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COUPLED, HIGH-RESOLUTION STORM SURGE MODELING OF AN INLET SYSTEM

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THESIS

COUPLED, HIGH-RESOLUTION STORM SURGE MODELING OF AN INLET SYSTEM

by

Matthew Reffitt

December 2018

Thesis Advisor: Mara S. Orescanin
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COUPLED, HIGH-RESOLUTION STORM SURGE MODELING OF AN INLET SYSTEM

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Model simulations using an ocean circulation model (ADCIRC) coupled with a wave model (STWAVE) are compared to observations made in the shallow, two-inlet tidal system Katama Bay during Hurricane Irene. Integrating high-resolution grids of this system with the North Atlantic Coast Comprehensive Study (NACCS) performed by the United States Army Corps of Engineers enabled a study of the effect on storm surge modeling accuracy of boundary condition representation of ephemeral inlets and wave model coupling. The high-resolution coupled model reduced error by over 20 percent compared to the NACCS during the peak storm surge period, representing a 14 percent improvement over the high-resolution circulation model simulation alone. Contrary to prior research that shows a lack of setup in the Katama Bay system from wave forcing, this research shows that in extreme wave forcing events, the flux through the Edgartown Channel cannot provide an adequate drainage path to prevent an increased water elevation in the bay. Furthermore, the presence of Katama Inlet in the south enhances the velocity along the entire southern part of Martha's Vineyard during peak storm conditions by more than a factor of two, highlighting the need for adequate model resolution for local storm surge predictions.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADCIRC	advanced circulation model
CSTORM-MS	coastal storm modeling system
NACCS	north Atlantic coast comprehensive study
NOAA	National Oceanic and Atmospheric Administration
OWI	Oceanweather, Inc.
SLOSH	sea, lake, and overland surges from hurricanes
SMA	southern Massachusetts
STWAVE	steady-state spectral wave model
SWAN	simulating waves nearshore
USACE	United States Army Corps of Engineers
WAM	wave action model

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I. MOTIVATION

The fundamental nature of the Navy forces a concentration of valuable assets in areas vulnerable to hurricanes and the accompanying storm surge. This is particularly true for assets positioned on the Eastern Seaboard of the United States and in Japan. Current operational storm surge forecasts frequently are obtained using the Sea, Lake, and Overland Surges from Hurricanes, or SLOSH, model. While the SLOSH model can be run quickly, it does not take into account all of the complex physics involved and thus can miss important processes.

This thesis aims to contribute to the growing body of research focused on the coupling of wind and circulation models in order to accurately predict storm surge. In particular, by verifying the accuracy of the United States Army Corps of Engineers' (USACE) Steady-State Spectral Wave Model (STWAVE) in a complex inlet system when coupled with the Advanced Circulation Model (ADCIRC), opportunities can be explored to use these models to gain a better understanding of the Navy's vulnerability to storm surge events. These models could be used to build a "hurricane handbook" (much like the USACE Coastal Hazards System) that contains high-resolution storm surge forecasts based on an envelope of probable storm tracks, speeds, and strengths to provide decision makers with an easily available resource that can be referenced without needing to choose between computationally expensive operational model runs (whose results may be too late for timely decision making) or fast models that may not completely capture complex oceanographic interaction within a harbor.

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II. INTRODUCTION

A. BACKGROUND

Storm surge, or the increase in water level associated with a meteorological event, often accounts for a significant percentage of the property damage caused by hurricanes (Neumann et al. 2015). In addition, coastal flooding associated with storm surge can create a hazard to residents in the path of these storms that is often a major contributor to higher death tolls (Blake et al. 2007). These hazards necessitate accurate storm surge predictions in order to provide adequate warning to prevent the loss of life and property. This can be difficult when considering systems of a small spatial extent and complex bathymetry (Yin et al. 2016). Tidal inlet systems often cannot be fully resolved due to the larger model domain requirements of storm surge forecast modeling and the resultant coarse resolution, resulting in the inability to capture small scale dynamics. This was shown to be the case in inland areas of the Gulf Coast for Hurricane Ike in an extensive study by Kerr et al. 2013.

Coupled, high-resolution storm surge modeling is an active research field that is currently dominated by the coupling of the Simulating Waves Nearshore (SWAN) and Advanced Circulation (ADCIRC) models (e.g., Dietrich et al. 2012). Previous research shows that the traditional practice of ignoring small-scale processes can create a consistent low bias when modeling storm surge at high resolutions and small spatial scales (Orton et al. 2012; Sun et al. 2013). This result creates an opportunity for increasing the accuracy of high-resolution storm surge modeling by taking into account these traditionally ignored processes. The Steady-State Spectral Wave Model (STWAVE), unlike SWAN, accounts for wave diffraction and reflection (Gonçalves et al. 2015) and thus is a better fit for the complex bathymetry and high spatial resolution associated with a tidal inlet system where observations show high gradients of currents, waves, and bathymetry. STWAVE and ADCIRC coupled modeling of storm surge has been shown to be skillful on a larger scale (Bryant and Jensen 2017), but less research has been conducted at the higher resolutions needed to resolve most inlet systems. Model domain sizes that are not sufficiently large have been found to underestimate storm surge (Blain et al. 1994), therefore nested model domains are an option to increase resolution in areas of interest while minimizing computational cost.

B. STUDY PARAMETERS

Here, research will be focused on the Katama Inlet system, as shown in Figure 1, of Martha's Vineyard, Massachusetts, and will utilize in-situ measurements made coincident to previous research (Orescanin et al. 2016) during Hurricane Irene. A coupling of wave and circulation models will be utilized with an emphasis on the performance of this higher resolution coupled domain when compared to a coarser resolution coupled model. Katama Bay is an area of complex bathymetry that includes a migrating inlet mouth separating the bay from the Atlantic Ocean. This bathymetry covers a relatively small spatial extent and thus makes the area an ideal location for study. Previous modeling research in this area has focused on wave-current interaction (Hopkins et al. 2016), sediment transport processes (Hopkins et al. 2017), and the effect of temporally varying inlet geometry on bay circulation (Orescanin et al. 2016). When aggregated, this research shows that changes in the bathymetry caused by Hurricane Irene modified the tidal signature of the inlet system which in turn changes the tidal modulation of wave direction in the area affecting sediment transport and deposition. Without the ability to simulate the fine scale bathymetric and current field features in this inlet system, predicting the tidal modulation and sediment transport would be highly inaccurate. This research aims to use an exploration of storm surge modelling to improve this ability.

Atlantic storm number 09, named Irene, impacted the research area primarily on 28 August, 2011, as it passed approximately 300 nautical miles to the west. Wave heights measured at the closest offshore NOAA buoy (number 44097) reached a peak of 14.74 meters at 12:38 on August 28, much higher than the approximate normal value of 1 meter. Maximum sustained winds at the time of the closest point of approach were approximately 50 knots as measured at the NOAA buoy at Buzzards Bay 30 nautical miles to the west of the research area. Storm surge associated with Irene propagated northward through the research area measuring 0.7344 meters at the southernmost observation station in Katama Bay on August 28 at 14:45, or model run day 22.6146 of this study.

