Modeling Tides in the Chesapeake Bay

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1.0 Introduction

The Chesapeake Bay is home to 348 species of finfish, 173 species of shellfish, and more than 2700 species of plants. It is the migratory home of 29 species of waterfowl and over one million individual waterfowl winter in the bay every year (EPA, 2003). This abundance of plant and animal life supports large scale commercial fishing, tourism, and recreation in the bay. The National Marine Fisheries Service reports that 508,953,559 pounds of fish were caught in the Chesapeake Bay in 2005, with a monetary value of $218,931,248. These numbers underestimate the total monetary value of the fishing industry in the bay since they do not consider the tourism industry built around recreational fishing and the service and distribution industries reliant on commercial fishing in the bay. These industries, along with many others in the bay are greatly reliant on the environmental conditions of the bay. Things such as water clarity, dissolved O_2, and the presence of various contaminants are all concerns.

Environmental quality factors are directly dependant on the tides in the bay. Tides and freshwater inputs from the various tributaries of the Chesapeake Bay control the hydraulics of the bay. Storms also play a role, but they are transient phenomena that do not greatly affect the mean conditions of the bay. Water clarity and dissolved O2 are directly tied to the mean velocity field in the bay. Increased velocities result in increased turbulence and mixing. Mixing helps transport dissolved O2 from surface waters to O2 depleted bottoms waters. While this processes is dominated by temperature driven density differences, tidal mixing also plays a role. Water's ability to maintain sediment in suspension is dependant turbulence and therefore dependant on velocity. Contaminants are also advected through the system by the flow of water. The goal of this study is to develop a quantitative and predictive model of hydraulics in the Chesapeake Bay. This model will be used to examine the hydraulic factors controlling water quality and transport in the bay, as well as to predict the bay's response to environmental change.

2.0 Model Developement

2.1 ADCIRC Description

For this report, ADCIRC, a state of the art coastal circulation model will be used. For our study we will use the ADCIRC 2DDI, the two dimensional depth integrated version of the software. ADCIRC 2DDI consists of the equations for conservation of mass and momentum of water with baroclinic forcing, tidal forcing, quadratic bottom stress, and a homogeneous and isotropic eddy diffusion/dispersion model (Luettich, 1992). It should be noted that in wind-driven flows, stratified flows, Ekman layers, or when wave orbital velocities or suspended sediment gradients are significant near the bottom, the assumptions made in the two dimensional model become inadequate. This model may also introduce error in transport models with a velocity at a given depth is necessary, due to the use of depth averaged velocity. The ADCIRC model has been verified to match observed data well in numerous studies (Luettich et al., 1991; Fortunato et al., 1997; Blain and Rogers, 1998;).

ADCIRC uses an unstructured triangular finite element grid for the model domain. It can employ a variety of boundary conditions, including specified periodic elevation, specified normal flow, slip or no slip, surface stress due to wind, and atmospheric pressure. The model is forced with elevation boundary conditions, normal flow boundary conditions, tidal potentials, surface stress boundary conditions, and self attraction tides (earth deformation) (Westerink et al., 1992). ADCIRC can output elevation and velocity data either as instantaneous values or periodic functions. Instantaneous values can be saved at any desired time step, global or point values can be saved. Periodic data can also be saved globally or for individual user specified points. In order to generate periodic functions for elevation and velocity ADCIRC performs harmonic analysis with user specified constituents.

2.2 Domain Construction

Three types of data were used to create the model domain: 1) coastline location data; 2) open boundary location data; and 3) bathymetry data. Coastline data was taken from the USGS Coastline Extractor using the World Data Bank II database. The open boundary was arbitrarily created and designed to be a sufficient distance away from the Chesapeake Bay to insure that the effects of boundary conditions were minimized. Bathymetry data within the Chesapeake Bay was taken from the US Coastal Relief Model with a grid cell size of 15 seconds. Bathymetry outside of the bay was taken from the ETOPO2v2 database with a grid cell size of 2 minutes. The coastline was post processed in order to insure that it was relatively smooth and that data points were consistently spaced. A boxcar-type filter was used on the coastline to smooth it, and then evenly spaced points were interpolated onto the coastline with a spacing of 1km. Bathymetry was also down sampled in order to shrink our domain to a more manageable size.

These data were used to make a triangular irregular network (TIN). The boundaries of the TIN were created from the coastline data and the open boundary data. Interior nodes were created from bathymetry data. A Delaunay Triangulation was done on the data with a specified minimum angle constraint of 30 degree and a maximum element size of 10 square kilometers. A section of the final grid is shown in figure 1.

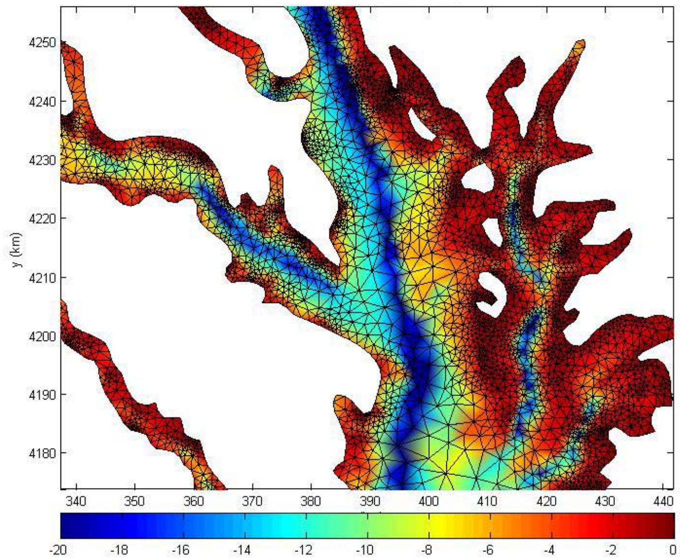

Figure 1: Grid elements near the mouth of the Potomac River in Chesapeake Bay. Color represents bathymetry in meters relative to mean low water.

In order for the model to be stable, element area must be sufficiently small in relation to the wavelength of the waves that will be passing through elements. In order to insure this, our domain was filtered to require a ratio of average depth to area of an element greater than 5 x 10^{-7}, see figure 2 for a plot of the values of this ratio. The use of depth in this constraint is justified by the fact that in shallow water tidal waves, wavelength is proportional to the square root of depth. A second constraint we imposed on our grid was that in all elements the ratio of the change in depth to the depth should be less than one (This ratio is referred to as the topographic length scale, or TLS). This constraint increases resolution in areas where bathymetry is quickly changing in order to insure model stability, see figure 3 for a plot of the values of this ratio.

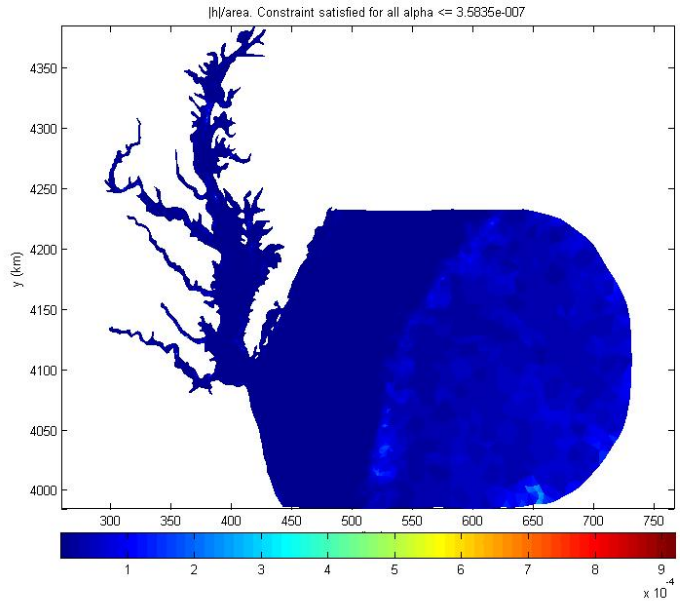

Figure2: values of the element depth to element area ratio.

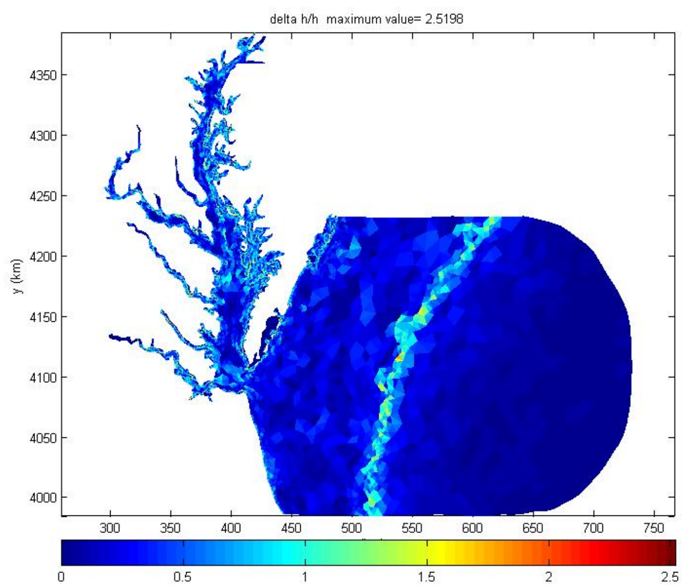

Figure 3: values of the change in depth to depth ratio

The bathymetry data available in the US Coastal Relief Model is given referenced to a datum of mean low water. ADCIRC assumes that bathymetry data is given in terms of mean sea level; therefore bathymetry had to be adjusted. In order to do this an initial model run was done in ADCIRC with data referenced to mean low water. Harmonic analysis of water surface elevations in the bay was done on the model's output. From this harmonic analysis, values of mean sea level and mean low water were calculated throughout the domain. The difference between the calculated values of mean sea level and mean low water was then subtracted from the depth of each node. Subsequent model runs were done with the adjusted data, comparing the difference between mean sea level and mean low water to the previous run and adjusting bathymetry accordingly. Eventually the difference between mean sea level and mean low water converges to zero; in our case this process took three iterations. This process is described in detail by Feyen et al. (unpublished).

