An Assessment of the Long Island Sound Circulation and Storm Surge Model

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1. Introduction

The prediction of the effects of climate change on the statistics of coastal flooding is essential to the development and evaluation of designs for risk reduction. Though the physical processes that link tides and wind forced motions to sea level variations are well established and understood, computing solutions to the equations is difficult because of their intrinsic nonlinearity and the complex, and wide variations in scales in, the geometry of the coastline. In addition, the coastal ocean is inherently linked to the global ocean and the conditions imposed at the edges of the smaller domain inherently have errors. The forcing imposed by the wind is also approximate. Many choices and judgements are therefore built into coastal models and the consequences of these need to be assessed empirically. In this document we describe the assessment of a model we have develop to guide the projection of sea level rise on coastal flooding in Connecticut.

In the next section we summarize the development of the model of Long Island Sound (LIS) and the initial tests we conducted using NOAA tide gage data. We then describe a more detailed examination of the model performance in prediction of currents in a complex area. We then show the performance of the model when realistic winds are used to force the motion and then summarize the results.

2. Model Development and Preliminary Calibration

We have developed a high resolution model of the circulation and hydrography in Long Island Sound (LIS) and Block Island Sound (BIS) in collaboration with Prof. C. Chen of University of Massachusetts, Dartmouth. The domain of the model and the resolution in the study area are shown in Figure 1. The model is an implementation of FVCOM (Chen et al., 2007) and is designed to exploit forecasts of the northwest Atlantic regional model operated as the Northeast Coastal Forecast System. This approach is computationally efficient since it allows the effect of the larger-scale processes to be simulated at coarse resolution and allows UConn's computing resources to focus on the smaller scale structures in LIS and BIS. In this section we outline the model forcing, the process of calibration and the model performance, and then comparison to measurement collected in the study.

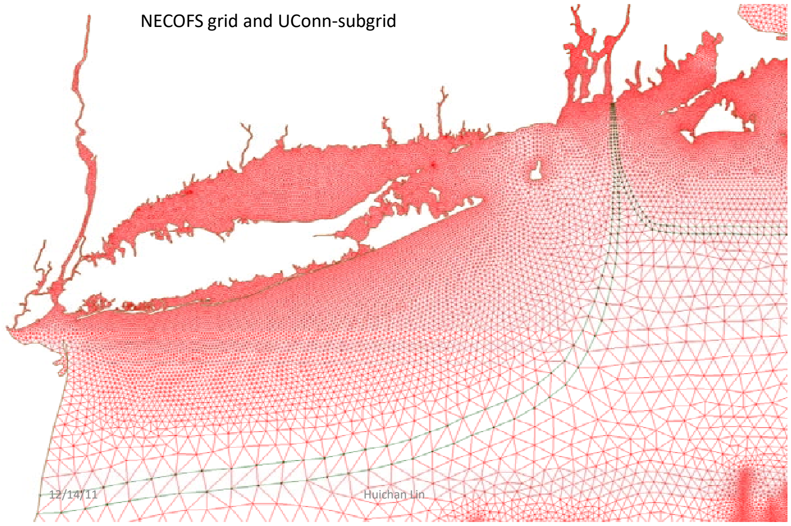

Figure 1. Map of southern New England shore showing the model grid (red). Blue cells show the boundary locations where the regional model NECOFS and the nested LIS-BIS sub-domain overlap.

FVCOM was initialized using a temperature and salinity climatology dataset derived via objective interpolation (OI) from CTDEEP station and offshore buoy records. This climatology has been constructed for times representing four seasons: 15 Oct, 15 Jan, 15 Apr, and 15 Jul. In order to be input into FVCOM, these OI fields are interpolated from sigma level depths to a set of standard depth levels. The standard depths were chosen as: [0. -2. -4. -6. -8. -10. -12. -15. -20. -25. -30. -40. -60. -80. -100.m]. The model simulations are started in the fall for the subsequent year in order to provide an adjustment period.

FVCOM is forced at the open boundaries by sea level variations. We employ constituents derived from the from the TOPEX model using the Foreman algorithm. These boundary conditions are then iteratively adjusted to achieve an optimal representation of the amplitude and phase at each tidal frequency using NOAA tidal height observations from 2012 at Montauk, New London, CT, New Haven, CT, Bridgeport, CT, and King's Point, NY. Each constituent amplitude was adjusted by the mean of the relative amplitude. Fig 2 shows an example of the result of this procedure on the observed and predicted level at the NOAA Bridgeport tide gauge. The mean tidal skill, defined using the model tidal height errors normalized by the tidal amplitudes, was improved from 88% to better than 96%. Figure 3 show a comparison of the predicted and observed sea level variation at a NOAA ADCP near Hammonassett Point.

