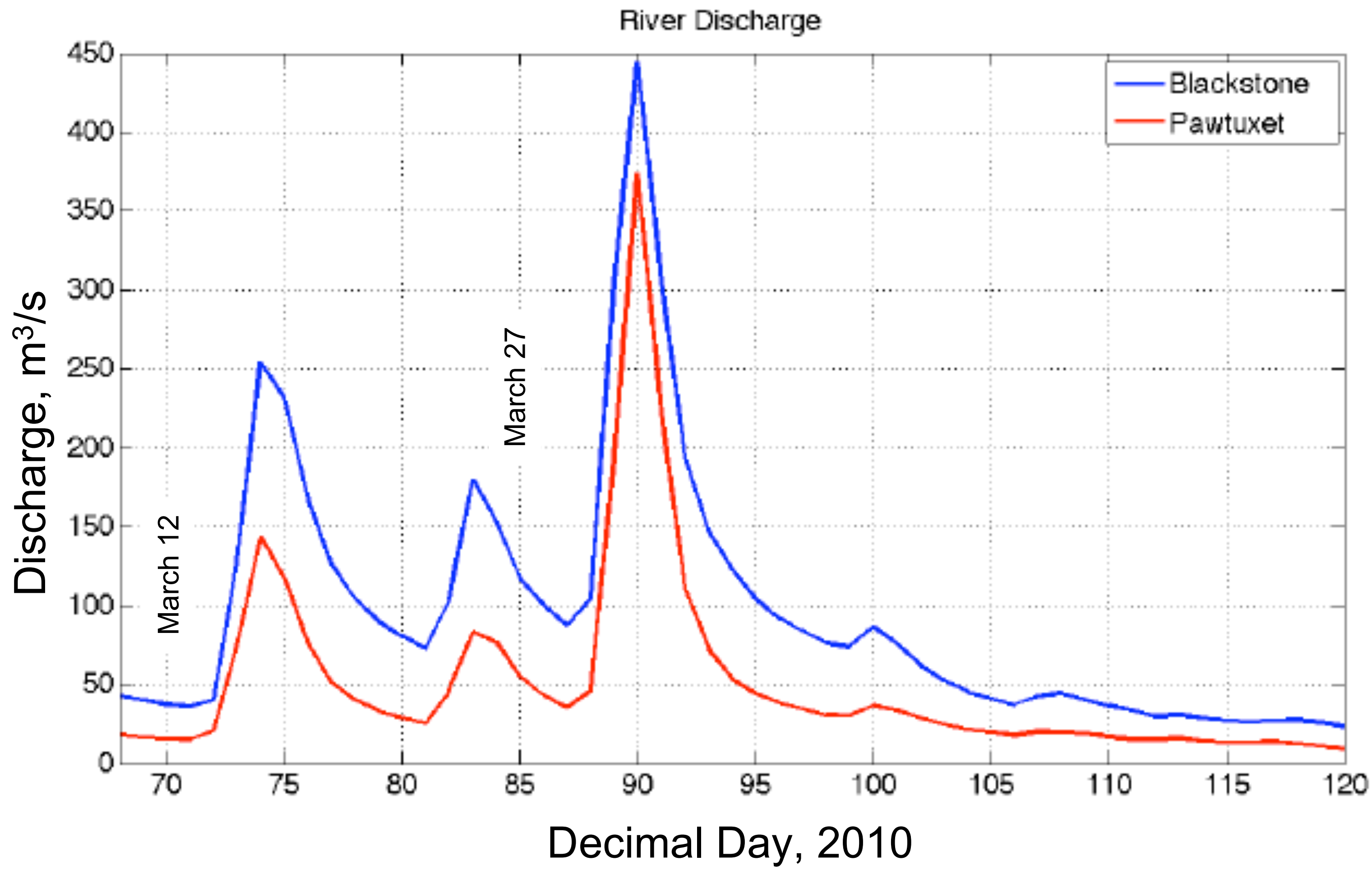


Figure 17a. Plot of river discharge for the Blackstone and Pawtuxet Rivers for the TCM deployment period in 2010. Plots show the large flood event that occurred at the end of March, 2010. This event was preceeded by two smaller runoff events in mid-March, 2010. Discharge was low during the end of the deployment period .

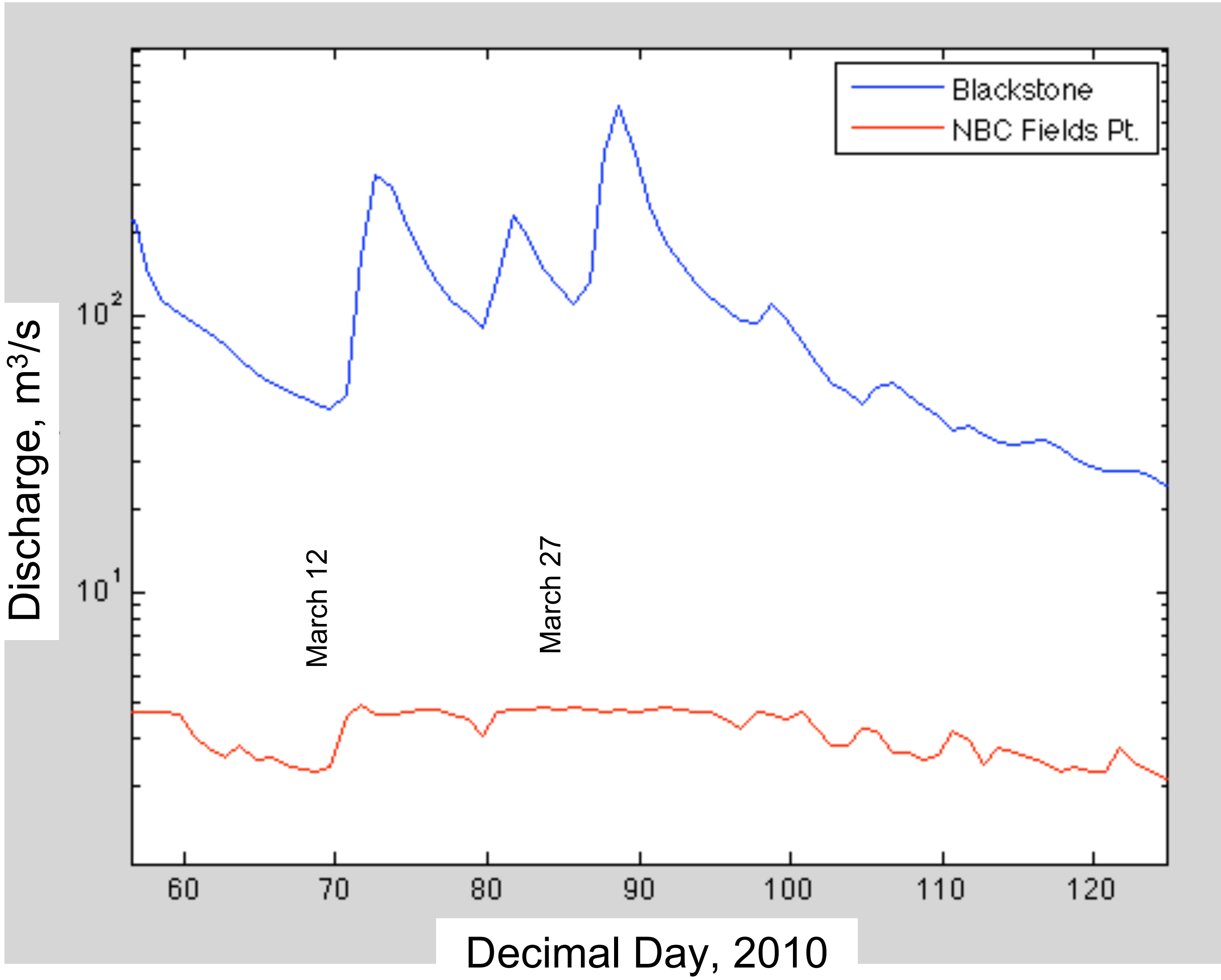


Figure 18. Plot of river discharge for the Blackstone River and the Fields Pt. WWTF for the TCM deployment period in 2010. The plot highights the fact that the large runoff events in the rivers are not seen in the Fields Pt. discharge record.

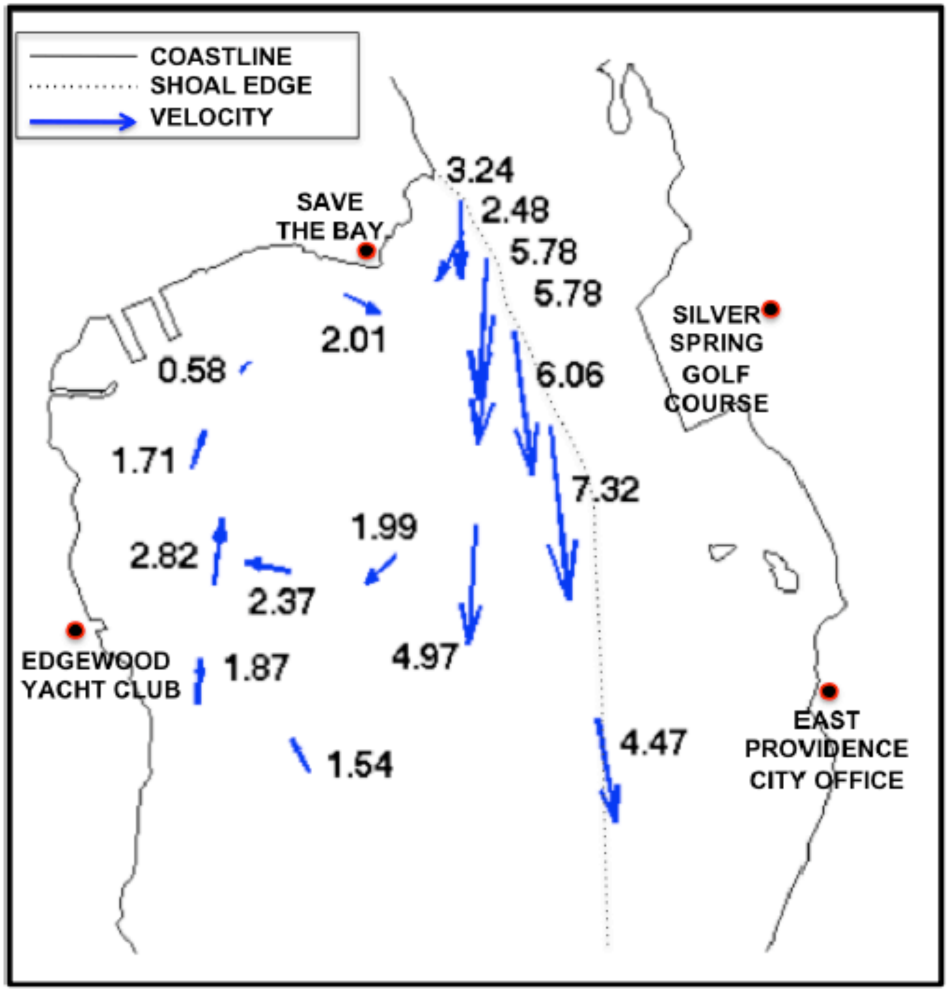


Figure 19. Map showing plots of velocity vectors at each TCM station. The arrows represent flow vectors for data that is averaged over the entire TCM deployment (locations of the tilt current meters (TCMs) deployed in the Providence River during Spring, 2010. Arrows show average directions. Flow speeds (cm/s) are listed by each arrow. TCMs at stations PR01-07 lie along the eastern edge of the Shoal, at the boundary with the shipping channel. Stations PR09-13 are distributed along a transect running from east to west across the Shoals. Station PR12 lies in the small Port Edgewood

