# Modeling Storm Surge in a Small Tidal Two-inlet System

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## ABSTRACT

Model simulations using a depth-averaged ocean circulation model (ADCIRC) two-way coupled with a wave model (STWAVE) through the Coastal Storm Modeling System Coupling Framework (CSTORM-MS) are compared with observations made in the shallow, two-inlet tidal Katama Bay system on the Atlantic coast of Martha's Vineyard, Massachusetts during Hurricane Irene. The CSTORM-MS framework integrates high-resolution bathymetric grids of this system with the North Atlantic Coast Comprehensive Study (NACCS) performed by the United States Army Corps of Engineers. The effects of bathymetric resolution and wave-flow coupling on the accuracy of modeled storm surge were investigated by comparing observations with the high bathymetric resolution, coupled model (CSTORM), a high-resolution uncoupled ADCIRC model, and a low bathymetric resolution, coupled model (NACCS). During the peak storm surge period, the coupled model using high-spatial resolution bathymetry reduced error in the study area by over 30 percent compared with the lower-resolution NACCS model, and by 16 percent compared with the high-resolution, uncoupled ADCIRC model. In addition, the high-resolution models indicate alongshore flows with magnitudes over 2.0 m/s along the southern coast of Martha's Vineyard, and a net northward circulation through Katama Bay and Edgartown Channel, which are not apparent in the lower-resolution simulations. Contrary to prior research suggesting small, if any setup in the Katama Bay system from wave forcing, in the extreme wave forcing event discussed here, the northward flux through Katama Inlet on the south side of the bay does not exit completely through Edgartown Channel on the north side of Katama Bay.

Thus, the drainage path is not adequate to prevent increased water elevation in the bay, resulting in a setup within Katama Bay during the peak surge event, highlighting the need for adequate model resolution for local storm surge predictions.

# 1.INTRODUCTION

## 1.1 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 that often is a major contributor to high death tolls (Blake et al. 2007). To provide adequate warning to prevent the loss of life and property, storm surge must be predicted accurately. However, storm surge in spatially small systems with complex bathymetry, such as tidal inlets, can be difficult to predict with regional-scale storm-surge forecast modeling systems that necessitate coarse spatial resolution (Yin et al. 2016). For example, storm surge in inland areas of the US Gulf Coast was not predicted accurately with low-resolution models during Hurricane Ike (Kerr et al. 2013), nor was storm surge predicted accurately for barrier island systems along the US East Coast (Lawler et al., 2016; Bennett et al., 2018).

Coupling high-resolution storm-surge models with nearshore wave models is an active research field (Dietrich et al. 2012; Orton et al. 2012; Sun et al. 2013; Mao and Xia, 2018; Kang and Xia, 2020) motivated by observations of wave effects on water levels in back lagoons and currents within tidal inlets (Bertin, et al. 2009; Malhadas et al., 2009; Dodet et al. 2013; Orescanin et al. 2014). There are several examples of such modeling systems, including the coupling of the unstructured version of the Simulating Waves Nearshore (SWAN) and the Advanced Circulation (ADCIRC) models (Dietrich et al. 2012), coupling of Delft3D and SWAN (Bennett et al. 2018), the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) model, (Kumar et al. 2012), and FVCOM/SWAVE (Chen et al. 2013). Neglecting small-scale bathymetric features, such as tidal inlets or shoals, and the associated hydrodynamics, can lead to under prediction of storm surge relative to simulations that include high-resolution bathymetry and small-scale processes (Orton et al. 2012; Sun et al. 2013).

The Steady-State Spectral Wave Model (STWAVE) accounts for both wave diffraction and reflection (Gonçalves et al. 2015), which may be important near the complex bathymetry of tidal inlet systems where observations show large spatial gradients of currents, waves, and bathymetry. Using the Coastal Storm Modeling System Coupling Framework (CSTORM-MS) (Massey et al. 2011), STWAVE and ADCIRC coupled modeling of storm surge is skillful on large spatial scales (Bryant and Jensen 2017). Less research has been conducted at the higher resolutions needed to resolve most inlet and small bay systems that are common along barrier island coastlines. Model domain sizes that are not sufficiently large 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.

### 1.2 STUDY PARAMETERS

The focus here is the Katama Inlet system, Martha's Vineyard, Massachusetts (Figure 1), during Hurricane Irene. Pressure sensors were deployed in the Bay from Katama Inlet in the south to Edgartown Channel in the north in early August, 2011, and remained in place until after Hurricane Irene (Figure 1, and Orescanin et al. 2014). The observations are used here to examine the skill of coupled wave and circulation models with different spatial resolutions.