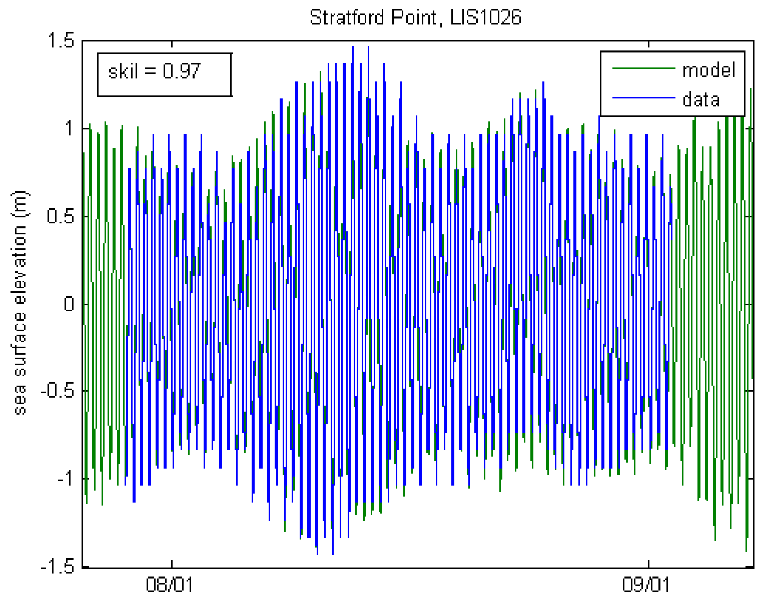

Figure 2. Comparison of model prediction and observation of sea level at the NOAA ADCP LIS1026.

Although the calibration procedure did not involve ADCP current observations, the model captures tidal currents and tidal constituents of depth-averaged currents well. Minor differences appear where the topography is steep or the data did not cover a full spring-neap tidal cycle. Time series comparisons (below) between field measurements and model simulations of the same time period demonstrate the model successfully predicts tidal currents. (See Fig. 3.)

Heat fluxes in FVCOM are prescribed; the model makes no internal calculations of these fluxes. FVCOM can be linked to an atmospheric model and thereby calculate surface heat fluxes in a coupled ocean/ atmosphere manner, but we have not implemented this capability yet. The model is therefore sensitive to the heat fluxes imposed. Domain-uniform fluxes are derived using the WHOI/USGS air-sea toolbox, and then iteratively tuned so as to reproduce the water temperature climatology. The heat flux forcing used is thus neither year nor location specific, but replicates the annual warming and cooling cycle near Stratford Shoals well. Figure 4 shows a comparison of the FVCOM prediction for bottom temperature in the study area for the interval Oct 2012 - Oct 2013 and compares it to the temperatures measured by the bottom frames.

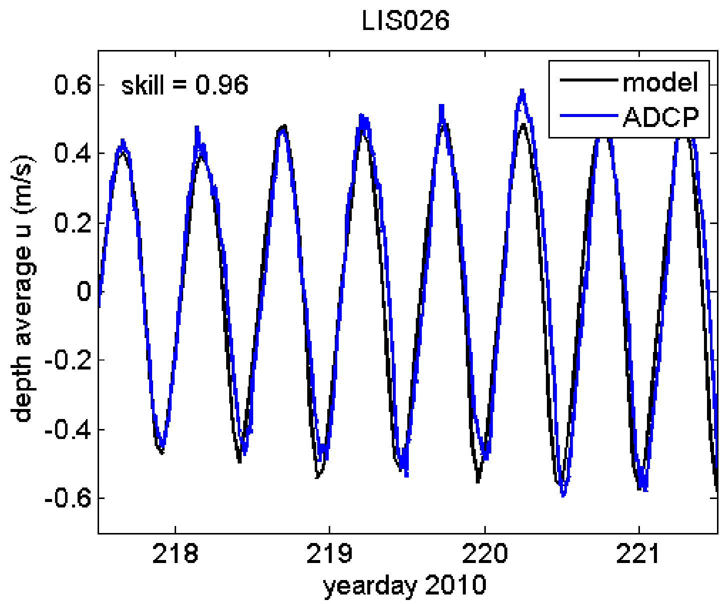

Figure 3. ADCP deployment (blue) compared to those predicted by the FVCOM model (black).

