ROMS Hydrodynamic-Transport Model Development for the Providence and Seekonk Rivers

Final Report

prepared by Chris Kincaid and Justin Rogers,
University of Rhode Island, Narragansett, RI
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1.0 Introduction.

The Narragansett Bay (NB) estuary is an essential natural resource for the state of Rhode Island. This system has, over the past few decades, experienced significant increases in ecological stress driven by natural and anthropogenic sources. Episodic summer hypoxic events are of growing concern for the upper parts of Narragansett Bay, the Providence River and Greenwich Bay. Proper management of this estuarine system requires multidisciplinary work combining science and policy management. A number of ongoing efforts focus on multidisciplinary approaches to understanding how the ecosystem functions, and how past and predicted changes are likely to effect the Bay's ecosystem. At the heart of this has been the deployment of moored sensor arrays throughout the bay for measuring temperature, salinity, dissolved oxygen, pH, chlorophyll and additional physical/chemical data. An understanding of the hydrodynamic response of the estuary to different modes of environmental forcing (tides, wind, runoff, density variations) is crucial for making informed management decisions.

Under the auspices of the Narragansett Bay Commission (NBC), a combined observational and modeling effort has been undertaken to better constrain the physical processes that drive mixing and transport of key chemical and biological species. This includes the most comprehensive physical data set ever collected for upper Narragansett Bay. Time series current meter records (using moored acoustic Doppler current profilers or ADCPs) have been collected in the Providence and Seekonk Rivers (Bergondo and Kincaid, 2007) and upper Narragansett Bay (Rogers, 2008). Data sets have been collected involving 4 months of continuous (6 minute interval) water velocity measurements from mooring locations within the Providence River (4 m and 12 m depths) and in 6 m of water at the Seekonk River mouth (reported in Bergondo and Kincaid, 2007). ADCP records provide water flow as a function of depth, where vales are recorded in discreet vertical depth bins spaced from 0.5 to 1 meter apart. Data were also collected during a four month period during summer, 2006 within the mid-Bay region of the estuary (East Passage shipping channel, East Passage shoal and West Passage channel) (reported in Rogers, 2008). Mooring deployments were guided by prior spatially detailed, underway ADCP surveys supported by the NBC within the Providence and Seekonk Rivers for each seasonal period (Kincaid, 2001; 2002a, b, c) and within the upper Narragansett Bay (Rogers, 2008).

To develop a predictive capability for circulation and related mixing, flushing and transport processes, the Regional Ocean Modeling System (or ROMS version 2.2; Warner et al, 2005; Shchepetkin and McWilliams, 1998; 2003; 2005) hydrodynamic transport model has been developed for the Narragansett Bay estuarine system. The ROMS model simulates three-dimensional (3-D) circulation of estuarine water along with the 3-D transport of salt and temperature. The development of a Narraganset Bay ROMS modeling capability has been funded by a combination of National Oceanographic and Atmospheric Association (NOAA) and Narragansett Bay Commission (NBC) funding. The goal of the NBC-funded work has been to develop modeling capabilities which are capable of simulating flushing and transport of salt, temperature and additional chemical species within the Seekonk River, the Providence River and upper Narragansett Bay, which is the receiving water for the Providence River outflow and provides the supply of ocean water to the Providence River system. Successful development and application of such a model requires adequate data along model boundaries for assigning velocity, temperature and salt boundary conditions. Additional observational records are needed within the model domain in order to allow for statistical comparisons between predicted model records and corresponding time series data on velocity, temperature and salinity. The NBC ROMS model development builds off a solid observational foundation which includes the spatially detailed underway ADCP data and the temporally detailed time series ADCP data described above and summarized in Figure 1.

This report summarizes our most recent efforts in the development of a new ROMS model grid for the Narragansett Bay system, where the design of the model domain has evolved from discussions with NBC personnel and an environmental consultant, Dan Mendelsohn. The key change in this Full Bay model was the movement of the open ocean boundary from far out in Rhode Island Sound (RIS) to the mouth of the bay. Tasks reported here include development of the new model grid, construction of the appropriate forcing files for the new grid, a set of simulations (Table 1) and efforts to develop statistical data-model comparisons (Tables 2-7) from routines supplied by Mendelsohn. Finally, we summarize the application and testing of ROMS using the new model grid, referred to as the NBC Full Bay ROMS model. Model simulations have been completed which involve a 2 month spin-up period (late spring 2006) and a 1-2 month runtime period (summer, 2006 conditions). Results show the Full Bay model (Table 1) produces very good data-model comparisons for tidally driven, or instantaneous, water velocity and density fields (model skills of > 0.7 for tidally driven velocity). However, ROMS is having only moderate success in producing non-tidal or residual solutions for velocity, salt and temperature which match well with time series data collected within the East and West Passages of upper NB during summer, 2006. The RIS-NB version of the ROMS model (or RIS-NB ROMS) described by Rogers (2008) does a better job at non-tidal, or residual data-model comparisons. Additional efforts have been made to improve the Full Bay ROMS model by making use of a technique called nesting, where the ocean boundary conditions for the NBC Full Bay ROMS model is driven by model data from the larger, RIS-NB model. Results of these efforts to improve data-model comparisons for residual, non-tidal signals are also reported here.

In the following sections we summarize the historical development of different ROMS modeling activities for Narragansett Bay.

1.1 Previous NBC ROMS Model Development

NBC ROMS modeling work has evolved roughly in line with the computational resources available for running model simulations. In numerical modeling of coastal systems, the accuracy of the solutions are highly dependent on the number of grid cells that are employed. The more tightly spaced the grids, the more accurate the model solutions. However, when the number of grid cells that are used becomes too large, the time that it takes to produce a simulation of a desired length of time becomes exceedingly long. There exists, therefore, a fundamental trade off between the number of grids that can be employed (defining the accuracy of a solution) and time that it takes to produce results, defined here as the ratio of model simulation time (days) to the time (days) that it takes the computer to produce that simulation (referred to here as Tcpu). It is our experience that Tcpu values of 5 or less (5 days of model simulated time produced from 1 day of the computer running the model) is unacceptable. Attempts are made to ensure that Tcpu ranges from 10-20.

Another important tradeoff that arises from the model design is the choice of location for the ocean boundary of the model. This is where water and water properties either leave or enter the model domain. The data requirements for accurately specifying how material/information enters and exits the domain over the appropriate time scales (seconds to months) are prohibitive. Because the ocean boundary is difficult to adequately characterize, it is common to choose a location for this boundary that is far removed from the region of interest within the model domain. In our case, the NBC regions of interest are the Seekonk River, the Providence River and the receiving waters just outside the mouth of the Providence River. One can immediately see that this location choice feeds back directly to the issue of total grid cells and how this influences solution accuracy versus computational run time. Combining the need for high model grid resolution with a choice for the ocean boundary far to the south in Rhode Island Sound produces exceedingly high grid cell count and very low Tcpu values.

1.2 Bergondo Providence River ROMS Model (B-PRS ROMS)

Figures 1 and 2 show the spatial extent of the first NBC ROMS model that was generated by D. Bergondo. Bathymetry and coastline information was obtained from the National Geophysical Data Center (NGDC) at a 3 arc-second resolution. The model domain extended north to include the Seekonk River. The southern, or open ocean boundary for the model was located at the northern tip of Prudence Island, in the region of Narragansett Bay commonly referred to as Upper Narragansett Bay (UNB). These runs were conducted on a network of 4 stand-alone Dell PC Workstations. The computational capacity (e.g., speed, memory) of these machines allowed for a grid of 100 cells in the east-west direction and 200 cells in the north-south direction. All Narragansett Bay ROMS models are 3-D, and for these cases we used 15 cells in the vertical direction. Bergondo's model simulations had Tcpu values of roughly 20. The horizontal grid spacing in the midsection of this model (e.g., the Providence River), or the north-south and east-west distance for each grid cell, was on the order of 100-150 m.

1.3 Rogers Providence-Seekonk River ROMS Model (R-PRS ROMS)

Former URI-GSO Master of Science (MS) student J. Rogers was also supported by the NBC to work on ROMS model development. Rogers' first experience with ROMS was to upgrade to Regional Ocean Model (ROMS) version 2.2 and get it working on our lab's new 16 node PC Supercomputer Cluster. The specific goal was to apply a more highly resolved (e.g., more closely spaced grid cells) model of the Providence and Seekonk Rivers to enable better resolution of processes within the narrow and shallow regions of the Seekonk River. The boundaries of the grid extended in longitude from 71.41° W to 71.30° W and from 41.71° to 41.88° N in latitude. The mouth or ocean boundary of this model coincided with the mouth of the Providence River. The model grid consisted of 240000 nodes with 400 nodes in the east-west direction (x) and 600 nodes in the north-south (y) direction. Each computational element had uniform spacing in the horizontal (x-y) orientation at a grid resolution of 35m x 35m. Vertical resolution varies spatially because the ROMS model uses a constant number of depth bins which are distributed throughout the water column. In this case we utilize ten vertical bins such that element (grid) resolution in z varies between 0.2 m and 1.8 m, depending on water depth. Bathymetry and coastline information was obtained from the NGDC at a 3 arc-second resolution.

Results from both of these modeling studies were reported in Bergondo and Kincaid (2007). Cases focused on documenting how various ocean boundary conditions, turbulent closure (mixing) schemes and individual mixing coefficients influenced the solutions. The fine resolution Rogers-Seekonk modeling revealed strong lateral flow structures, particularly through the mouth of the Seekonk River. These results demonstrate the importance of considering the position of fixed data moorings with respect to lateral flow structures when making data-model comparisons for non-tidal velocity fields. Bergondo's modeling also documented important lateral flow structure and was able to re-create the basic, first order features of flow within the upper Providence River. In particular, model results showed a residual outflow that focuses along the western side of the shipping channel, a residual inflow that concentrates along the eastern side of the estuary and a weak recirculation eddy occupying the broad, shallow western portion of the estuary (e.g., weak northward flow opposite the focused residual outflow jet occupying the western side of the shipping channel).

1.4 Rogers RIS-NB ROMS

Rogers continued working with the ROMS model on the URI Supercomputer Cluster. With funding from NOAA, he developed a model where the ocean boundary was very far removed from the region of interest for this project, which was the whole of Narragansett Bay. Figure 3 shows the extent of the model domain for the RIS-NB ROMS model, results from which are reported in a URI MS Thesis (Rogers, 2008).

Here we summarize basic aspects of these RIS-NB models by Rogers because they represent a foundation from which this next stage of NBC modeling has evolved. Models were forced by tides, volume transport and temperature of river runoff, boundary temperature and salinity, solar heat flux, air temperatures and humidity, rainfall, and winds. Open boundaries in the RIS-NB ROMS model were placed in Rhode Island

Sound (Figure 3) to keep them far from Narragansett Bay. Output from the Advanced Circulation Model (ADCIRC) for 2006 was used to determine the 8 strongest tidal forcing constituents at the southern, eastern, and western boundaries (Mukai et al., 2002). Free surface and velocity ellipses for the eight largest tidal constituents were applied to the southern, eastern, and western boundaries. Tides were applied to the open boundaries using the Chapman free surface and Flather barotropic velocity boundary conditions, which combine to properly radiate barotropic waves out of the domain. Active tracers (temperature and salinity) were applied using a nudging-radiation condition where inflowing water was relaxed towards available data, while outflowing water was allowed to leave the domain. Temperature and salinity were allowed to radiate out of the domain but nudged towards data values upon inflow with relaxation timescales of 1 day for inflow and 15 days (weak) for outflow. Physical oceanography data are limited in RIS. Models made use of hydrographic and ADCP data collected during two cruises by Kincaid during summer and winter periods, 2005 (funded by the Rhode Island Endeavor Program) and data from Shonting and Cook (1970). To construct a temperature time series for the ocean boundary we also made use of surface temperatures from the Advanced Very-High-Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data maintained by the University of Maine, School of Marine Science (2007). Data on winds, air temperature and humidity for 2006 were from NOAA stations at Providence, Quonset and Newport. Rainfall data were from Theodore Francis Green Airport and river runoff data were from the United State Geological Survey (USGS) gauging stations. River temperatures were estimated from air temperature.

Vertical mixing was applied using the turbulent closure scheme, chosen based on its skill in simulating wind-mixed layers and estuarine circulation as shown in Warner et al. (2005b). Values for mixing coefficients were chosen based upon a combination of Bergondo's Providence River modeling, Rogers' Seekonk River modeling, comparisons between model velocity output at the north Prudence ADCP mooring locations (Figure 3) and local stability requirements within the domain. For example, a higher tracer mixing constant was necessary to avoid instabilities near areas of large tracer gradients, such as river inputs. The grid resolution in the RIS-NB ROMS model was 150 cells in the east-west and 300 cells in the north-south, with 15 (vertical) cells. The model made use of a curvilinear Arakawa C-grid with varying horizontal and vertical resolution. Vertical grid spacing is determined by height h at each grid cell and ranges from a minimum of 13cm at a depth of 2 meters to a maximum of 3 meters at a depth of 45 meters.

1.5 B-PRS Modeling of Transport Pathways

URI-GSO student N. LaSota has, in her MS research, built upon previous NBC funded modeling work by D. Bergondo. LaSota has added individual dye concentrations for all river sources into the Providence and Seekonk Rivers and also tags the output from 4 wastewater treatment facilities within the Providence River- Seekonk River system by assigning a dye concentration input flux to each. LaSota has been investigating the transport, dilution and flushing of the distinct dye sources within the estuary for a wide variety of environmental forcing conditions (Table 8). LaSota's thesis has been submitted in draft form (a copy will soon be available upon request). LaSota's primary goal is to determine which sources of dye and concentration levels for each dye accumulate within key retention areas of the river linked with low water quality, versus which are well flushed from the system. Flushing, retention and transport patterns for each dye field are characterized for a wide range in environmental forcing conditions expected for the estuary (winds, tides, runoff). LaSota's work also attempts to quantitatively gauge the impact of management-engineering schemes for reducing total nutrient concentrations being output from the NBC treatment facilities.