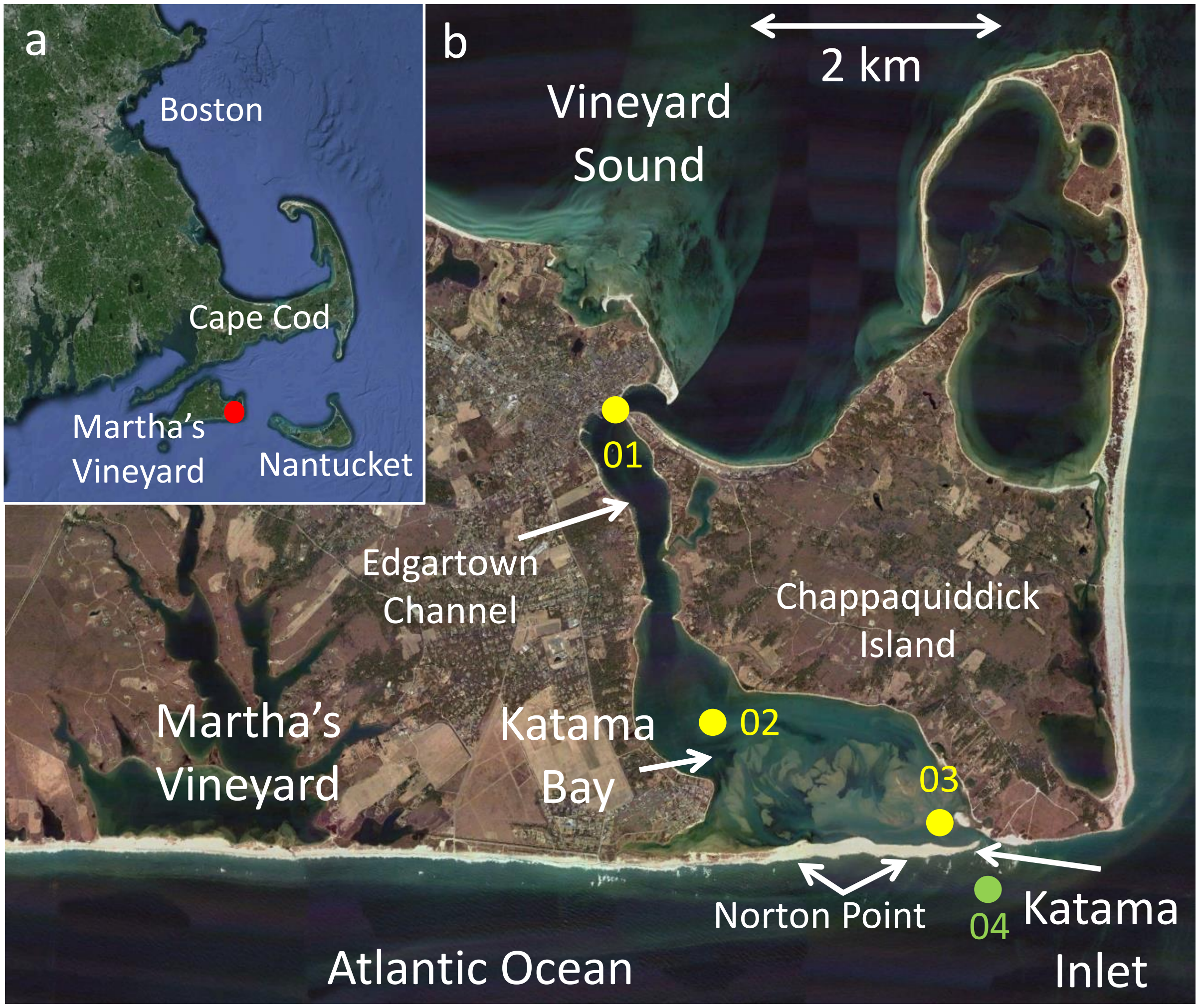


**Figure 1:** Location of (a) Martha's Vineyard, MA, with the Katama system inside the red circle, and (b) the south-eastern part of Martha's Vineyard, showing Katama Bay, with Edgartown Channel to the north and Katama Inlet to the south. The yellow circles are sensor locations and the green circle (04) is located on the ebb shoal where model results are compared with each other.

Irene (Atlantic storm number 09) passed approximately 550 km to the west on 28 August, 2011. Significant wave heights measured at the closest offshore NOAA buoy (number 44097) reached a peak of 14.7 m at 12:38 EDT on August 28, much higher than the typical non-storm value of 1.0 m. Martha's Vineyard Coastal Observatory (MVCO) recorded significant wave heights over 5 m in 12-m water depth (Figure 2a). Maximum sustained winds at the NOAA buoy at Buzzards Bay located 55 km to the west of the research area and at MVCO (Figure 2b) at the time of the closest point of approach were approximately 25 m/s. Storm surge associated with Irene propagated northward through the research area, and was 0.7 m at the southernmost observation sensor in Katama Bay (Station 03 in Figure 1, red time series in Figure 2e) on August 28 at 14:45 EDT.