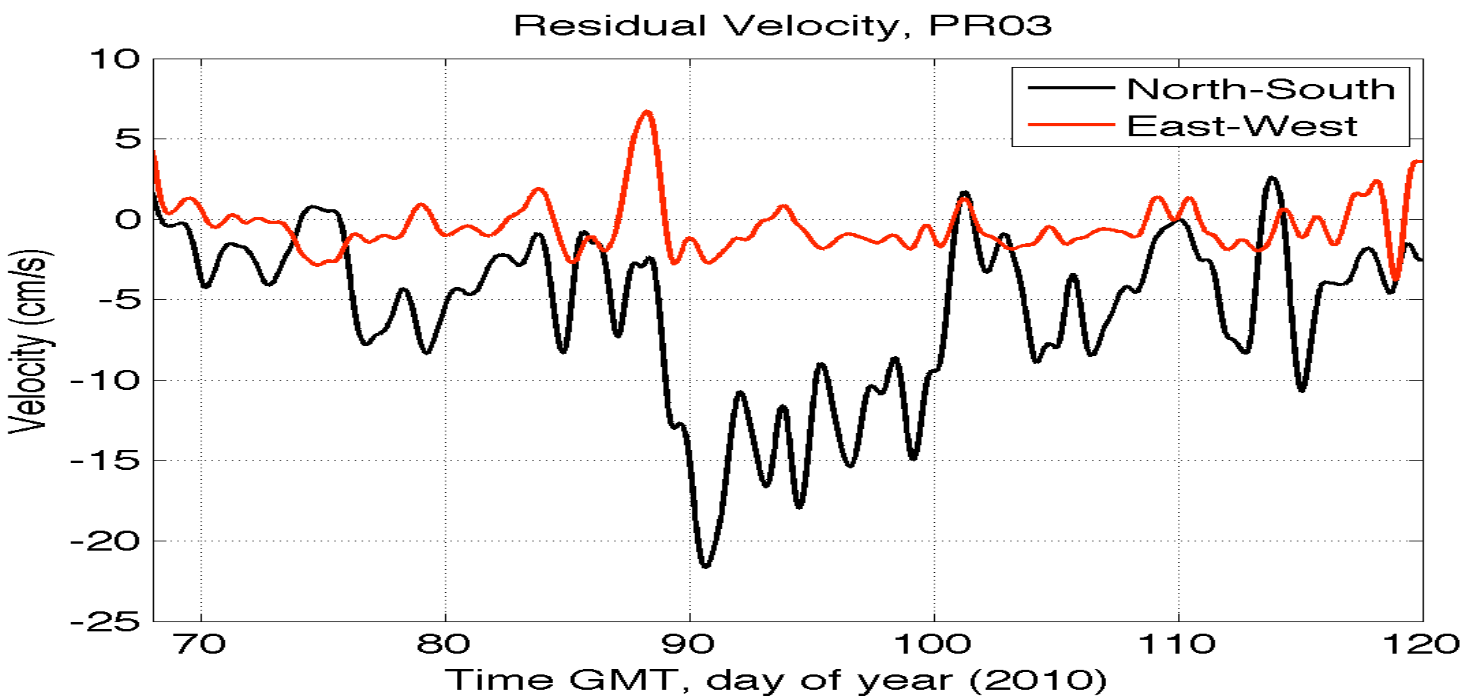


Figure 20. Plot of north-south (black) and east-west velocity values recorded at NBC-sponsored TCM (TCM station 3) during spring, 2010 (see Figure 13). The station is located in the cluster of TCMs situated on the Edgewood Shoal, near the northeastern confluence of the shoal and the shipping channel. The record has been filtered to remove tidal oscillations and the residual record shows average non-tidal outflow (southward) in this region of ~5cm/s before (<day 88) and after (>day 104) the large flood event of spring 2010. During the flood event (days 89-100) the average southward flow is -10 to -20 cm/s.

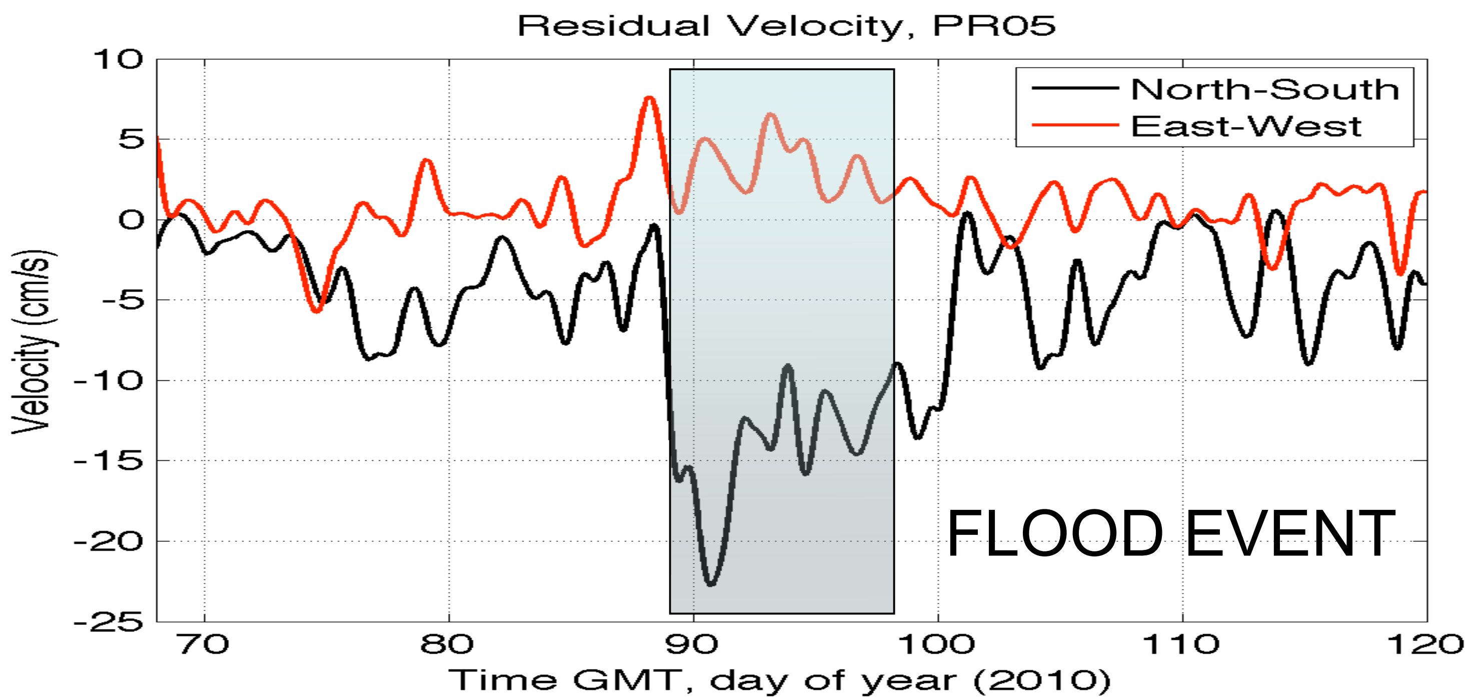


Figure 21. Plot of north-south (black) and east-west velocity values recorded at NBC-sponsored TCM (TCM station 5) during spring, 2010 (see Figure 13). The station is located in the cluster of TCMs situated on the Edgewood Shoal, near the northeastern confluence of the shoal and the shipping channel. The record has been filtered to remove tidal oscillations and the residual record shows average non-tidal outflow (southward) in this region of ~5cm/s before (<day 88) and -5 to -10 cms after the large flood event of spring 2010. During the flood event (days 89-100) the average southward flow is -10 to -24 cm/s.

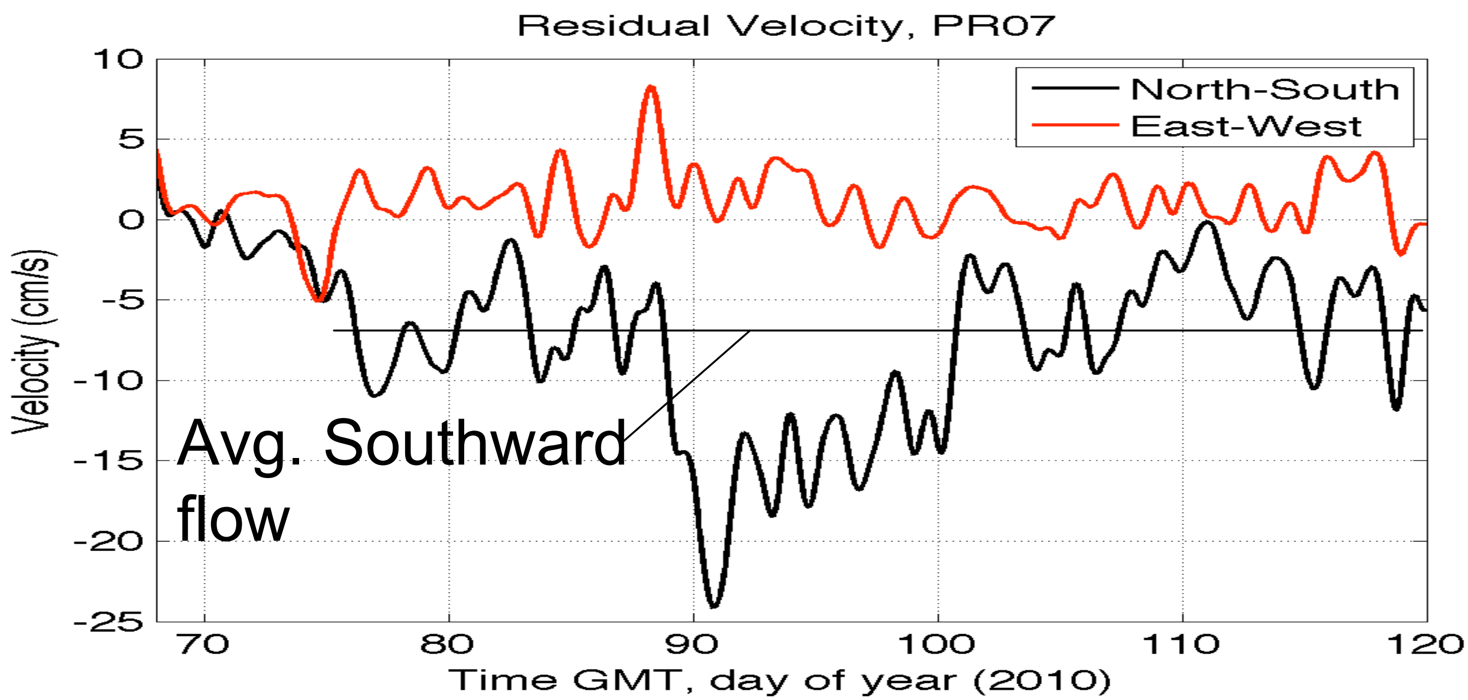


Figure 22. Plot of north-south (black) and east-west velocity values recorded at NBC-sponsored TCM (TCM station 7) during spring, 2010 (see Figure 13). The station is located at the southern end of the cluster of TCMs situated on the eastern side of Edgewood Shoals. The record has been filtered to remove tidal oscillations and the residual record shows average non-tidal outflow (southward) in this region of ~5 to -10 cm/s before (<day 88) the spring 2010 flood and from 0 to -10 cm/s after (>day 104) the flood. During the flood event (days 89-100) the average southward flow is -15 to -25 cm/s.