2.0 Project Goals

The NBC supported modeling work with the B-PRS ROMS grids and the higher resolution R-PRS ROMS grid was reviewed by D. Mendelsohn and discussed at length by Kincaid, Rogers, Mendelsohn and NBC personnel. The key points of the written review and the ensuing discussion are summarized here. The key points focused on grid resolution, proximity of the ocean boundary and proper, quantitative statistical data-model comparisons. The Bergondo model was decided to be too coarse to adequately resolve processes within the Providence River or the Seekonk River. The ~100-150m horizontal grid resolution was too coarse for the shipping channel within the Providence River, which is on the order of 500m in width, and the Seekonk River which in areas narrows down to <200m. Rogers' Seekonk River model did a better job at resolving spatial features of the flows, particularly within the Seekonk River. Results of discussions on model design resulted in the consensus opinion that the model's ocean boundary was too close to the region of interest, for both the Bergondo and Rogers Providence-Seekonk River ROMS models. Finally, it was agreed that more quantitative statistical comparisons needed to be performed between the time series output from moored data and model output. The RIS-NB ROMS model grid used by Rogers in his thesis work (section 1.4) is clearly not adequate for the NBC region of interest, as horizontal grid cell dimensions are on the order of 300m within the Providence River, or roughly two grid cells to resolve the width of the shipping channel.

2.1 Protocols for Quantitative Data-Model Comparisons

Here we describe procedures for making statistical comparisons between model data output and observational data from key regions of the Bay. Tide height comparisons are the first metric for model validation, though not necessarily the most important to net transport. Model skill was evaluated as in Warner et al. (2005a) with equation 1 or,

$$\text{Skill} = 1 - \sum | X_{Model} - X_{Data} |^2 / \sum ((|X_{Model} - X_{Data}|) + (X_{Data} - \text{mean}(X_{Data})))^2 \qquad (1)$$

A skill of 1 means the model matches both the mean and variance of the data. A number of additional statistical quantities are calculated including the root mean square (RMS) difference between model output and both ADCP and hydrographic data. Also calculated are the maximum, minimum, mean and standard deviation of the data (summarized in table 2, Appendix A, B). Data-model comparisons are run using a Matlab script (Mstats.m, Appendix A) developed by J. Rogers which incorporates all of the statistical quantities provided by D. Mendalsohn (defined in Appendix B). Comparisons require time series data records from the moored instruments and model output from corresponding locations to be sampled at similar frequencies. The Matlab script

Mstats.m (Appendix A) utilizes subroutine FillNan.m to eliminate data gaps and the subroutine Dalign.m to resample the higher frequency of the two records in order to insure that data and model records match in length and frequency. For this model development 20 ROMS time series stations are defined. A time series station is designated as an east-west and north-south grid cell pair, where time series data on surface elevation, velocity, temperature, salt and a range of additional tracer and model information are output at 10 minute intervals. Time series stations lie along the mouth of the Bay, at distributed locations along east-west lines located at the southern and northern ends of Prudence Island, in locations where hydrographic buoys are currently maintained, or have been maintained and in the locations where moored ADCP data have been collected. While the focus of this work is on 2006, additional ADCP and hydrographic information exists for 2002-2005.

3.0 Model Development

The primary goal of this project is to develop a new ROMS model grid domain that a) maintains an open ocean boundary that is far removed from regions of interest, b) has sufficient grid resolution in both the Providence River and Seekonk River, c) resolves the slope and width of the shipping channel in the Providence and Seekonk Rivers, and d) allows for simulation times that are reasonable (Tcpu~10-20). A compromise was chosen between the prior NBC-supported B-PRS ROMS model grid (e.g., ocean boundary at North Prudence Island, Figures 1 and 2) and the NOAA-funded RIS-NB modeling (Figure 3). The consensus reached through discussions with Mendelsohn and NBC representatives was to locate the ocean boundary at the mouth of Narragansett Bay (Figure 2; Figure 4). One lesson learned from the RIS-NB model is that it is important to consider data availability when choosing an ocean boundary. Placing the ocean boundary at the mouth of the Bay enables us to take advantage of prior underway and moored ADCP data and CTD data collected along and across this interface (Kincaid et al., 2003; Kincaid et al., 2008; Ullman et al., RI Sea Grant Funded Project, unpublished data, 2007; Pfeiffer-Herbert et al., 2015). The proximity of the long running Newport, RI station for tidal elevations and the NOAA Physical Oceanographic Real Time System (PORTS) station at Newport, RI are additional resources that may be used to better characterize this ocean boundary. The ocean boundary is much closer to the NBC region of interest than the ocean boundary used in the RIS-NB model (Rogers, 2008) and there exists more information that be used in assigning proper boundary conditions at this new ocean boundary.

Even with the ocean boundary located at the entrance to Narragansett Bay, a challenge remained in balancing the speed at which model simulations could run to completion on the computer relative to the goal of achieving high grid resolution in the upper Bay. Our goal was to maintain a high Tcpu (>15) while ensuring <50m grid spacing within the uppermost Bay. Figure 4 shows how curvilinear grid generation was employed to keep the grid cells relatively coarse in the south, away from the areas of interest, while maintaining finer grid resolution in the Providence and Seekonk Rivers. The lateral (east-west) extent of the model grid narrows by a factor of 5 moving from the lower Bay to the upper Bay. Figures 5-8 show the grid spacing (displayed relative to coastline features) for key regions of the domain. Grid cell length scales vary from roughly 30m in the Seekonk and Providence Rivers to 200m near the mouth of the Bay. An important step in the development of model grids is to test that the parameter describing the local bottom slope (rise (m)/run(m)) does not exceed ~0.6. The grid bathymetry is run through a series of smoothing filters to ensure slopes are reduced below 0.6 everywhere in the model domain. Figures 9 and 10 show contour images of the slope parameter before and after smoothing. An improvement over the B-PRS ROMS model is that a local Matlab-based smoothing function is employed instead of a local smoothing step. Local smoothing allows overly steep regions of the model domain to be smoothed without over-smoothing key bathymetric features such as the shipping channel. This procedure was developed by Rogers during his work on the R-PRS ROMS grid.

The new Full Bay ROMS model does fit the requirements that were outlined by Mendelsohn and NBC, namely that ocean boundary is removed further to the south from its previous location at North Prudence Island while at the same time grid resolution is maintained in the uppermost estuary and run times (Tcpu) remain reasonable. Figure 11 summarizes Tcpu results for Bergondo's coarse Providence River cases (Tcpu~30) and Rogers high resolution thesis model (Tcpu~1). The compromise location combined with curvilinear grid generation allows Tcpu to remain in the 10-15 range, while keeping grid resolution high in the rivers.

3.1 Preliminary grid development and calibration

There are a number of test steps that occur during the initial stages of deciding on the final grid shape and grid cell sizes and resolutions. Figure 11 summarizes a range in simulation times, plotted as the ratio of simulation elapsed time to the time the computer processors have been running to reach this point in the simulation (Tcpu). Test grids of 100 (east-west) x 200 (north-south) cells on the cluster ran with a very high efficiency at Tcpu of 30, or 30 days of model simulation for every day of processing time. With only 300,000 total grid cells, this model did not provide sufficient resolution (order 300 m) in the upper Bay. At the opposite extreme, a grid with 300x600 cell divisions in the horizontal dimension, with 20 vertical levels, ran at Tcpu=2, which is close to modeling in real time. This case, with 5 million total grid cells ran at an unacceptably slow rate. Seven different grids were developed ranging from 100-150 cells in the east-west orientation and 300-500 cells in the north-south direction, before choosing the final grid dimensions of 125x450, in the horizontal and 15 vertical levels for a total of nearly 1 million grid cells (as summarized in Figures 4-10). This grid runs with acceptable speed and is able to resolve the shipping channel in the Providence River, the mouth of the Seekonk River and the shipping channel connecting the lower East Passage with Quonset Point. Keeping the ocean boundary at the mouth of the Bay maintains a spacing of roughly 6 tidal excursion lengths between this boundary and the region of interest, or the Providence and Seekonk Rivers.

4.0 Results

The next stage in the process of developing the NBC Full Bay ROMS model involves testing the character of the solutions which are produced. A partial list of model simulations is provided in Table 1. Cases 1-13 represent the stages of testing the NBC Full Bay ROMS model where different modes of boundary forcing are tested along the southern ocean boundary. The subsequent runs, labeled Nfull1, involve a technique called nesting for supplying information along the southern ocean boundary. There are two aspects to these stages of model development, one is to produce stable solutions, or simulations that are free of numerical instabilities which cause the run to stop. The other aspect of this process is to compare the model output to data. In these models we build off of the work that Rogers did with the RIS-NB grid in his MS thesis, and so we chose to drive the models with data from June-October, 2006. Therefore, data-model comparisons are between 2006 ADCP velocity data collected at four sites (red stars/line in Figure 1) and temperature-salinity data from buoys in the mid-Bay, which are also shown in Figure 1 (black squares).

The cases listed in Table 1 show the range in parameters that are tested during the model development. In all these cases we used 2006 Newport tidal elevation data to drive the free surface of the model. Information on tracers (salt/temperature) were approximated from Rogers thesis model run RISC8 within the RIS-NB model. These data were applied as an average vertical gradient along the mouth, but without any time variation. Different modes of treating the southern boundary included clamped versus Chapman conditions. The former makes the information at this boundary conform to the boundary conditions supplied regardless of what the solution is passing to these boundary nodes, and regardless of whether the flow is moving out of the model domain into RIS, or is being drawn into the Bay from RIS. The latter utilizes information from grid nodes just inside the mouth when flow is out of the estuary. Additional parameters that were tested include the manner in which the southern boundary handles tracer information (radiation versus nudging), and methods for handling both the 2-D (vertically integrated) and 3-D (baroclinic) modes of momentum transfer through the southern boundary.

Within each category listed in Table 1 are a large number of additional runs which deal with instabilities encountered within the simulations. A large problem came about due to the manner in which the code deals with the introduction of river water into the system. Boundary files which ran for the RIS-NB model no longer worked for the much finer resolution NBC Full Bay model, where the horizontal grid dimensions were an order of magnitude lower and volumes of the boundary cells where river water was being introduced were 2-3 orders of magnitude lower. A technique where individual rivers were divided into multiple input locations was employed to produce a more diffuse volume flux into receiving grid cells. Cases also tested the efficiency of wetting and drying, a new capability in ROMS, for keeping grid cells near the river input locations stable, or free of numerical instabilities which cause infinitely high salinity, temperature and velocity. During this stage of the model testing a number of sub-runs also test the influence of varying mixing parameters, time step size and grid smoothing in small, localized areas with large bathymetry gradients. Often instabilities develop in a region where there is a discontinuity in the slope of the bathymetry field. Often going back in and running the local smoothing routine on the grid in these “hot” areas eliminated the instability.

Figure 12 shows plots of modeled north-south velocity within the West Passage and the East Passage channels for locations shown in Figure 1, for the case with our optimal set of parameters (case 2 in Table 1, version-k). This run has river sources broken into multiple input locations, while maintaining the same total volume flux. The grid has bathymetric slope discontinuities smoothed out. River runoffs are scaled up by the percentage of discharge area that exists below gauging stations (Kremer et al., 2010). Both the model output and the ADCP data are plotted in figure 12. These plots show the instantaneous records which include the influence of tides, which are the dominant source of kinetic energy. Surface velocity varies between +/- 0.25 m/s during neap tides and >0.5 m/s during spring tides in the West Passage. Modeled velocities are lower in the bottom water of the West Passage and within both surface and bottom regions of the East Passage channel.

The model performed well in terms of higher energy tidally forced flows and elevation records. Tables 2 and 3 provide statistical parameters for comparing model output and data in these two locations, which are the channels of the East and West Passages (see Figure 1). The model skill parameter (equation 1) provides a quantitative measure of how the two records compare (Willmott, 1981; Wilken et al., 2005; Warner et al., 2005). For both tidal elevations and tidal currents, the model-data skill parameter values are in the range of 0.9 to 0.95 for the near-surface water, which compared with literature values are considered very high or very good. Values are roughly 0.7 in the near bottom water, which are considered good for data-model comparison. RMS values for flow are also very slightly low compared to overall magnitude of the tidal flow rates in both these mid-Bay locations (Table 3). For example, the maximum and minimum tidal currents within the near surface water of the West Passage were -0.48 m/s and 0.49 m/s for the model and -0.52 m/s and 0.55 m/s for the observations (Table 3). In general, the model under predicts the magnitudes of the tidal flows.

The model does not do as well at predicting instantaneous records for salt and temperature, or the non-tidal or residual records for velocity. Residual currents are those that remain after the oscillatory motion of the tides is filtered out. These are important for estuaries as they control the long term transport and exchange of water. Figure 13 shows the comparison between observed and modeled residual currents for these two locations. The observational records for near-surface and near-bottom locations show significant variability (~0.3 m/s total range) that roughly correlates with the north-south component of the wind (Figure 13c). The modeled residuals are far less energetic, with a total variation of <0.1 m/s in the West Passage and 0.15 m/s in the East Passage channel. The largest modeled residual signal occurs on decimal day 202 in association with a southward to northward wind event. The trend in the residual flow variations during this period are similar between the model and the observational record, but the magnitudes of the responses are off. Figure 14 shows that similar patterns exist for model versus observed salinity at three stations within the mid-Bay (see Figure 1). Table 3 lists the skill parameters and RMS values for the residual flow and salinity for comparisons between data and model values. Skill parameter values are quite low for the residual flows in both West (0.2-0.3) and East (0.2-0.4) Passages. Table 2 shows that in some respects, the model is capturing the basic style of estuarine circulation in this region, particularly in terms of the long term mean records (e.g., role of both winds and tides filtered out). In the East Passage channel the model captures the long term northward flow water in both surface and bottom sections of the water column. Modeled and observed means are 0.04 and 0.06 m/s, respectively.