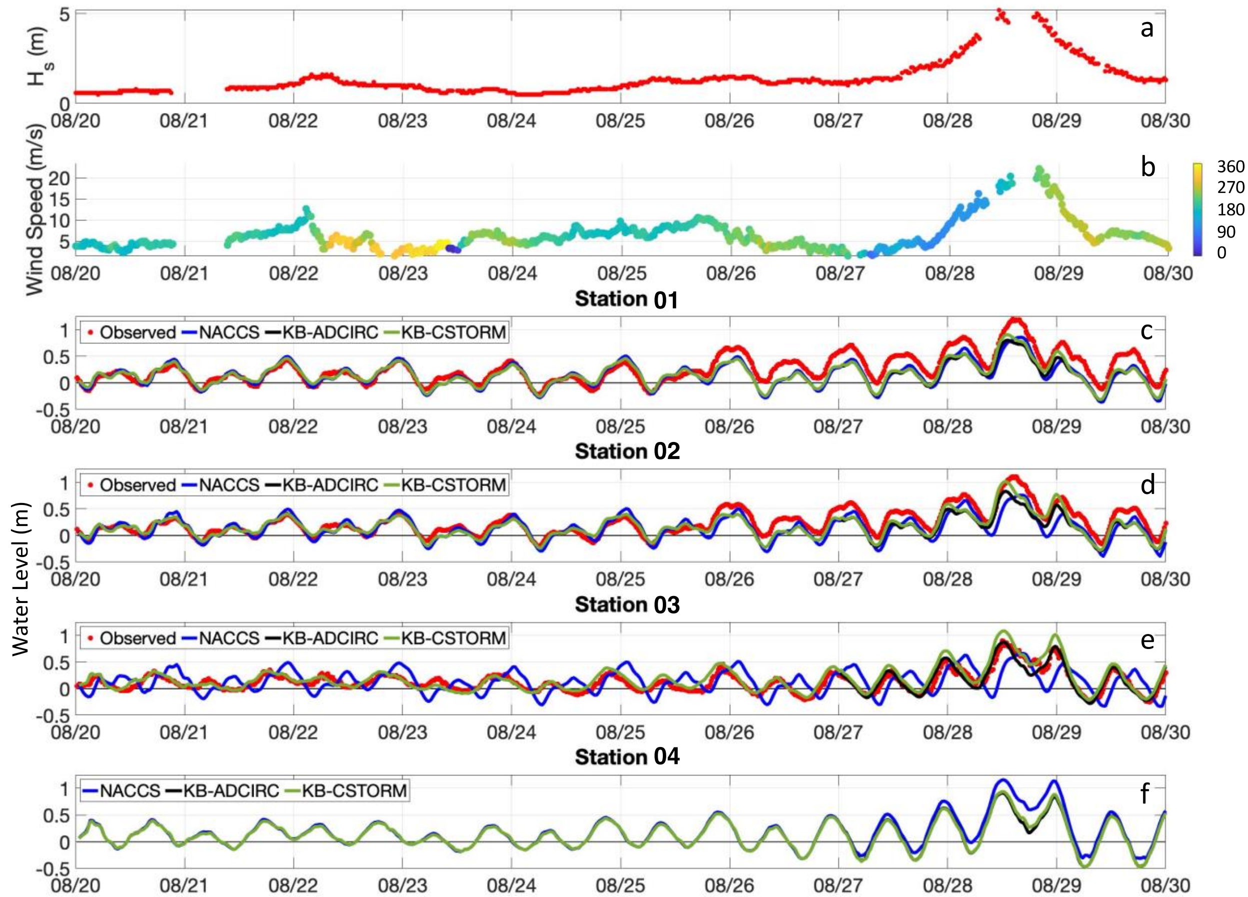


**Figure 2:** Time series of waves, wind speed and direction, and water level for the Katama Bay system: a) Significant wave height ($H_S$) and b) wind speed (colored by direction, scale on the right) for MVCO (12 m depth), and water-surface elevation for c) Station 01, d) Station 02, e) Station 03, and f) Station 04 versus time during Hurricane Irene, which had maximum impact in this area mid-day on 08/28. The curves are for observations (red), NACCS (blue), KB-ADCIRC (black), and KB-CSTORM (green). Observations were not obtained at Station 04.

Katama Bay and the surrounding Atlantic Ocean (including Wasque Shoals, south of Katama Inlet) is an area of complex bathymetry that includes the migrating Katama Inlet that, when open, connects the southern part of the bay with the Atlantic Ocean (Figure 1). Katama Inlet last opened during a nor'easter storm in 2007, and slowly migrated 1.5 km to the east until it closed in 2015, producing complicated, evolving ebb and flood shoals. These shoals and

Norton Point are comprised of medium sand. Katama Bay is connected to Vineyard Sound in the north by the continuously open Edgartown Channel (Figure 1). Thus, when Katama Inlet is open, this site is a double inlet system. The M2 tide at Edgartown Channel in Vineyard Sound is approximately three hours out of phase (delayed) with the Atlantic M2 tides at Katama Inlet. This phase difference results in strong tidal flows in the inlets and the bay. However, under normal conditions sub-tidal changes in the bay sea level are small because water can flow out of the inlets (Orescanin et al., 2014). In addition, there is no significant freshwater input to the system that would distort the tidally driven flows.