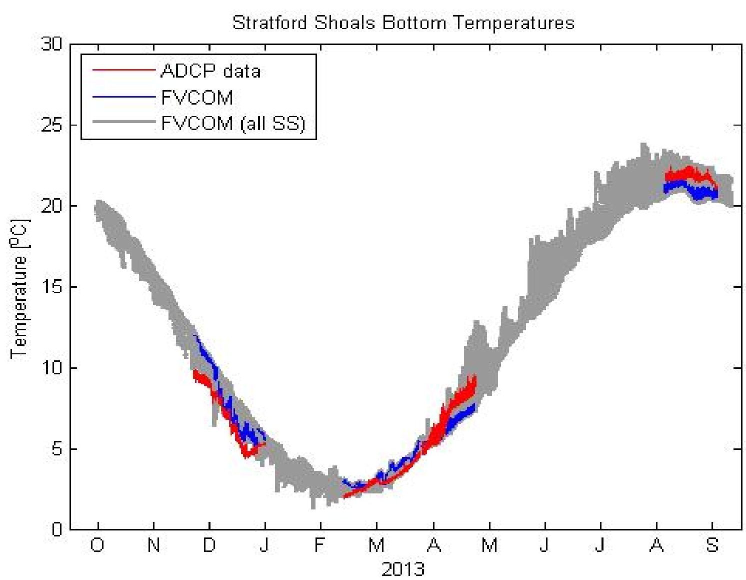

Fig. 4. Comparison of bottom temperatures (°C) in the FVCOM model with those measured during the six ADCP deployments at Stratford Shoals (SS). The temperatures measured by the ADCP sensors are shown in red; shown in grey are the FVCOM model solutions for the entire year at all six SS deployment sites; the FVCOM results at the individual sites for each deployment period are shown in blue. Based on these six data sets, the overall model skill with respect to bottom temperatures in this region is 98%. (Calculated as $l = 1 - \frac{1}{N}\sum_{1}^{N}\frac{(model-data)^2}{\sigma^2}$)

Freshwater is input into the LIS FVCOM domain at 5 points corresponding to the locations of the Rivers Thames, Niantic, Quinnipiac, Housatonic, and Hudson rivers. The fluxes are gauged flows measured by USGS and increased by 20% to account for below-gauge watershed. The gauged flows are lagged by one day to account for the distance between the head of the Connecticut River in our model and Thompsonville. Each river, R_i, is adjusted using the USGS Thompsonville data as $R_i = 1.20 \frac{R_{CT}}{\overline{R_{CT}}} \overline{R_i}$ where R_{CT} is the day-specific Connecticut River flow, $\overline{R_{CT}}$ is the mean Connecticut River flow, and $\overline{R_i}$ is the mean flow for river *i*. An additional fixed input of 40 $m^3\ s^{-1}$ was added to the East River to represent the freshwater fluxes from the Bronx River and New York City Sewage Treatment Plants. Fig. 5 shows a comparison of the model salinity in the western LIS at the LISICOS ARTG buoy location (near CTDEEP station E1) with climatology derived from the CTDEEP surveys and with the 2013 buoy measurements.

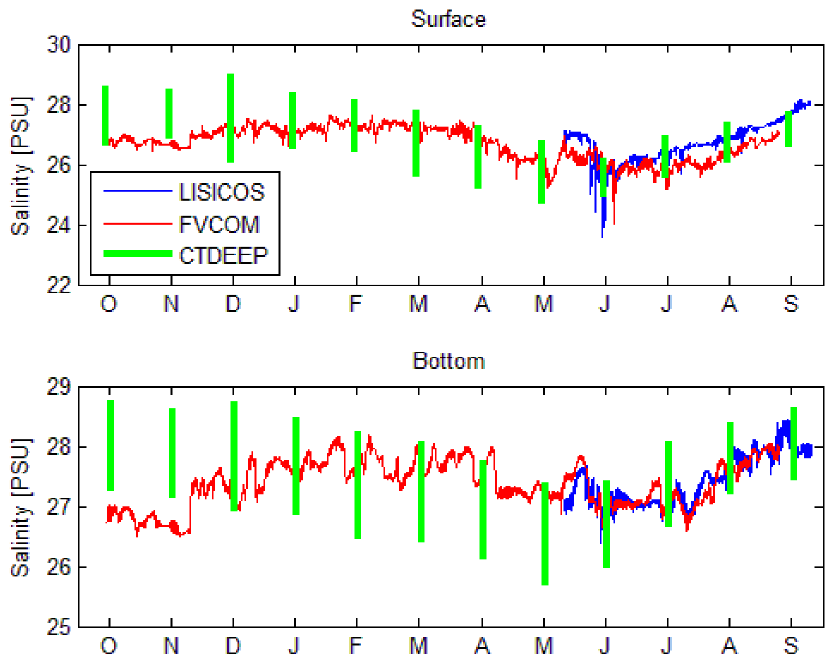

Fig.5. 2012-2013 salinity at ARTG/ E1 for the near surface (top panel) and near-bottom (bottom panel). The FVCOM model predictions are shown in red. Shown by the green bars are the means ± one standard deviation of the CTDEEP data at station E1 binned by month for 1993-2012. Shown in blue are the salinities measured by the LISICOS ARTG buoy for water year 2013. Note that the model is closer to the buoy observations for the near-bottom observations than the climatology is, indicating that the model has a positive Brier skill compared to the climatology at this location.

The model is forced with domain-uniform winds obtained from the LISICOS Western Sound Buoy. Because FVCOM expects 10 m wind speeds, while the buoy winds are measured at 3.5 m, the wind speeds in the buoy record are converted to W_{10} values as $W_{10} = W_{3.5}\frac{\log(10\text{m}/z_0)}{\log(10\text{m}/z_0)}$ using z_0=0.01 m. Gaps in the buoy record are then filled in using W_{10} data from Bridgeport/ Sikorsky airport (BDR). Because of the disparity in the observational locations, contemporaneous data from both the buoy and BDR were regressed using a total least squares methodology and the regression results were applied to the BDR data for those periods where the buoy data was missing. Fig. 6 shows a comparison of the subtidal bed stresses predicted by the model during two wind events in 2013 with those calculated from the ADCP deployment data.