The final domain consisted of 17612 elements and 10196 nodes, figure 4 shows a histogram of the areas and edge lengths of the elements. Analyses were done to determine the quality of the domain and the maximum time step allowed in our model. Because ADCIRC uses an explicit method, it is subject to the Courant-Friedrichs-Lewy Condition which limits the maximum time step allowable while maintaining numerical stability. The maximum time step is a function of element length and wave speed. Each element was analyzed to determine the maximum allowable time step by this criterion. In addition, triangle shape was analyzed in order to determine element quality. Equilateral triangles are desirable because they insure that element area is related to the distance across elements in a regular way, this is important since the filters applied assume equilateral triangles and so does the calculation for the max time step. Figure 5 is a plot containing the calculated values for the maximum time step as well as measurements of element quality, with a value of 1 being an equilateral triangle. Figure 6 is a histogram of TLS and the ratio of wavelength to grid size for each element. Wavelength is calculated using the shallow water wave assumption.

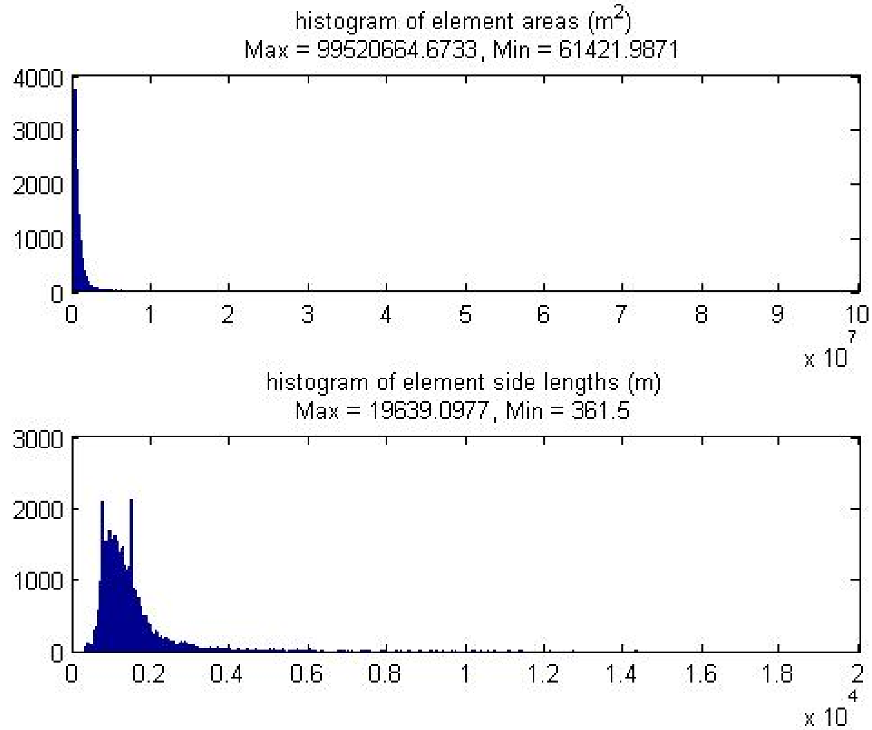

Figure 4: Histogram of element areas and element side lengths.

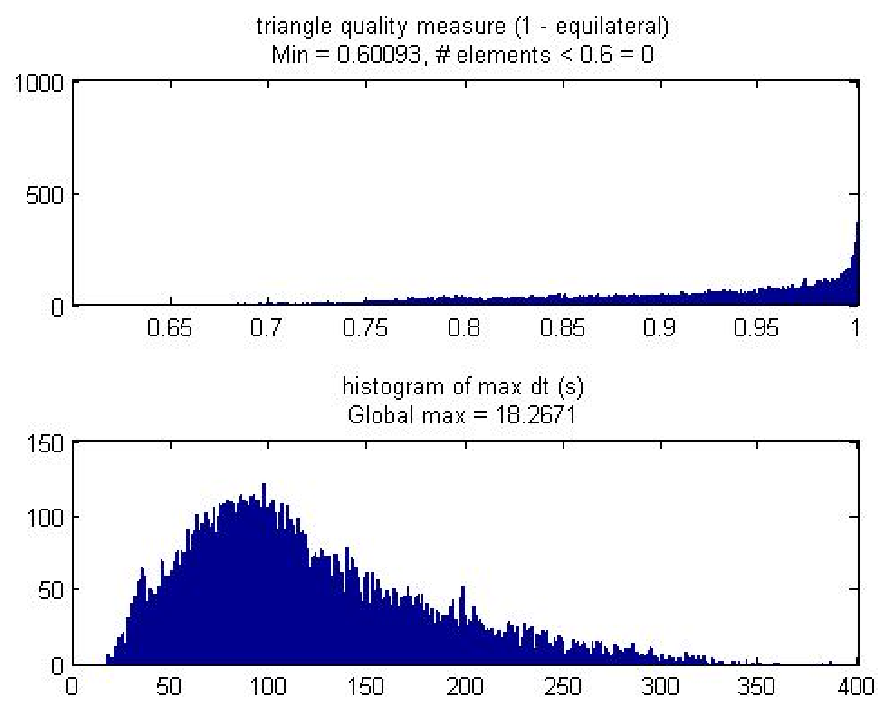

Figure 5: histograms of triangle quality and maximum time step for the model domain

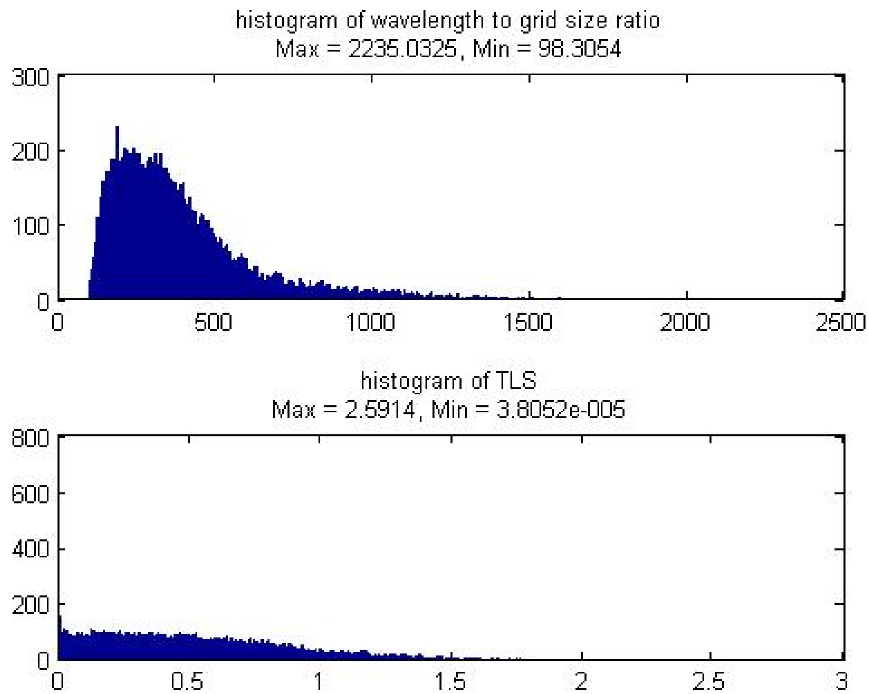

Figure 6: Histograms of wavelength to grid size and TLS for each element

2.3 Model Parameters

Specified boundary conditions are necessary both at the coast and along the open boundary of the domain. The coastal boundary condition was either no tangential flow and no normal flow or no tangential flow with a specified normal flow. Specified normal flows were given along the coast at the mouths of the Susquehanna, Potomac, and James rivers. Discharge data for these rivers was collected from the USGS National Water Information System. The open boundary was forced with specified periodic elevation functions corresponding to nine tidal constituents, the K1, O1, Q1, M2, S2, N2, K2, M4, and M6 tides. The forcing frequency, nodal factor, and equilibrium argument was specified for each of these constituents, and the amplitude and phase were given at each point along the boundary. The values for amplitude and phase were taken from the ADCIRC Western North Atlantic, Caribbean and Gulf of Mexico Tidal Database. This database was generated from another ADCIRC model that was run with a coarser, much larger domain. It does not provide high resolution data in small features such as the Chesapeake Bay, but does resolve deep ocean tides well. A section of the domain of this model is shown in figure 7. Wetting and drying, non-linear bottom friction, finite amplitude terms, convective acceleration and the time derivative of convective acceleration are all options in ADCIRC that add considerable complexity to model runs. All of these options were enabled for this study.