The complex bathymetry covers a relatively small area, and thus is an ideal location to study the effects of spatial resolution on models for storm surge. Previous modeling in this area 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). Numerical results suggest that high-spatial-resolution bathymetry, both within Katama Bay and in the Atlantic Ocean offshore of Katama Inlet, combined with accurate wave models are critical to simulate the hydrodynamics of the system.

Here, the importance of spatial resolution and wave forcing to simulations of storm surge through small coastal bays and inlets is investigated. Specifically, STWAVE and ADCIRC are dynamically two-way coupled using the CSTORM coupler, and the peak storm surge and flow predictions are compared with the predictions of uncoupled or lower-resolution modeling systems. 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. 2015; Cialone et al., 2017) are utilized and merged with higher resolution grids.

# 2 CSTORM NUMERICAL MODELS

The Coastal Storm Modeling System (CSTORM-MS) is a system of numerical models used to simulate coastal storm waves and water levels, as well as a comprehensive methodology of how those models are applied to provide accurate inputs for assessing risk to coastal communities. The CSTORM-MS makes use of nonlinear physics-based models with higher-order-accurate numerical discretization methods and resolutions. The numerical models used within the CSTORM modeling system for the NACCS consisted of the deep water Wave Model (WAM) for producing offshore wave boundary conditions for use with the nearshore STWAVE model. ADCIRC model was used to simulate two-dimensional depth-integrated surge and circulation responses to the storm conditions. The STWAVE model was used to provide the nearshore wave conditions, including local wind-generated waves. The CSTORM coupling framework (Massey et al. 2011) was used to tightly two-way couple the ADCIRC and STWAVE models to allow for dynamic interactions between the surge, circulation, and waves, resulting in improved modeling results.

**2.1 WIND AND PRESSURE FIELDS**

The wind and pressure fields used for the Hurricane Irene simulations were produced by Oceanweather, Inc. (OWI, 2015) and are the same winds and pressures used and documented as part of the NACCS (Cialone et.al 2015). Two levels of wind and pressure fields were used. (Figure 3). The first level included a larger domain covering the western Atlantic and from 99.0 to 60.0 degrees west longitude and from 7.500 to 46.125 degrees north latitude using a 0.125-degree grid resolution (larger grid, Figure 3a). The second level covered an area from 78.00 to 72.00 degrees west longitude and from 34.00 to 42.05 degrees north latitude using a grid resolution of 0.05 degrees (smaller grid, Figure 3). The wind and pressure field records were sampled every 15 minutes, and covered the period from 08/20/2011 0 hr UTC to 08/30/2011 0 hr UTC. The study area (red X, Figure 3a) was located in the larger wind and pressure domain with a gridded resolution of 0.125 degrees.