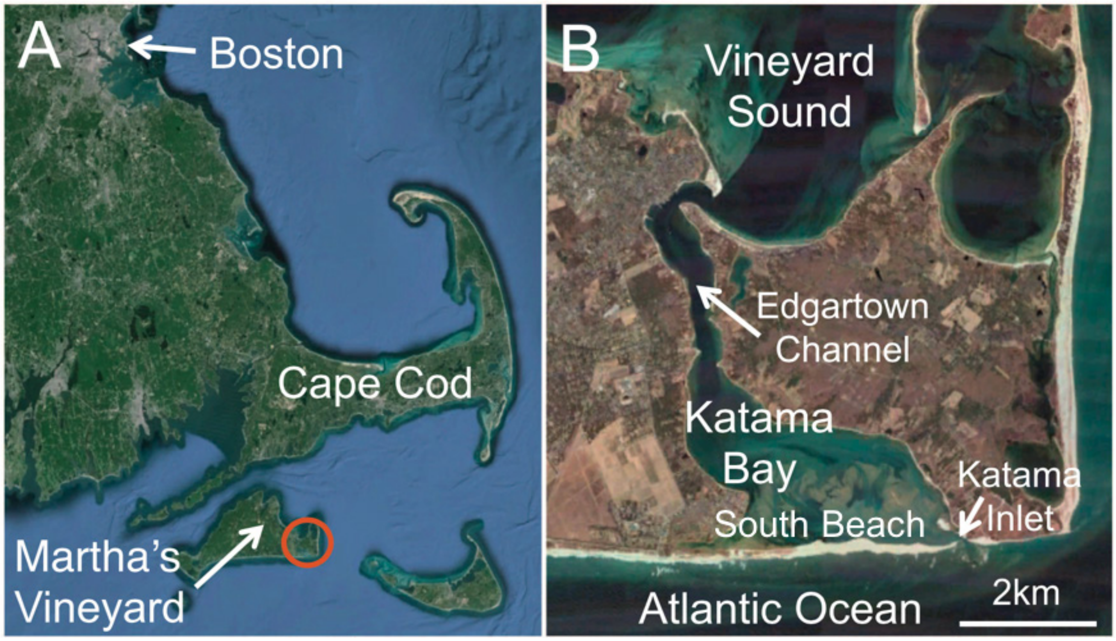

Figure 1. Location of (A) Martha's Vineyard, MA, with the Katama system inside the red circle, and (B) Katama Bay showing Edgartown channel to the north and Katama Inlet to the south. Adapted from Orescanin et al. (2016).

The hypothesis of this research is that the STWAVE and ADCIRC models can be coupled in order to provide highly localized storm surge forecasts that reduce the low bias in peak storm surge prediction. Furthermore, this reduction in underestimation combined with an increase in bathymetric resolution will increase the ability to predict the flow pattern of an inlet system at large. Large domain ADCIRC meshes and STWAVE grids created by the United States Army Corps of Engineers for the North Atlantic Coast Comprehensive Study (NACCS) (Cialone et al. 2017) will be utilized and merged with higher resolution grids. Model results will be compared to in-situ measurements to test this hypothesis.

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III. NUMERICAL MODELS

A. STEADY-STATE SPECTRAL WAVE MODEL

1. Model Description

STWAVE is a model developed by the United States Army Corps of Engineers to estimate nearshore wave transformation and wind-wave growth of nearshore processes including shoaling, breaking, and refraction. STWAVE is classified as a finite-difference, phase-averaged spectral wave model that uses the wave action balance equation as a framework and uses a Cartesian, rectangular grid to characterize the domain (Massey et al. 2011). STWAVE has two modes: half-plane mode, which only allows propagation of energy from offshore, and full-plane mode, which allows forced wave generation from all 360 degrees. Full-plane mode is used exclusively for this study. Being a steady-state model, STWAVE operates under the assumption that the duration of meteorological forcing is not a limiting factor in the generation of wind waves over the domain. STWAVE model outputs used here include wave height, peak wave period, mean wave direction, radiation stress gradients, and wave spectral characterizations.

2. Model Setup and Domain

Two STWAVE grids of differing domain size and resolution were used for this research and are shown in Figure 2. A larger grid covering the southern Massachusetts (SMA) area was developed for the North Atlantic Coast Comprehensive Study (NACCS) (Bryant and Jensen 2017) with a resolution of 200 meters by 200 meters and was used to generate nesting spectra for the smaller grid covering Katama Bay with a resolution of 10 meters by 10 meters. These grids were both oriented at 101.5 degrees in order to capture areas of interest. The SMA grid was produced for the NACCS and as such was forced with output from the Wave Action Model (WAM) and Hurricane Irene wind fields produced by Oceanweather, Inc. (OWI 2015). The Oceanweather wind field, along with their pressure field product, were used for all meteorological forcing in this research. Model runs using STWAVE independently, with a static water elevation, were run for the time periods of

August 27, 2011, at 0000Z to August 30, 2011, at 0000Z in order to capture the effects of Hurricane Irene, which produced a peak surge in the research area on the afternoon of August 28, 2011. Model time steps, or snaps, were set at every 30 minutes. Bathymetry values for the SMA grid were interpolated from the NACCS ADCIRC mesh which combined bathymetry data from numerous sources to obtain the most accurate data possible and are detailed extensively in the model development discussion for the NACCS (Cialone et al. 2015, 2017).

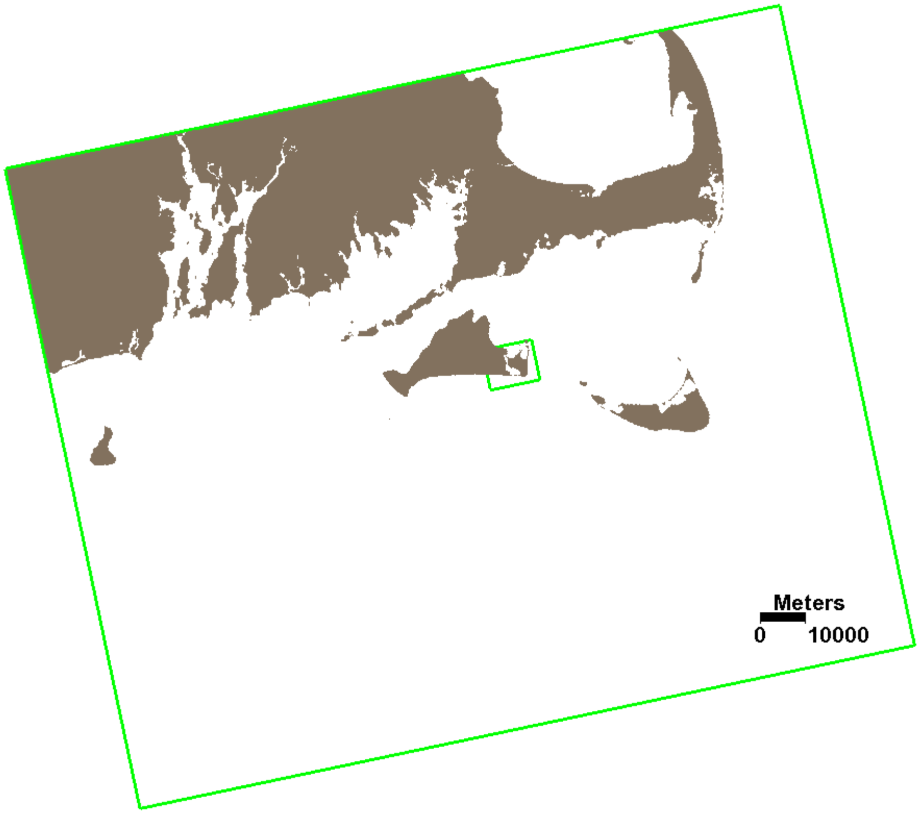

Figure 2. Domain size comparison between the Southern Massachusetts grid (outer) and the Katama Bay grid (inner).