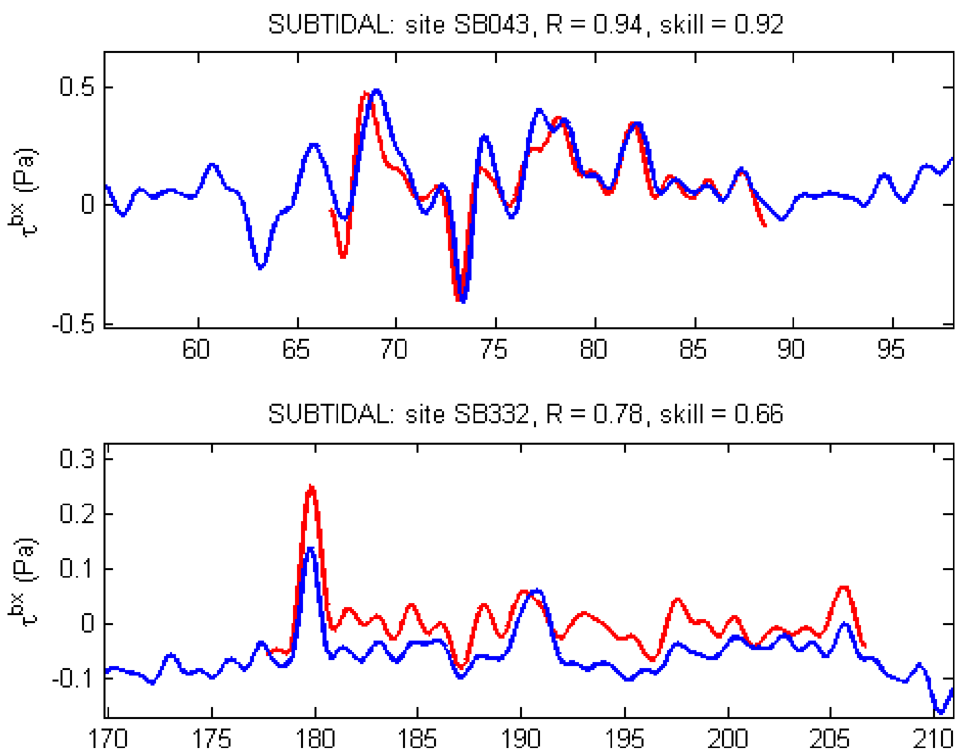

Fig. 6. Subtidal bottom stresses calculated from ADCP records (red) using the SB043 (top) and SB332 deployment data compared with those calculated from the FVCOM model predictions (blue) during wind events (wind speed > 15 m s^{-1}).

The model captures the spatial variation in the amplitude of the M2 tidal component very well. The M_2 is the primary tidal frequency in LIS and is responsible for the bulk of the semi-diurnal tide. Figure 7 shows a comparison of the M_2 amplitudes at the four LIS tidal gauges from the model (green) with those estimated from NOAA gauge data (blue.)

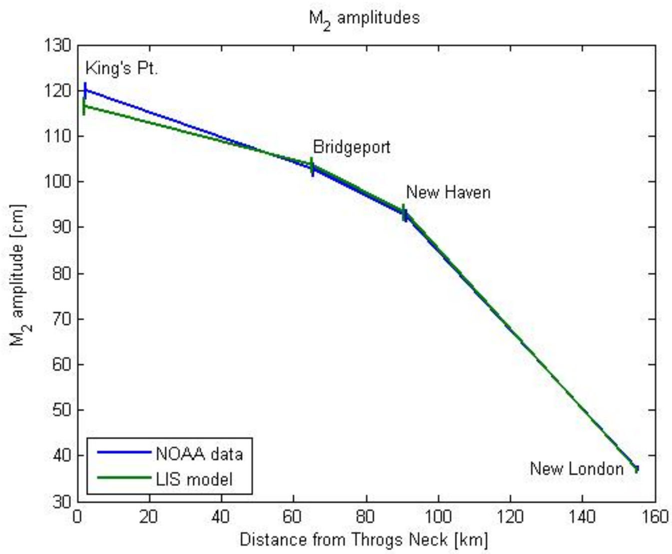

Figure 7. M_2 amplitudes plotted by along-Sound distance from the Throg's Neck estimated from NOAA tide gauge observations (blue) and from the LIS-FVCOM model results (green) using T_TIDE (Pakolwicz et al, 2002). The error bars show the uncertainties in the T_TIDE harmonic analyses.

The model also captures the along-estuary SSH gradient that results from the along-Sound density gradient as well as the mean wind stress. This is a result that is difficult to obtain from data. Figure 8 shows a plot of the model mean along-Sound model sea level predictions referenced to MSL at New London.