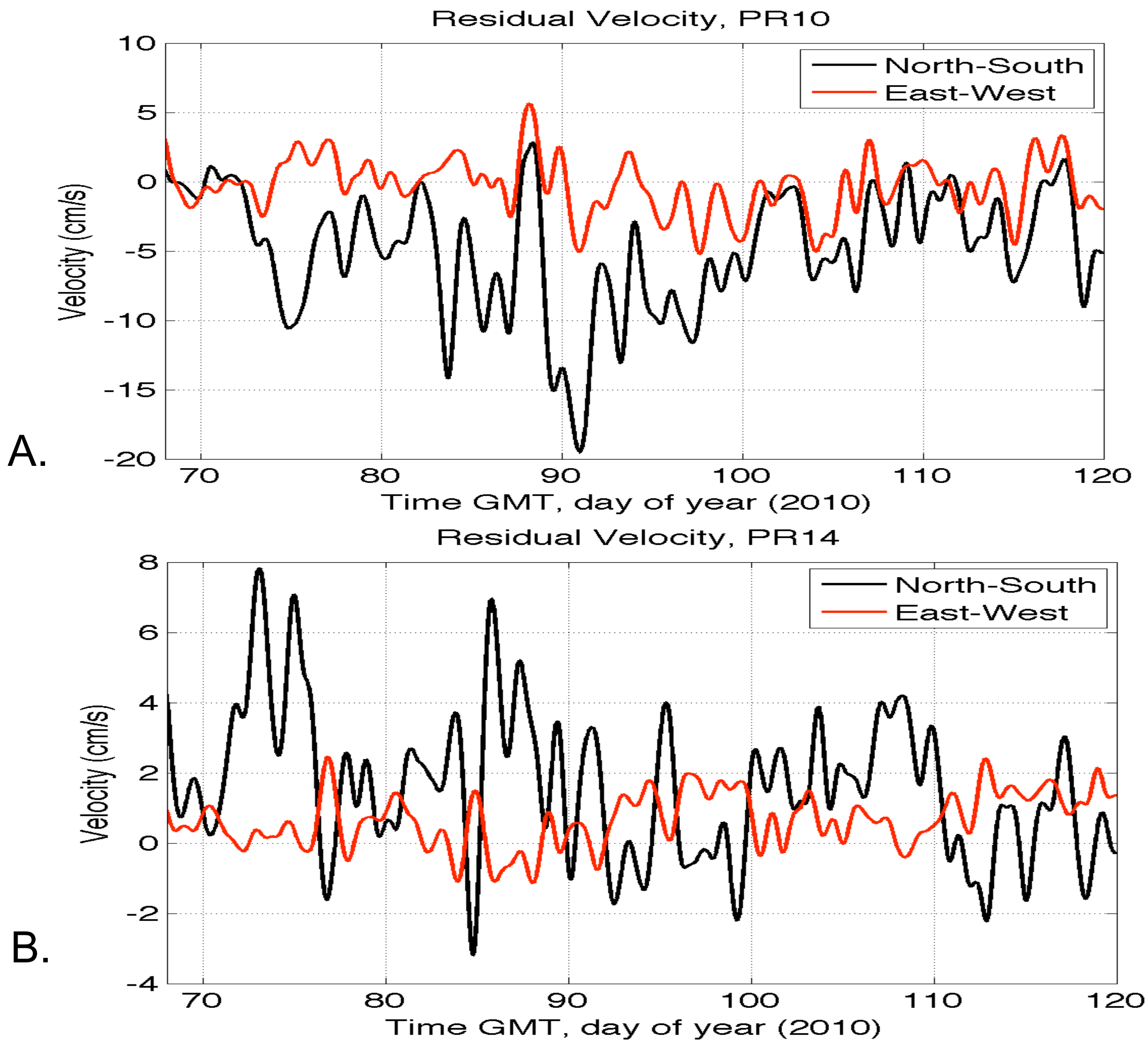


Figure 23. Plot of residual north-south (black) and east-west velocity values recorded at NBC-sponsored TCM shoal locations at TCM stations (A) 10 and (B) 14. (see Figure 13). A. Station 10 is mid-shoal, where the flood signal is much reduced. B. Station 14 is on the western shoal. Non-tidal flows in this region are on average northward, which is consistent with a clockwise gyre seen in prior ADCP data (Figure s 9-11). This record does not record a noticeable signal in response to the flood event. A very weak pulse of eastward flow is seen during the this flood period.

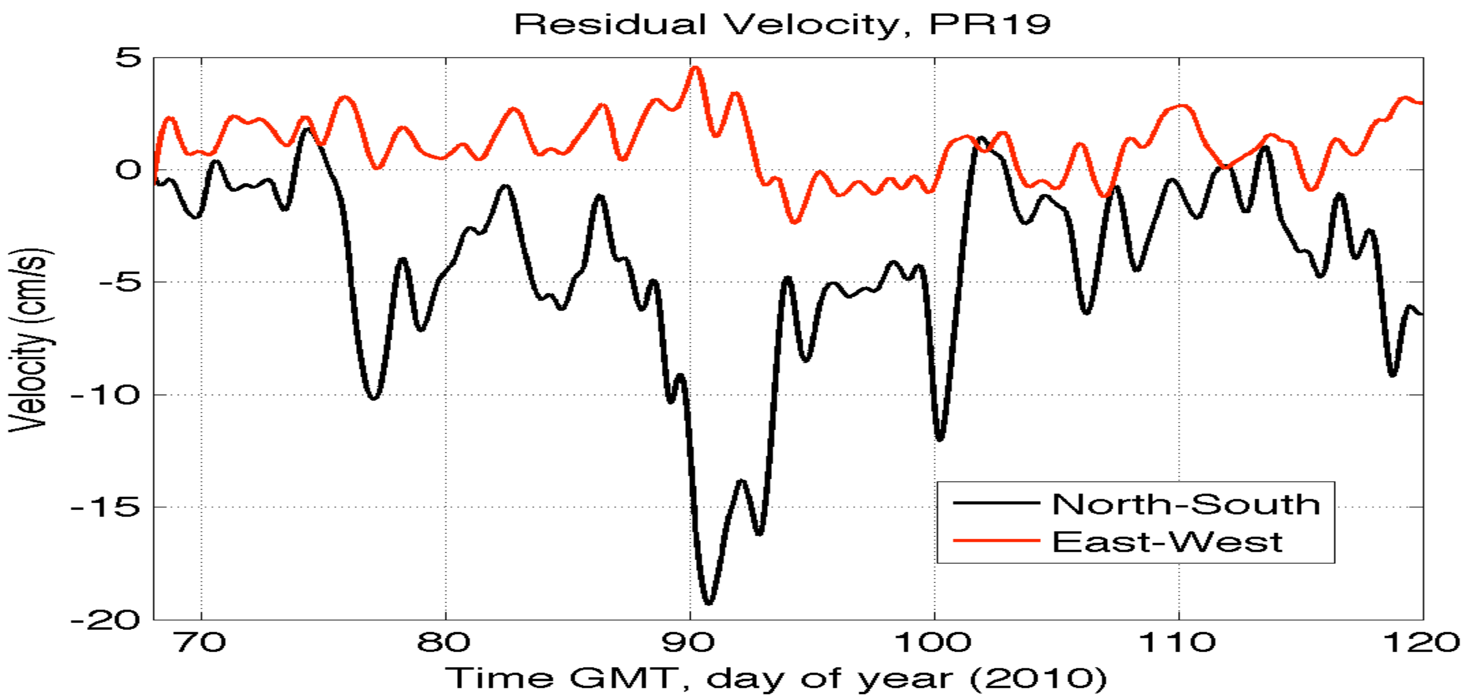


Figure 24. Plot of residual north-south (black) and east-west velocity values recorded at NBC-sponsored TCM (TCM station 19) during spring, 2010 (see Figure 13). This is the southernmost station located along the interface between the Edgewood Shoals and the shipping channel. As in the records from stations 3,5 and 7 the flood is apparent with a -15 to -20 cm/s outflow, but over a shorter period of time.

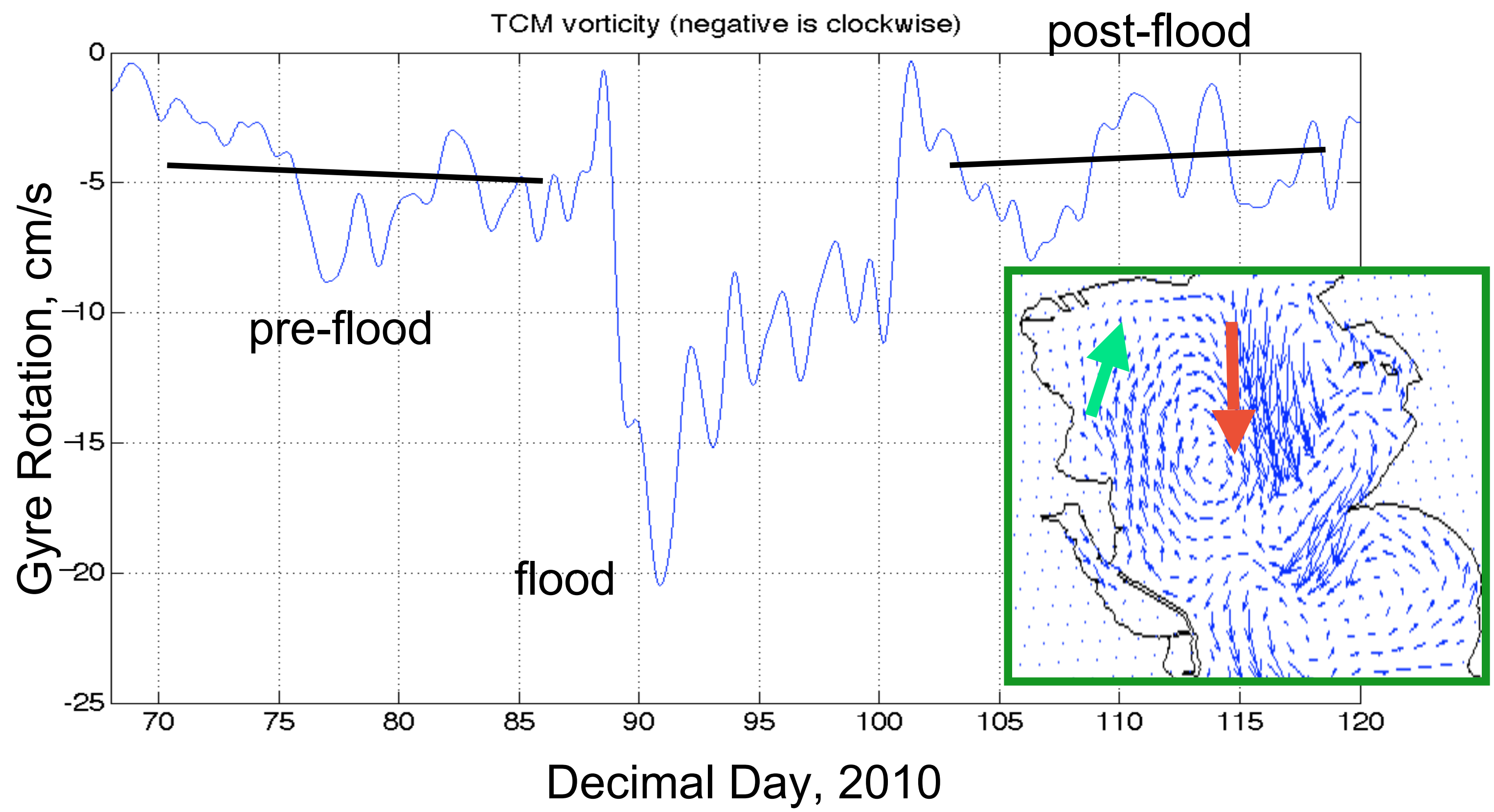


Figure 25. To illustrate the rotational nature of the Edgewood Shoals gyre, the difference in northward velocity at the shoal-channel boundary relative to the northward velocity on the western side of the shoal is plotted for the deployment period (Spring 2010). Negative values equate to clockwise spin of the gyre. The plot highlights the three regimes of pre-flood, during flood and post-flood.