The smaller Katama Bay grid was developed with a resolution of 10 meters by 10 meters in order to capture the smaller scale bathymetric contours of the bay and offshore region, particularly in the vicinity of the inlet and ebb shoal. A comparison of the resolution of the bathymetry between the SMA grid and Katama grid is shown in Figure 3. Both nested (Smith and Smith 2002) and un-nested model runs were conducted for the Hurricane Irene time period using this grid to check stability prior to coupling and were found to be stable. The un-nested case used a zero spectrum at the southern boundary and the nested case was forced with the spectral output from the SMA grid. Meteorological forcing was again the OWI Hurricane Irene wind field. Bathymetry for the Katama grid was obtained from surveys conducted with personal watercraft and a 10-meter resolution digital elevation model produced by NOAA in 2008 (Orescanin et al. 2016).

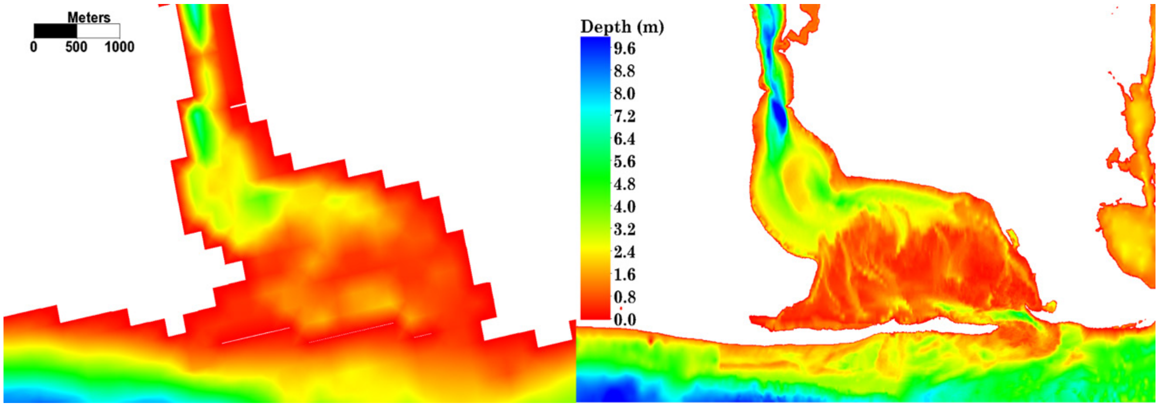

Figure 3. Comparison of model bathymetry between the SMA grid (left) and the Katama grid (right).

B. ADVANCED CIRCULATION MODEL

1. Model Description

The Advanced Circulation model (ADCIRC) is a physics-based model that captures the relevant physics associated with ocean circulation. The two-dimensional variant of ADCRIRC is classified as a finite-element, depth-averaged model that applies the shallow water equations for conservation of mass and momentum and applies Boussinesq and hydrostatic pressure approximations (Luettich et al. 1992; Westerink et al. 1992). Because

ADCIRC is a finite-element model, the resolution can be varied across the domain in order to capture complex processes in areas of interest while minimizing computational cost by relaxing the resolution where conditions are expected to remain homogeneous.

2. Model Setup and Domain

Two ADCIRC meshes of differing resolution were used for this research. The coarser mesh was taken from the NACCS and detailed in Cialone et al., 2017. The finer mesh was developed by merging a Katama Bay mesh (Orescanin et al. 2016) with the NACCS mesh in order to achieve the resolution required in the research area while simultaneously capturing the basin scale effects shown to be crucial to accurately modeling storm surge (Blain et al. 1994). The difference in resolution in the area of interest is shown in Figure 4. It is important to note that the NACCS mesh treats South Beach, along the southern border of Katama Bay as seen in Figure 1, as a hard boundary while the high-resolution mesh has that region fully modeled due to the somewhat ephemeral nature of Katama Inlet and the low elevation of South Beach. Tidal forcing was applied to both meshes at the boundaries. Consistent with the STWAVE grids, meteorological forcing was applied from Oceanweather Hurricane Irene wind and pressure fields. ADCIRC model runs were run for a period of 24 days consisting of a 14-day tidal spin-up before winds were applied to the domain from August 20, 2011, to August 30, 2011. The model time step for ADCIRC model runs was 0.5 seconds. Nodal attributes, including bottom friction, sea surface height above the geoid, horizontal eddy viscosity, and primitive equation weighting of the continuity equation, were interpolated from the NACCS mesh with the exception of Manning's *n* for friction, which was also interpolated from the NACCS mesh but was further updated in the higher resolution area by deriving values for Katama Bay from the previous study by Orescanin et al. 2016.

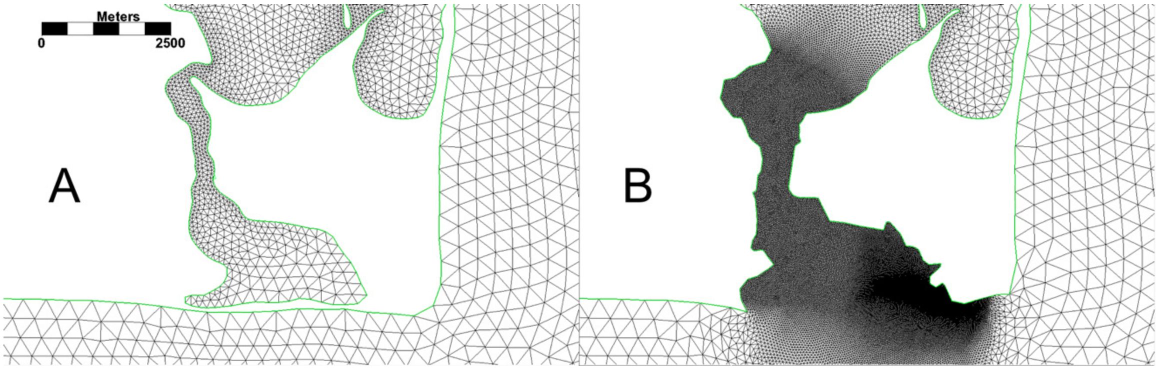

Figure 4. Mesh element resolution comparison between the NACCS mesh (A) and the NACCS and Katama merged mesh (B) used for this study.

3. Model Coupling

In order to capture surge levels, wind waves, current velocities, and the interaction between these fields, ADCIRC and STWAVE were coupled using the Coastal Storm Modeling System (CSTORM-MS) coupler (Massey et al. 2011). This coupling enables ADCIRC to pass water levels and current velocities to STWAVE and receive gradients of wave radiation stresses. This exchange of information is initiated at every STWAVE snap, or 30 minutes, during coupling. With this coupling, inundated regions during high surge events will generate wind waves. Both ADCIRC and STWAVE were run in their parallel computing modes by partitioning the domain in order to utilize high-performance computing resources. The Hamming cluster at the Naval Postgraduate School and the Topaz SGI system at the United States Army Corps of Engineers High Performance Computing Center were utilized for this research.