4.1 Nesting

The primary change in the NBC Full Bay ROMS model relative to the RIS-NB grid used in Rogers (2008) is the location of the southern boundary. The RIS-NB ROMS model, with the ocean boundary removed far to the south, does a better job at matching residual velocity (Figure 15) and tracers (e.g., salt) (Figure 16) within the mid-Bay region. Figure 16 shows how model and observational records for salinity compare far better for mid-Bay locations using the RIS-NB model. Tables 4 and 5 also show higher skill parameters for key parameters in the data-model comparisons done in Rogers (2008), using the RIS-NB model.

The key factor missing from the NBC Full Bay model is the non-local variability that is occurring in flow and transport between RIS and the Bay, driven by larger scale wind and density forcing. An attempt was made to incorporate this missing information by building nested models. The nesting technique involves running the coarser RIS-NB model, which includes RIS and maintains the ocean boundary far from Narragansett Bay, and using output from this model at stations located along the Bay-RIS interface to drive the NBC Full Bay ROMS model. Table 1 lists the cases that have been attempted to date with nesting (Nfull1; a-k). The codes for interpolating the RIS-NB model information into the boundary forcing files for the NBC Full Bay ROMS model have been completed. Different cases have been exploring the role of nudging parameters on the solutions. Nudging parameters control how the values for velocity, elevation, salt and temperature vary through time along the boundary, between what the RIS-NB model is prescribing, and what the NBC Full Bay model is calculating. A comparison of tidal water level and velocity records from data and model output in the Providence River is shown in Figure 17. Tables 6 and 7 summarize the results of nesting in terms of statistical data-model comparisons. The nesting procedure improves the modeled residual fields relative to observed residual fields. For example, in Table 7 the skill parameter values calculated by comparing modeled and observed residual velocity fields for the East and West Passages are all close to 0.4. This is an improvement over the values of 0.2 to 0.3 seen in the non-nested full bay cases, but falls short of the values form Roger's Thesis models with the ocean boundary much further south and driven by ADCIRC model forcing (Luettich et al., 1992) (e.g., skill values of 0.55-0.8).

Further work is needed to better understand how non-local forcing (e.g. Rhode Island Sound processes) are contributing to residual flows within the Bay, and how such processes can be incorporated into the Full Bay models. Future observational work should also utilize more finely spaced ADCP moorings in order to determine how much of the mismatch between observed and modeled residual fields is due to the relative placement of time series data stations in the models and the actual estuary. This work should also consider how the time variability in laterally heterogeneous flow structures within the data relative to the models might contribute to the apparent mismatch in residual data-model statistics.

5.0 Conclusions

1. A new model grid has been developed which balances the need for higher grid resolution in the Providence and Seekonk Rivers and upper Narragansett Bay with the need for removing the southern open ocean boundary from the region of interest. Multiple grid configurations have been tested, with the final grid utilizing curvilinear cells where grid edges become narrower in the north, allowing the grid spacing in the east-west direction near the Providence River – Upper Narragansett Bay interface to become finer. A grid with 125 east-west cells and 450 north-south cells provides the required resolution (~30-40m) in the rivers while allowing the model simulation to move forward at a rate of 15 simulated days for each day of computer run time.
2. Forcing files have been developed for driving velocity, surface elevation, temperature and salinity along the new southern ocean boundary, coincident with the mouth of Narragansett Bay. Forcing files have been modified for the river inputs into the upper Bay which provide the same total volume flux, but input over a broader area to maintain numerical stability.
3. We have incorporated a list of statistical quantities for making data-model comparisons in coastal systems provided D. Mendelsohn into Matlab postprocessing scripts which ensure both observed and modeled data records are at the same sampling frequency and are free of data gaps. The scripts calculate all of the recommended statistical quantities.
4. A series of 13 basic model cases have been run, where within each case set, there are 10-15 runs testing various factors for stabilizing model simulations. A best case simulation has been identified and statistical comparisons have been calculated for a 1 month simulation for summer 2006 conditions. The models generally do very well (by literature standards) in terms of matching observed tidal or instantaneous water levels and flows. These are important for validating that the model is representing the overall kinetic energy of the most energetic circulation mode, in response to the M2, semi-diurnal tide. Good data-model matches in tidal response provides confidence that the model is representing the mixing reasonable well. Residual, or non-tidal flows are significantly less energetic and harder for models to match. This is the case in these data-model comparisons. Because residual flows are important for simulating long term transport/exchange, it is important to continue efforts to understand what causes differences in model predictions versus observations at these subtidal frequencies.
5. In an attempt to improve solution accuracy, particularly in terms of residual, non-tidal flows, a strategy of nesting the Full Bay models within previous 2006 models which included all of Rhode Island Sound (Rogers, 2008) has been tested. Scripts have been developed which interpolate time series output from across the Narragansett Bay- Rhode Island Sound interface into ocean boundary forcing files for the NBC Full Bay model. Future work should ensure that RIS-NB output matches what is known in terms of spatial structures for exchange through the mouth the Bay (Kincaid et al. 2003) and amplitudes for time variability in Bay-Rhode Island Sound exchange as reported by Kincaid et al. 2008. Rogers (2008) did not focus attention on calibrating the RIS-NB model to these

types of data sets. Future nesting runs are also needed to better understand the role of nudging parameters in influencing solutions within the NBC Full Bay ROMS model.
6. A literature search has shown that there has not been significant attention paid to statistical comparisons between observed and modeled residual fields (Holt et al., 2005). Indeed, the NBC funded research on collecting spatially detailed observation records collected with underway ADCPs shows why it will be extremely difficult to make sense out of the data-model comparisons for the residual fields. As shown in Kincaid (2001a-c; 2002; Rogers, 2008) there is extreme lateral variability in de-tided patterns in inflow/outflows within a 2-D cross section through the estuary. Patterns in inflow/outflow migrate significantly with environmental factors. Such variability cannot be resolved with single point ADCP moorings. Future work should focus on defining the stability of inflow/outflow structures that have been defined with underway surveys using a distributed, spatially detailed current meter network.

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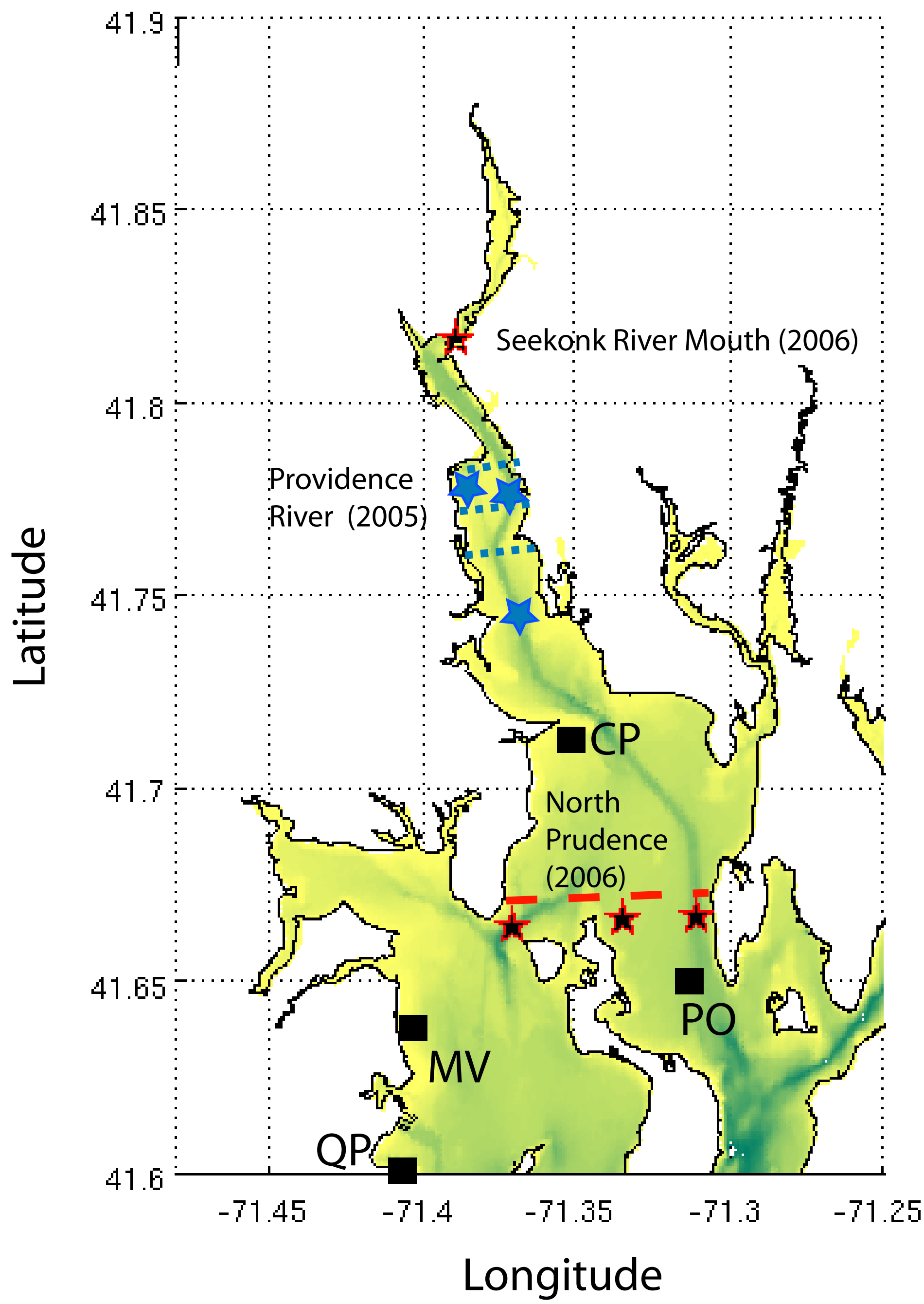

Figure 1. Map of Upper Narragansett Bay showing locations of current meter data collected in support of modeling activities using the ROMS hydrodynamic model. Star symbols=moored ADCP data. Dashed lines = underway ADCP data. Squares show locations of buoy data for water column salinity and temperature. PO=Poppasquash Point. MV=Mount View. CP=Conimicut Point. QP=Quonset Point

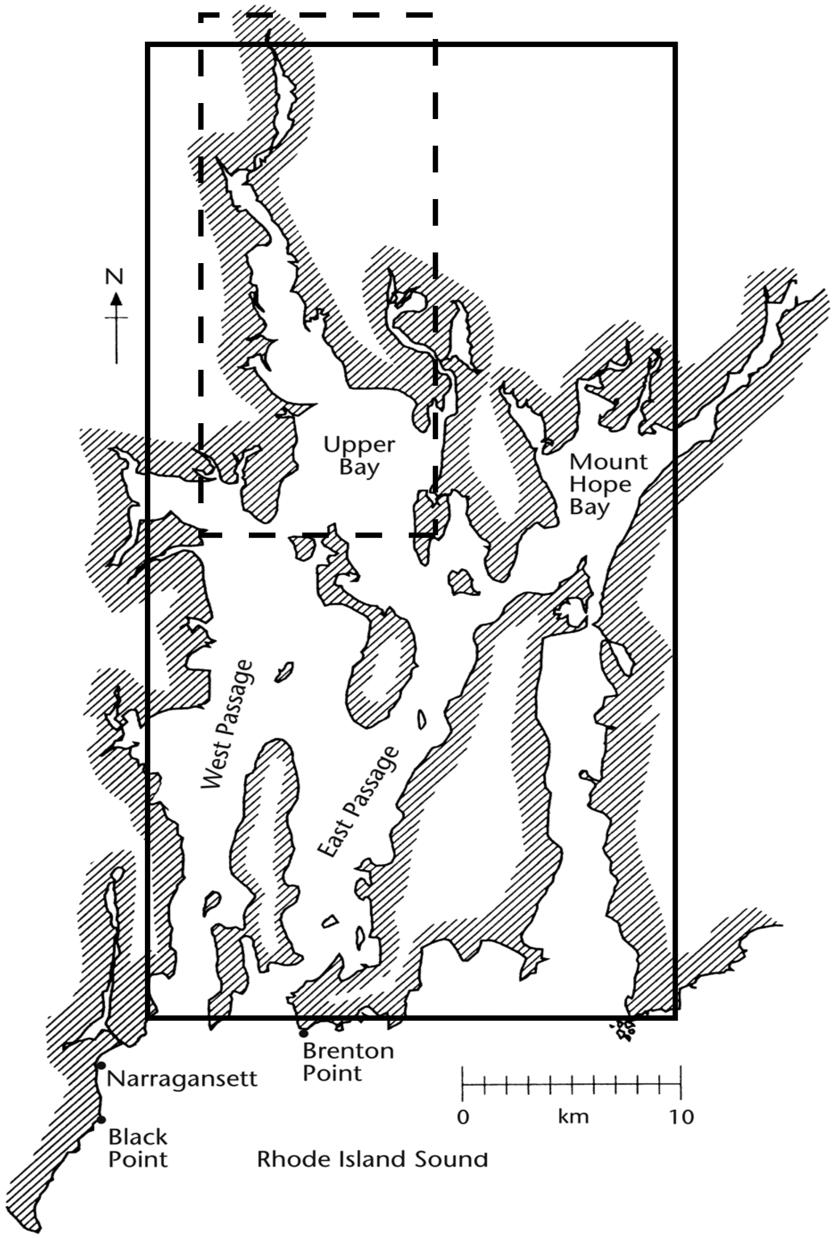

Figure 2. Map of Narragansett Bay showing the extent of ROMS model domains for earlier work by Bergondo (dashed) and the present study (ROMS Full Bay Grid).