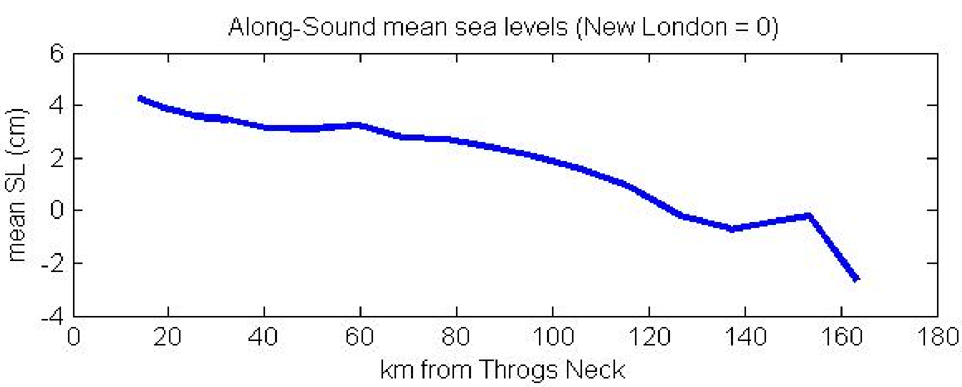

Figure 8. Mean model sea-level predictions (blue) along an along-Sound transect plotted by distance from the head of the Sound at the Throg's Neck.

3. Simulation Evaluation of the Stratford Shoals Area

To evaluate the performance of the model in the prediction of currents and stress in the study area, in Figure 9 we compare the M2 tidal current ellipses for the vertically averaged flow computed from the data acquired by the moored RDI ADCPs, to that estimated from the model. Note that the northern (SB043) and southern (SB332) most deployments are in excellent agreement with the observation-based ellipses and that the discrepancies in direction and amplitude are slightly larger at the station in the region of the most complex bathymetry.

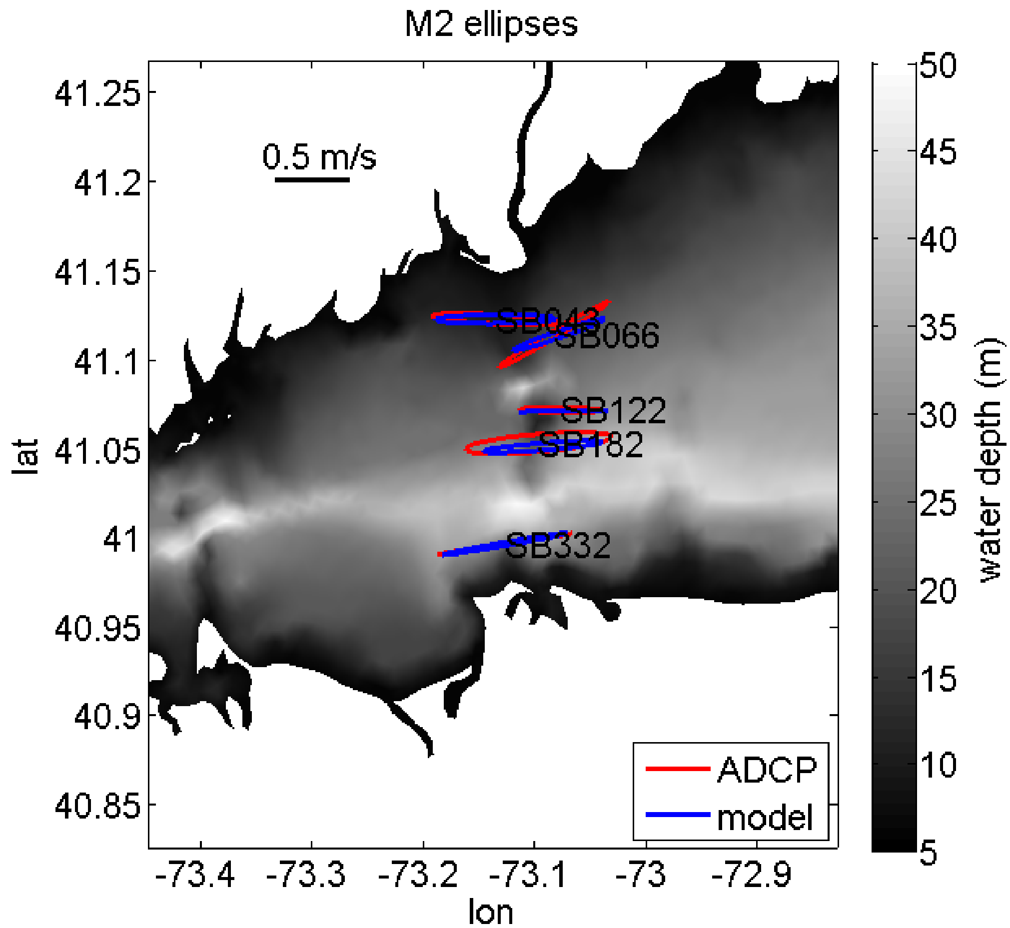

Figure 9. M2 ellipses for depth-average velocities from ADCP measurements (red) and FVCOM model (blue) at 5 sites on Stratford Shoals. ADCP deployments ranged from 13-44 days duration in the summer of 2013. Model ran from fall 2012 to fall 2013. The grey shading represents mean water depth.