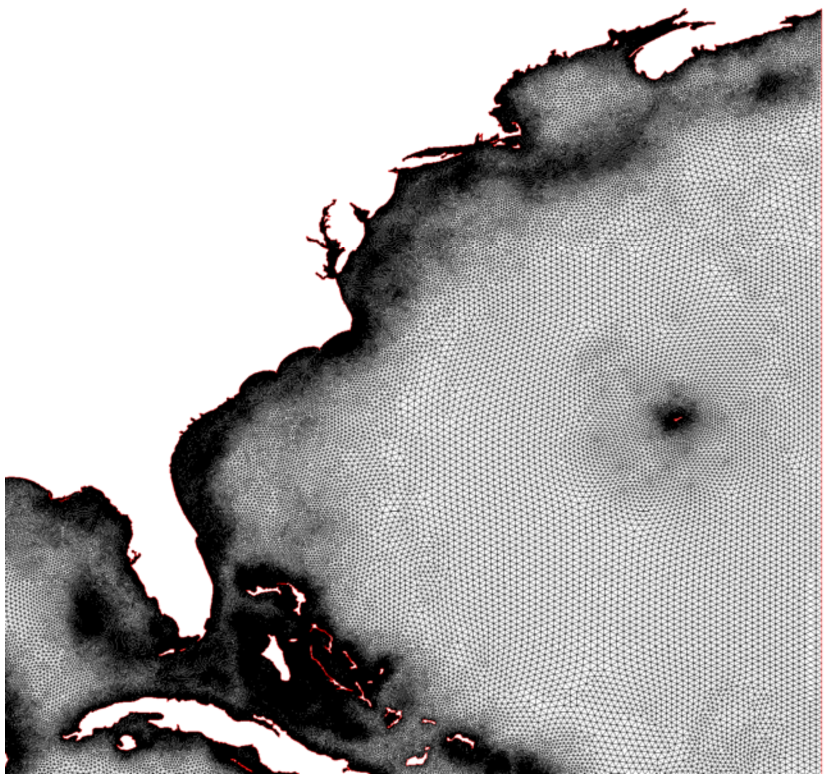

Figure 7: Section of the domain of the ADCIRC Western North Atlantic, Caribbean and Gulf of Mexico Tidal Model. (Mukai et al., 2002)

3.0 Results and Discussion

3.1 Validation

To use ADCIRC as a coastal analysis tool, the validity of the model had to be analyzed. By validating the accuracy, the model could be used in coastal investigations. Whenever using any computer model validation is necessary.

To test its accuracy, ADCIRC performed a fourteen day simulation with seven days of coastal elevation data at the same locations as National Oceanic and Atmospheric Administration (NOAA) tidal stations. The tidal stations are run by National Water Level Program (NWLP) and the National Water Level Observation Network. The program has approximately 175 stations throughout the coastal United States (http://tidesandcurrents.noaa.gov). The stations are used to maintain records of tidal elevation data. Three tidal stations in the Chesapeake Bay were selected. The stations were chosen based on the availability of the data and their distribution within the Chesapeake Bay. Figure 8 shows the locations and names of the three stations within the Chesapeake Bay, with a red dot indicating the location.

Figure 8: Tidal Station in Chesapeake Bay used for validation (http://www.chesapeakebaysampler.com/EasternShoremap.jpg)

ADCIRC simulated the tide conditions from October 1st, 2006 through October 14th, 2006 with output for the final seven days. The ADCIRC elevation data were compared with the recorded results and NOAA's predicted sea level at the locations of the tidal stations. Figure 9-11 below illustrates the results.

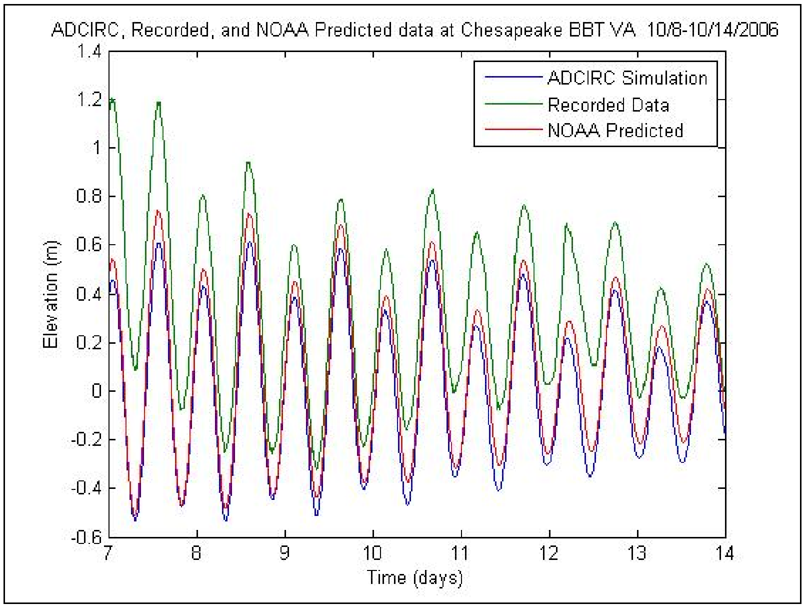

Figure 9: Simulated, Recorded, and NOAA Predicted Data at Chesapeake BBT, VA

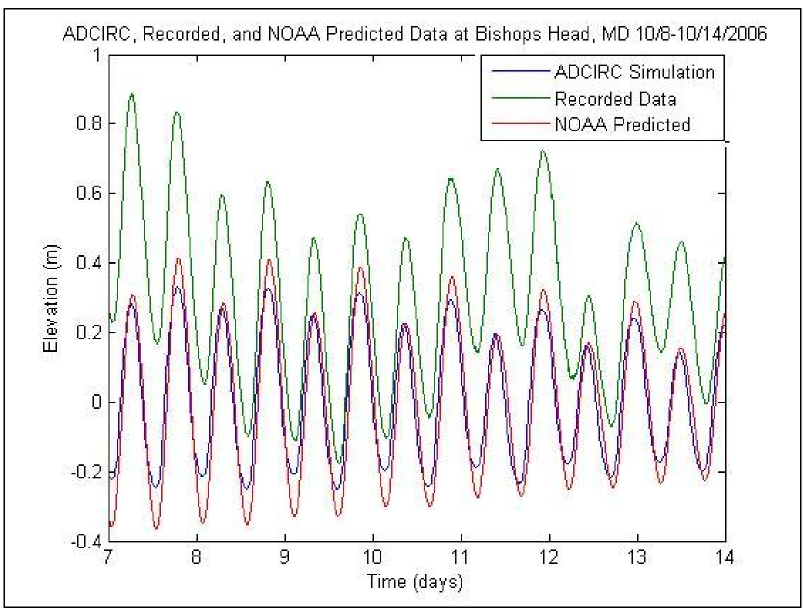

Figure 10: Simulated, Recorded, and NOAA Predicted Data at Bishops Head, MD

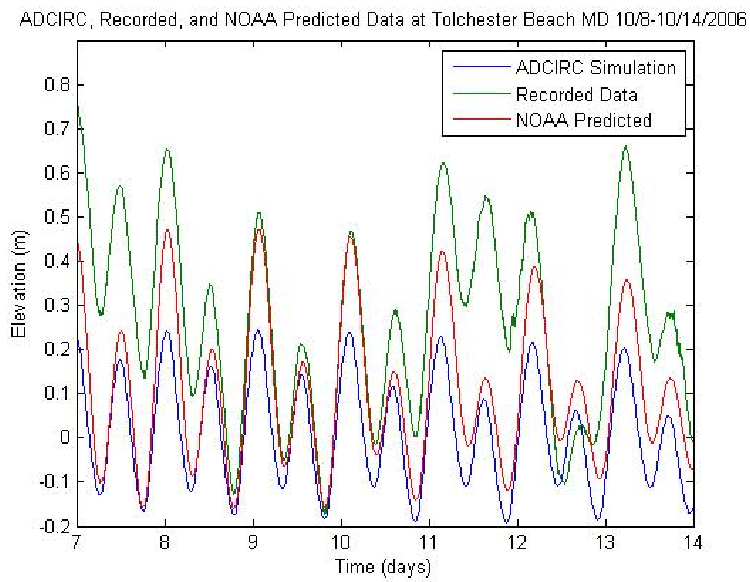

Figure 11: Simulated, Recorded, and NOAA Predicted Data at Tolchester Beach, MD

Based on the results, the simulated data consistently underestimated the recorded tidal elevations. Only one circumstance occurred where the simulated data results were higher then those recorded at the station and that was at Tolchester Beach, MD at the end of day twelve. This is not unusual because none of the simulations took into account the affects of wind and pressure on wave height. These factors have a significant effect on the height of waves. The reason that wind forces were excluded from the study was for simplicity. However comparing ADCIRC model to the sea level predicted by NOAA, the results were reasonably close. The only significant difference in tides occurred at Tolchester Beach.

In spite of the underestimation compared to the recorded data, the simulated results were considered valid. The time of arrival of the crests and troughs correctly corresponded to the actual recorded results. Barring the effects of wind and pressure, the ADCIRC model did an adequate job of replicating the tidal fluctuations as proven by its similarity to the NOAA predictions. The difference between the ADCIRC results and the NOAA predictions at

Tolchester Beach MD did cause some concern, but its error could be attributed to its close proximity to the beach, which could cause errors in the results.

3.2 Impact of Rising Sea Level

Global warming is a hot button issue in today's news. Some current scientific studies predict that as the heating of the earth's surface continues, there will be significant glacial melting at the earth's poles. Other studies have concluded that if enough of the ice caps at the poles melt, the depth of the earth's seas could significantly rise. From this the question arises, how will an increase in depth affect coastal processes around the nation?

To investigate this question in the context of the Chesapeake Bay, long term (90 day) simulations were performed at the current sea depth and with the depths increased one and two meters. Harmonic analysis output was then used to quantify long term averages of the elevation and velocity fields. First, tidal datums such as mean low low water (MLLW) and mean high high water (MHHW) were calculated at all nodes in the domain. Second, the root-mean-square (RMS) tidal speed was computed throughout the domain. RMS speed is used in other coastal studies to determine the amount of mixing in the water, which is important for ecological purposes.