Flood- Skip past shoal-gyre

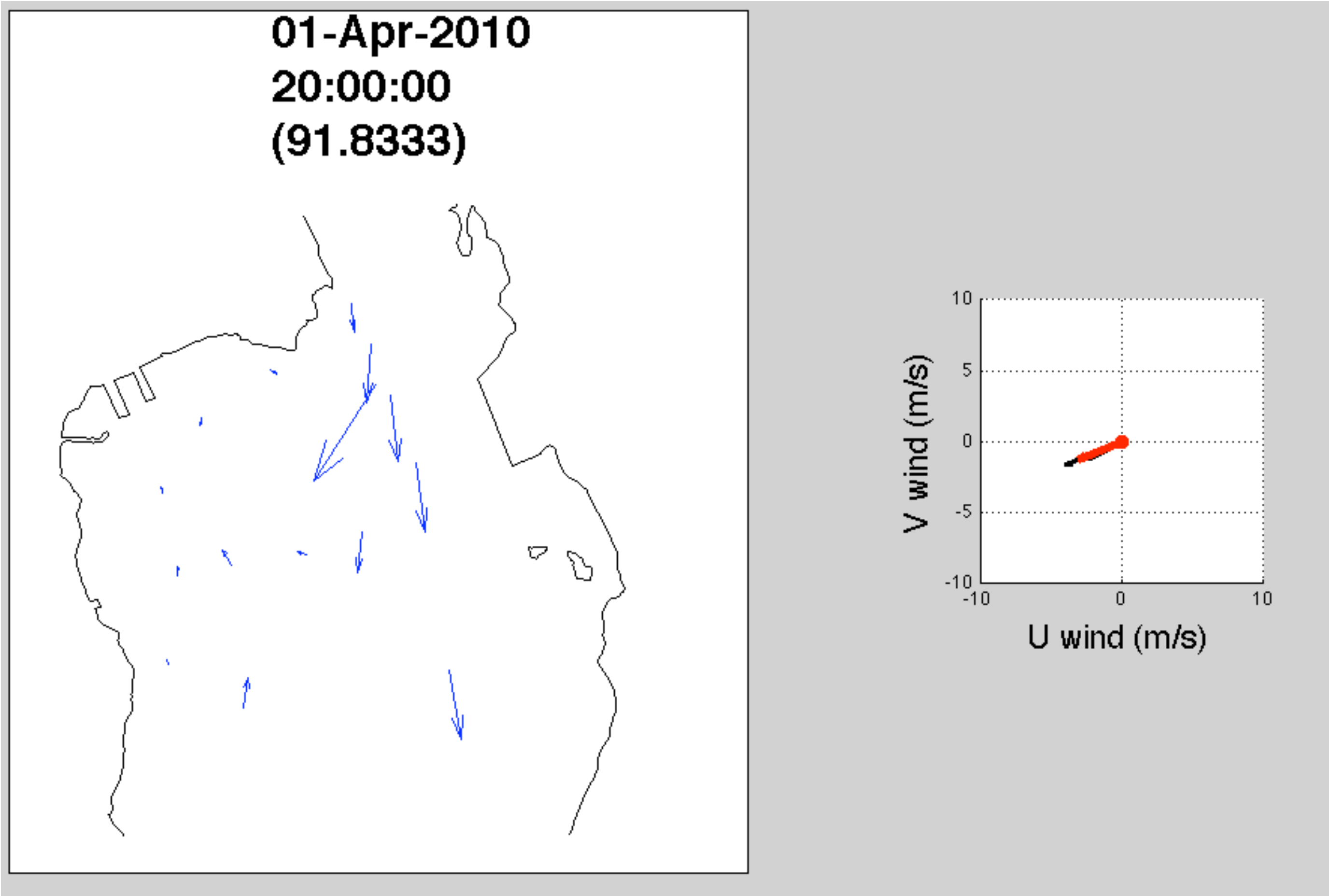


Figure 26. Map showing plots of residual velocity vectors recorded for bottom water on the shoals from TCMs. The red line plot shows the direction and magnitude (length of line) that the wind is blowing towards. (Uwind = eastward wind speed; Vwind = northward wind speed). This frame is from during the flood and shows how the energy from the strong outflow along the eastern shoal is not seen at the western stations.

Flood- Skip past shoal-gyre

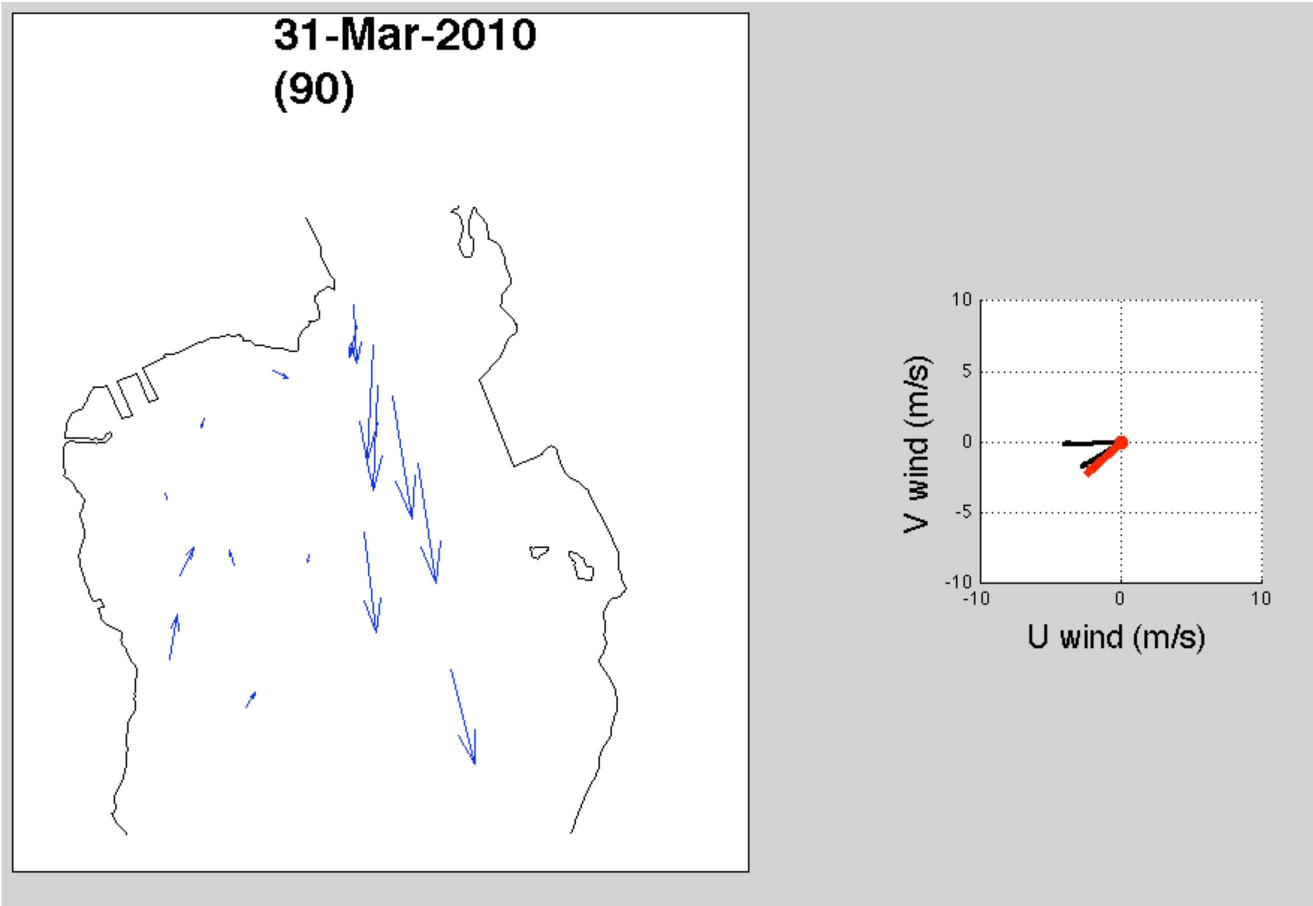


Figure 27. Map showing plots of residual velocity vectors recorded for bottom water on the shoals from TCMs. The red line plot shows the direction and magnitude (length of line) that the wind is blowing towards (the dark lines show earlier 6 hour wind wind information). (Uwind = eastward wind speed; Vwind = northward wind speed). This frame is from during the flood and shows how the energy from the strong outflow along the eastern shoal is not seen at the western stations.

No wind: Weak gyre

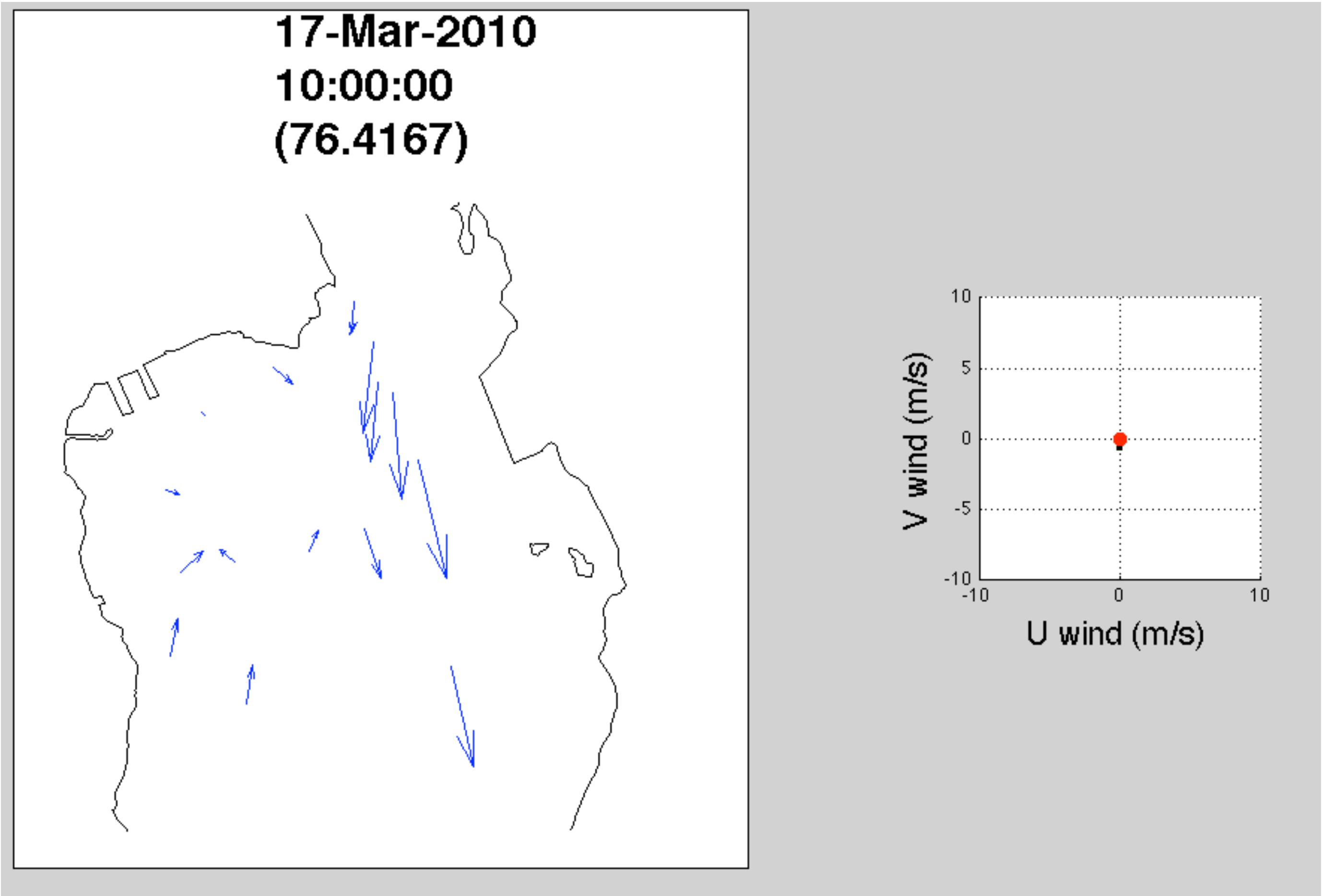


Figure 28.   Map showing plots of residual velocity vectors recorded for bottom water on the shoals from TCMs.   The red line plot shows the direction and magnitude (length of line) that the wind is blowing towards.   (Uwind = eastward wind speed; Vwind = northward wind speed). This frame highlights the system response during low wind conditions when there is northward flow along the western shore.