Perhaps the most ecologically relevant parameter after temperature is the bottom stress. In Figure 10 we compare the model's estimate of the near bottom stress at the M2 frequency to that estimated by the moored instruments. The agreement at the northern and southern boundaries of the study area are within 10%, however, in the center the error is closer to 20%. This is clearer in

Figure 11 which shows a comparison of the time series of the stress components in the principle axis directions. There scale is chosen to clarify the intra-tidal variations. Stress magnitudes vary from -1.5Pa to 1.5Pa at the northern station and by substantially less at the central stations. The model resolves this spatial structure well. Skills are all over 90% and correlations vary from 80 to 92%.

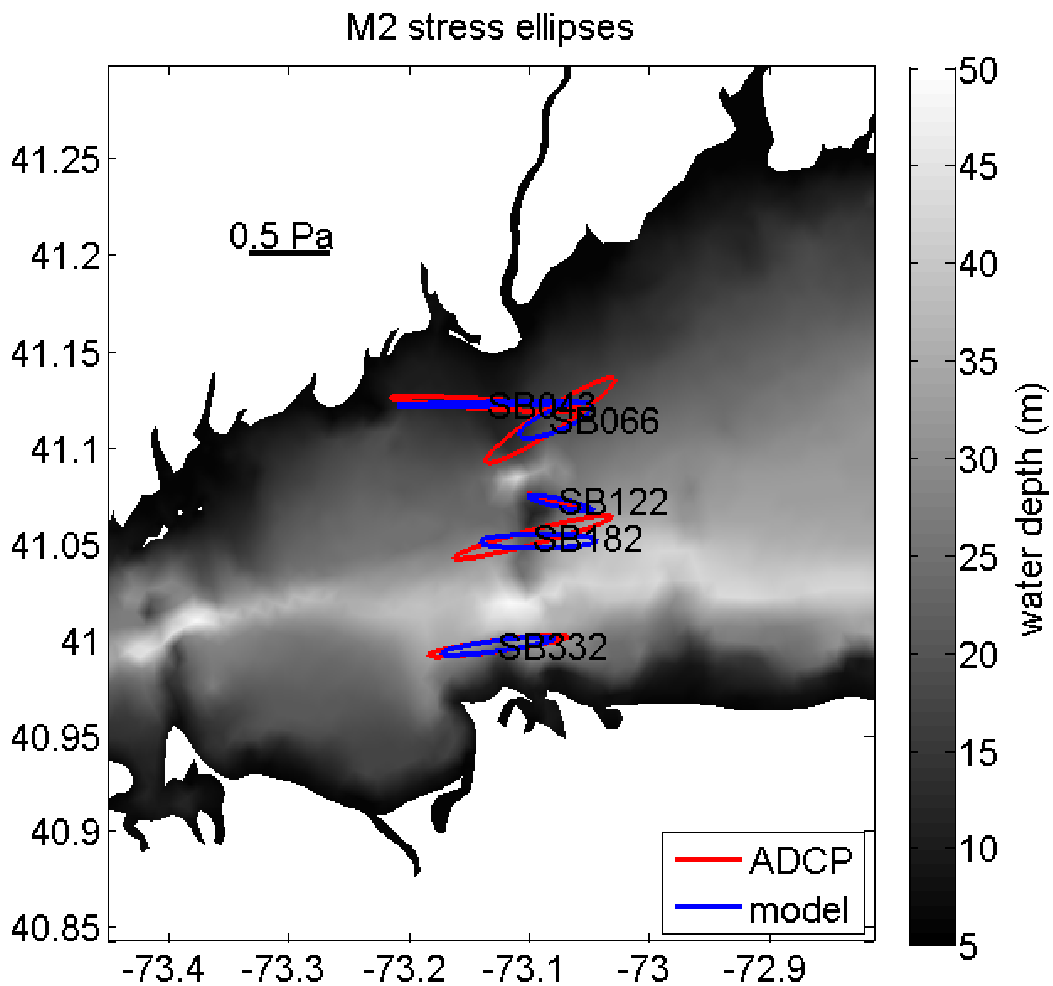

Figure 10. M2 ellipses for bottom stresses, calculated from lowest ADCP velocity measurement (red) and FVCOM model at similar elevation (blue) at 5 sites on Stratford Shoals. ADCP deployments ranged from 13-44 days duration in the summer of 2013. Model ran from fall 2012 to fall 2013.

The performance of the model in simulation of the longer term evolution of the bottom stress is demonstrated in Figure 12 which compares the low pass filtered observation and predictions at

SB043 (northern station) and SB332 (southern station) during times when the wind was strong (greater than 15 m/s). The results are very good in that the correlations are high and the magnitude as very close. There appears to be a slight low bias in the southern station.