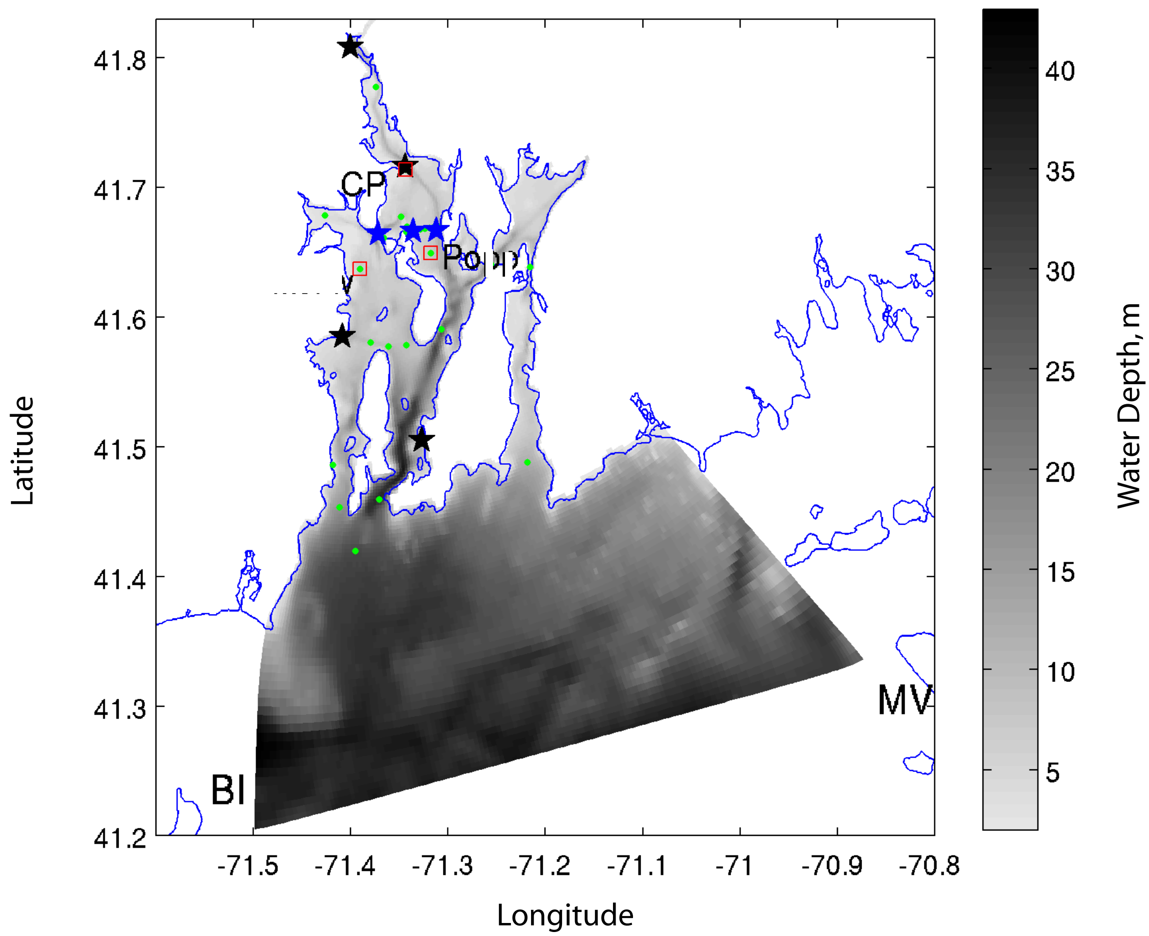

Figure 3. Bathymetry map showing the extent of the large ROMS model grid developed by J. Rogers for his MS Thesis work modeling Narragansett Bay (Rogers, 2008). The grid extends from Rhode Island Sound in the south to the Seekonk River in the north. Black stars show locations of PORTS data collection sites. Green circles show locations of ADCP data collected by URI-Kincaid. Red squares show locations of buoys where water column hydrographic data are collected. Blue stars show locations for the primary ADCP time series records used in the model calibration for this work. BI=Block Island. MV=Martha's Vineyard

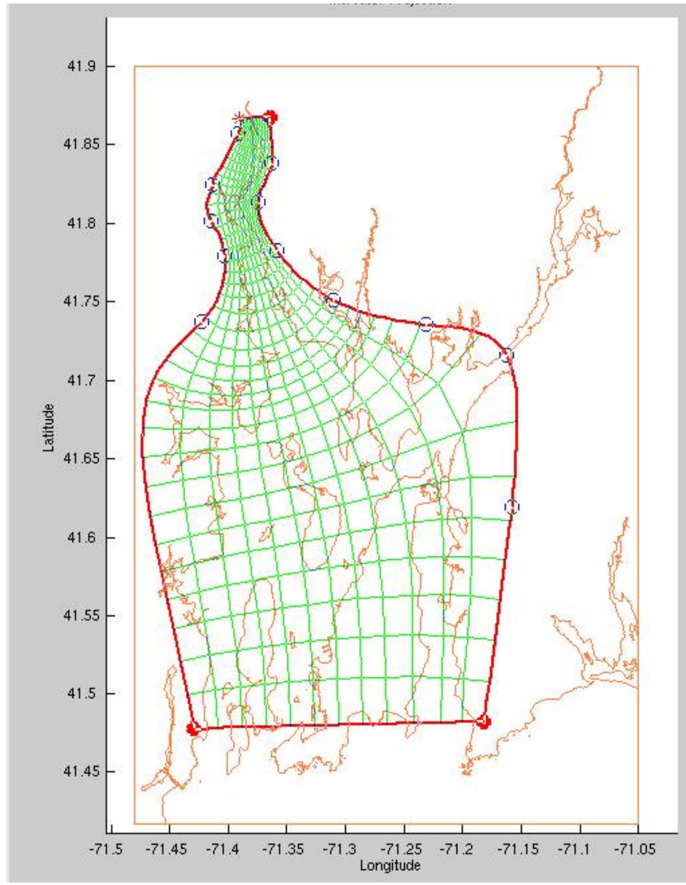

Figure 4. Overlay of the map of Narragansett Bay and the curvilinear ROMS full Bay model grid showing how the grid is modified to maintain higher grid resolution in the northern region of the Bay.

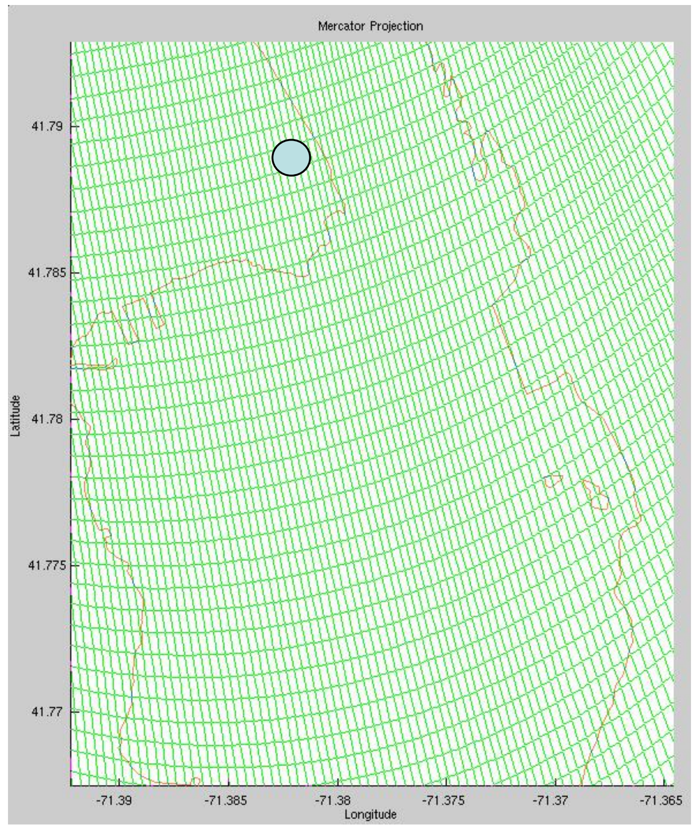

Figure 5. Overlay showing a map of the upper Providence River with lines (green) representing grid cell geometry and orientation near the Field's Point facility (approximate location shown with a circle). Horizontal grid resolution in this region is 30m.

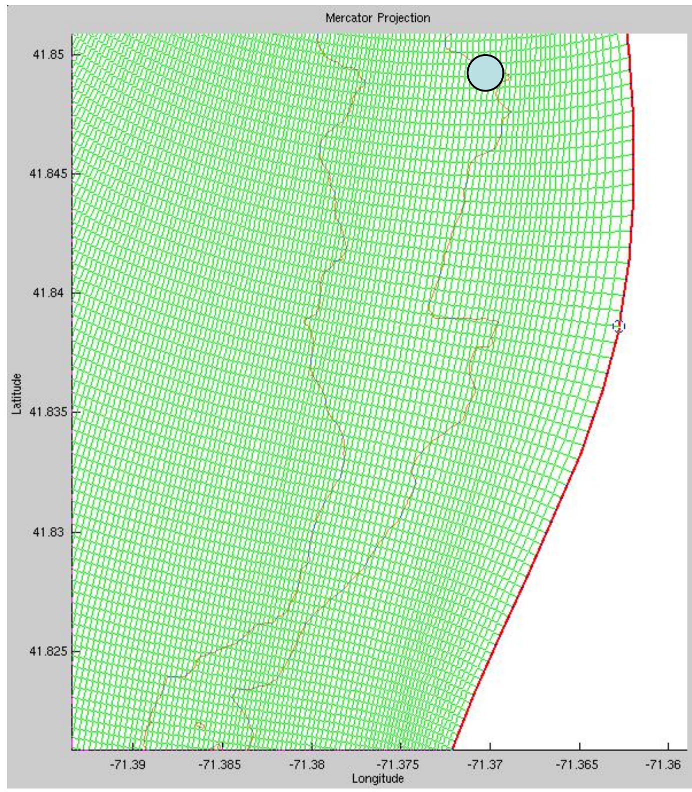

Figure 6. Overlay showing a map of the Seekonk River with lines (green) representing grid cell geometry and orientation near the Bucklin Point facility (approximate location shown with cicle). Horizontal grid resolution in this region is 30m.

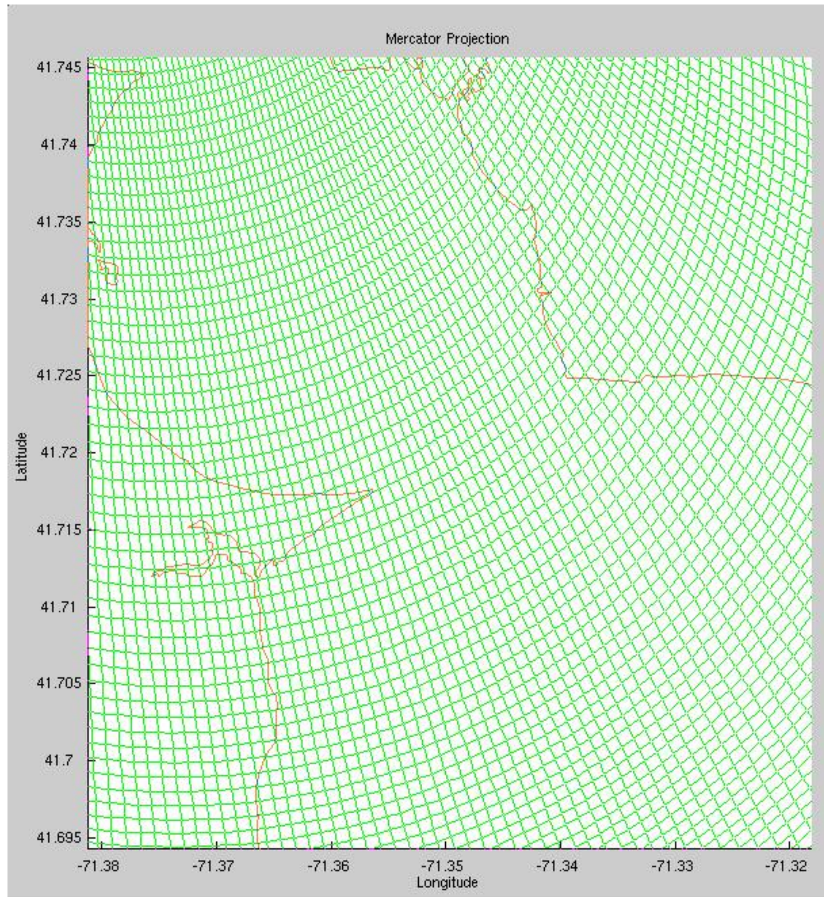

Figure 7. Overlay showing a map of the lower Providence River near the interface between the Providence River and upper Narragansett Bay at Conimicut Point. The green lines show the locations and orientations of grid cells in this area. Horizontal grid resolution in this region is 100m.