Westward wind component: Strong gyre

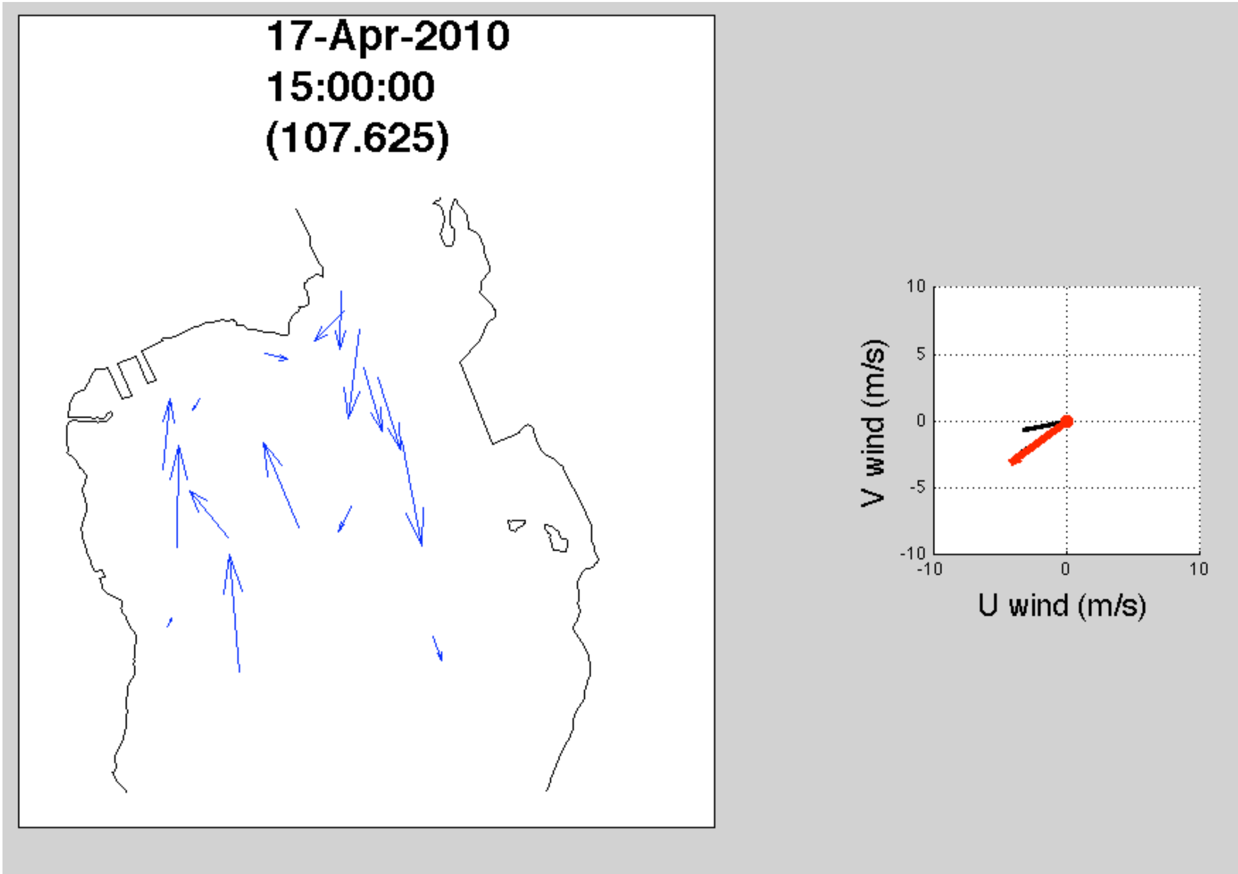


Figure 29.   Map showing plots of residual velocity vectors recorded for bottom water on the shoals from TCMs.   The red line plot shows the direction and magnitude (length of line) that the wind is blowing towards.   (Uwind = eastward wind speed; Vwind = northward wind speed). This frame illustrates how the strongest northward flows up the western side of the shoals are in response to westward blowing wind.

Westward wind component: Strong gyre

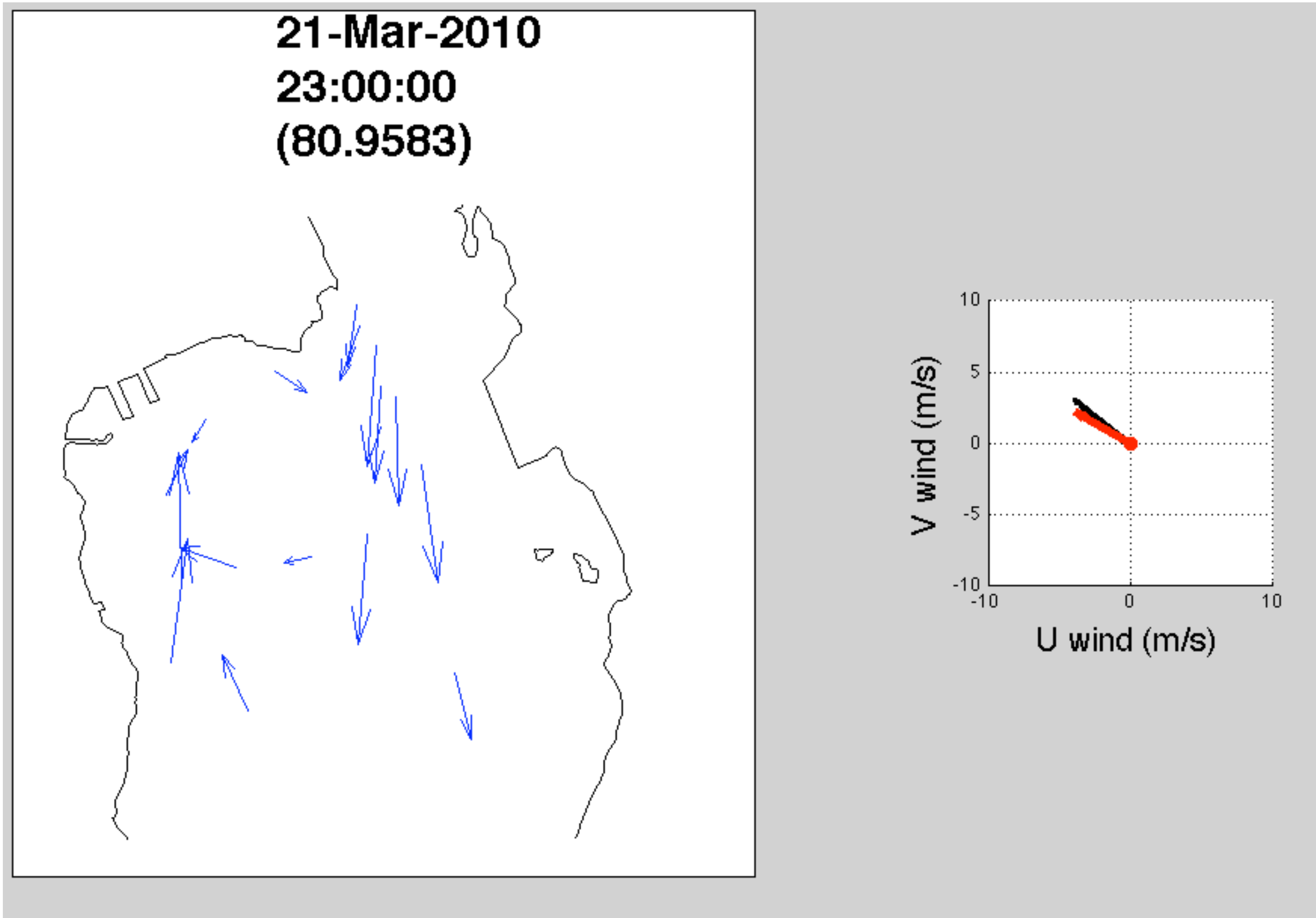


Figure 30. Map showing plots of residual velocity vectors recorded for bottom water on the shoals from TCMs. The red line plot shows the direction and magnitude (length of line) that the wind is blowing towards. (Uwind = eastward wind speed; Vwind = northward wind speed). Similar to figure 29, this frame illustrates how the strongest northward flows up the western side of the shoals are in response to westward blowing wind.

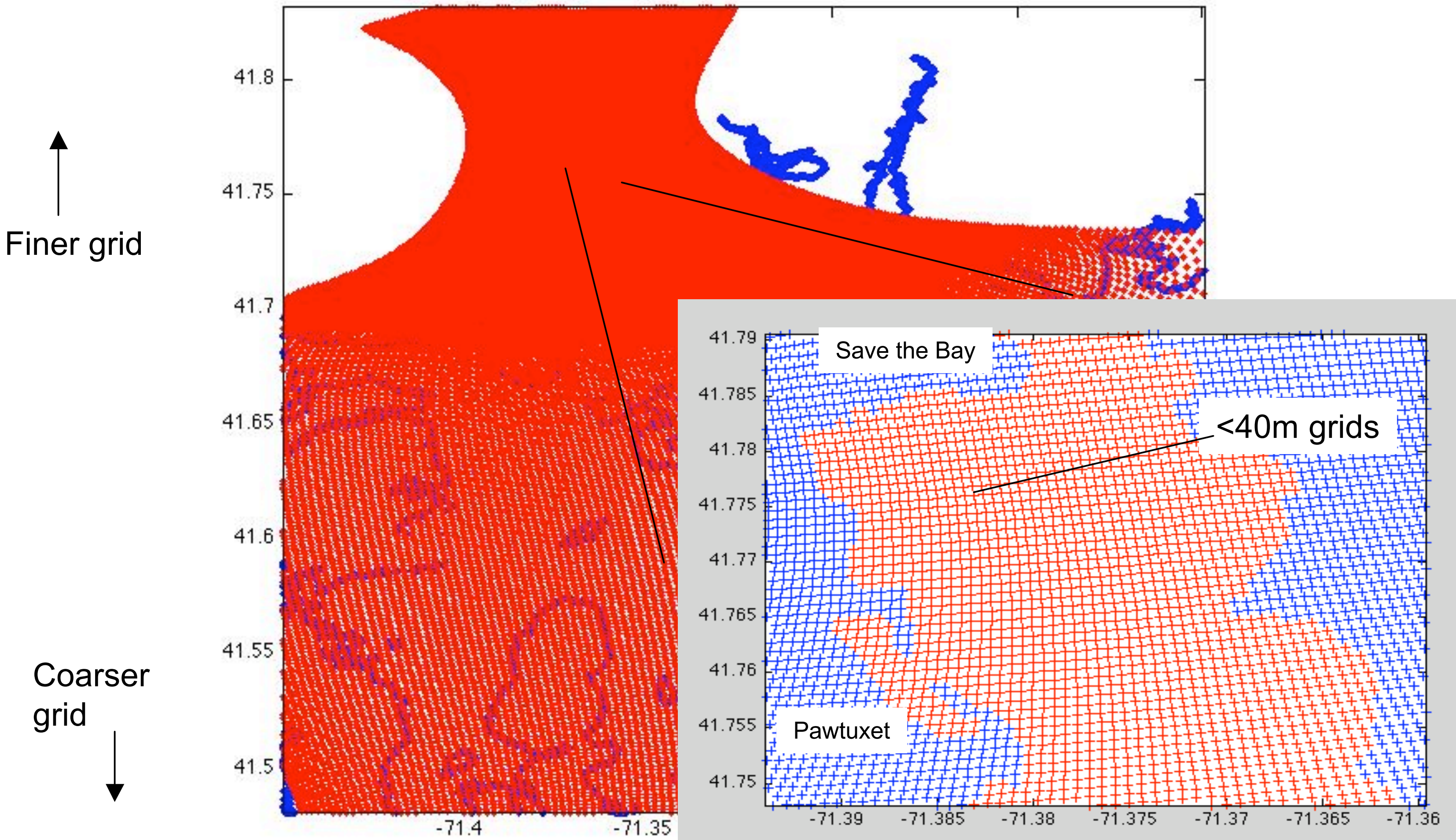


Figure 31. The first step towards building better chemical transport models for Providence River was to construct a finer grid version of the NB-ROMS model. With support from NBC, a grid covering the full extend of Narragansett Bay was developed that tapered towards the north (red dots represent grid points). This focussed grid resolution within the Providence River (inset). For example, 43 grid boxes span the east-west line across the shoals as opposed to 12 in PR-ROMS model. This results in <35m grid spacing around Fields Pt and Edgewood Shoals.