It should be noted that to simulate the one and two meter increases in sea depth, only the bathymetry elevations at the each nodes were increased. This is not the most accurate method, because if the ocean depths did increase it would encroach on coastal land and change the overall shape of the bay. But for the purposes of the study the method was acceptable.

a. Tidal Datums

Once the harmonic analysis completed the tidal datums at each node were calculated. To see the maximum differences in tidal depth between MHHW and MLLW that would be experienced with a one and two meter increase in sea levels the tidal range was evaluated. Figures 12-14 are plots of the results throughout the bay for all three runs.

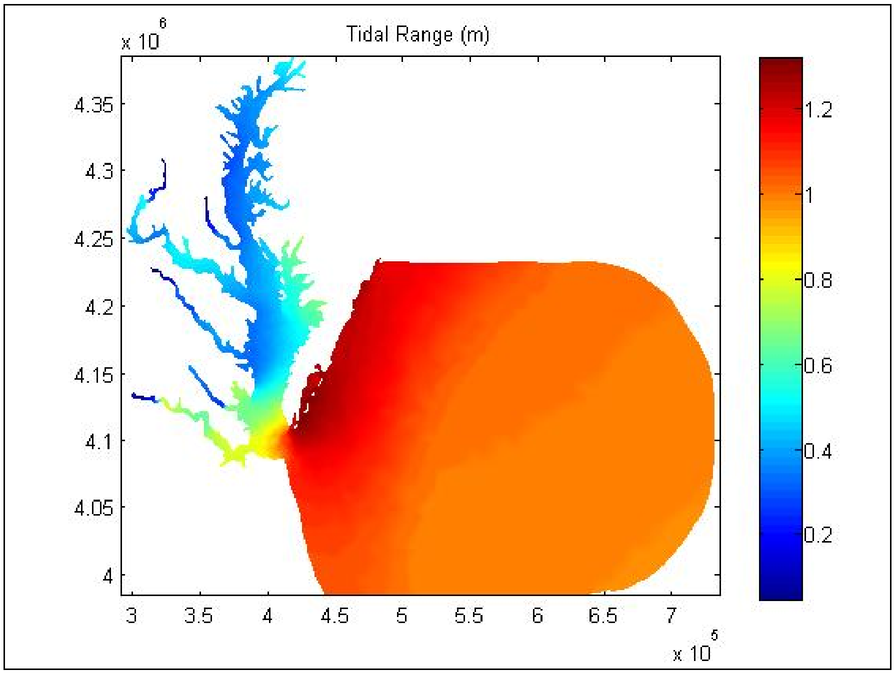

Figure 12: Tidal range for current ocean depths

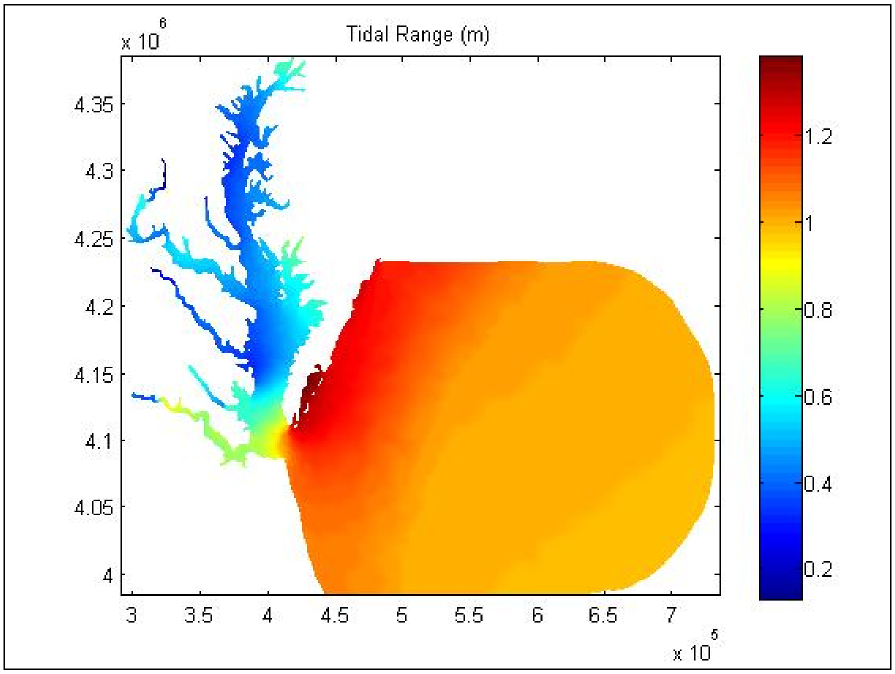

Figure 13: Tidal range for a 1 meter rise in ocean depths

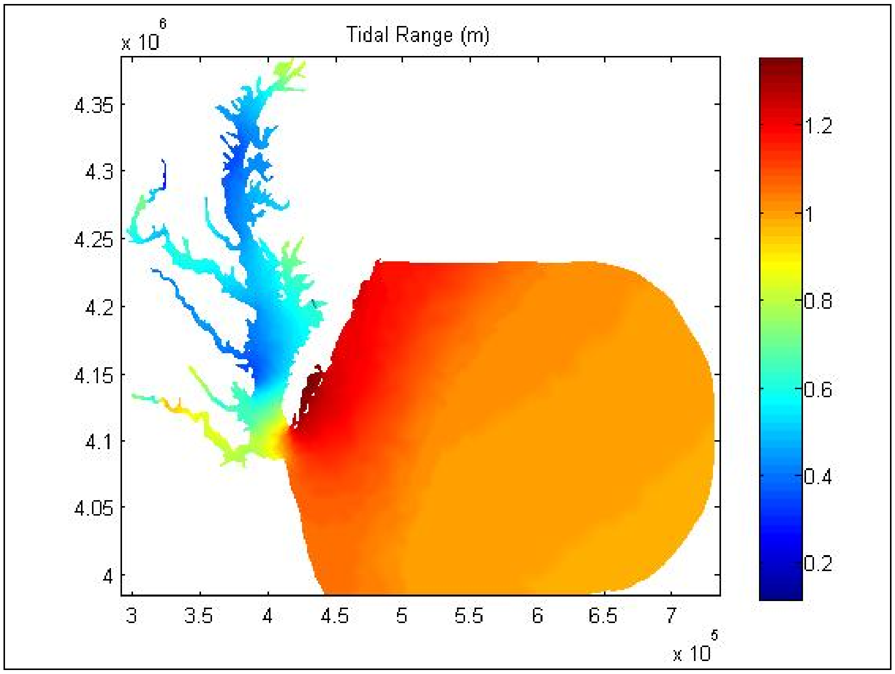

Figure 14: Tidal range for a 2 meter rise in ocean depths

The changes in tidal range with increased ocean depths are not immediately apparent. Even the differences from the original depth to a two meter increase were very slight. The most change was observed at the "fingers" of the bay. This made sense, because those areas area where depths begin to decrease rapidly and the widths narrow, which amplifies the wave depth. But even at these spots the change was still less then a half a meter.

Although the plots were a good visualization tool in establishing the fact that there was some change of the tidal datums, it did not illustrate the amount of change. To determine the magnitude of change in tidal datums from the one and two meter harmonic analyses the percent change from the original data was calculated. A percent larger then 100% indicated an increase in the tidal range and less then 100% indicated a decrease. Plots were made of the percent change in the tidal range throughout the bay, which are shown in figure 15 and 16.