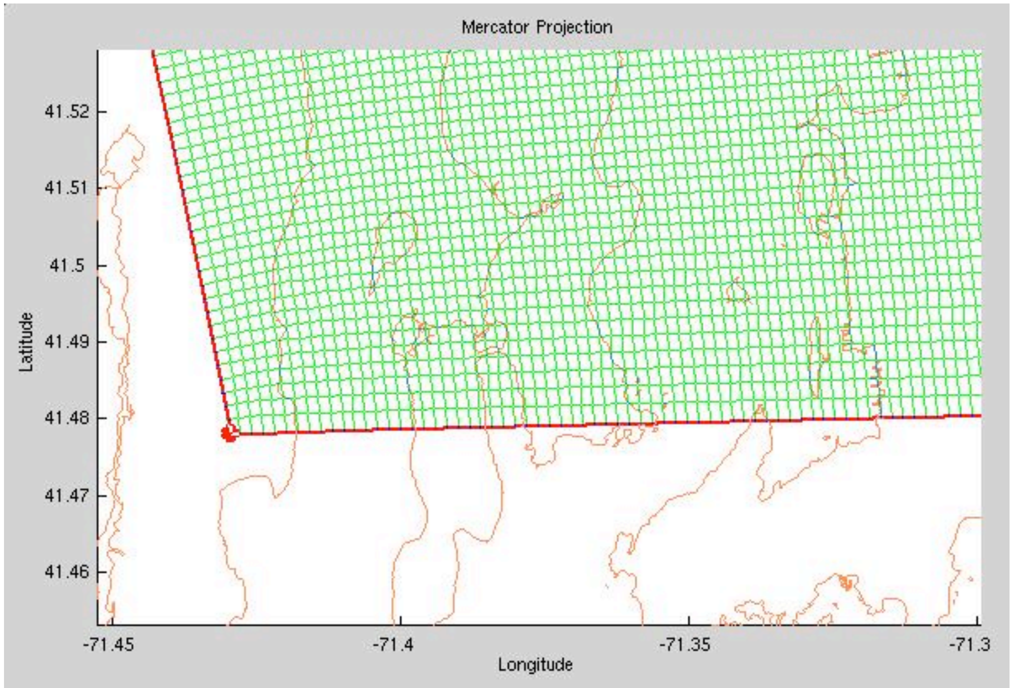

Figure 8. Overlay showing a map of lower Narragansett Bay with grid boxes. In this full bay model domain, curvilinear coordinates are used to maintain grid coverage at the mouth of the system and very high grid resolution in the northern portion of the system. Grid resolution at the mouth is ~200m.

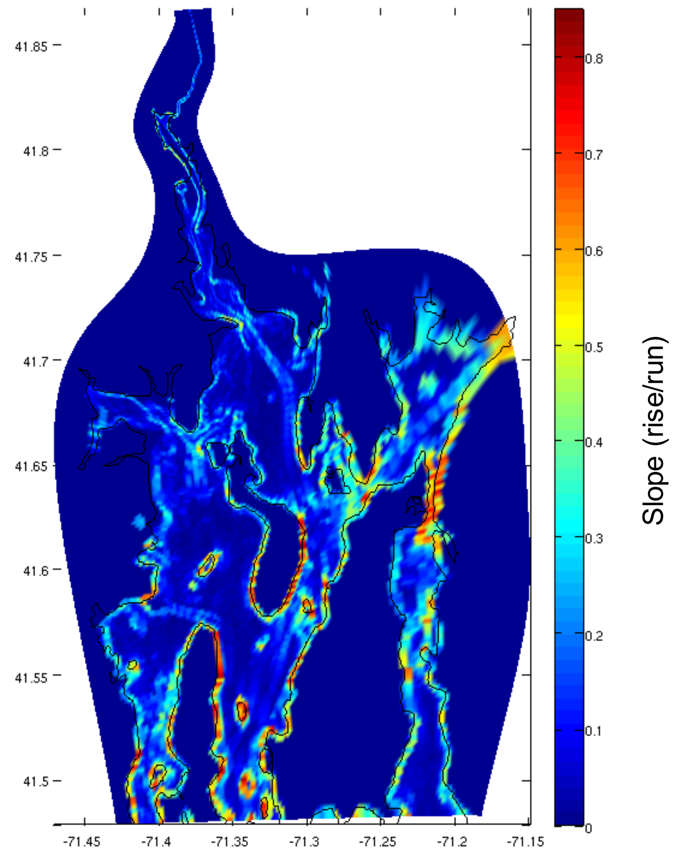

Figure 9. Color contours of the slope parameter (rise/run) of the bottom bathymetry after combining model grid file with bathymetry from NGDC data base. Values initially range from ~0 to 0.9. Recommended maximum values for slope parameter to ensure stability are <0.4. This grid produces instabilities in the solutions for flow and transport.

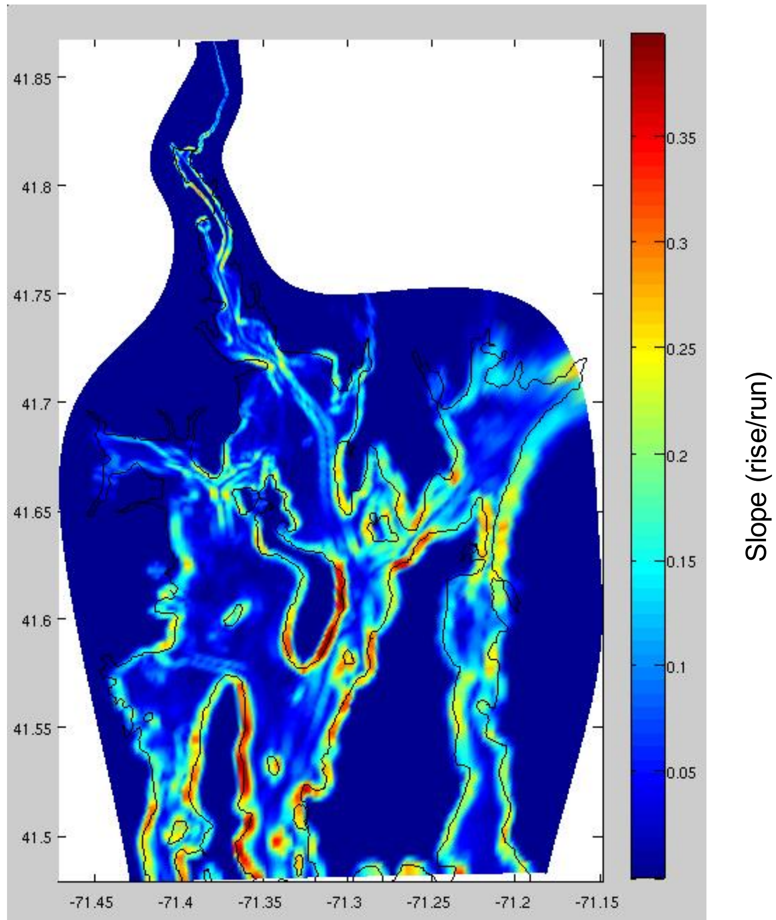

Figure 10. Similar color contours of the slope parameter (rise/run) of the bottom bathymetry as in Figure 9. Slopes have been reduced by using Matlab routine Runsmooth.m, developed by J. Rogers for locally smoothing high values without producing excess smoothing of key features such as channel bathymetry. Slopes are less than the suggested value of 0.4.

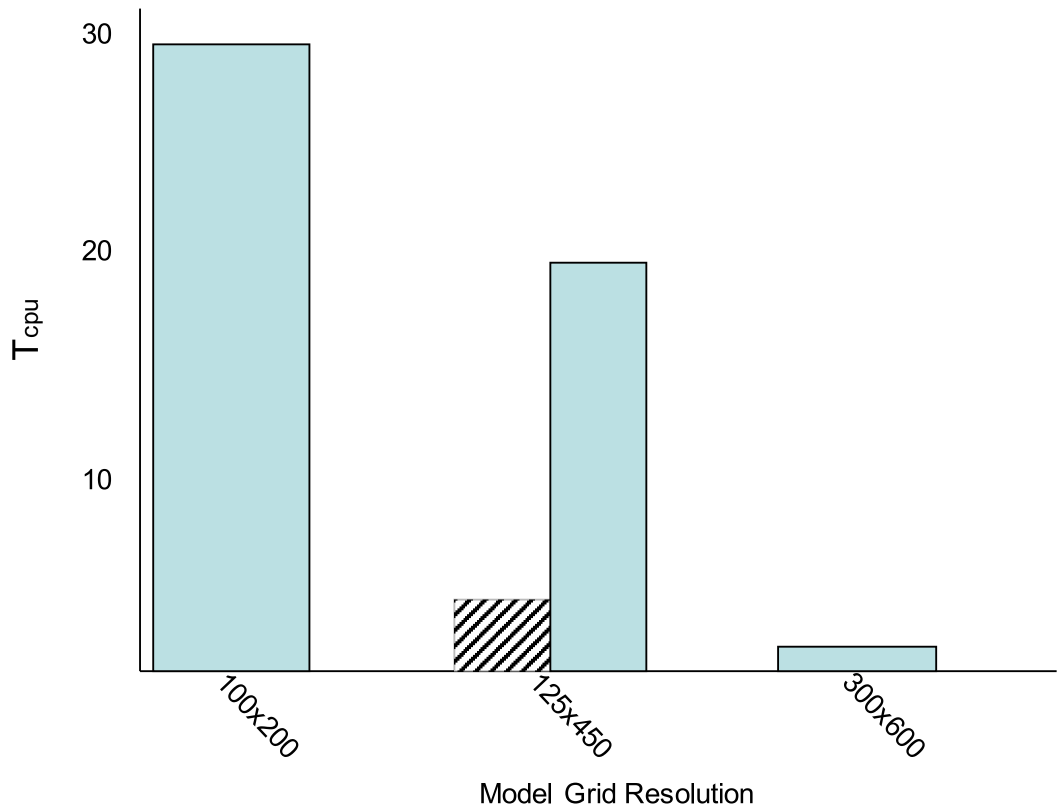

Figure 11. Plot summarizing the efficiency of the ROMS model for different grid resolutions. In each case the numbers on the x-axis represent the number of grid cells in the east-west and the north-south direction, respectively. Time on the y-axis is the ratio of number of modeled, or simulation days for every day of computational time on the URI-GSO PC Cluster. Shaded columns represent times for simulations that have been spun up beyond the effects of the initial conditions. Hatched columns represent times for simulations running with a reduced time step during initial spin-up.

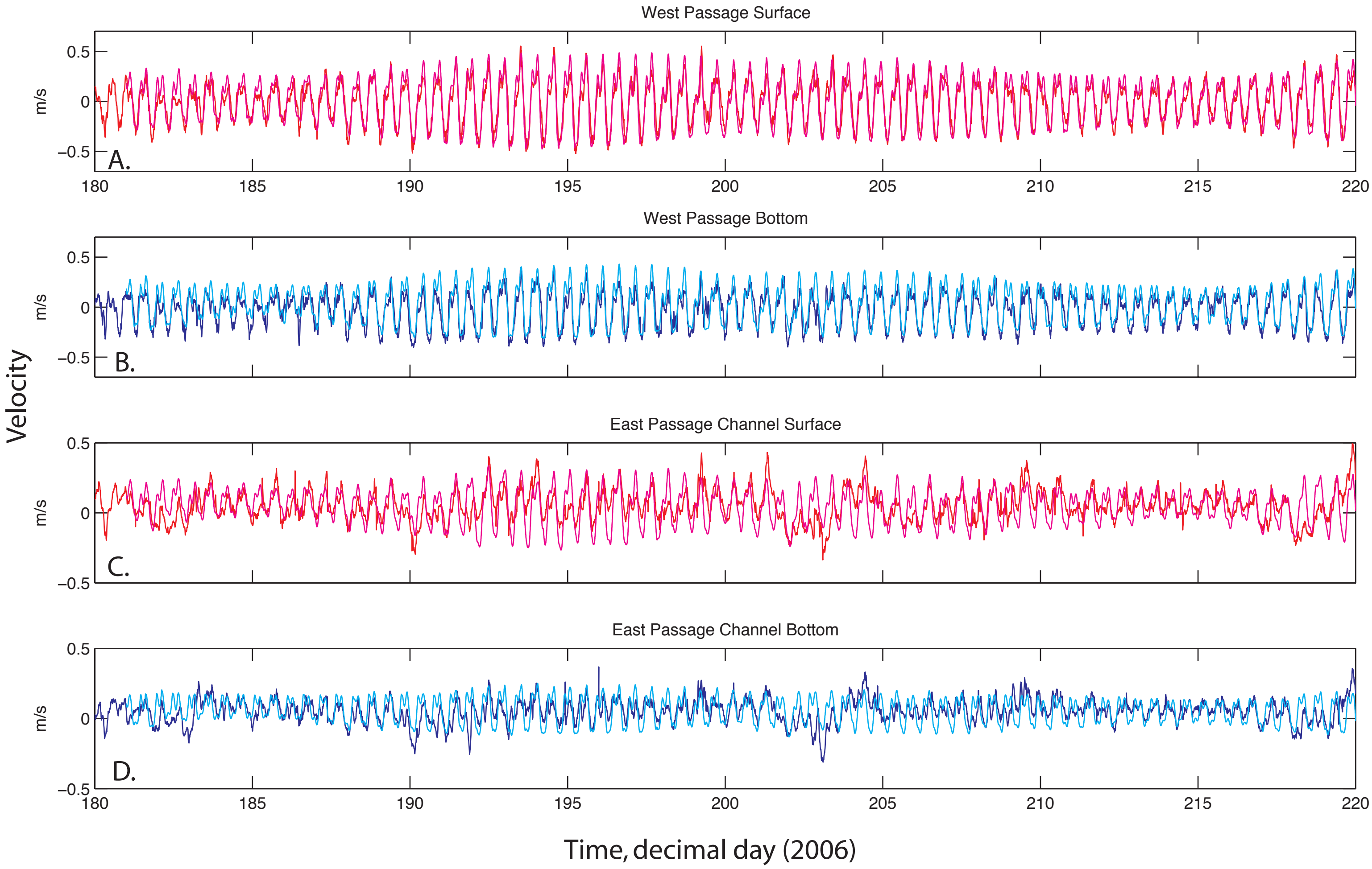

Figure 12. Results for 2006 seasonal simulation using ROMS and the new full bay model domain. Plots of instantaneous velocity in the north-south direction for model output relative to observational records are displayed. Locations and depths of records are West Passage near-surface (A) and near-bottom (B) and within the shipping channel within the East Passage (C: near-surface) and (D: near-bottom). The stations for model output and ADCP data are located along an east-west line running across the northern end of Prudence Island (see Figure 1). Time is plotted as decimal day for 2006. Data records are red/blue. Model records are magenta/cyan.