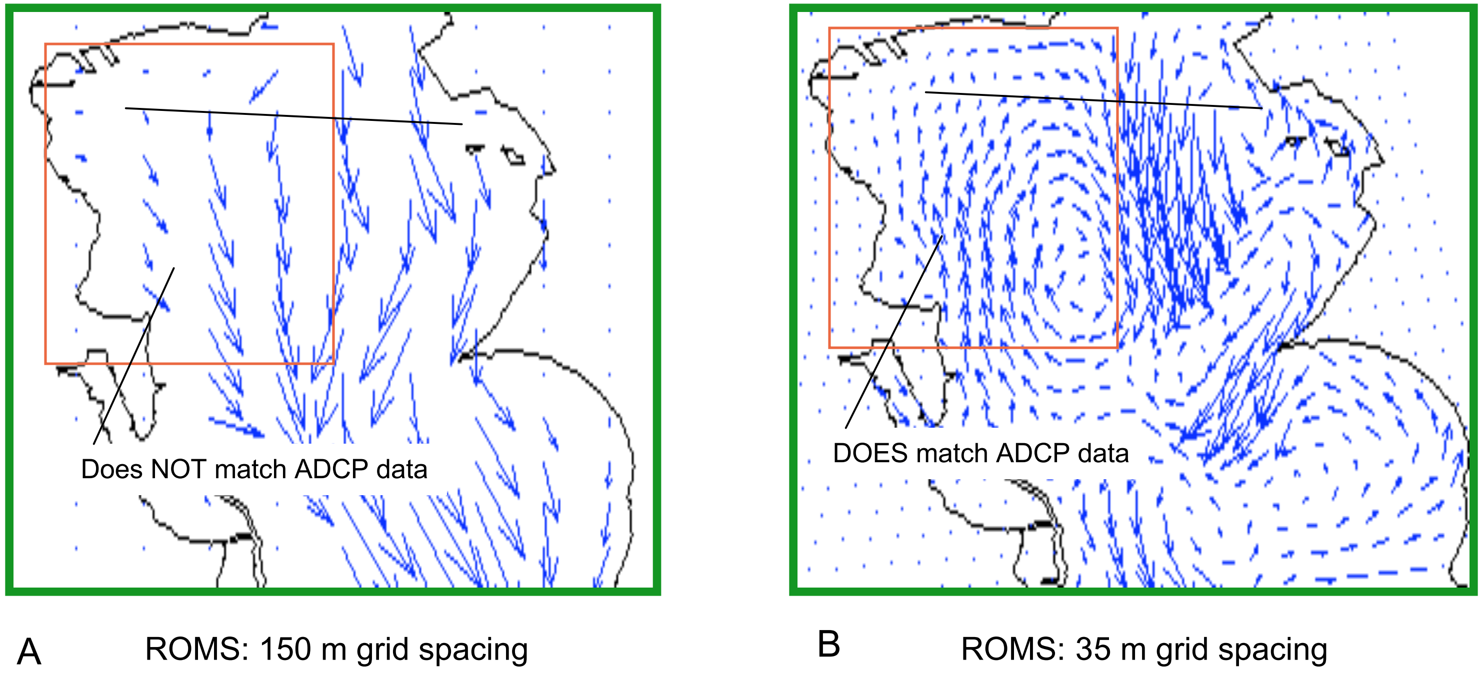


Figure 32. Mapview plots showing vertically averaged flow vectors for the Edgeswood Shoals region (red box) of the Providence River highlight the importance of grid spacing on computational accuracy. The blue arrows indicate the direction and flow speed (length of arrow) for data at each grid node location within the ROMS model domain for similar 2006 forcing conditions, at similar ebb stages of the tide cycle. The plots are shown to compare how different the flow fields are for ROMS runs with coarse grid spacing (A) and fine grid spacing (B). In A, there is no flow field on the western shoals that matches data (e.g., Figure 5a). But in the fine grid model run (B), a very stable clockwise flow gyre produces a flow field that matches very closely with trends seen in ADCP data (NBC Reports on 2001, 2002 ADCP data). . The dark line shows location of ADCP data transect shown in Figure 5a.

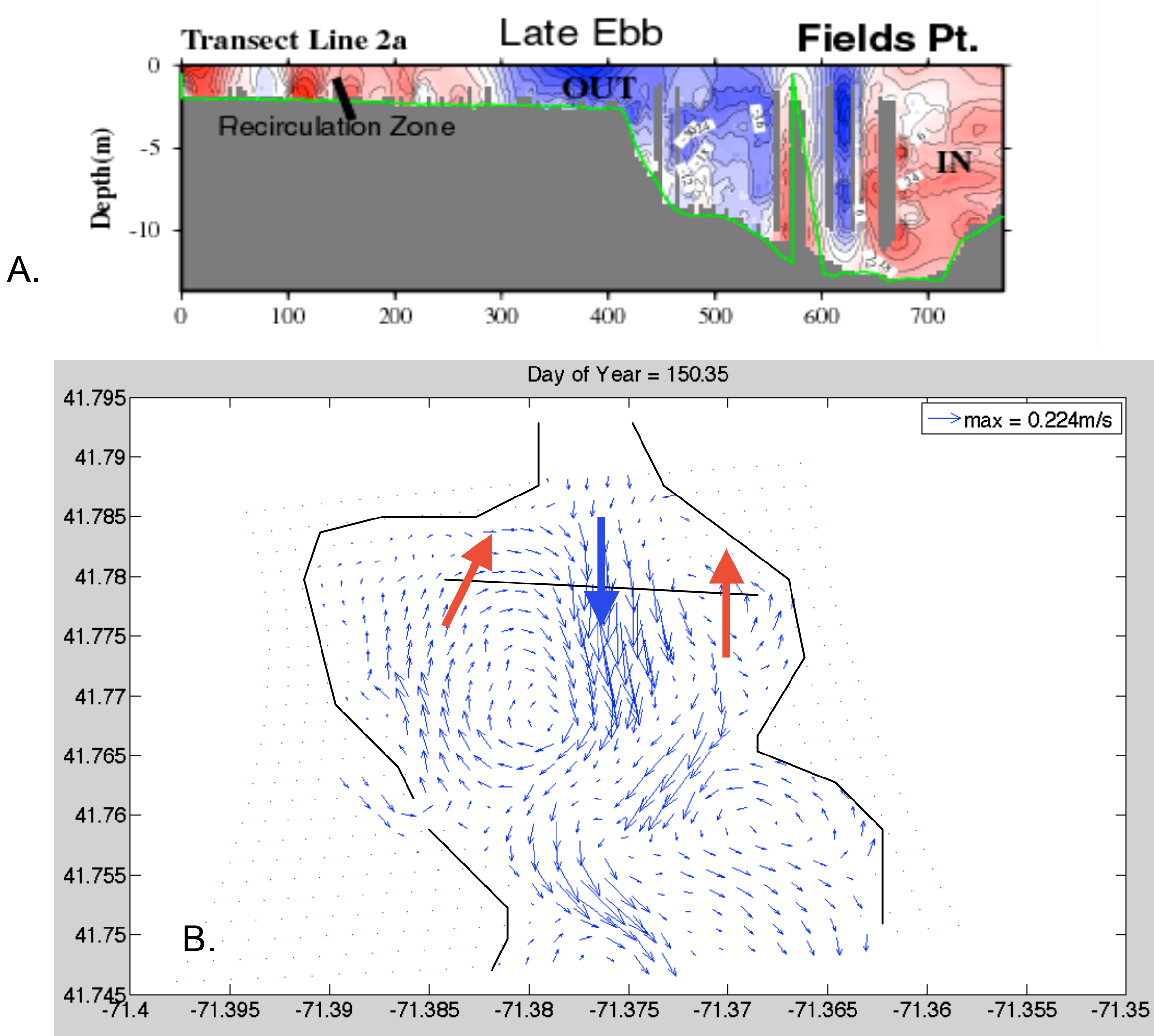
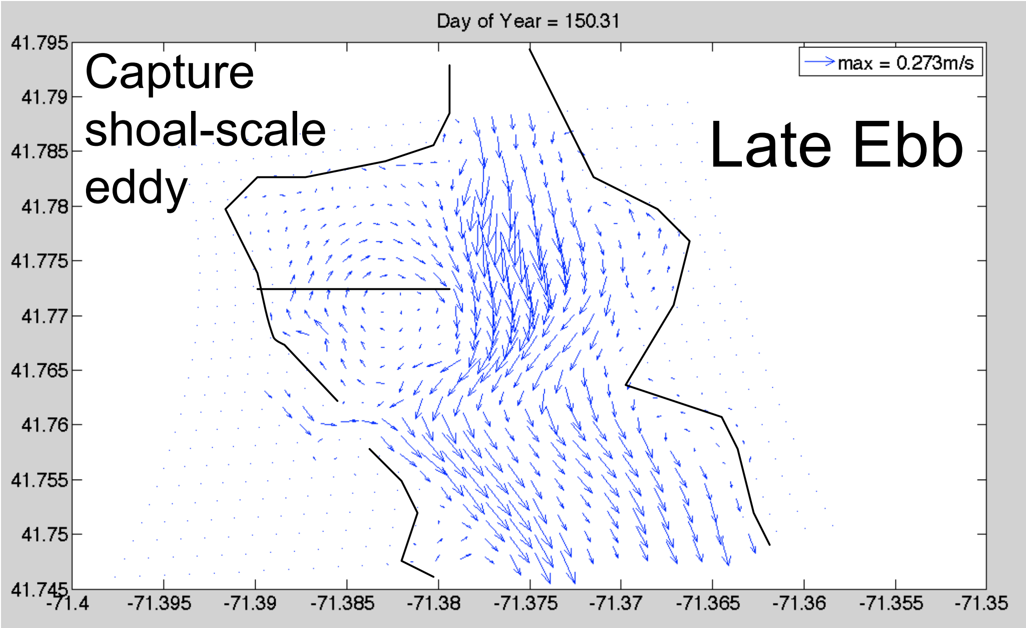


Figure 33. A Underway ADCP and recent TCM data show the presence of a persistent clockwise gyre on the Edgewood Shoals, with a pervasive northward flow of water along the western shore of the shoals. Whereas previous coarse grid models could not capture this aspect of the residual flow fields, the new fine grid ROMS model is able to reproduce this basic style of flow in this region. B. Mapview plots of ROMS simulated, vertically averaged velocity vectors for Providence River. The location of the ADCP cross section is (A) is shown with the dark line. Flow patterns are consistent with those seen in underway ADCP and TCM data.



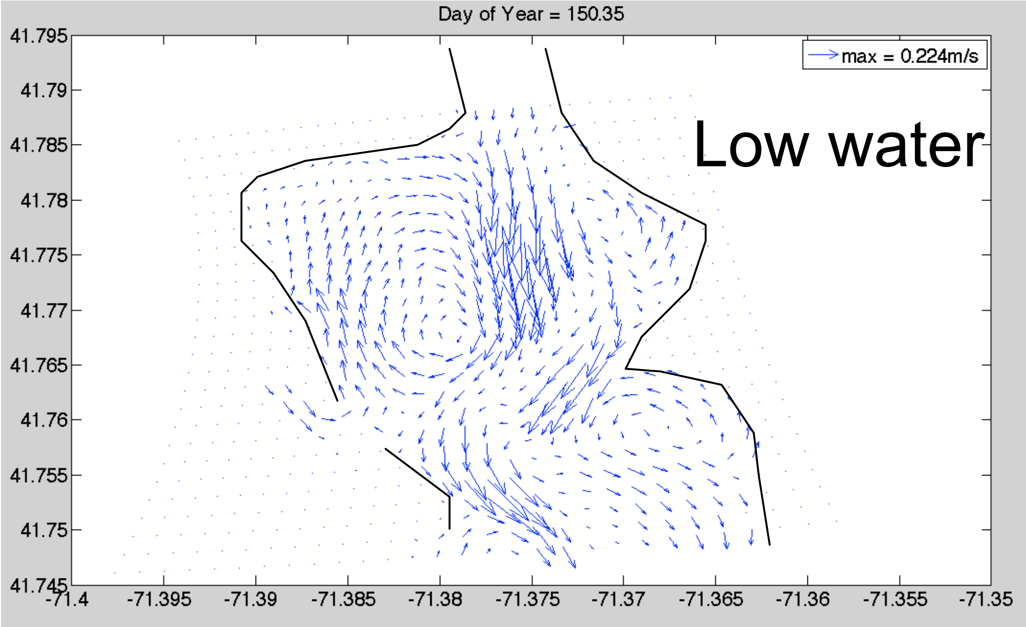


Figure 34. Similar to figure 33, mapview plots of a ROMS 2010 model simulation of flow in the Providence River show that clockwise recirculation on the Edgewood Shoals is a common prediction of the calculated flow fields. This version of ROMS does a better job, in a qualitative sense of matching observed residual flows than preior coarse grid models. Statistical comparisons are needed to quantitatively assess how the models do in simulating residual flows.