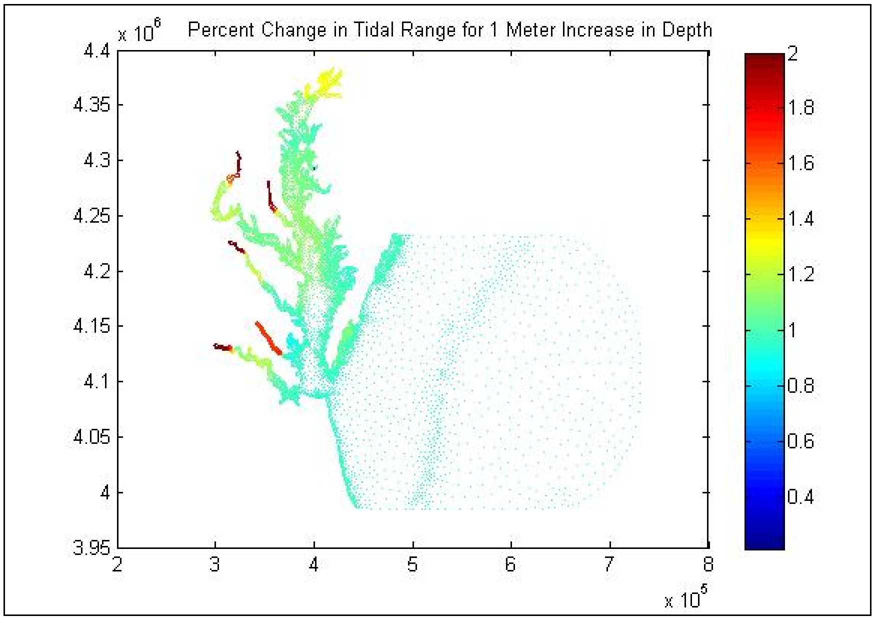

Figure 15: Percent Change in Tidal Range for 1 Meter Increase

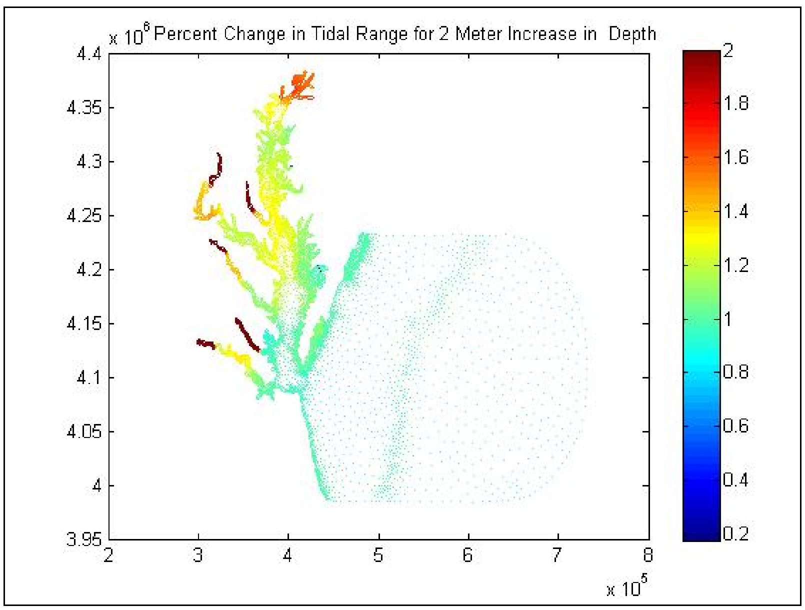

Figure 16: Percent Change in Tidal Range for 2 Meter Increase

The results verify that the greatest increases in tidal ranges took place at the "fingers" of the bay. Also as expected, the two meter increase in sea depth yielded a greater change in tidal range. The main channel of the bay looked as if it experienced little change from the one meter rise, but it did experience an increase for the two meter rise. The sharp changes in color can be attributed to the wetting and drying option being turned on during the long term run. At the fingers without the increase in depth drying takes place during low tides, but if the depth is increased drying no longer takes place and the full effect of low tides are realized. This dramatically increases the tidal range and this will display a large percent change in the plots. It should be noted that, to see better at the lower range of percent change, any outliers were reduced to 200%. Although this altered the results of the plots, it still gave indication of how the percent change was distributed.

To further investigate the percent change in the tidal range a histogram was developed, which can be viewed in figure 17.

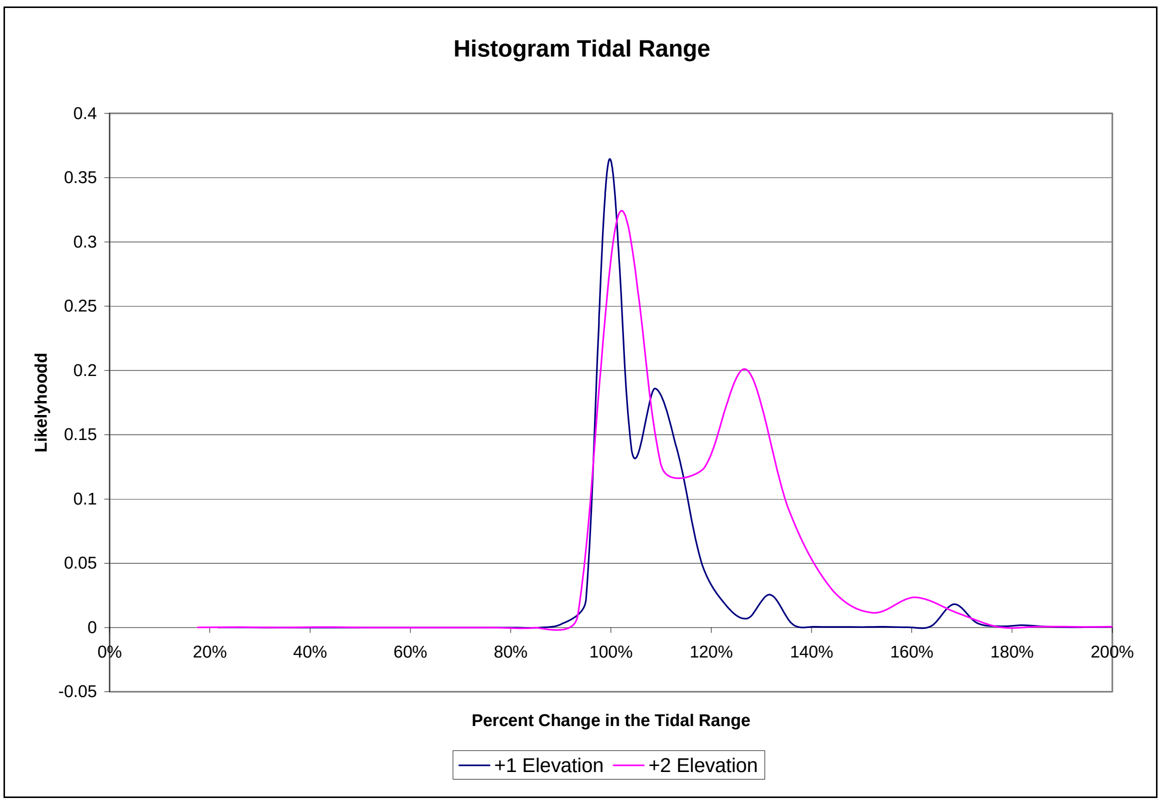

Figure 17: Histogram of percent change in Tidal Range

The histograms again show that a significant amount of nodes experienced only a slight change in tidal datums. Little or no change was experienced by approximately 35% of nodes during the run with a one meter increase, and 32.5% experienced no change for the two meter increase. Interestingly though, the histogram had a bimodal distribution. The second rise was attributed to the increase at the "fingers" of the bay. This second peak occurs around 110% for the one meter rise and 125% for the two meter rise. Lastly, the main peak of the two meter run is shifted slightly to the right of the one meter run. This shift was thought to represent the slight increase in tidal ranges in the main channel for the two meter run.

There were a few outliers that experienced over a 200% increase in tidal range, but the majority of data created a histogram with a justifiable curve. The table below shows the means and standard deviations for the percent change in tidal range.

Table 1: Mean and Standard Deviations of Tidal Range

	Mean	Std. Dev.
1 meter increase:	110.45%	35.36%
2 meter increase:	126.66%	73.93%

Overall the changes in the range at in the Chesapeake Bay were not as far reaching as expected. The most significant increase appeared to occur at the "fingers" of the bay. This analysis was slightly flawed because it didn't take into account the change in the shape of the bay with increased sea depths.

b. RMS

In addition to tidal datums, the RMS speeds at each node were calculated with the harmonic analysis output. Evaluation took place into where the maximum change in flow would be experienced with a one and two meter increases in sea levels. Figures 18-20 below are plots of RMS speed throughout the three analyses.