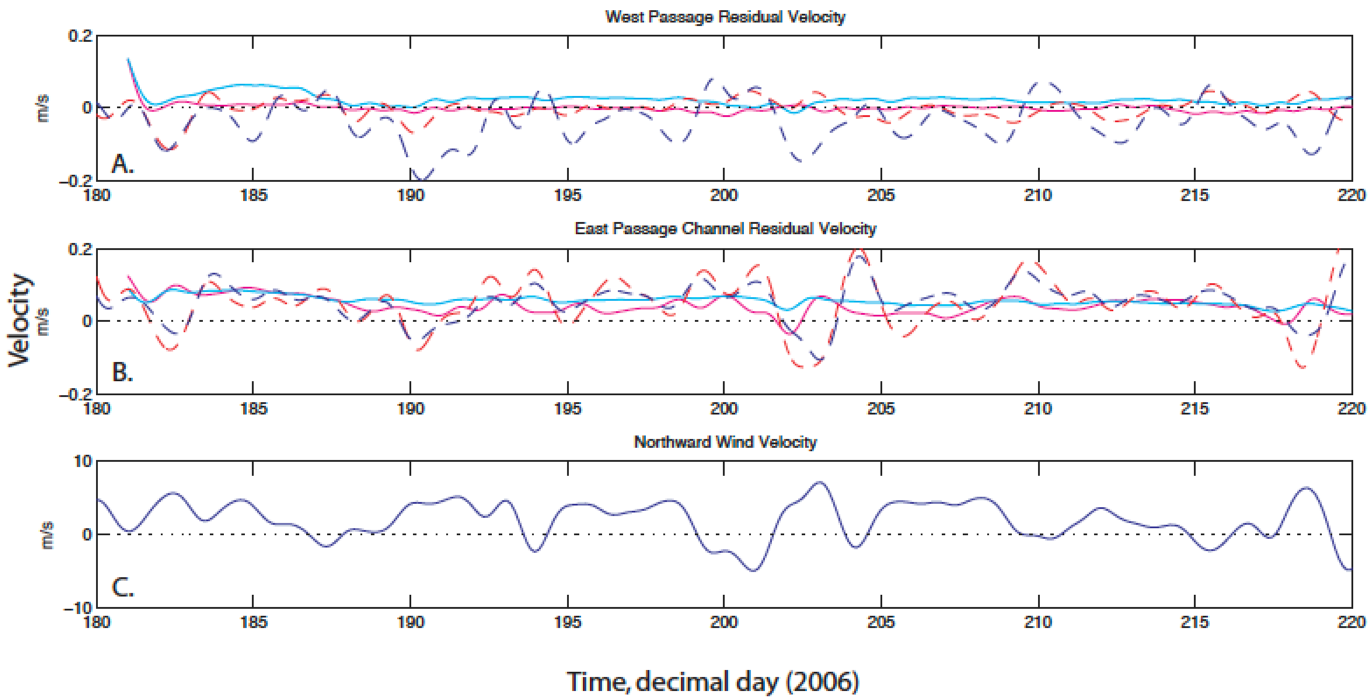

Figure 13. Plot of residual velocity fields (north-south component) from the modeling for stations within the (A) West Passage and (B) the shipping channel of the East Passage (see Figure 1). These records have been filtered to remove the tidal response. Here red lines are near-surface values and blue lines are near-bottom values (dashed=data and solid=model).
C. The north-south component of the wind velocity is plotted.

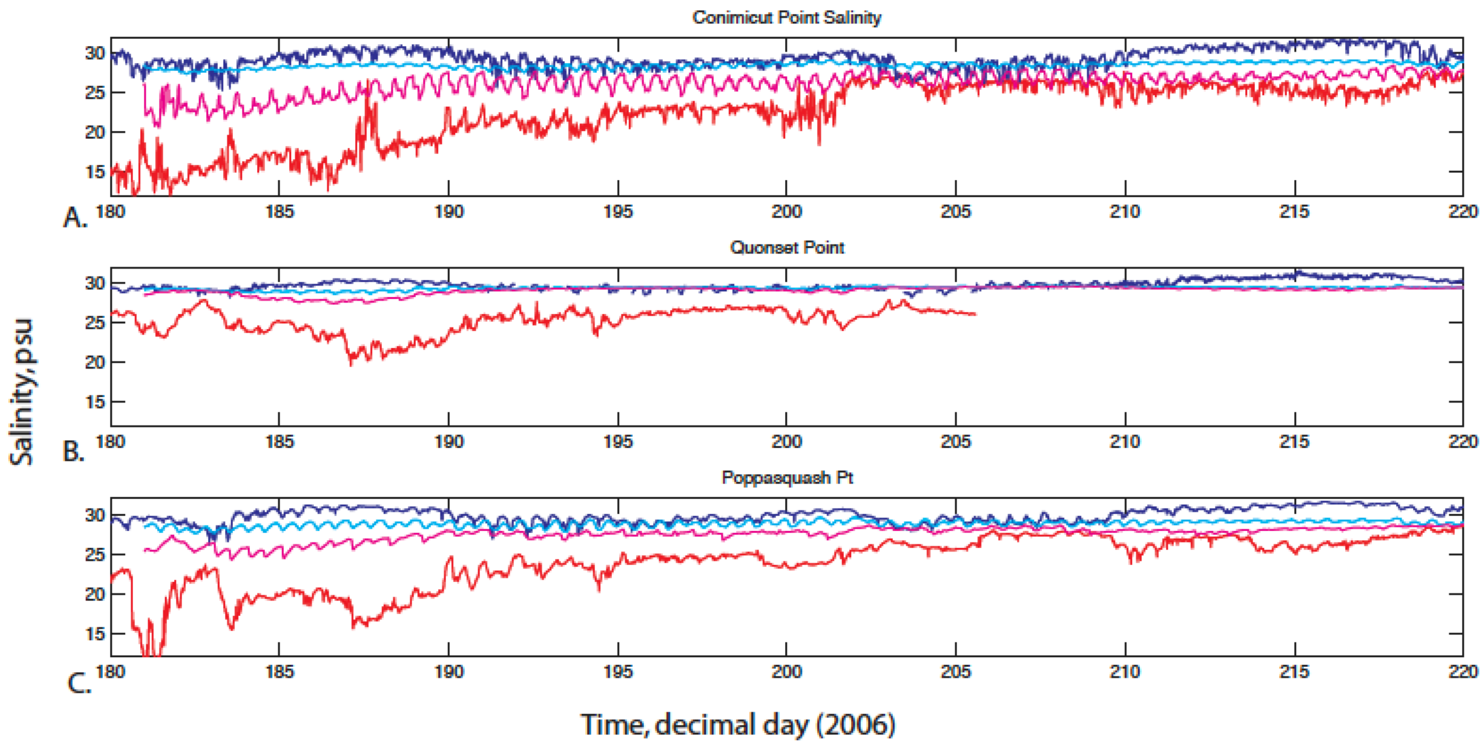

Figure 14. Plots of model salinity compared with observational records within the upper Bay for 2006 seasonal simulations using ROMS and the new full bay model domain. Locations of data-model comparisons are shown in Figure 1. Here observations are shown in red (surface) and dark blue (near-bottom values). Cyan is modeled bottom values and magenta is modeled surface values.

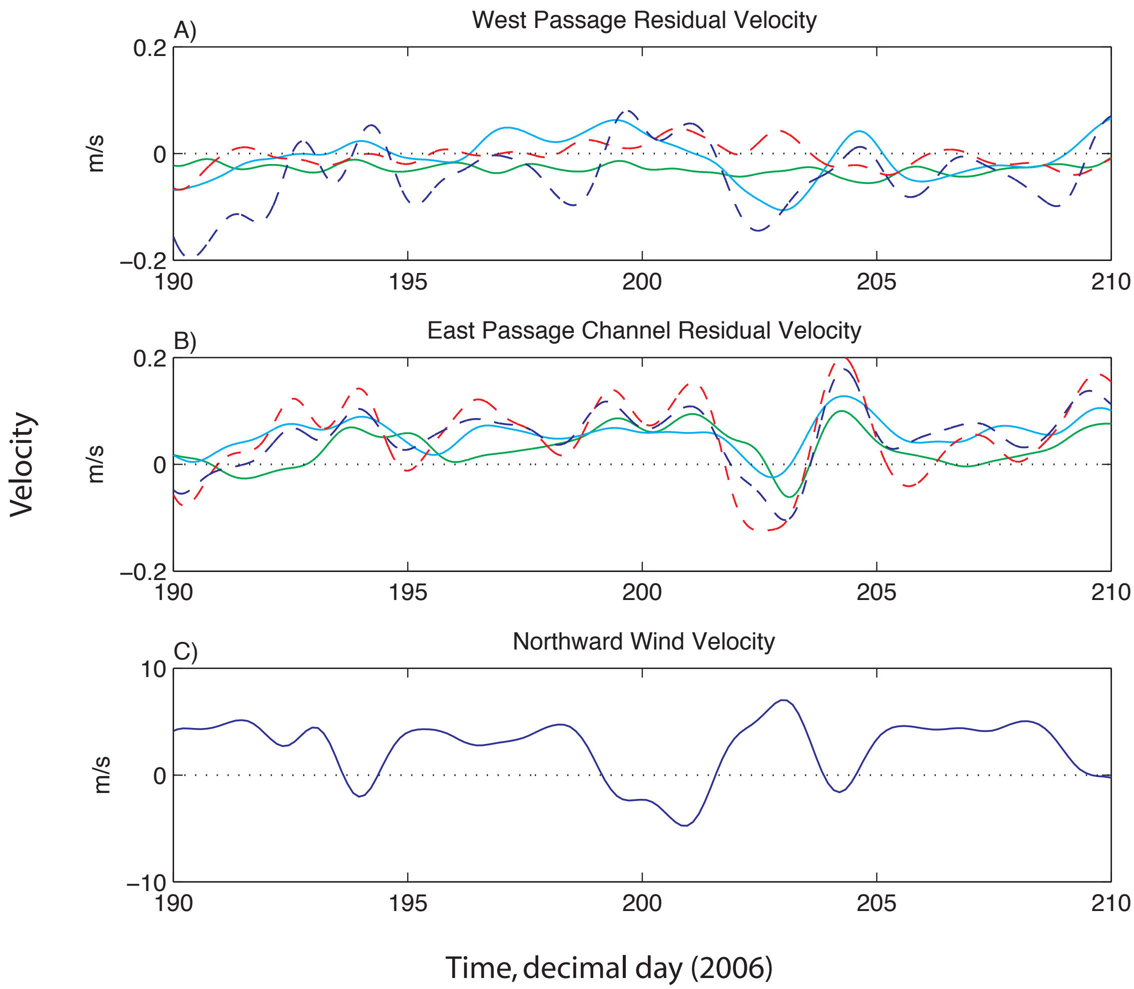

Figure 15. Results for 2006 seasonal simulation J. Rogers MS Thesis research using ROMS and the model domain extending out into Rhode Island Sound (see Figure 3). Plots in A,B are residual velocity fields for July, 2006 for model output (solid lines) relative to observational ADCP records (dashed lines). Results are shown for near-surface records (data=red; model=green) and near-bottom records (data=blue; model=cyan). C. Plot of north-south average speed during this period of 2006.