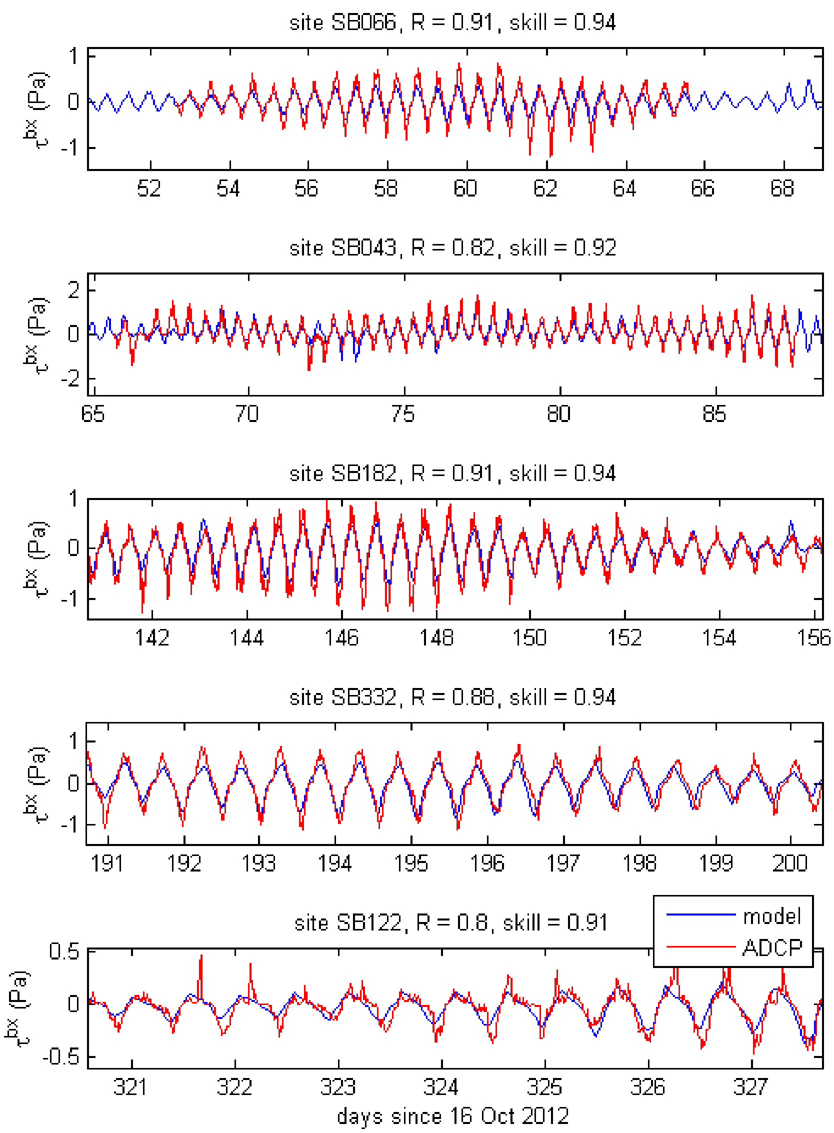

Figure 11. Time series of bottom stress at 5 sites on Stratford Shoals from the summer of 2013 calculated from ADCO (red) and FVCOM model (blue) velocity data.