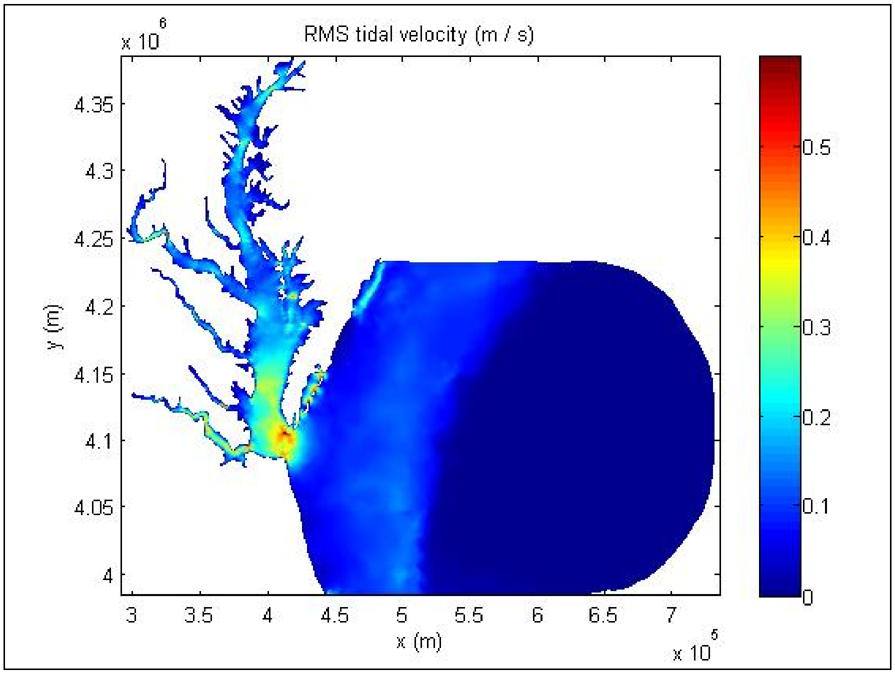

Figure 18: RMS Speed for current ocean depths

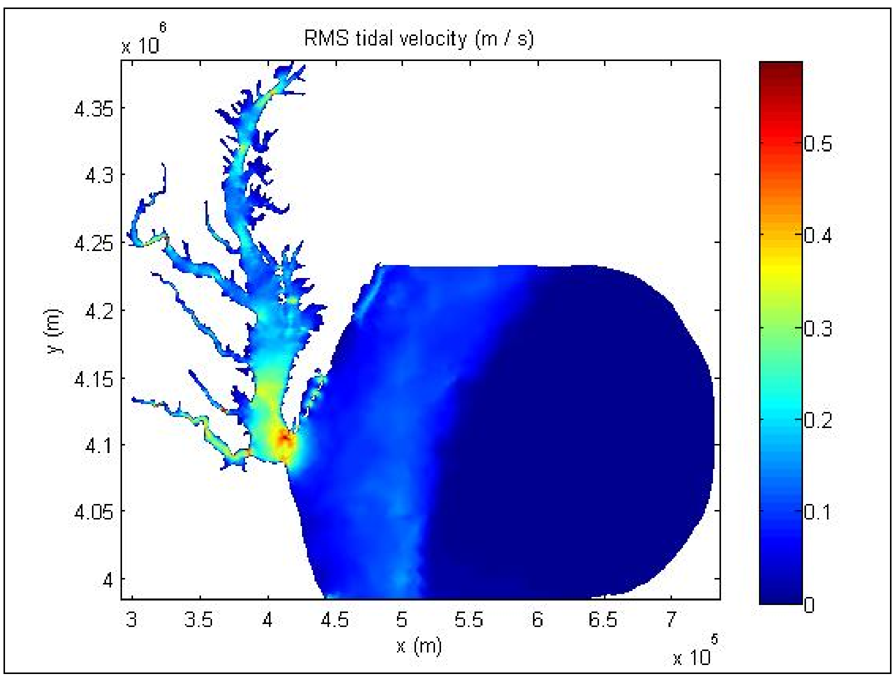

Figure 19: RMS Speed for a 1 meter rise in ocean depths

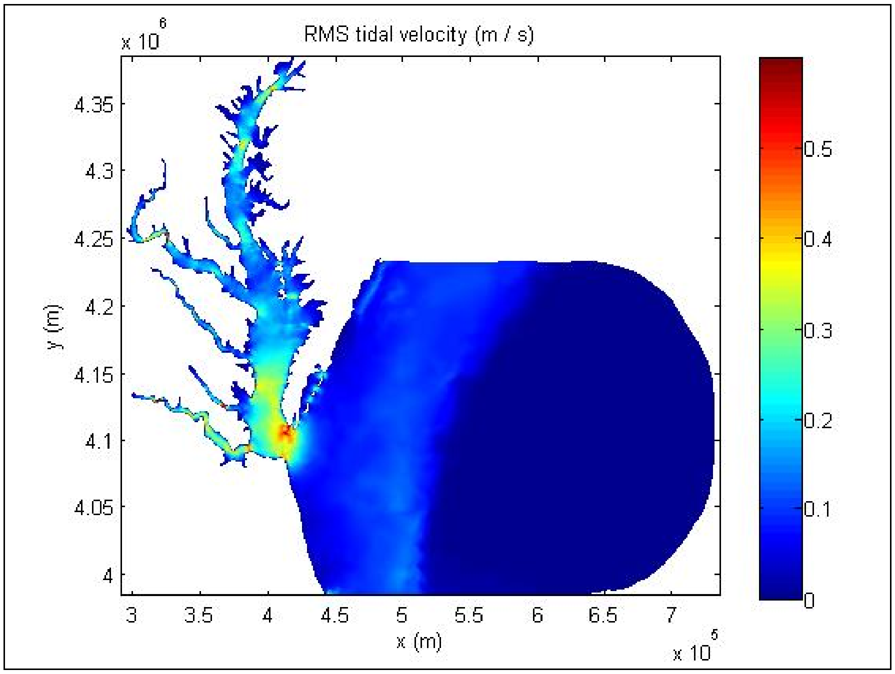

Figure 20: RMS Speed for a 1 meter rise in ocean depths

Little changes in RMS speeds with increased depths were observed. Even where there are changes, they were extremely slight.

To determine amount of change, if any, in RMS speed during the one and two meter simulation, the percent changes in RMS speed was calculated. To evaluate where the most change occurred, plots were made of percent change in RMS speed throughout the bay, which are shown in figure 21 and 22.

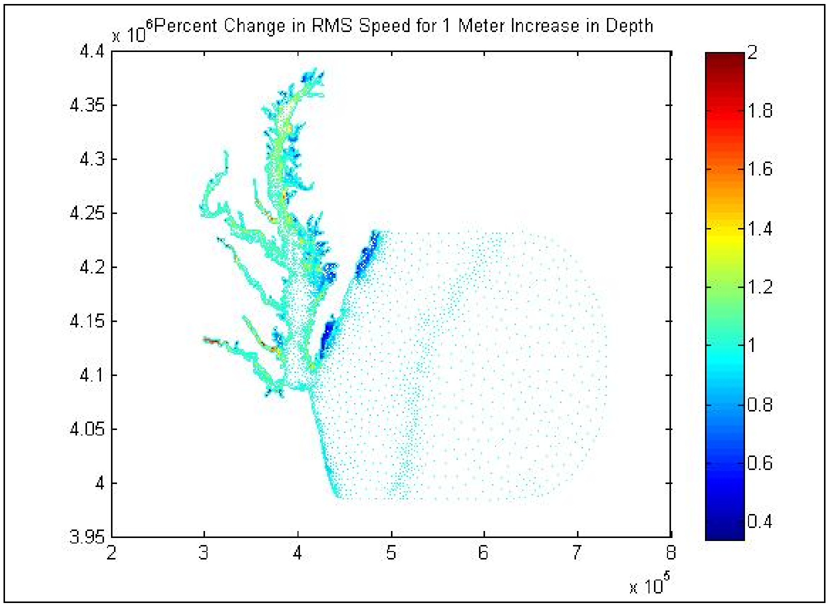

Figure 21: Percent Change in RMS Speed for 1 Meter Increase

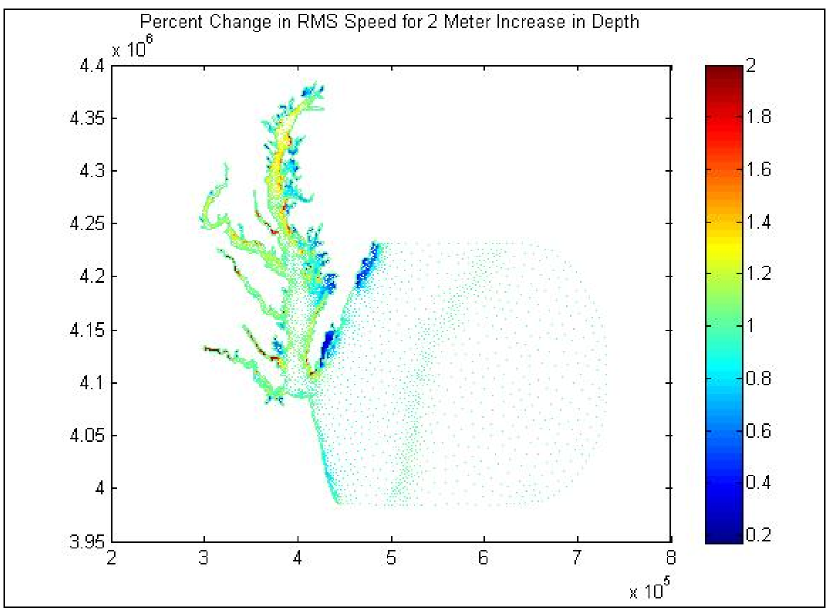

Figure 22: Percent Change in RMS Speed for 2 Meter Increase

Most of the increases in RMS speed were found at the north end of the bay.

Unlike the tidal range, there was just as many reductions in RMS speed as increases. In the main channel, the two meter simulation observed a noticeable increase in RMS speed from the one meter simulation. Again it should be noted that any outliers (greater than 200%) were removed from the plot.

To further investigate the percent change in RMS speed, a histogram was developed, which can be viewed in figure 23.

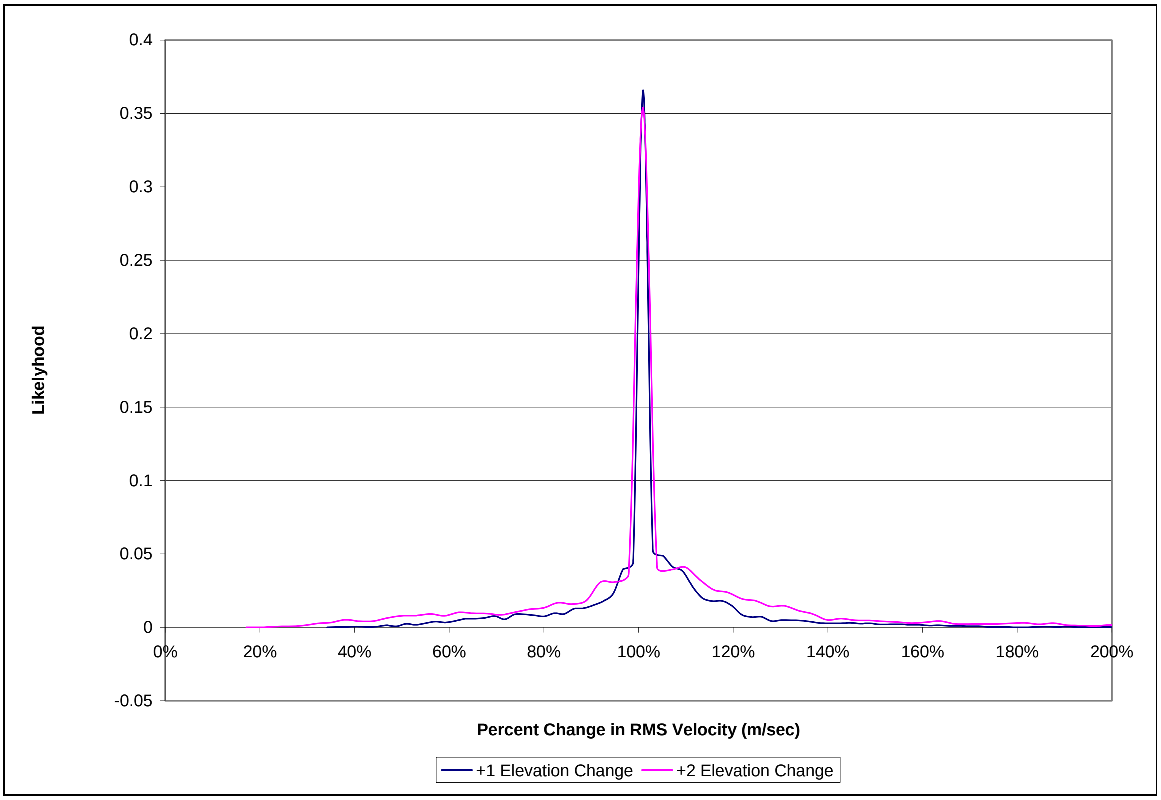

Figure 23: Histogram of percent change in RMS Velocity

The results of the histograms vindicated what was illustrated in figure 21 and 22. The graph showed little change with increased elevation, and both increases and decreases in RMS speed. Approximately 35% of the nodes for both the one and two meter increase experienced only slight changes.