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IV. RESULTS AND DISCUSSION

A. OBSERVATIONAL DATA

In order to assess the accuracy of the model output, comparisons were made with observations taken during Hurricane Irene in Katama Bay. Three categories of model run were used in these comparisons: NACCS, high-resolution uncoupled (both ADCIRC and STWAVE), and high-resolution coupled. Water elevation measurements were obtained using buried sensors at stations numbered from 01-05, north to south, as illustrated in Figure 5 at 2 Hz and have a +/- 5cm error. Further details concerning measurement collection can be found in Orescanin, et al., 2016. Ten additional stations were modeled in order to capture a complete range of conditions within the bay as well as a station (station 06) to model shoal conditions outside of the bay. After careful analysis, stations 01, 04, and 05 were chosen as a focus due to their ability to successfully describe spatial in temporal patterns in the data. Station 01, being the northern most station, captures the inlet dynamics associated with the transition from Vineyard Sound and the Edgartown Channel. Station 04 characterizes Katama Bay and is the farthest from any land boundary interaction. Station 05 is the observational station closet to Katama Inlet and captures the dynamics associated with the transition from Katama Bay to the Atlantic Ocean.

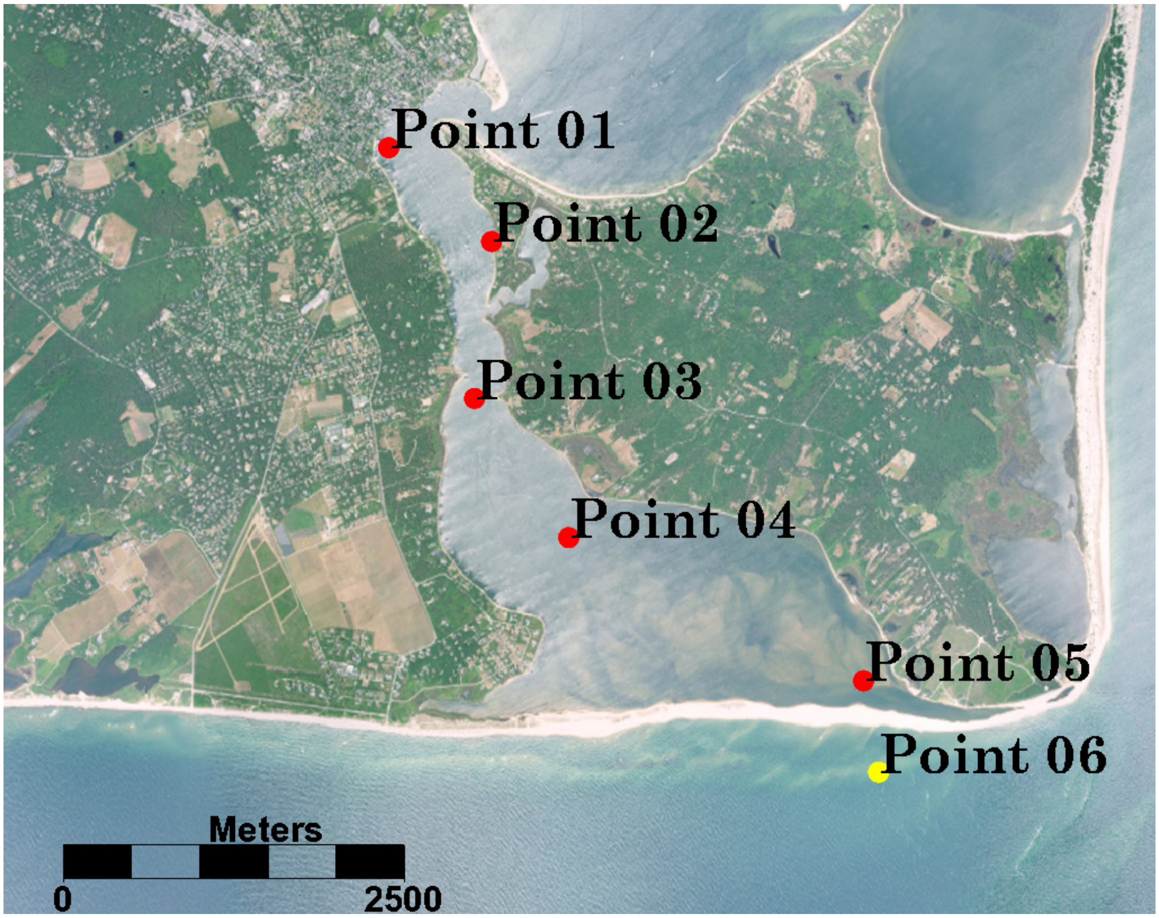


Figure 5. Katama Bay observation stations during Hurricane Irene (red) and a modeled station representing shoal conditions outside of the bay (yellow).

B. MODEL EVALUATION

1. Error Statistics

As is seen in many storm surge modeling efforts, water elevation levels modeled in this research consistently showed a low bias when compared to the observations. When comparing the high-resolution model results to the lower resolution NACCS results, as in Figure 6, we see that both high-resolution model domains showed an improvement in correcting the underestimate of surge. This is also shown when comparing the root mean square error for all observation stations as seen in Table 1. An examination of Figure 6 shows that the high-resolution models are also more accurate in predicting the timing of the peak storm surge. Importantly, the coupling of STWAVE and ADCIRC showed an improvement over ADCIRC alone for the high-resolution domains, particularly during the 12-hour period of peak storm surge, as seen in Table 2. The reduction in error percentage by incorporating the wave model is minor (but still existent) during normal conditions, but markedly increases during the peak surge period. This suggests that in addition to the improvement seen due to the more accurate bottom topography effects modeled by increased bathymetric resolution, incorporating wave effects, such as reflection, diffraction, and wave-current interaction also decreases the error in storm surge predictions