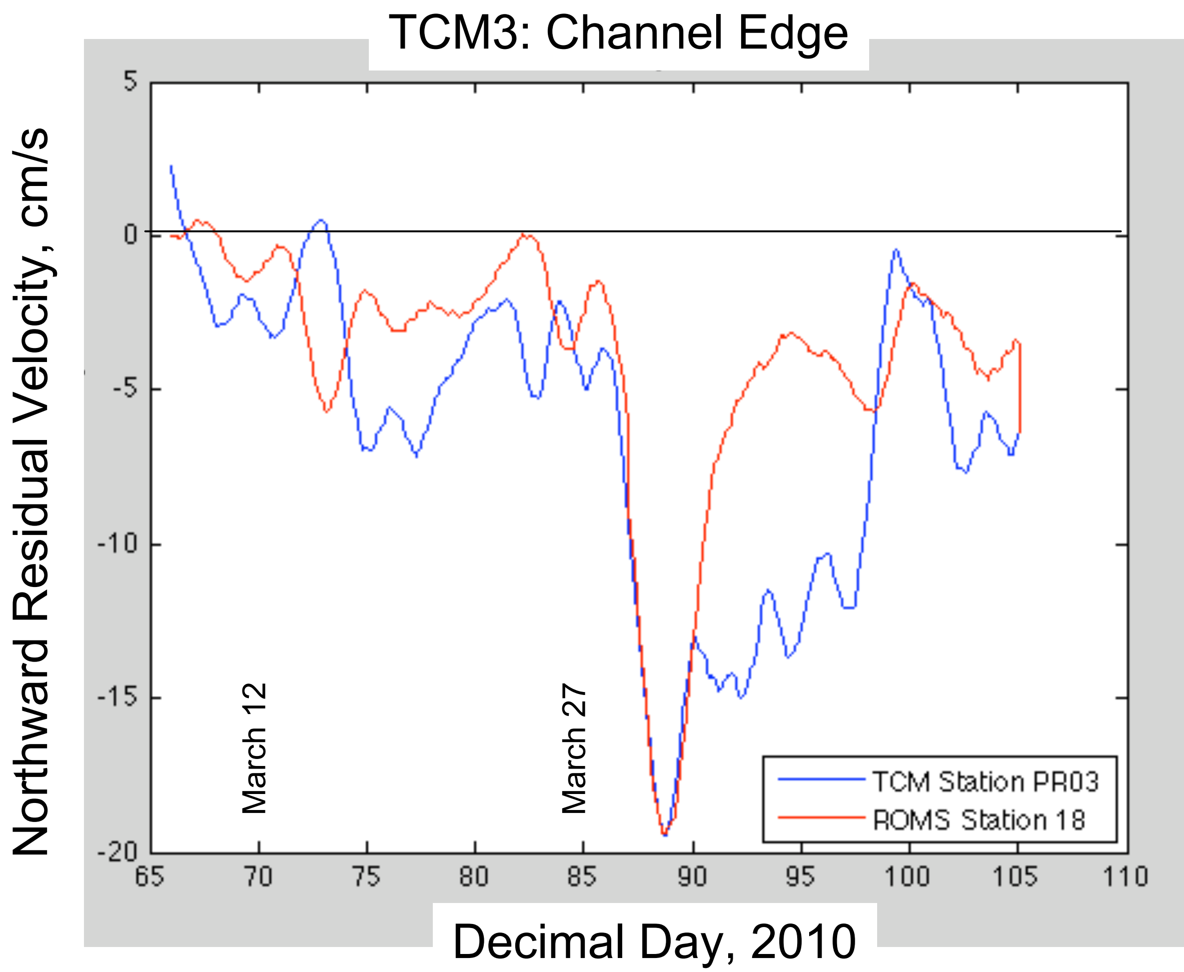


Figure 35. Plot that overlays the TCM record and ROMS simulation output for 2010 conditions at TCM station 3, at the northeastern boundary of the shoals and the shipping channel. The model output (red) does an excellent job of matching TCM observations during the pre flood stage. ROMS captures the amplitude and onset of the flood, missing slightly the decay of the flood signal. This could be due to drift of the outflow feature in ROMS.

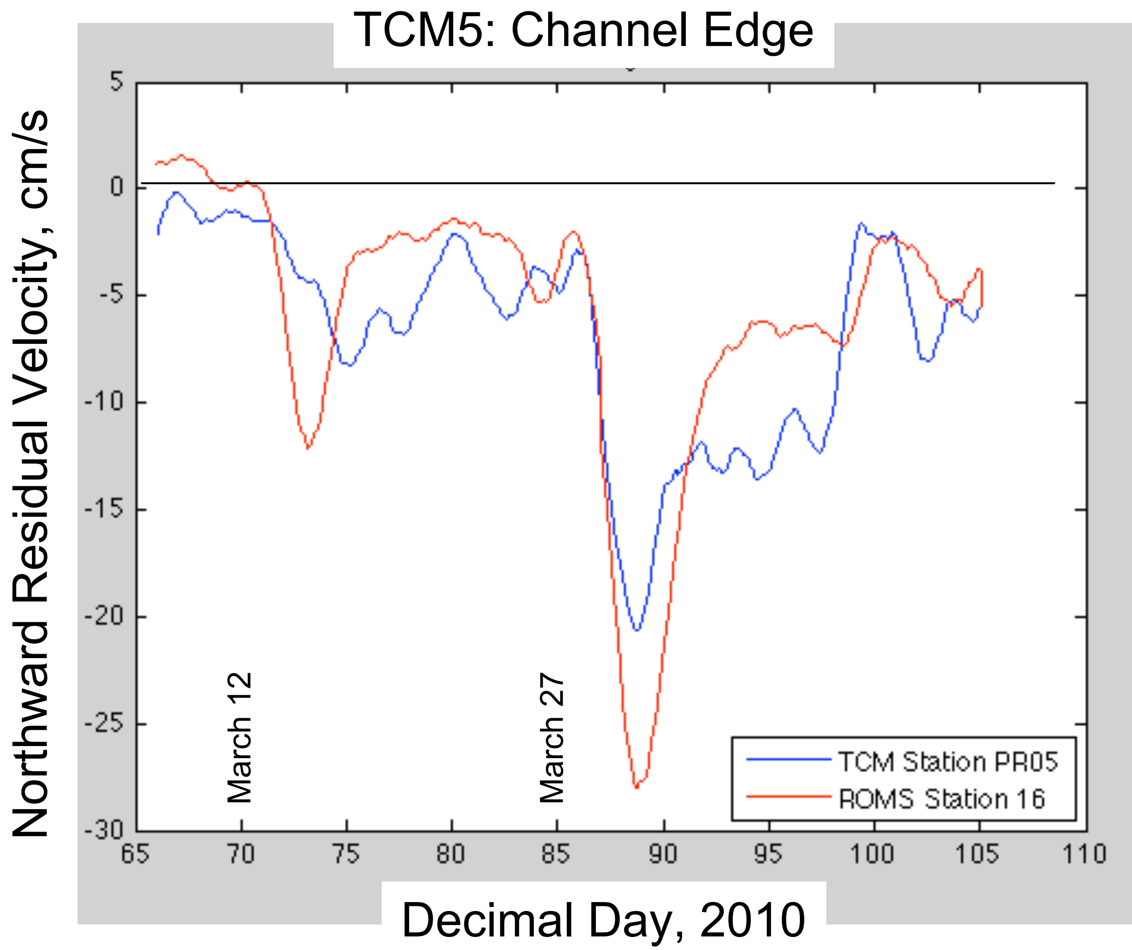


Figure 36. Plot that overlays the TCM record and ROMS simulation output for 2010 conditions at TCM station 5, at the northeastern boundary of the shoals and the shipping channel. The model output (red) does a remarkable job of matching the residual, or non-tidal nature of TCM observations during the pre flood, flood and post flood stages of the record.

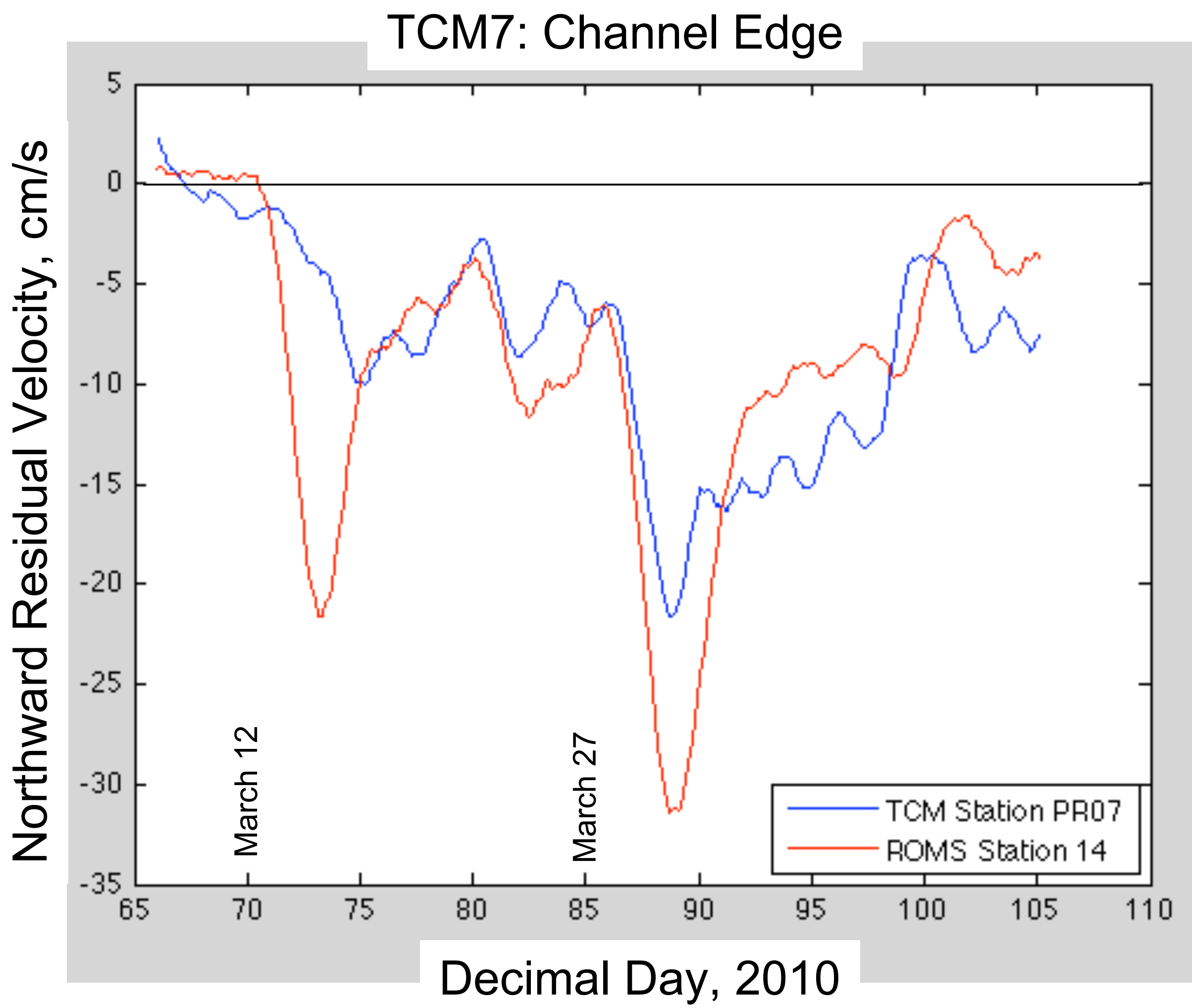


Figure 37. Plot that overlays the TCM record and ROMS simulation output for 2010 conditions at TCM station 7, at the northeastern boundary of the shoals and the shipping channel. The model output (red) captures very well many of the features of the observed residual flows in the TCM record, with the exception of two over-predictions of the outflow.