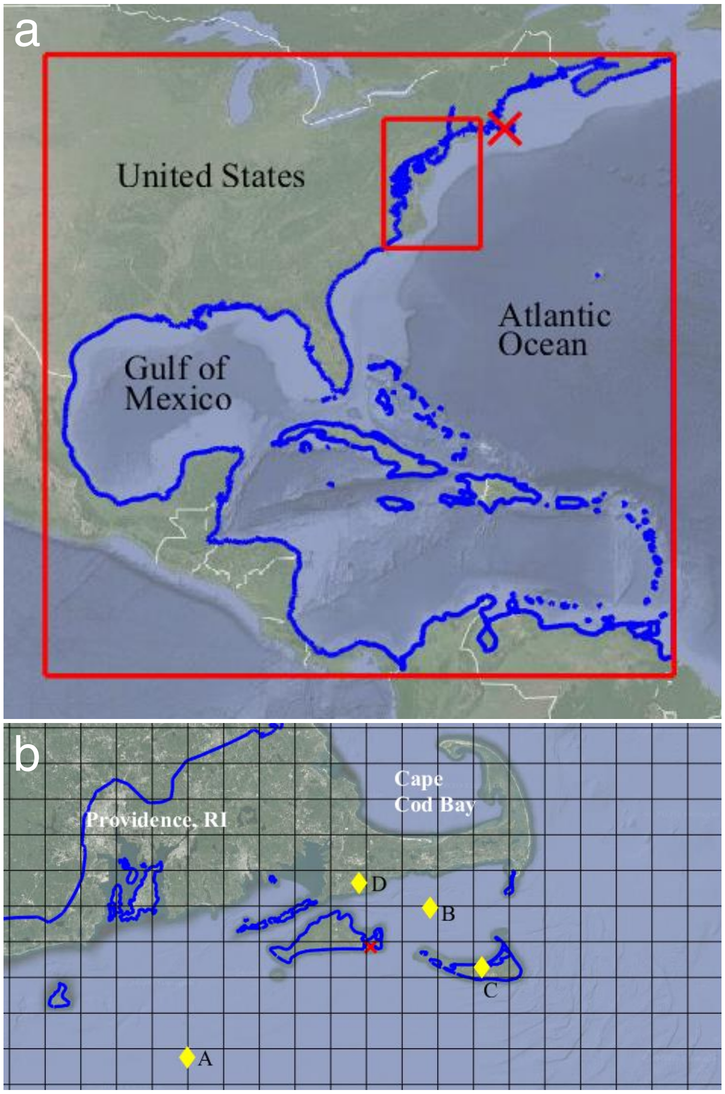


Figure 3: a) Map showing the outline of the ADCIRC model domain boundaries in dark blue and the boundaries of the two wind and pressure field domains in red. A red X demarks the study area. b) Map showing a more detailed view of the project area, with the ADCIRC model domain boundaries in dark blue and the black gridded lines showing the grid cells for the level 1 wind and pressure fields. Winds were observed at the 4 locations marked with yellow diamonds, with waves observed at yellow diamonds A and B. The red X demarks the study area.

Several National Data Buoy Center (NDBC) and one National Estuarine Research Reserve System (NERRS) locations recorded wind speeds and directions during Hurricane Irene near the study area. Of those, three representative sites were selected to compare wind speeds and directions, and two sites were selected to compare wave statistics (yellow diamonds in Figure 3b). The selected NDBC sites for wind comparisons are NTKM3 (“C” in Figure 3b) on

Nantucket Island, MA (Figure 4a,b) and Station 44020 ("B" in Figure 3b) in Nantucket Sound (Figure 5). The measured and modeled wind speeds are similar (Figures 4-5), with the modeled values for peak wind speeds slightly over-predicted by approximately 5 m/s at Station NTKM3 and the Waquoit Bay Reserve NERRS (Figures 4a and 4c). The wind directions at these locations (Figures 4b, 4d, and 5f) also compare well, although there is an approximately 30-degree shift in the wind directions at the NERRS location. Considering the 0.125 degree resolution of the modeled winds, the simulated values are considered to represent the storm well in this small bay.