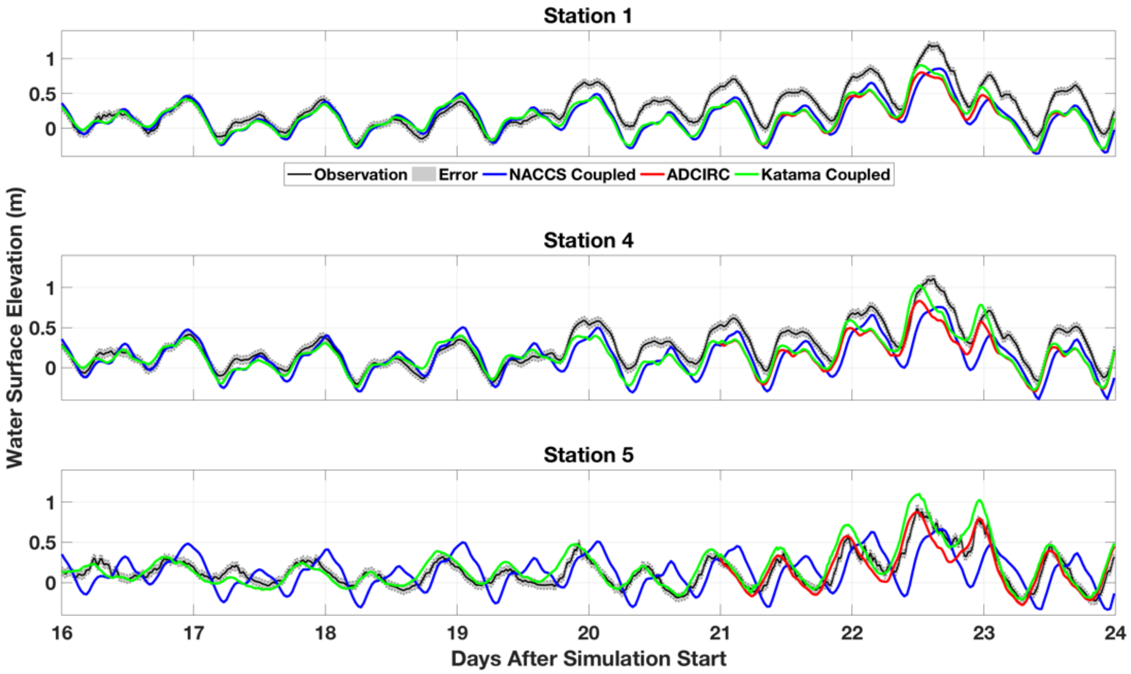
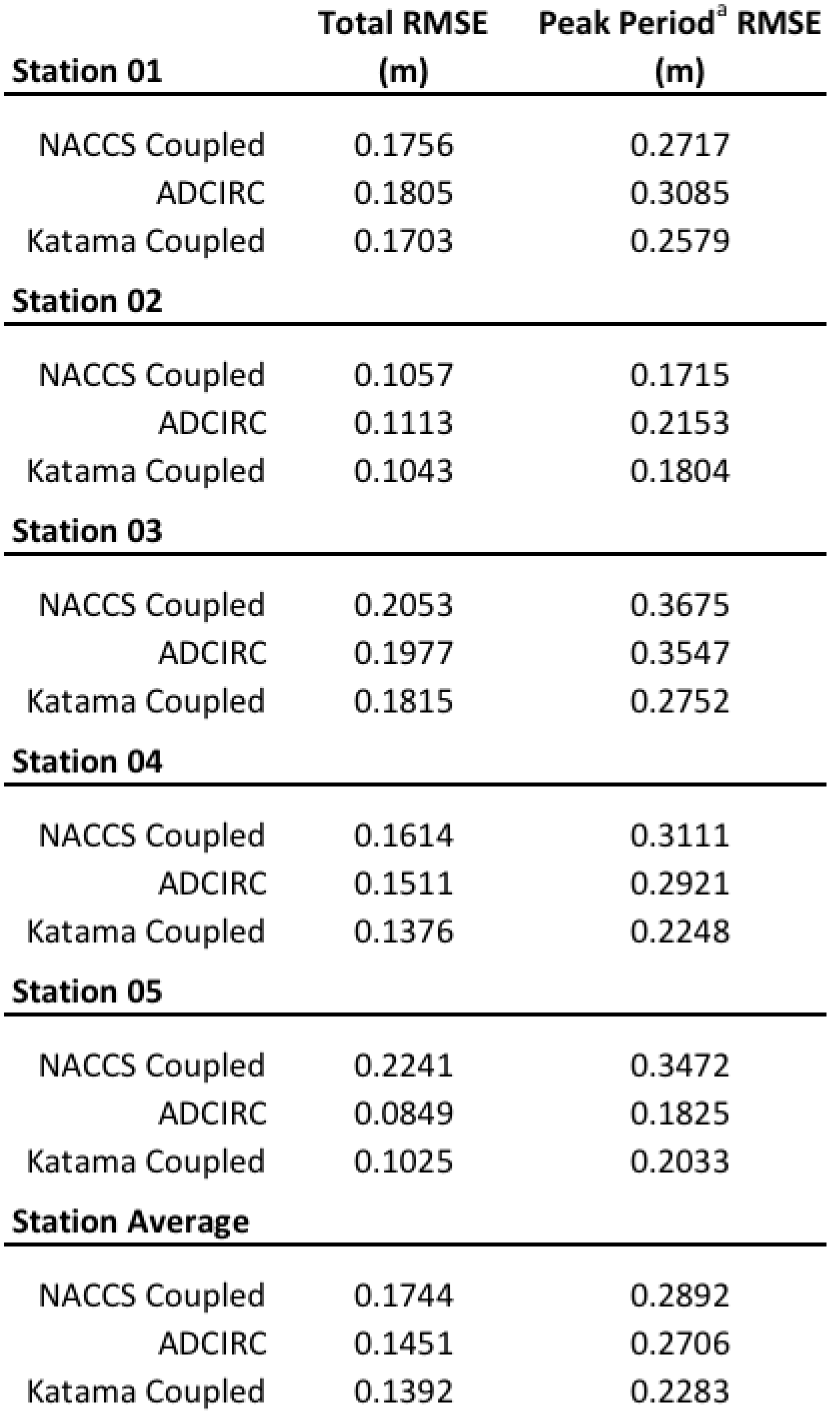


Figure 6. Water elevation time series comparison for stations 01, 04, and 05 during Hurricane Irene.

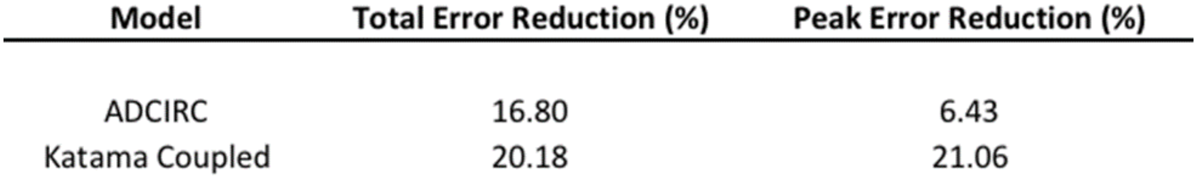
Table 1. Root mean square error values for all observation stations.



Station 01	**Total RMSE (m)**	**Peak Period[a] RMSE (m)**
NACCS Coupled	0.1756	0.2717
ADCIRC	0.1805	0.3085
Katama Coupled	0.1703	0.2579
Station 02		
NACCS Coupled	0.1057	0.1715
ADCIRC	0.1113	0.2153
Katama Coupled	0.1043	0.1804
Station 03		
NACCS Coupled	0.2053	0.3675
ADCIRC	0.1977	0.3547
Katama Coupled	0.1815	0.2752
Station 04		
NACCS Coupled	0.1614	0.3111
ADCIRC	0.1511	0.2921
Katama Coupled	0.1376	0.2248
Station 05		
NACCS Coupled	0.2241	0.3472
ADCIRC	0.0849	0.1825
Katama Coupled	0.1025	0.2033
Station Average		
NACCS Coupled	0.1744	0.2892
ADCIRC	0.1451	0.2706
Katama Coupled	0.1392	0.2283

[a] Peak surge period is defined as the 12-hour window containing peak surge at the six-hour mark. For this study, peak period is run day 22.2646 through 22.7646.

Table 2. Error reduction values



Model	Total Error Reduction (%)	Peak Error Reduction (%)
ADCIRC	16.80	6.43
Katama Coupled	20.18	21.06

2. Spatial Comparisons

a. Resolution Effects

It is generally accepted that an increase in model resolution will lead to more accurate modeled values up to an upper convergence point, which is consistent here. However, there appears to be another explanation for the difference in accuracy between the NACCS model run and the high-resolution runs. During NACCS mesh development, a decision was made to make the South Beach a hard boundary. This does not allow for either flow through Katama inlet or the overtopping of the beach that did in fact happen during Hurricane Irene. The lack of overtopping and the resultant flow patterns associated with it can explain many of the differences between the high-resolution models and the NACCS. This is most evident when looking at a spatial representation of the modeled velocities for the NACCS (Figure 7) and the coupled high-resolution run (Figure 8). In addition, the presence of the inlet and ebb shoal amplify the eastward velocities on the southern coast of Martha’s Vineyard. These velocities are also amplified within the bay.