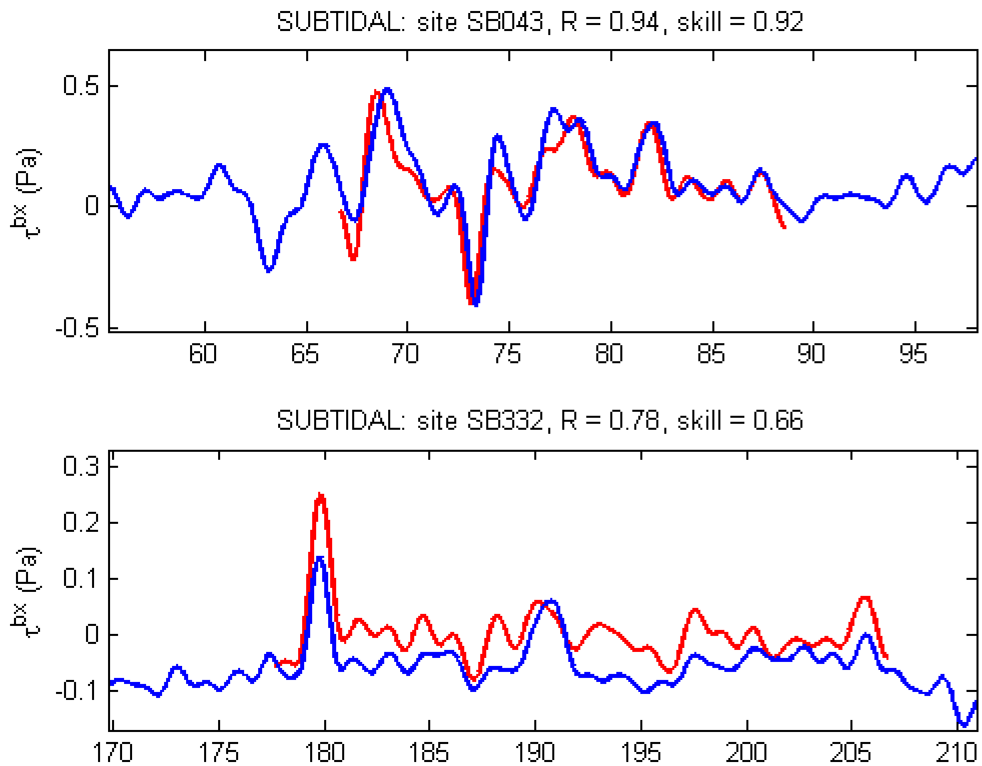

Figure 12. Subtidal bottom stresses calculated from the ADCP (red) and model (blue) at two sites on Stratford Shoals that experienced wind events (speed > 15 m/s) while the ADCP was deployed there.

4. Model Performance Summary

The comparison of the model simulations to temperature, salinity, current and bottom stress measurements are all show excellent agreement. The discrepancies between predictions and observations may be improved in the future to better represent high frequency fluctuations but the model results clearly support the model's use as a tool to interpolate spatially between the observations for the purpose of making maps of the characteristics of the bottom environment that are ecologically important.

LIS-FVCOM is forced at the seaward boundaries by sea level variations. The sea level is initially prescribed using tidal constituents derived from the global tidal model (Egbert et al., 1994). Since the Egbert et al. (1994) constituents are not precise in shelf areas, the amplitudes and phase of the major constituents were iteratively adjusted to achieve an optimal representation of the amplitude and phase at each tidal frequency using NOAA tidal height observations from 2010 at Montauk (NY), New London (CT), New Haven (CT), Bridgeport (CT), and King's Point (NY). Each constituent amplitude and phase was adjusted by the proportional amplitude error and phase error to optimize the model. Subtidal fluctuations at the open boundary are incorporated from the NECOFS system by de-tiding and low-pass filtering the NECOFS solution at the open boundary locations using t-tide (Pawlowicz et al., 2002) and a 25-hour raised cosine low-pass filter. The model's subtidal performance was further optimized by removing the low-passed error in the NECOFS subtidal forcing as determined by comparing the NECOFS solution with NOAA sea-surface height (SSH) gauges at Newport, RI and Atlantic City, NJ. These station are near the open boundary of the LIS model. The detided and adjusted NECOFS subtidal solution was then combined with a time series of tidal heights generated using the optimized tidal constituents.

To evaluate the performance of LIS-FVCOM, we use the "skill," s, statistic defined as (von Storch and Zwiers, 1999)

$$s_f = 1 - \frac{\langle (f_m - f_d)^2 \rangle}{\langle (f_d - \langle f_d \rangle)^2 \rangle} \qquad (1)$$

where f_m and f_d represent the model and data values and the $\langle\ \rangle$ notation represents the mean of the argument over the simulation interval (e.g., $< f_d >$ is the mean of the data).

Table 1 shows the model sea-surface-height (SSH) skill (Eq 1) from a realistic simulation of the year 2017 compared to hourly measurements at the four NOAA tidal gauges in LIS: New London, New Haven, Bridgeport, and King's Point. The first row shows the skills when simulated sea surface heights (relative to MSL) are compared to the raw observations. The second and third rows shows the skills when the model and data series are divided into tidal and weather components using harmonic analysis (Pawlowicz et al, 2002). The errors in the simulation of tides are small - the skills all exceed 93%. The errors in the simulation of the total water level (SSH) mainly arise from the errors in the simulation of the meteorologically driven motions and are, to a large extent due to inadequacies in the atmospheric model used to prescribe winds.

In conclusion, though this model is not perfect and some aspects can be improved, it is an excellent tool with which to develop guidance for the effects of sea level rise on tides, storm surges and flooding. The errors are bounded in this project and so the uncertainties that are inherent in the simulation can be considered in design guidance.

Table 1: Model skills (Eq 1) when model elevations are compared to NOAA gage data at New London, New Haven, Bridgeport, and Kings Point. The first row (Total SSH skill), shows the skills when sea-surface heights (relative to MSL) are compared, the second row shows the skills at tidal frequencies, the third row shows the skills for the subtidal residuals.

	New London	New Haven	Bridgeport	King's Point
Total SSH skill	91%	92%	93%	93%
Tidal skill	94%	93%	94%	94%
Subtidal skill	77%	75%	77%	54%

Egbert, G.D., A.F. Bennett and M.G.G. Foreman. 1994. TOPEX/POSEIDON tides estimated using a global inverse model. *J Geophys Res*. 99:C12:24821-24852.

Pawlowicz, R., B. Beardsley, and S. Lentz. 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Computers and Geosciences* 28:929-937.

von Storch, H. and F.W. Zwiers. 1999. *Statistical Analysis in Climate Research*. Wiley. ISBN-10: 0521012309