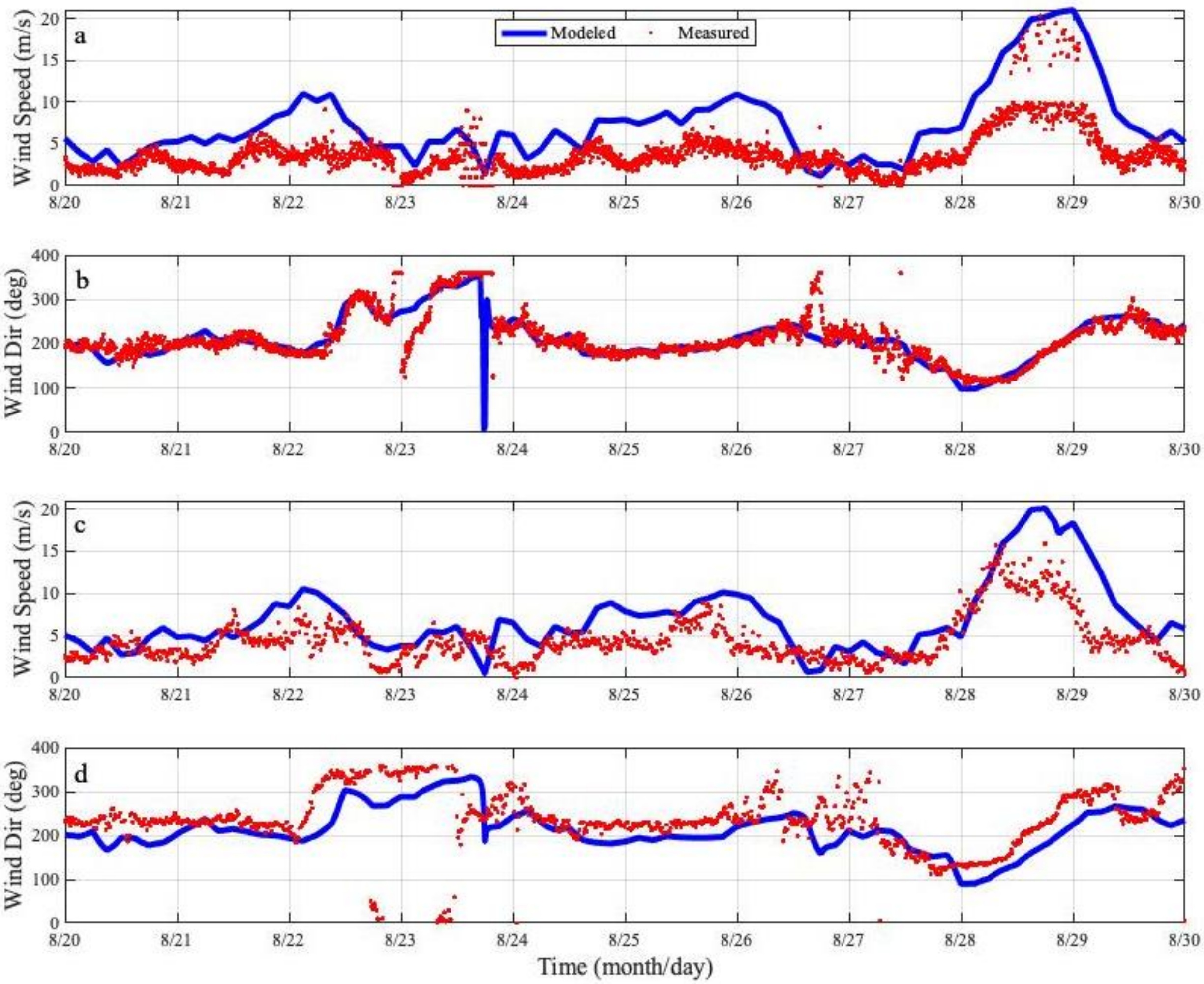


Figure 4: Time series of wind speed and direction at (a-b) NDBC NTKM3 (Nantucket) and (c-d) NERRS Waquoit Bay Reserve. WAM model inputs used for the NACCS (blue) compared with observations (red). Locations for NTKM3 and Waquoit Bay are shown in Figure 3b (positions C and D, respectively).

## 2.2 WAM WAVE MODEL

The deep-water wave model used to generate the offshore wave estimates for the NACCS and consequently for this study, is the 3rd generation wave model WAM (Komen et al., 1994). WAM is similar to other 3rd generation wave models like WaveWatch III (Tolman, 2014) or SWAN (The SWAN Team, 2017). WAM makes no a priori assumptions governing the spectral shape of the waves and the source term solution is formulated to the wave model's frequency/directional resolution. WAM was developed by a consortium of wave theoreticians and modelers over a ten-year period and is used by the European Center for Medium Range Weather Forecasts researchers and in the private sector. The accuracy of the WAM model's results is dictated by the accuracy in the bathymetric grid and wind forcing data used in the simulations.

The WAM results are used to provide spectral energy boundary conditions to the nearshore STWAVE model. This splitting up of waves between deep water and nearshore, allows for a more computationally efficient workflow for CSTORM and the use of wave models specifically designed for deep water and shallow water respectively. Since the WAM model uses a coarser spatial resolution than STWAVE and uses integer values for water depths, the WAM model is insensitive to changes in the geometry of the nearshore areas or water depth changes on the order of a meter or two. The STWAVE model, as most other nearshore wave models, is comparatively more computationally expensive than a 2D circulation model such as ADCIRC, and in general requires between 4 and 18 times the computational effort. As such, reducing the simulation region of the nearshore wave models, without significantly compromising nearshore results for waves and water levels, is desirable. Using the WAM model results to force the boundary of the STWAVE model allows swell propagating from far offshore to be included in the simulations, while reducing the computational time required by STWAVE. The WAM model setup used in this study is exactly the same as that used in the NACCS (Cialone et al., 2015, Jensen et al., 2016). Those reports provide significant details of the WAM model setup and validation results applied to several historical tropical and extra-tropical events, including Hurricane Irene. A sample of the WAM model result for Hurricane Irene are compared with measurement data at two NDBC buoys located near the study area, Station 44020 (Figure 5) and Station 44097 (Figure 6). In the more open water areas around buoy 44097, the WAM results represent the significant wave heights, peak and mean periods very well.  However, buoy 44020 is located near Nantucket and Martha's Vineyard islands, including the Katama Bay system, and the WAM model resolution is not designed specifically to capture them.  This can be seen in the time series (Figure 5), where the periods from the model indicate swells and the measurements indicate wind-seas.  Nevertheless, the model does well at reproducing the significant wave heights.