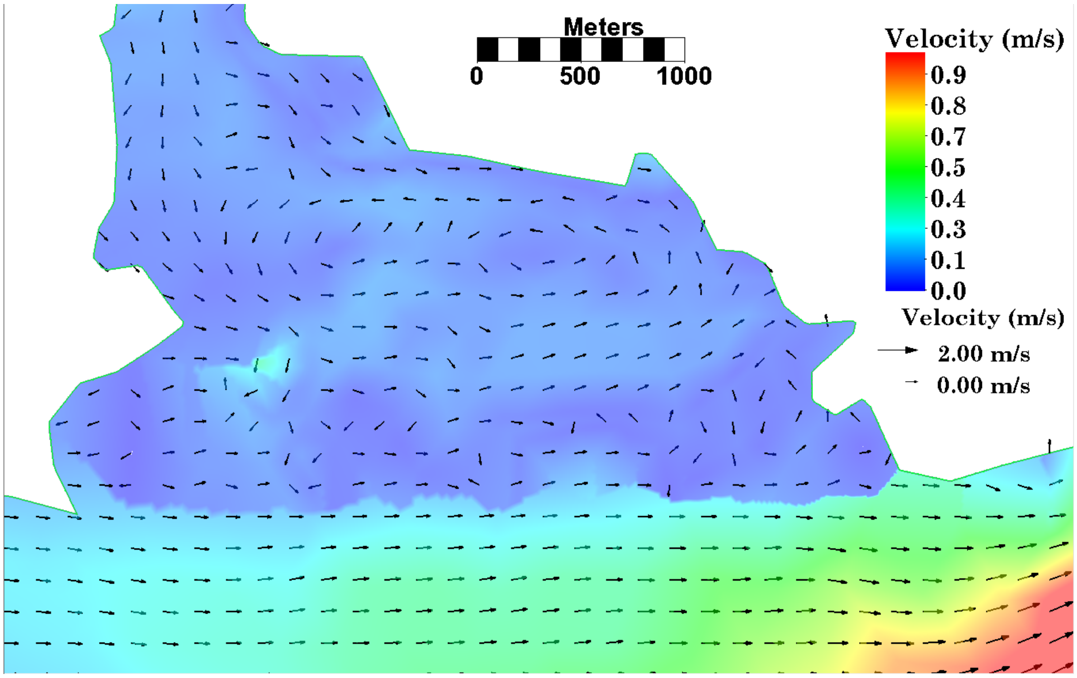


Figure 7. NACCS modeled velocity vectors and contours during peak surge showing no flow into or out of the southern border of Katama Bay.

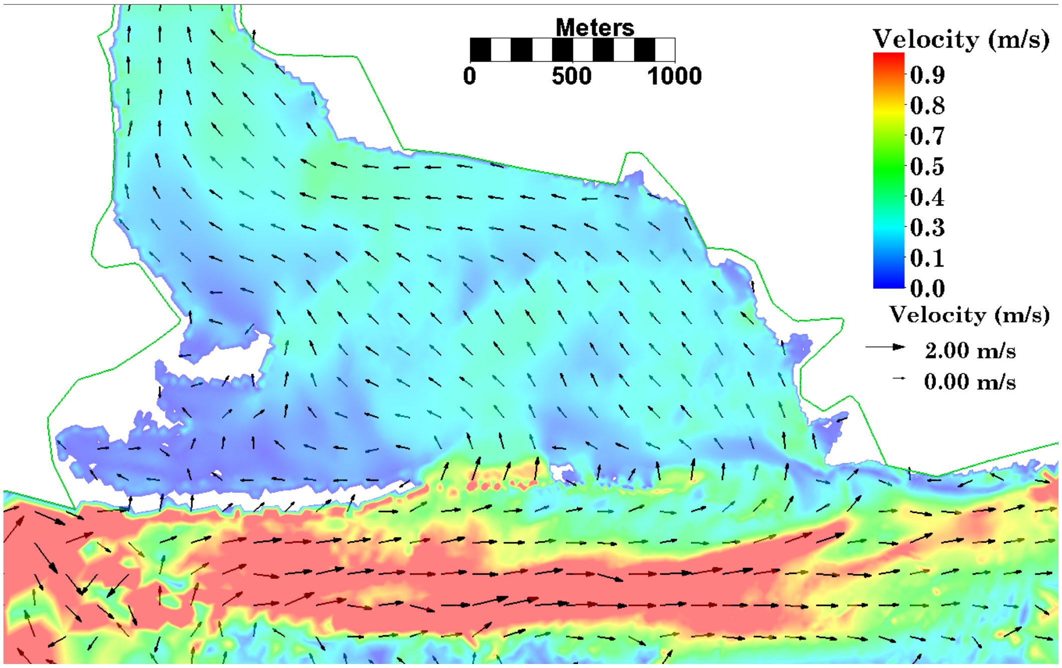


Figure 8. High-resolution, coupled modeled velocity vectors and contours showing the flow associated with the overtopping of South Beach.

In order to assess the net flow potential through Katama Bay, it is useful to compare the pressure gradient (or difference in water elevation) across the system. Changes in this gradient will indicate changes in the amplitude and timing of the surge at Katama Inlet (station 05) versus Edgartown channel (station 01). In figure 9 we see that the pressure gradient in the high-resolution runs points to the north while the opposite is true for the NACCS run. Figure 10 shows that during the peak surge when the modeled station outside of the bay to the south (station 06) is compared with station 01, as a result of no inlet on the southern part of Katama Bay, there is an enhanced northward (positive) pressure gradient within the NACCS run, which was not seen in either of the high-resolution runs. This suggests a larger influence of storm surge modification to the area (higher water on the southern coast of Martha's Vineyard) than might be expected owing to the small size of Katama Inlet. The general agreement of the models throughout the remainder of the time series, when compared to the lack of coherence in the station 05 and 01 comparison signals, further serves to illustrate the extent to which the inability of the NACCS run to model inlet flow and overtopping effects the accuracy of the overall flow pattern of the system.

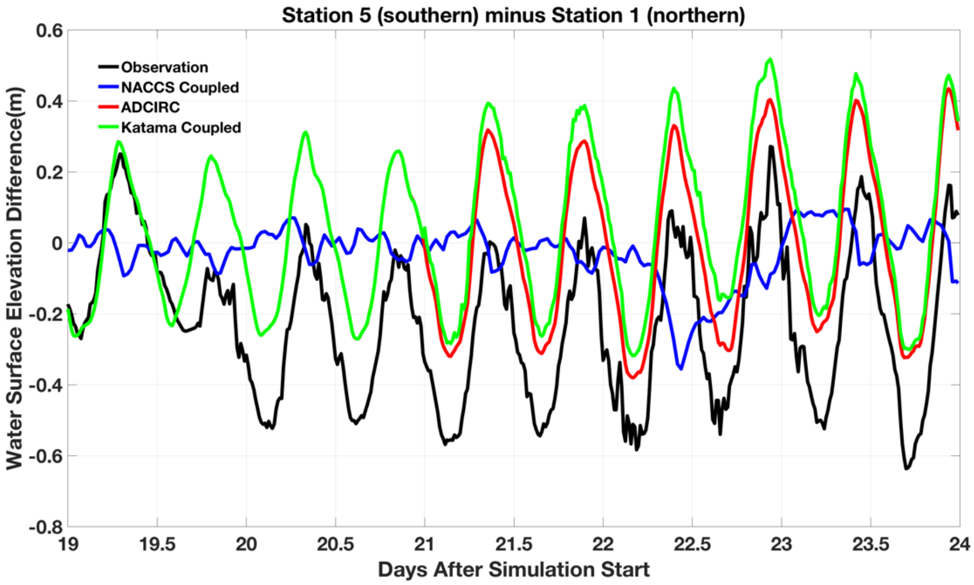


Figure 9. Water elevation difference between the southernmost observation station (05) and the northernmost (01) where positive values are indicative of flow to the north.