The curve had a straightforward distribution unlike the tidal ranges. The table below shows the means and standard deviations for the percent change in RMS speed.

Table 2: Mean and Standard Deviations of RMS velocity for each run

	RMS Velocity	
	Mean	Std. Dev.
1 meter increase:	101.17%	17.35%
2 meter increase:	102.03%	27.12%

The conclusion from the investigation was that flow patterns in the bay were not as affected by rising tides as the tidal range. Again, it should be noted that the results may have differed if the changes in the shape of the bay had been taken into account with increasing sea depth.

3.3 Effects of Inclusion of River Velocity

The Chesapeake Bay has three main rivers which make up approximately 90% of fresh water input (http://md.water.usgs.gov/monthly/bay.html). The three rivers are the Susquehanna, Potomac, and James. The Susquehanna is by far the largest, making up 60% of the fresh water inflow. According to the USGS, an average flow of 192,300cfs of fresh water comes into the bay. Rivers have the potential to significantly influence the flow of the bay. The investigation studied whether rivers need to be accounted for by the ADCIRC model.

ADCIRC can designate areas along the coastline as boundaries which allow inflow. These allowable boundaries were specified where the Susquehanna, Potomac, and James rivers resided. Smaller rivers entering into the Chesapeake were not accounted for. The average yearly inflow, which was provided by the USGS, at the three rivers was used. For comparison purposes, both a fourteen day simulation and a harmonic analysis were run with and without the rivers accounted for.

From the fourteen day run, velocity vector arrows were extracted at a specific time. The concentration was on the area around the mouth of the Susquehanna River. Below, figures 24 and 25 show the results with and without the rivers accounted for.

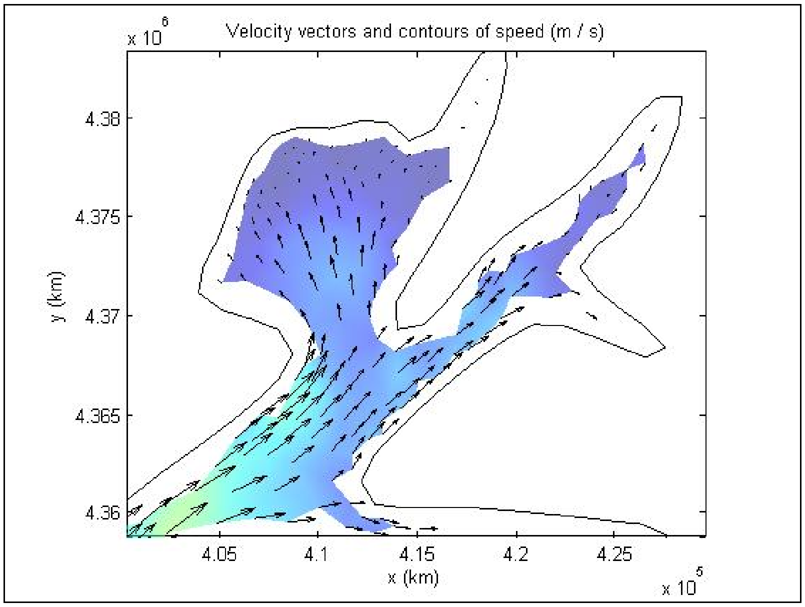

Figure 24: Velocity vectors without the Susquehanna River accounted for

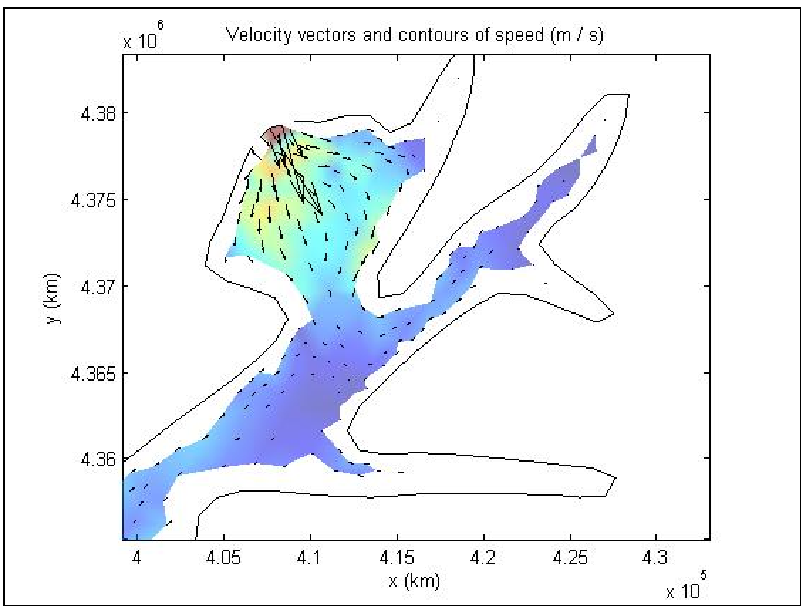

Figure 25: Velocity vectors without the Susquehanna River accounted for

The two figures demonstrate the impact of accounting for the river. The figures were from the exact same time, but they looked significantly different. In figure 24, the velocity vector arrows show the incoming tide, whereas figure25 the velocity vector arrows from the incoming tide are dampened from the flow from the Susquehanna River. The locations where the boundary conditions were changed to account for the river were near the large vector arrows in the upper left hand corner of figure 25. The two figures show that the inclusion of rivers changes the flow around the specified boundaries.

A particle tracking program was used to place particles anywhere within the model and track their location over time. For this analysis global velocities were computed for the final two days, and the data were recorded every ten minutes. The analysis again concentrated on the area near the mouth of Susquehanna River. Figures 26 and 27 show the results of the two experiments, the colored lines represent one particle and its movement over the course of two days.

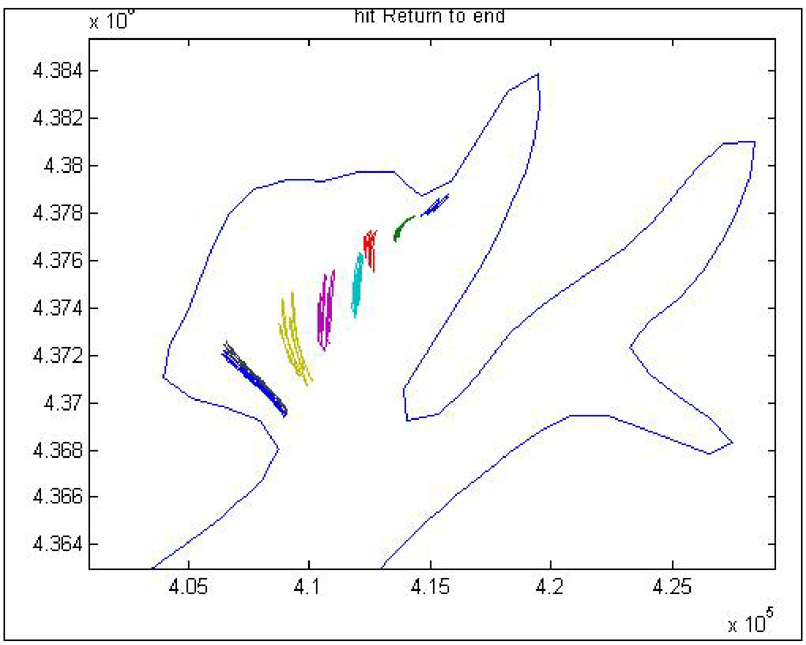

Figure 26: Particle Tracking without the River Accounted for

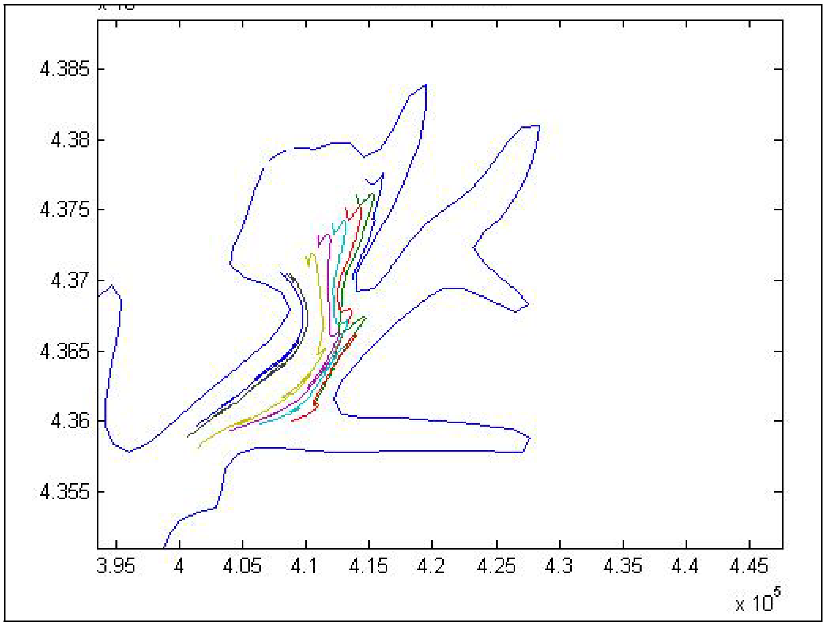

Figure 27: Particle Tracking with the River Accounted for

Through particle analysis, the importance of accounting for rivers is revealed. In figure 26, the particles largely stayed in one spot traveling back and forth with incoming and outgoing tide, whereas in figure 27, the particle traveled out of the bay with the current from the Susquehanna River. Like the velocity vector arrow analysis, particle tracking illustrated the effects of including rivers.