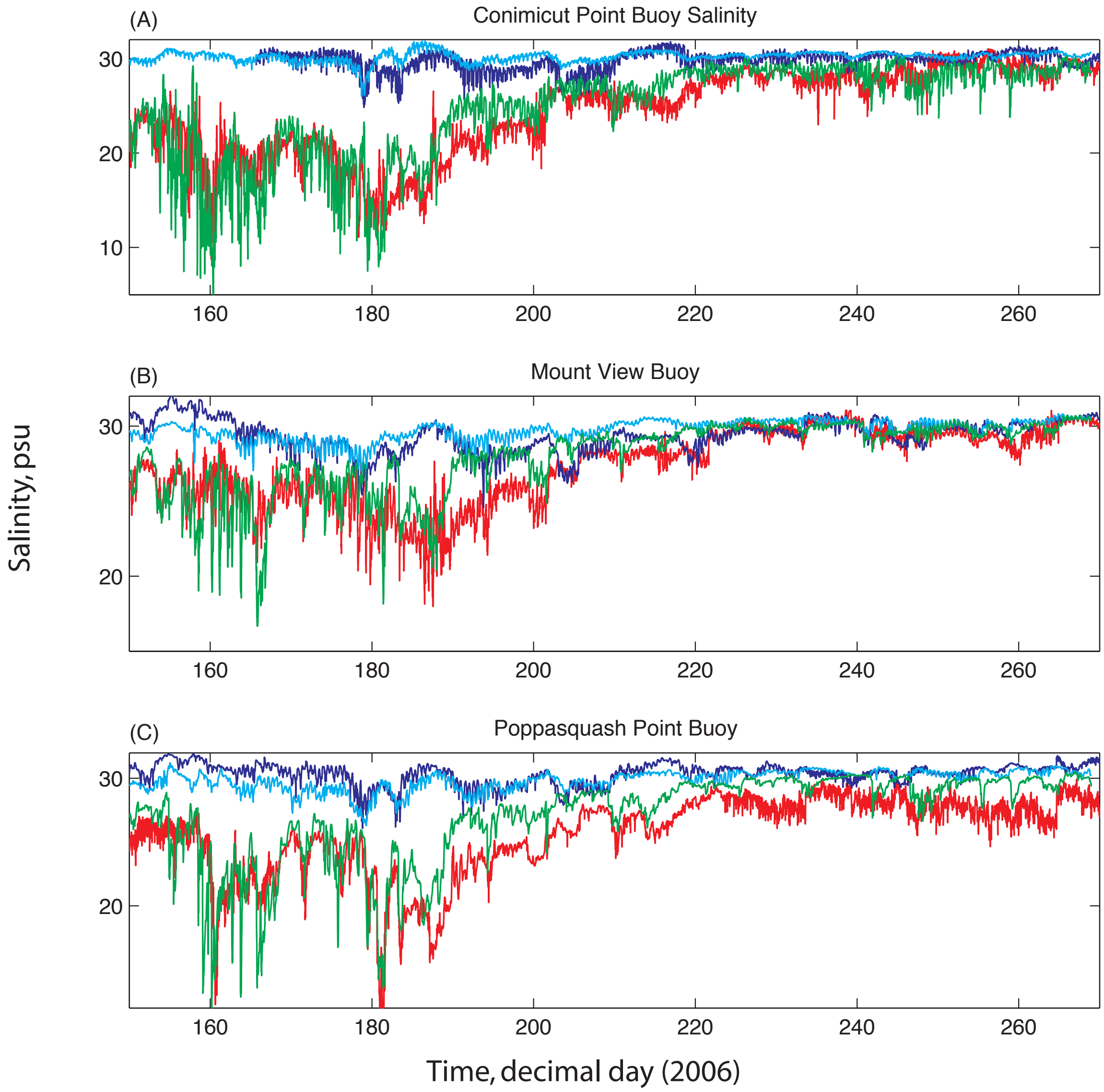

Figure 16. Results for 2006 seasonal simulation from J. Rogers MS Thesis research using ROMS and the model domain extending out into Rhode Island Sound (see Figure 3). Plots show salinity fields for July, 2006 for model output relative to data from moored hydrographic buoys. Near-surface and near-bottom data records are shown red and blue, respectively. Near-surface and near-bottom model records are shown in green and cyan, respectively.

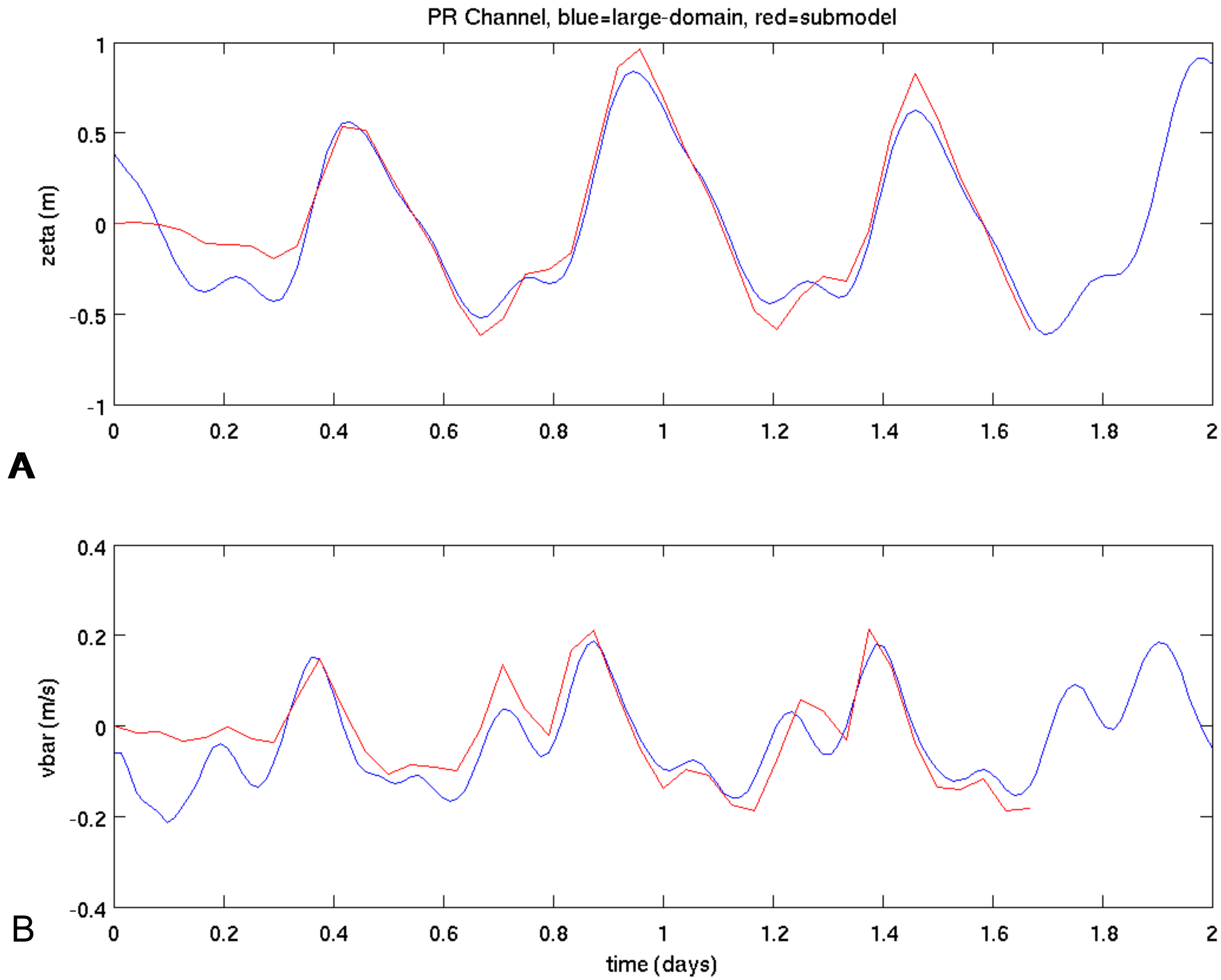

Figure 17. Plots of comparisons of modeled surface elevation (A) and vertically averaged velocity (B) from two model runs. One model output is for the J. Rogers (MS Thesis) simulations where the ocean boundary was at the southern edge of Rhode Island Sound (blue lines). The other model output is from recent simulations using the full bay model, where the southern boundary is at the entrance to Narragansett Bay (red lines). The comparisons are made for a station located in the Providence River, at the 2005 ADCP Edgewood channel location. In these cases, the ocean boundary is forced with output from the large domain (Rogers MS Thesis) model. Preliminary results match the output from the Rogers thesis model, which had higher skill levels than the previous simulations with the full bay model.

Table 1. Summary of model simulation test-development cases for the Full Bay ROMS work for Narragansett Bay, with the ocean boundary located at the mouth of the system. Cases Nfull1a-k are for testing the role of nesting on increasing skill in data-model comparisons. Cases use RISC8 model output, a model domain covering the Bay and Rhode Island Sound (Rogers, 2008), for summer 2006 conditions. RISC8 output is applied along the ocean boundary for these cases. Cases a-k all build off Nfull1, which is a successful run with nesting, where the model is driven by output from the larger RISC8 (Rogers, 2008) summer, 2006 simulation.

Run	Free Surface	Tracer	2d	3d	Wet/Dry	Point Sources	Advection Scheme	Comments
1	Clamped	Radiation	Reduced	Nudging	Off	UV	MPDATA	Use Newport tides with risc8 tracers, 3d velocity
2	Clamped	Radiation	Reduced	Radiation	Off	UV	MPDATA	
3	Clamped	Nudging	Reduced	Radiation	Off	UV	MPDATA	
4	Clamped	Nudging	Reduced	Nudging	Off	UV	MPDATA	
5	Clamped	Nudging	Reduced	Radiation	Off	UV	MPDATA	Rivers triggering instability
6	Chapman	Nudging	Reduced	Radiation	On	Q	Akima 4^{th}	
7	Chapman	Nudging	Reduced	Radiation	On	Q	MPDATA	Added bulk fluxes
8	Chapman	Nudging	Reduced	Radiation	On	Q	MPDATA	
9	Chapman	Nudging	Reduced	Radiation	On	Q	MPDATA	
10	Chapman	Nudging	Reduced	Radiation	Off	UV	MPDATA	
11	Chapman	Nudging	Reduced	Radiation	Off	UV	Akima 4^{th}	
12	Chapman	Nudging	Reduced	Radiation	On	UV	Akima 4^{th}	
13	Chapman	Nudging	Flather	Nudging	On	UV	MPDATA	
nfull1	Chapman	Nudging	Flather	Nudging	Off	UV	MPDATA	Fully nested run... Risc8 source FS, 2d, 3d, T

	Initial Cond	Rivers	Boundary	M3_Nudge	T_Nudge	M2_Nudge	AKV_BAK
a	Simple gradient	X1.5	June Risc8	0.8	7	0.04	1.00E-007
b	Interp from Risc8	X1.5	June Risc8	0.8	7	0.04	1.00E-007
c	Interp from Risc8	X1.5	June Risc8	0.1	7	0.04	1.00E-007
d	Interp from Risc8	X1.5	June Risc8	0.4	7	0.04	1.00E-007
e	Interp from Risc8	X1.5	June Risc8	0.4	7	0.04	1.00E-007
f	Interp from Risc8	X1.5	June Risc8	0.4	7	0.04	1.00E-006
g	Interp from Risc8	X1.5	June Risc8	0.4	7	0.04	1.00E-007
h	Interp from Risc8	X1.5	June Risc8	0.4	7	0.04	1.00E-006
k	Interp from Risc8	X1.5	June Risc8	0.4	0.5	0.02	1.00E-007

Table 2. Range of statistical comparisons between model and observed northward velocity for model simulation NBC2K using the new Full Bay model grid domain.

% Row Description 1 2 3 4 5 6
% --- ----------- ---
% 1 Model Min Mean Max Std Std/Mean -
% 2 Observations Min Mean Max Std Std/Mean -
% 3 Difference DMin DMean DMax RMSE SM(M)-SM(O) R
% 4 Summary REM AREM AME ECV - -

WP Instantaneous Top					
-0.4756	-0.0005	0.4860	0.2451	-543.7527	0
-0.5257	-0.0029	0.5523	0.2060	-71.1849	0
-0.3038	0.0024	0.3131	0.0967	-472.5678	0.9227
-0.8443	0.8443	0.0777	33.3965	0	0
WP Instantaneous Bottom					
-0.3754	0.0214	0.4381	0.1964	9.1851	0
-0.4185	-0.0152	0.5640	0.1669	-11.0117	0
-0.3278	0.0365	0.5223	0.1013	20.1968	0.8771
-2.4102	2.4102	0.0796	6.6816	0	0
WP Residual Top					
-0.0225	0.0003	0.1334	0.0101	37.7807	0
-0.1135	-0.0056	0.0478	0.0248	-4.4734	0
-0.0571	0.0058	0.1245	0.0289	42.2541	-0.1612
-1.0479	1.0479	0.0221	5.1963	0	0
WP Residual Bottom					
-0.0134	0.0220	0.1348	0.0131	0.5981	0
-0.1963	-0.0244	0.0803	0.0501	-2.0551	0
-0.0636	0.0463	0.2078	0.0690	2.6532	0.0493
-1.9020	1.9020	0.0535	2.8325	0	0
EP Channel Instantaneous Top					
-0.2986	0.0385	0.3409	0.1313	3.4107	0
-0.3517	0.0616	0.5117	0.1149	1.8665	0
-0.3587	-0.0231	0.3500	0.1209	1.5441	0.5422
-0.3747	0.3747	0.0980	1.9637	0	0
EP Channel Instantaneous Bottom					
-0.1526	0.0495	0.2509	0.0948	1.9164	0
-0.3110	0.0571	0.4075	0.0877	1.5348	0
-0.2700	-0.0077	0.3673	0.0948	0.3816	0.4662
-0.1340	0.1340	0.0752	1.6591	0	0
EP Channel Residual Top					
-0.0342	0.0388	0.1241	0.0231	0.5963	0
-0.1258	0.0617	0.2465	0.0727	1.1793	0
-0.2272	-0.0228	0.1821	0.0809	-0.5830	-0.0572
-0.3704	0.3704	0.0610	1.3113	0	0
EP Channel Residual Bottom					
0.0143	0.0497	0.0905	0.0153	0.3077	0
-0.1191	0.0573	0.1808	0.0523	0.9122	0
-0.1500	-0.0076	0.1684	0.0568	-0.6045	-0.1280
-0.1318	0.1318	0.0419	0.9915	0	0

Table 3. Values for model skill parameter and RMS for data-model comparisons in salinity and northward velocity using Full Bay Model Grid. Model Simulation Title: NBC2K

	Skill Surface	Skill Bottom	RMS Surface	RMS Bottom
SALINITY				
Bullocks	0.561	0.410	5.855	1.423
Quonset	0.513	0.499	2.816	0.912
Poppasquash	0.559	0.505	3.625	1.445

	Skill Surface	Skill Bottom	RMS Surface	RMS Bottom
WP Instant. Vel.	0.953	0.723	0.097	0.121
EP Instant. Vel.	0.919	0.688	0.101	0.095
WP Residual Vel.	0.226	0.337	0.029	0.081
EP Residual Vel.	0.429	0.217	0.069	0.057

Table 4. Comparisons of instantaneous and residual velocity from Rogers Thesis modeling using the ROMS model domain including Rhode Island Sound. Comparisons using skill parameter and RMS difference for summer, 2006 period. Units of RMS are m/s. East Passage (EP) data are from the shipping channel (see Figure 1).