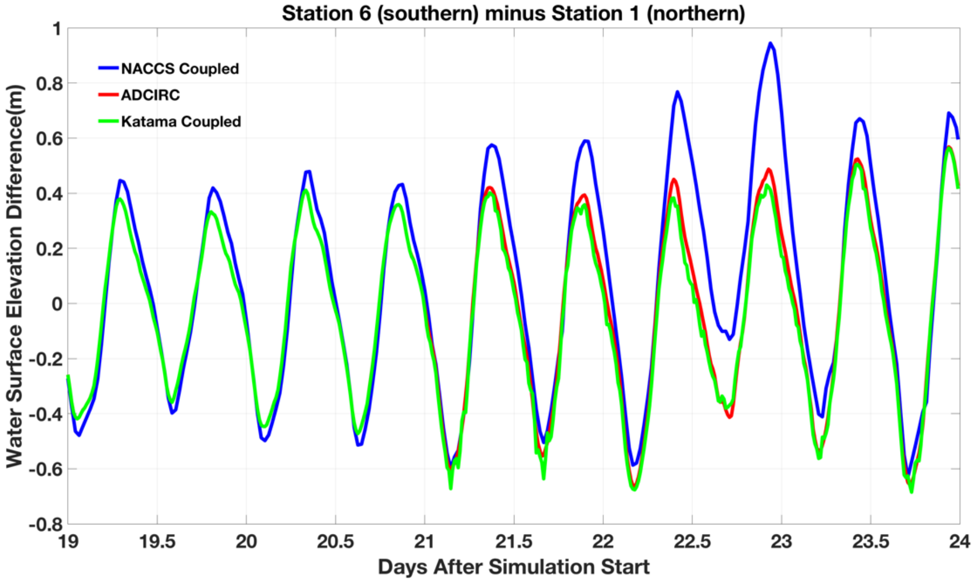


Figure 10. Water elevation difference between the southernmost modeled station (06) and the northernmost (01) where positive values are indicative of flow to the north.

b. Coupling Effects

Error statistics show that the coupling of STWAVE and ADCIRC improves prediction performance compared to using ADCIRC alone. It is also instructive to compare the differences between the two spatially as seen in Figure 11. During the peak storm surge, water elevation is higher in the southern part of Katama Bay and in the surf zone directly to the south in the model run that includes wind waves. This is an indication that the coupled model is including the wave setup inherent with breaking waves. In addition, the overall higher water levels within Katama Bay during peak surge indicates waves are contributing to an overall elevation change within the bay, consistent with Olabarrietta et al., 2011 and Malhadas et al., 2009. This suggests that while typical wave forcing may not increase bay levels (as seen in Orescanin et al., 2014), during surge events, not all momentum fluxed by waves can be radiated out through Edgartown Channel.

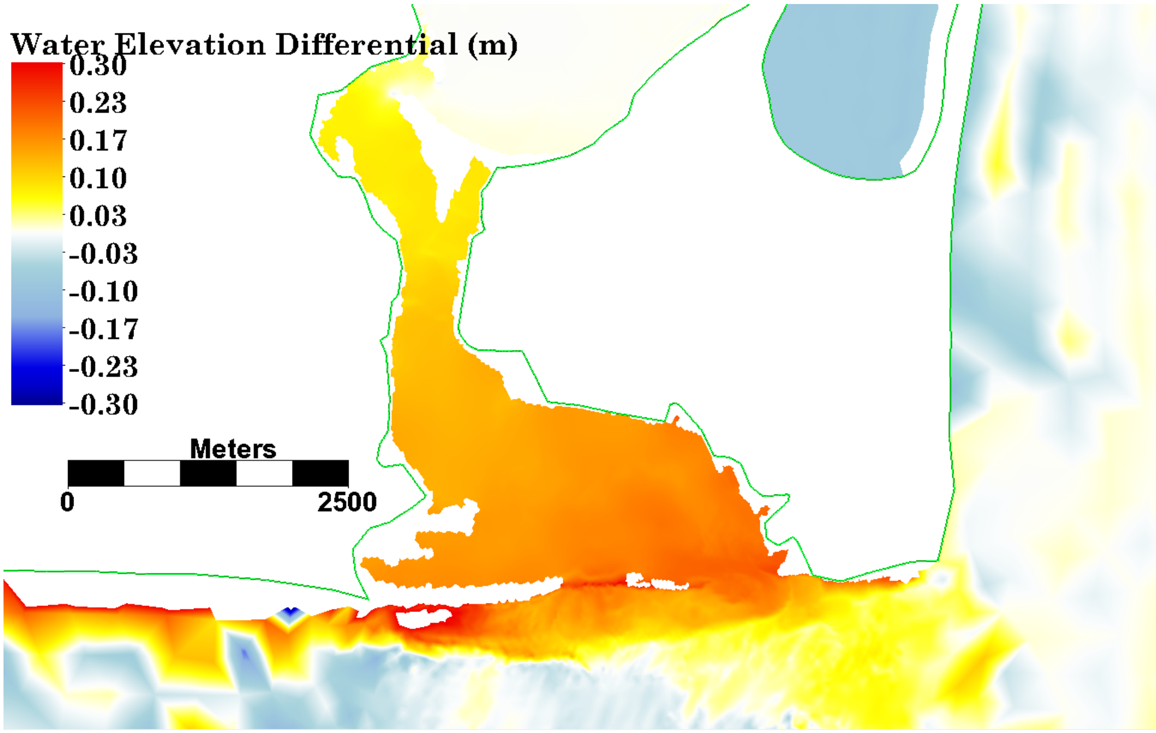


Figure 11. Water elevation differential between the coupled and uncoupled high-resolution model runs during peak storm surge.

A similar comparison can be made between the modeled wave heights as seen in Figure 12. It is evident here, keeping in mind the increased velocities in the shoal area seen in Figure 8 that the inclusion of wave-current interaction in the coupled run produces higher modeled wave heights. Surprisingly, however, when the modeled wave heights are compared to the observation, as seen in Figure 13, for station 04, the inclusion of this interaction improves the modeled timing and duration of the peak wave heights, but decreases the accuracy of the magnitude. Part of this is expected from the fact that the waves at station 04 are almost exclusively wind waves and have higher error bar estimates due to high frequency decay. While a direct comparison cannot be made due to lack of coincident observational data, the performance of the Katama coupled model does appear to more accurately handle magnitudes in the shoal outside of the bay (Figure 14) as the Martha's Vineyard Coastal Observatory measurements (located 12 nautical miles from shore) showed a minimum wave height of 1.9 meters.