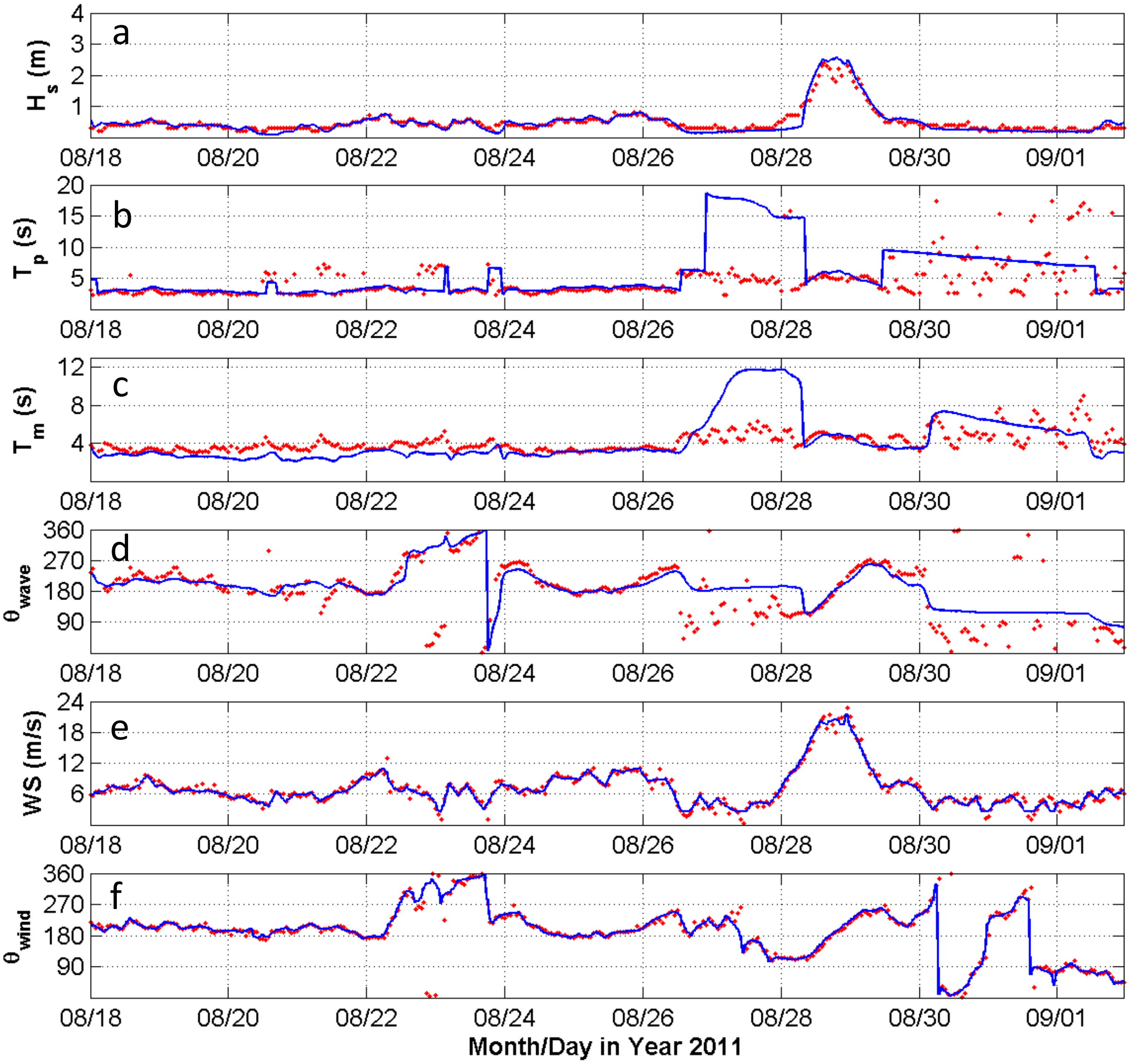


**Figure 5:** WAM model (blue curves) and NDBC buoy 44020 (red dots, "B" in Figure 3b) versus time. a) significant wave height, b) peak period, c) mean period, d) wave direction, e) wind speed, and f) wind direction.