	WP Skill	WP RMS	EP Skill	EP RMS
Surface	0.86	0.15	0.74	0.10
Bottom	0.83	0.14	0.71	0.08
Surface Residual	0.56	0.03	0.70	0.06
Bottom Residual	0.62	0.05	0.79	0.03

Table 5. Comparison of salinity output from Rogers Thesis modeling using the ROMS model domain including Rhode Island Sound with data. (see Figure 1).

Buoy	Skill	RMS (PSU)
Conimicut Top	0.87	4.18
Bottom	0.52	1.89
Mount View Top	0.88	1.61
Bottom	0.68	0.91
Poppasquash Top	0.89	2.14
Bottom	0.69	0.88

Table 6. Summary of statistical data-model comparisons on residual northward velocity for an additional series of test runs to explore the use of nesting, where output from the Rhode Island Sound – Narragansett Bay models from Rogers' MS thesis modeling is used to drive the full bay models. In these the open ocean boundary is at the mouth of the Bay. The first table provides a key for information in subsequent tables (descriptions match those provided in Appendix A and B). Each sub-table starts has a header corresponding to the name for the model run (see Table 1 for description of parameters for each case).

Model	**Min**	**Mean**	**Max**	**Std**	**Std/Mean**	**-**
Observations	**Min**	**Mean**	**Max**	**Std**	**Std/Mean**	**-**
Difference	**DMin**	**DMean**	**DMax**	**RMSE**	**SM(M)-SM(O)**	**R**
Summary	**REM**	**AREM**	**AME**	**ECV**	**-**	**-**

NFULL1k						
WP_top	-0.2	0.02	0.06	0.02	1.11	0
	-0.11	-0.01	0.05	0.03	-6.41	0
	-0.23	0.03	0.14	0.05	7.52	-0.11
	-5.14	5.14	0.04	9.74	0	0
WP_bottom	-0.18	0.07	0.19	0.05	0.72	0
	-0.2	0.05	0.05	0.06	-1.21	0
	-0.04	0.12	0.31	0.13	1.93	0.17
	-2.38	2.38	0.12	2.78	0	0
EP_top	-0.1	0.07	0.12	0.02	0.35	0
	-0.11	0.04	0.19	0.06	1.47	0
	-0.15	0.03	0.17	0.07	-1.11	0.09
	0.7	0.7	0.05	1.68	0	0
EP_bottom	-0.08	0.09	0.19	0.03	0.28	0
	-0.06	0.04	0.14	0.04	1.06	0
	-0.09	0.05	0.23	0.07	-0.78	-0.04
	1.25	1.25	0.06	1.77	0	0

NFULL1h						
WP_top	-0.2	0.02	0.06	0.02	1.11	0
	-0.11	-0.01	0.05	0.03	-6.44	0
	-0.23	0.03	0.14	0.05	7.55	-0.11
	-5.1	5.1	0.04	9.74	0	0
WP_bottom	-0.18	0.07	0.19	0.05	0.72	0
	-0.2	-0.05	0.05	0.06	-1.25	0
	-0.04	0.11	0.31	0.13	1.97	0.15
	-2.42	2.42	0.12	2.84	0	0
EP_top	-0.1	0.07	0.12	0.03	0.37	0
	-0.11	0.04	0.19	0.06	1.47	0
	-0.15	0.03	0.17	0.07	-1.09	0.15
	0.63	0.63	0.05	1.63	0	0
EP_bottom	-0.08	0.09	0.19	0.03	0.3	0
	-0.06	0.04	0.14	0.05	1.08	0
	-0.09	0.05	0.23	0.07	-0.78	-0.05
	1.18	1.18	0.06	1.75	0	0

NFULL1g						
WP_top	-0.2	0.02	0.06	0.03	1.13	0
	-0.11	0	0.05	0.04	-8.51	0
	-0.23	0.03	0.14	0.06	9.64	-0.12
	-6.32	6.32	0.04	12.68	0	0
WP_bottom	-0.18	0.07	0.19	0.05	0.65	0
	-0.2	-0.05	0.05	0.06	-1.15	0
	-0.04	0.13	0.31	0.14	1.81	0.25
	-2.42	2.42	0.13	2.75	0	0
EP_top	-0.1	0.07	0.12	0.03	0.41	0
	-0.11	0.04	0.19	0.06	1.64	0
	-0.15	0.03	0.17	0.07	-1.24	0.09
	0.76	0.76	0.06	1.89	0	0
EP_bottom	-0.08	0.09	0.19	0.03	0.3	0
	-0.06	0.04	0.14	0.05	1.2	0
	-0.09	0.06	0.23	0.08	-0.9	-0.01
	1.42	1.42	0.06	2	0	0

Table 7. Summary of statistical data-model comparisons for residual northward velocity. As in Table 6, these are for additional series of test runs that explore the use of nesting, where output from the Rhode Island Sound – Narragansett Bay models from Rogers' MS thesis modeling is used to drive the full bay models, where the open ocean boundary is at the mouth of the Bay. Values listed are for the skill parameter and root mean square. Skill values are higher than cases without nesting (e.g., Table 3), but not as high as in Roger's thesis work (Table 4). Parameters for each case are given in Table 1.

NFULL1k		
	RMSD	**RMSKILL**
WP top	0.05	0.36
WP bottom	0.13	0.4
EP top	0.07	0.38
EP bottom	0.08	0.41

NFULL1h		
	RMSD	**RMSKILL**
WP top	0.05	0.36
WP bottom	0.13	0.4
EP top	0.07	0.39
EP bottom	0.07	0.41

NFULL1g		
	RMSD	**RMSKILL**
WP top	0.06	0.35
WP bottom	0.14	0.41
EP top	0.07	0.37
EP bottom	0.09	0.42

Table 8. Model runs completed using the B-PSR model. Each variable was based on 10-year high, low and averaged values. These are unpublished results from N. LaSota, 2009.

Run #	River Flow	Winds	Wind Direction	Tides	Run #	River Flow	Winds	Wind Direction	Tides
1	Low	-	-	Neap	15	Average	High	Northeasterly	Neap
2	Low	-	-	Spring	16	Average	High	Northeasterly	Spring
3	Average	-	-	Neap	17	Low	Low	Southwesterly	Neap
4	Average	-	-	Spring	18	Low	Low	Southwesterly	Spring
5	Low	Low	Northeasterly	Neap	19	Low	Average	Southwesterly	Neap
6	Low	Low	Northeasterly	Spring	20	Low	Average	Southwesterly	Spring
7	Low	Average	Northeasterly	Neap	21	Low	High	Southwesterly	Neap
8	Low	Average	Northeasterly	Spring	22	Low	High	Southwesterly	Spring
9	Low	High	Northeasterly	Neap	23	Average	Low	Southwesterly	Neap
10	Low	High	Northeasterly	Spring	24	Average	Low	Southwesterly	Spring
11	Average	Low	Northeasterly	Neap	25	Average	Average	Southwesterly	Neap
12	Average	Low	Northeasterly	Spring	26	Average	Average	Southwesterly	Spring
13	Average	Average	Northeasterly	Neap	27	Average	High	Southwesterly	Neap
14	Average	Average	Northeasterly	Spring	28	Average	High	Southwesterly	Spring

Appendix A. Matlab script written by J. Rogers for developing statistical comparisons between ROMS model time series output and time series data from moored instruments.

```
function mstats=modelstats(mod,obs)
%
%  mstats=modelstats(mod,obs)
%
%  Daniel L. Mendelsohn, ASA 1998
%
%  Model Data Comparison Statistics
%       This function assumes that the mod and obs arrays are vectors
%       and that they have identical dimensions.
%  Produces a 4x6 matrix of the following statistics
%
%       Row     Description                1           2               3               4                       5                        6
%       ---     -----------                ------------------------------------------------
%       1               Model                   Min         Mean        Max         Std     Std/Mean            -
%       2               Observations    Min         Mean        Max         Std     Std/Mean            -
%       3               Difference              DMin    DMean   DMax    RMSE    SM(M)-SM(O)         R
%       4               Summary                 REM     AREM    AME         ECV          -                          -
%
%       where           Min             = minimum value of the time series
%                               Mean            = mean value of the time series
%                               Max             = maximum value of the time series
%                               Std             = Standard deviation of the time series
%                               Std/Mean    = Standard deviation divided by the mean
%                               Dmin            = Difference of the minimums (Model-Obs)
%                               Dmean           = Difference of the means (Model-Obs)
%                               Dmax            = Difference of the maximums (Model-Obs)
%                               RMSE            = Root mean square error
%                           SM(M)-SM(O) = Difference of the Std/Mean(Model) - Std/Mean(Observations)
%                               R                       = Correlation coefficient for Model on Observations
%                               REM                 = Relative Error of the Means
%                               AREM            = Absolute Relative Error of the Means
%                               AME                 = Absolute Mean Error
%                               ECV                 = Error Coefficient of Variation
%
[im jm] = size(mod);
[io jo] = size(obs);

if jm~=jo
   TempStr=['Array sizes do not match'];
   disp(TempStr)
   mstats=NaN;
   break;
elseif jm==0
   TempStr=['Zero array size'];
   disp(TempStr)
   mstats=NaN;
   break;
elseif jo==0
   TempStr=['Zero array size'];
   disp(TempStr)
   mstats=NaN;
   break;
end

%======================= Model own
mstats(1,1) = min(mod);
mstats(2,1) = mean(mod);
mstats(3,1) = max(mod);
mstats(4,1) = std(mod,2);
mstats(5,1) = mstats(4,1)/mstats(2,1); %Std/Mean

%======================= Data own
mstats(1,2) = min(obs);
mstats(2,2) = mean(obs);
mstats(3,2) = max(obs);
mstats(4,2) = std(obs,2);
mstats(5,2) = mstats(4,2)/mstats(2,2); %Std/Mean

%======================= Difference
diff = mod - obs;
absdiff = abs(mod - obs);
mstats(1,3) = min(diff);   % of the minimums (Model-Obs)
mstats(2,3) = mean(diff);  % of the means (Model-Obs)
mstats(3,3) = max(diff);   % of the maximums (Model-Obs)
[n junk] = size(diff);
mstats(4,3) = sqrt(sum(diff.^2)/n);   % RMS error
mstats(5,3) = mstats(5,1) - mstats(5,2);  %of the Std/Mean(Mod)-Std/Mean(Obs)

r = corrcoef(mod,obs);     % Correlation coefficient
mstats(6,1) = 0;
mstats(6,2) = 0;
mstats(6,3) = r(1,2);
```

```
mstats(1,4) = mstats(2,3)/mstats(2,2);      % Relative error of means
mstats(2,4) = abs(mstats(2,3)/mstats(2,2)); % Absolute Relative error of means
mstats(3,4) = mean(absdiff);                % Absolute mean error
mstats(4,4) = abs(mstats(4,3)/mstats(2,2)); % Error coeff. of variation
mstats(5,4) = 0.0;
mstats(6,4) = 0.0;
```

Appendix B. Statistical comparisons between model output from the 20 day simulation using the newly developed grid and 2006 observational ADCP current meter data. The statistical comparisons are made using the suite of statistical functions supplied by D. Mendelsohn.

```
>> WPstatst'

   -0.4663    0.0072    0.4662    0.2307   32.1683         0
   -0.5256   -0.0084    0.5522    0.2033  -24.2036         0
   -0.5133    0.0156    0.4472    0.1762   56.3718    0.6798
   -1.8540    1.8540    0.1378   20.9749         0         0

>> WPstatsb'

   -0.4389    0.0195    0.4208    0.1988   10.1667         0
   -0.4060   -0.0239    0.3939    0.1648   -6.8926         0
   -0.4342    0.0435    0.4939    0.1594   17.0593    0.6586
   -1.8178    1.8178    0.1263    6.6674         0         0

>> EPstatst'

   -0.2615    0.0274    0.3374    0.1157    4.2253         0
   -0.3362    0.0497    0.4320    0.1119    2.2510         0
   -0.4314   -0.0223    0.4227    0.1321    1.9744    0.3462
   -0.4491    0.4491    0.1032    2.6569         0         0

>> EPstatsb'

   -0.1771    0.0304    0.2210    0.0944    3.1010         0
   -0.3110    0.0477    0.3685    0.0880    1.8454         0
   -0.3597   -0.0173    0.3701    0.1137    1.2556    0.2424
   -0.3618    0.3618    0.0883    2.3837         0         0

%   Row   Description          1      2      3      4         5     6
%   ---   -----------          -------------------------------------------------
%   1      Model         Min      Mean   Max      Std       Std/Mean
%   2      Observations  Min      Mean   Max      Std       Std/Mean
%   3      Difference    DMin     DMean  DMax     RMSE   SM(M)-SM(O)   R
%   4      Summary       REM      AREM   AME      ECV       -         -
%
%    where   Min       = minimum value of the time series
%      Mean       = mean value of the time series
%      Max       = maximum value of the time series
%      Std       = Standard deviation of the time series
%      Std/Mean    = Standard deviation divided by the mean
%      Dmin      = Difference of the minimums (Model-Obs)
%      Dmean      = Difference of the means (Model-Obs)
%      Dmax      = Difference of the maximums (Model-Obs)
%      RMSE      = Root mean square error
%      SM(M)-SM(O) = Difference of the Std/Mean(Model) -                                Std/Mean(Observations)
%      R         = Correlation coefficient for Model on Observations
%      REM          = Relative Error of the Means
%      AREM      = Absolute Relative Error of the Means
%      AME          = Absolute Mean Error
%      ECV          = Error Coefficient of Variation
```