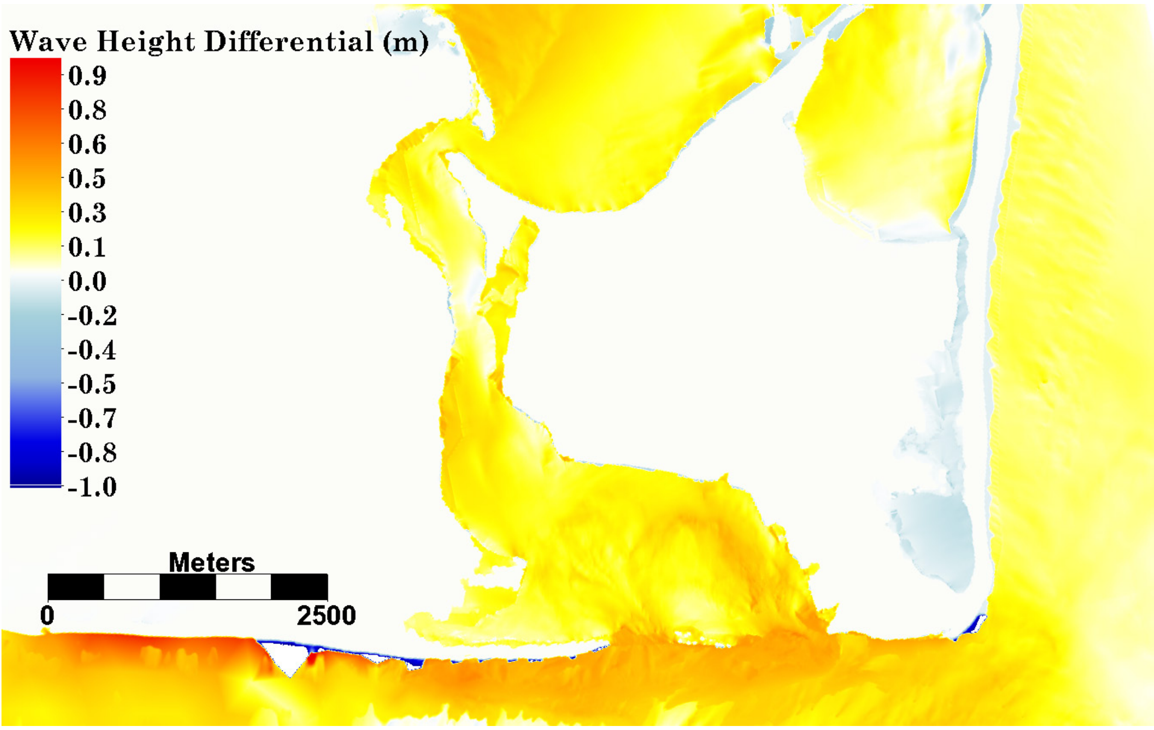


Figure 12. Wave height differential between the Katama coupled and ADCIRC high-resolution model runs during peak storm surge in Katama Bay.

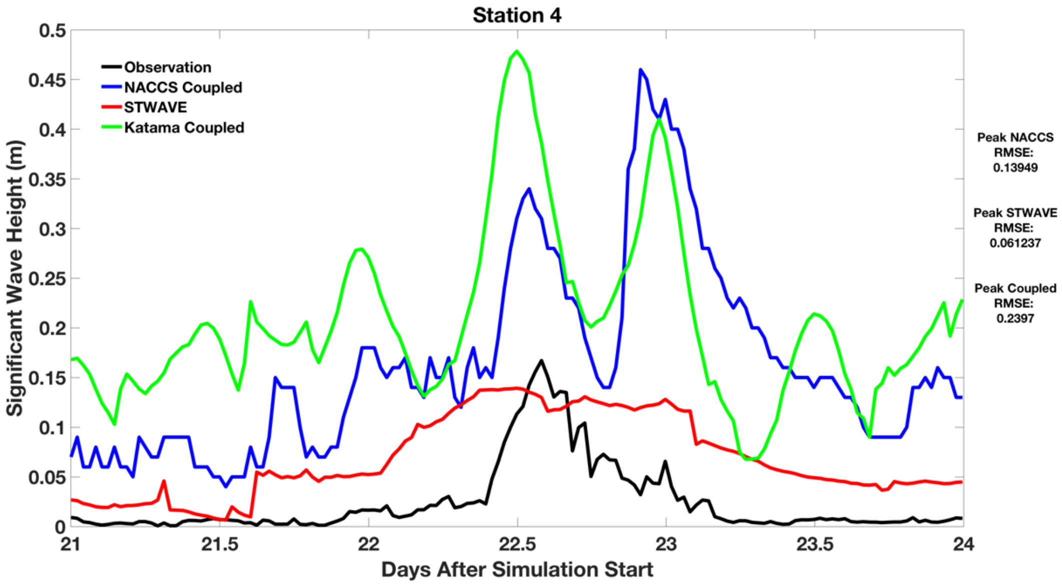


Figure 13. Modeled and observed wave heights at station 04.

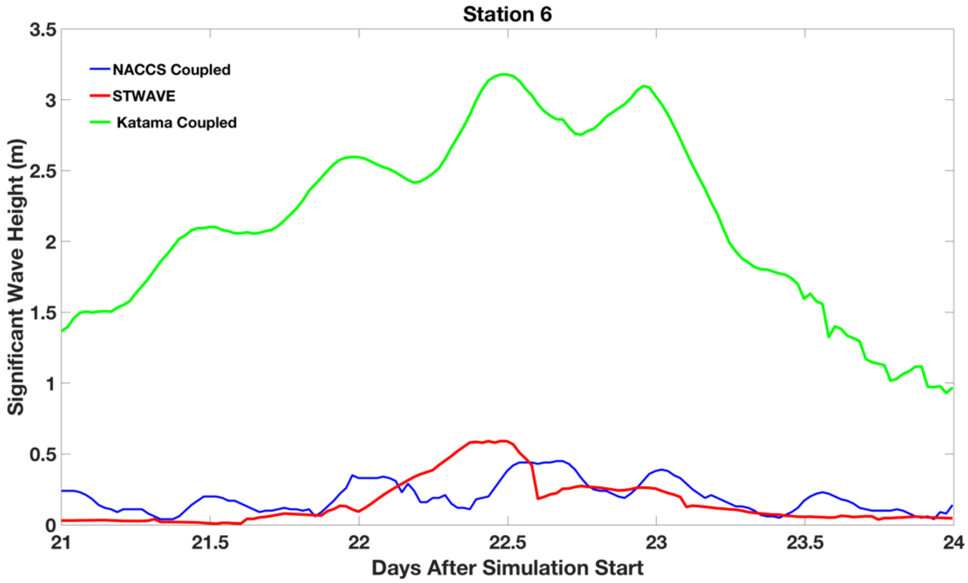


Figure 14. Modeled wave heights at station 06, located on the shoal outside Katama Bay.

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V. CONCLUSION

An examination of calculated error statistics and modeled time series show that the coupling of STWAVE and ADCIRC improves on the low bias present in the lower resolution NACCS, confirming the hypothesis. During the peak surge, error reduction exceeded 20 percent. This can largely be explained by the high-resolution model's ability to accurately describe the overtopping of South Beach and the associated flow patterns, including the significant increase in current velocities along southern Martha's Vineyard. The ability to accurately model these alongshore velocities has a profound impact on inlet migration and sediment transport predictions.

Contrary to prior research that shows a lack of setup in the Katama Bay system from wave forcing due to a compensating momentum flux through the Edgartown Channel, this research shows that in extreme wave forcing events, the flux through this northern inlet cannot provide an adequate drainage path to prevent an increased water elevation in the bay. Interestingly, the coupling of the wave and circulation models showed an improved ability to model the general behavior of wave heights in Katama Bay, but this inclusion of wave-current interactions decreased the accuracy of the magnitude of this field. It is important to note in the discussion of these wave heights, however, that the magnitude of these waves is quite small. Further research should examine the performance of the coupled model for an event that generates larger waves within an inlet system.

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