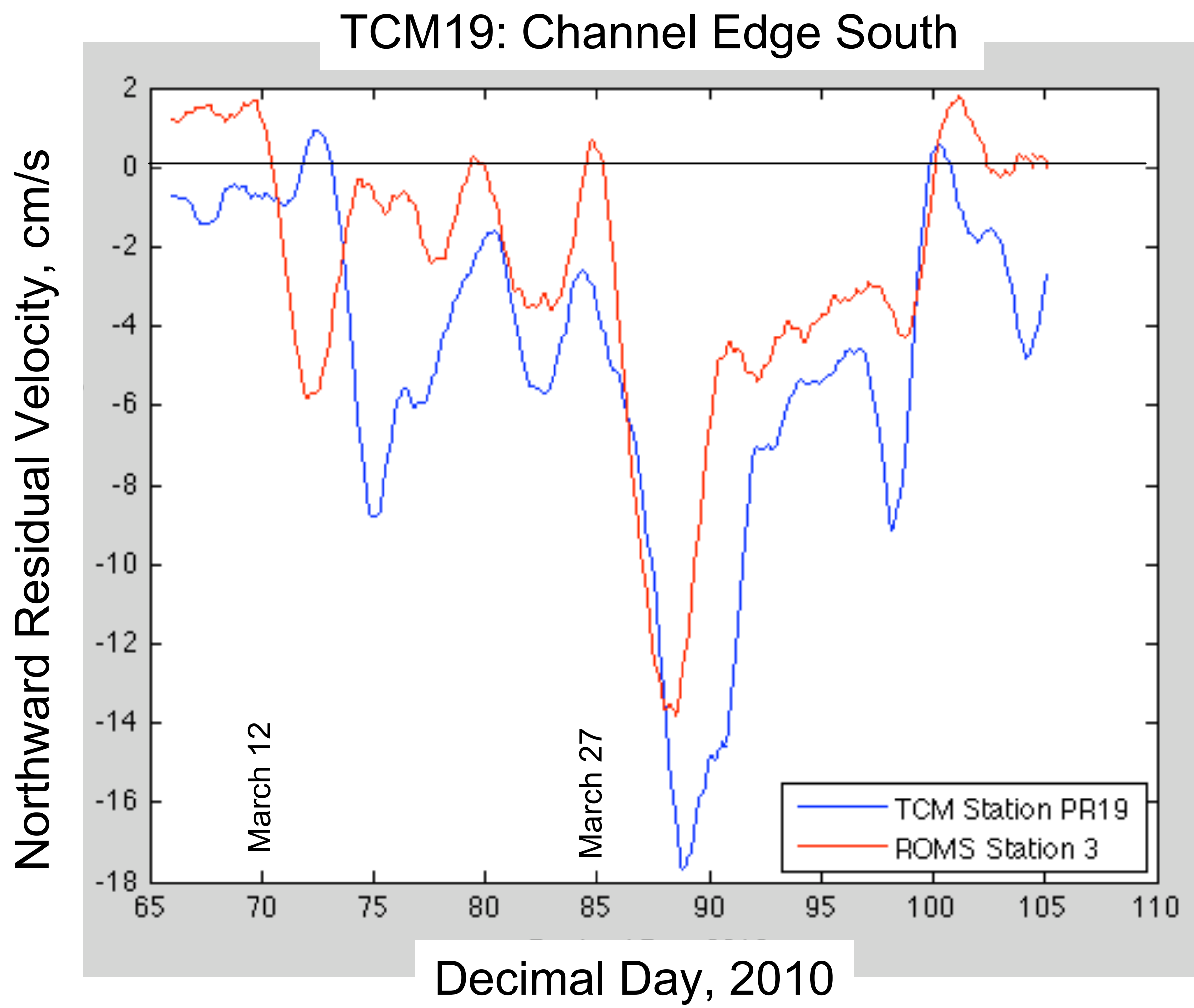


Figure 38. Plot that overlays the TCM record and ROMS simulation output for 2010 conditions at TCM station 19, the southernmost of the stations along the boundary of the shipping channel and the shoals. But for a slight offset in magnitude, the model output (red) matches almost exactly the the TCM record during the flood and during the decay from flood conditions to background conditions. Except for a slight time offset, ROMS does well at simulating the pre-flood record at TCM station 19.

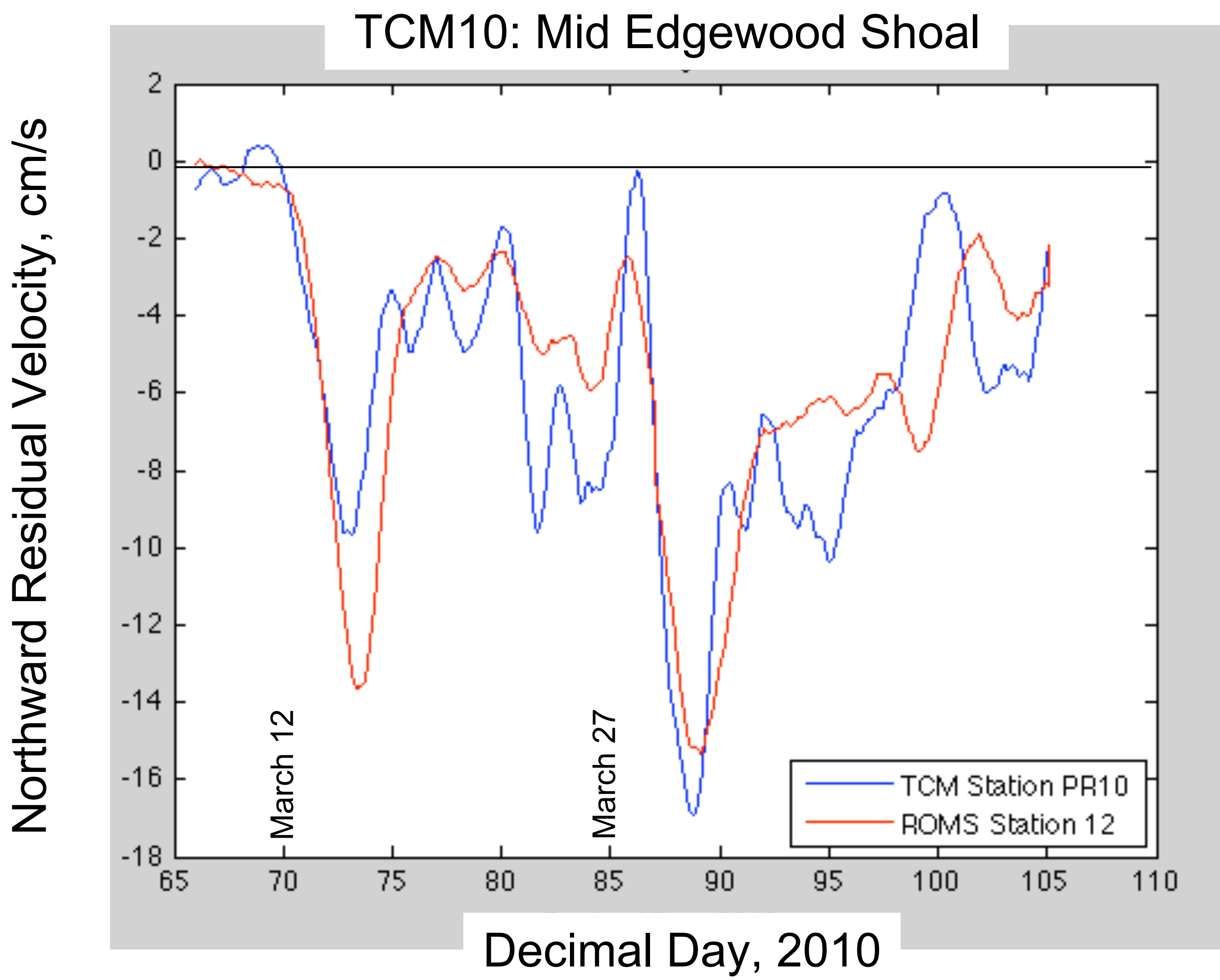


Figure 39. Many hydrodynamic models can readily recreate the instantaneous, or tidal, data records for estuaries. The residual, or non-tidal records are often very challenging to recreate. The Narragansett Bay ROMS does an excellent job of simulating non-tidal flow patterns. This is particularly apparent in the data-model comparison for TCM 10, where ROMS captures both the flood event and the decay of the flood in amplitude and timing. TCM 10 is west of the shoal-channel boundary, midway across the shoal.

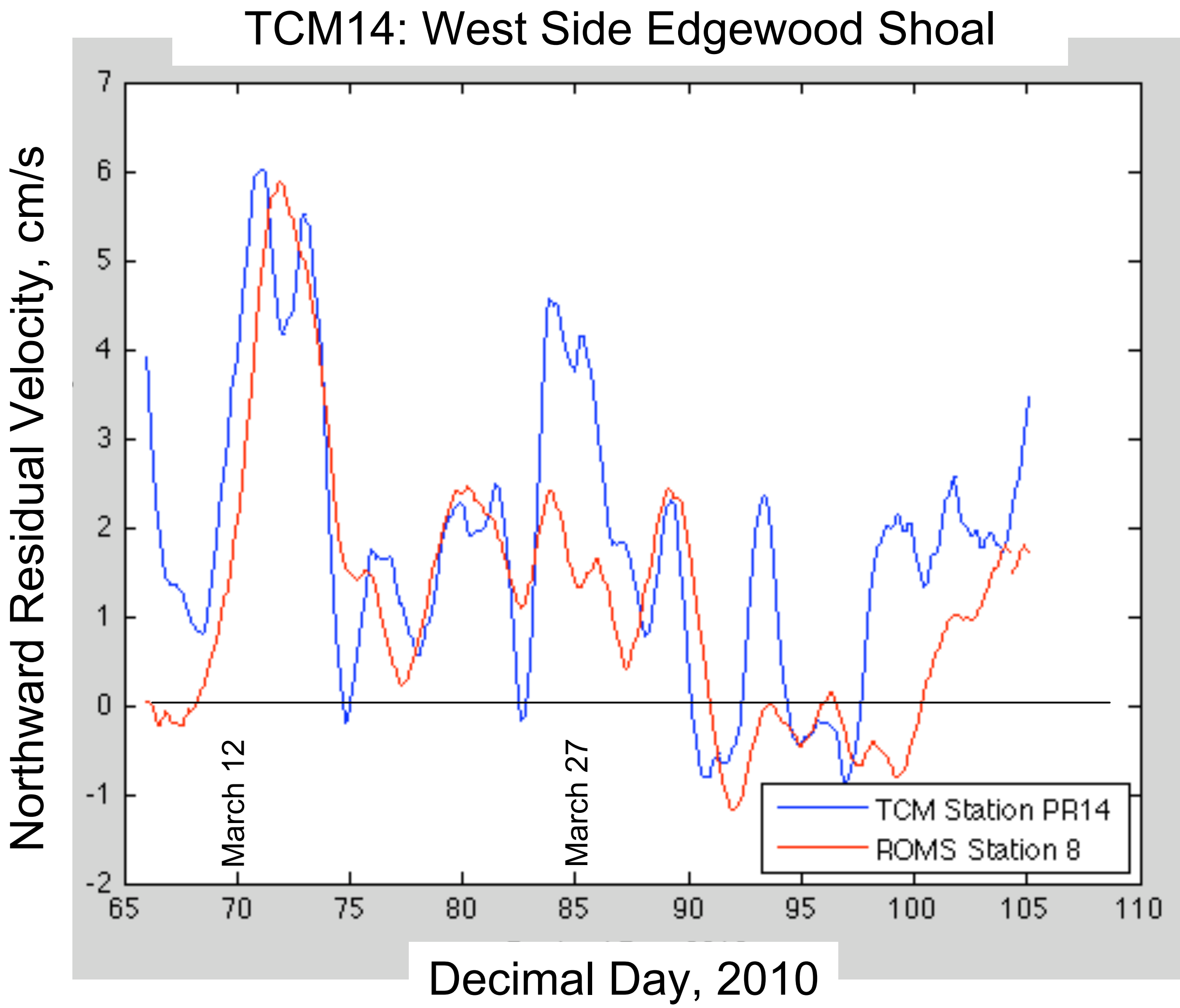


Figure 40. Plot showing the remarkable match between ROMS simulations and the TCM record at station 14 (see Figure 13) located along the western side of the shoals. ROMS captures the magnitude and timing of most of the oscillations recorded in the TCM data.