Based on the velocity vector arrow analysis and particle tracking, the indication was that inclusion of rivers changes the flow within the bay at least by the river outlet. To illustrate how the rivers impact the entire Chesapeake Bay, a harmonic analysis was run. Figure 28 was developed to illustrate the RMS speed throughout the bay, and it could be compared with figure 18, which does not account for the rivers.

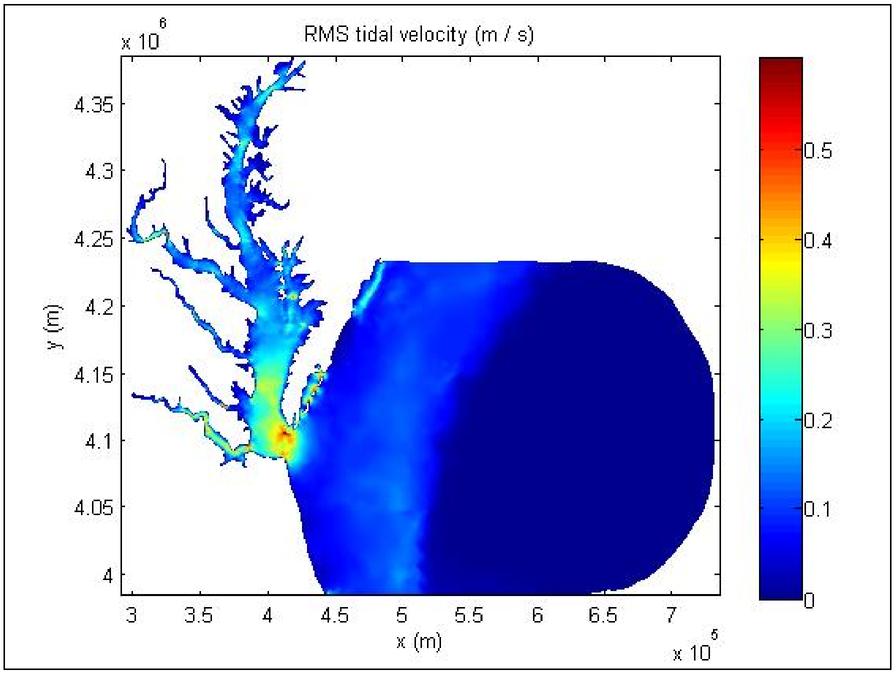

Figure 28: RMS velocities throughout the bay with Rivers accounted for.

Comparing figure 28 and figure 18, little difference is noted throughout most of the bay. To further investigate the change in RMS speed from the river being accounted for, the percent change was calculated throughout the bay, which can be viewed in figure 29.

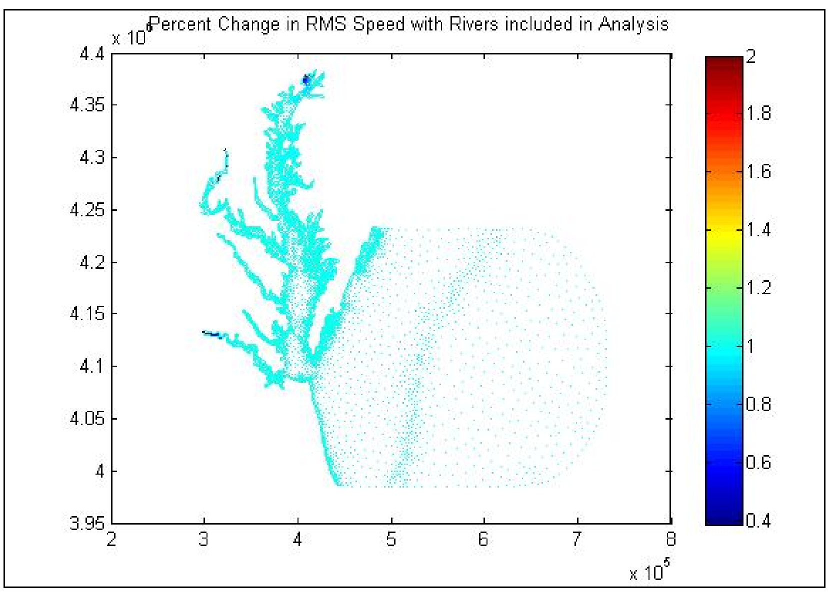

Figure 29: Percent Change in RMS Speed for Analysis with River

The plot looked as if the only change to RMS speed was near the river outlets. Surprisingly, this meant that rivers stop affecting the RMS speed not too far outside of the outlet. Again it should be noted that any outliers (greater then 200%) were removed from the plot.

A histogram was developed to take another look at how RMS speed changes, if at all, this can be viewed in figure 30.

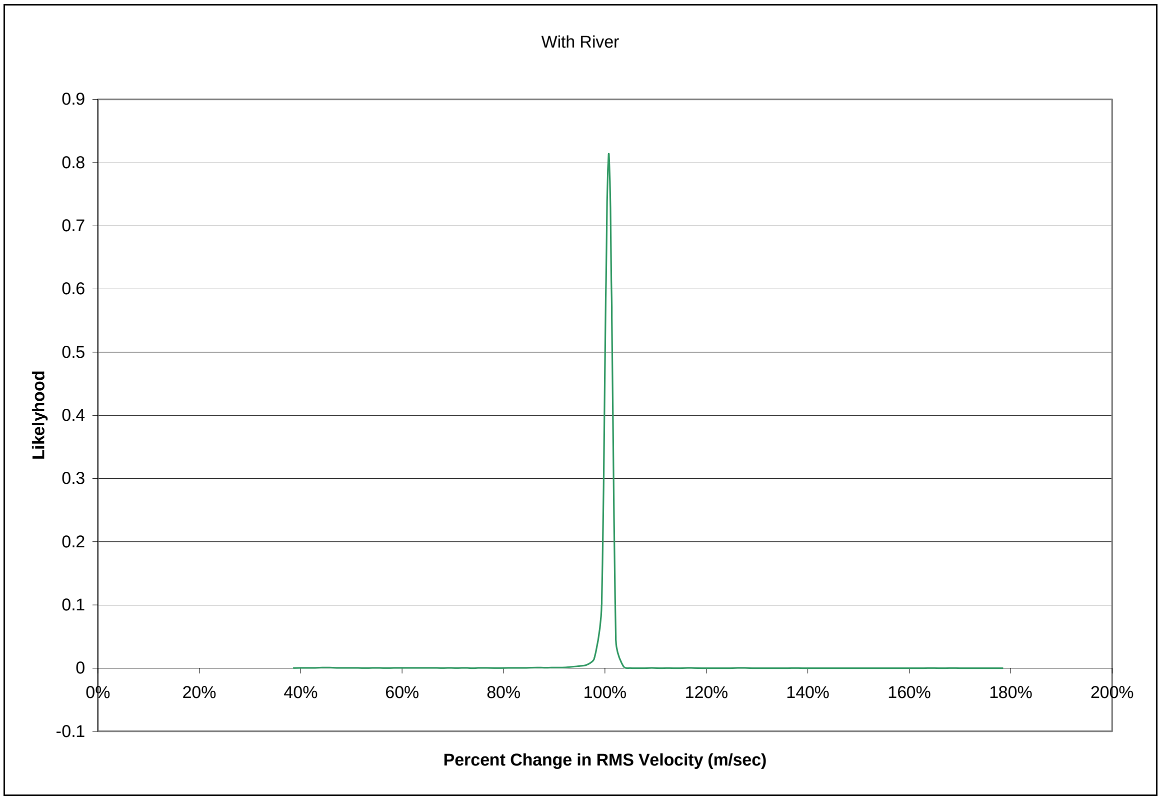

Figure 30: Histogram of percent change in RMS Velocity

The histogram matched what was observed in figure 29, that there was little change in RMS speed with rivers accounted for. Approximately 80% of the nodes within the bay were unchanged by the inclusion of the rivers. The few points that did change were mostly near the river outlets. The change in RMS speed had a mean of 100.3% and a standard deviation of 28%.

The velocity vector analysis and particle tracking illustrated that rivers had a significant impact on flow processes. But analysis into percent change of RMS speed revealed that these changes only affect areas around the outlets.

4.0 Conclusion

A quantitative numerical model was developed for the Chesapeake Bay. It was validated against real world tidal data and proved to be accurate. Numerical experiments were run in which sea level and river inflow were varied in order to determine the effects on the conditions of the bay. Particle tracking and harmonic analyses were done in order to analyze the results. The results show that sea level does not have a large effect on RMS velocities within the bay, with a maximum increase of two percent. The results also show that rivers entering the bay play a large role in transport of particles, whether they are sediment or contaminants.

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