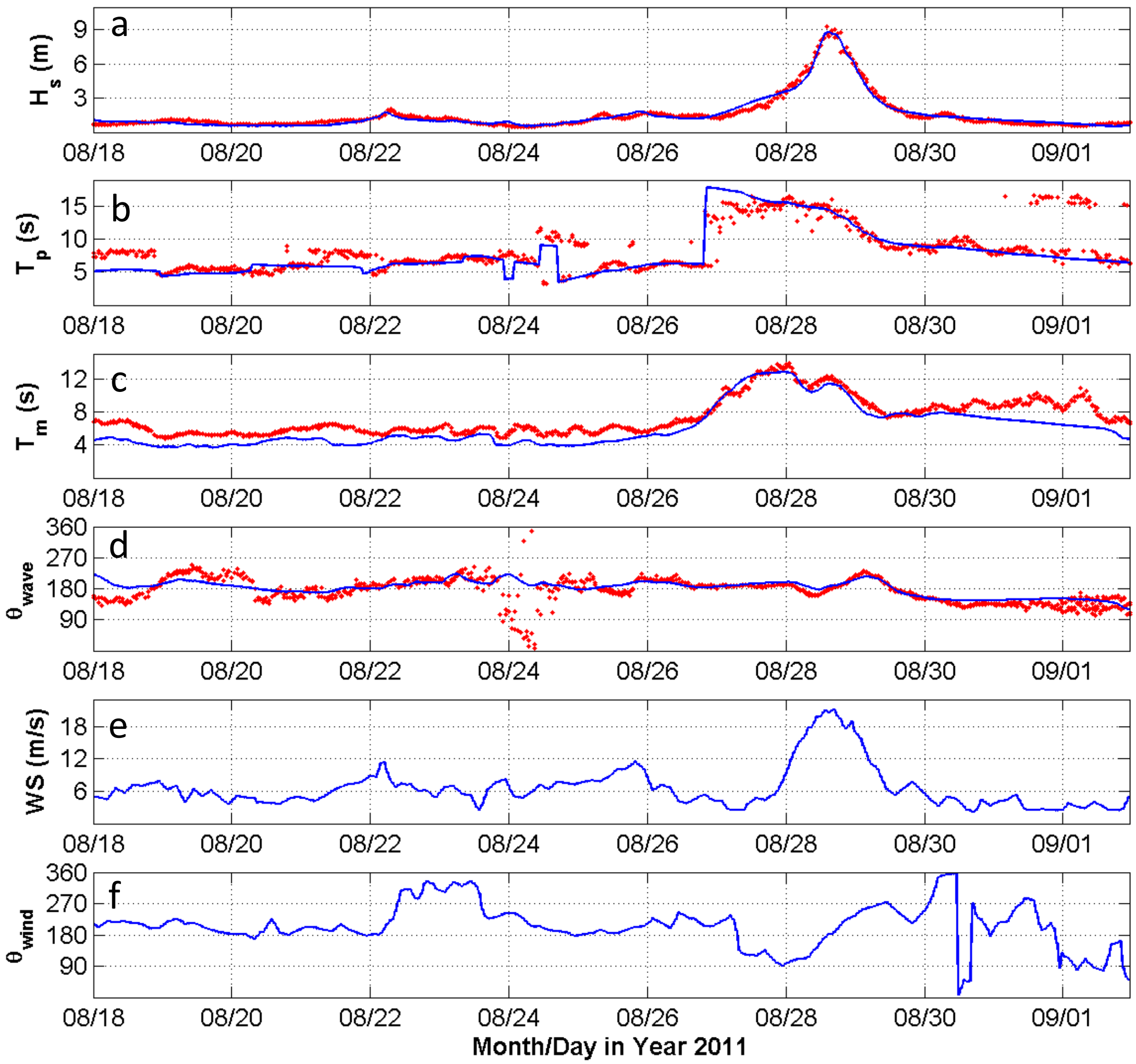


**Figure 6:** WAM model (blue curves) and NDBC buoy 44097 (red dots, "A" in Figure 3b) versus time. From top to bottom: significant wave height, peak period, mean period, wave direction, and model only wind speed, and wind direction.

## 2.3 STEADY-STATE SPECTRAL WAVE MODEL

### 2.3.1 Model Description

STWAVE is a model developed by the United States Army Corps of Engineers to estimate wind-wave growth and nearshore wave transformation, including shoaling, breaking, diffraction, and refraction. STWAVE is a finite-difference, phase-averaged spectral model that solves the wave action balance equation on a Cartesian, rectangular grid (Massey et al. 2011).

STWAVE is run in full-plane mode, which allows wave generation from all 360 degrees, and thus is better suited than half-plane mode for modeling waves during a hurricane. The steady-state STWAVE model operates under the assumption that the duration of meteorological forcing is not a limiting factor in the generation of wind waves over the domain.

### 2.3.2 Model Setup and Domain

Two STWAVE grids are used here (Figure 7). A larger grid covering the southern Massachusetts (SMA) area developed for the North Atlantic Coast Comprehensive Study (NACCS) (Bryant and Jensen 2017) with a resolution of 200 by 200 m was used to generate wave spectra for boundary conditions for the smaller 10 by 10 m grid covering Katama Bay. Both grids were oriented at 101.5 degrees (Figure 7). Both models used 72 angle bands separated by 5 degrees and 30 frequency bands ranging from 0.04 to 0.33 Hz in increments of 0.01 Hz. The SMA grid has an origin ($x_0$,$y_0$) located at (465575.3, 4518084.4) in the UTM zone 19 coordinate system measured in meters and is made up of 733 cells in the I-direction and 887 cells in the J-direction. The Katama Bay grid has an origin ($x_0$,$y_0$) located at (381625.68, 4577634.03) in the UTM zone 19 coordinate system measured in meters and is made up of 916 cells in the I-direction and 1134 cells in the J-direction. Waves on the NACCS SMA grid were forced with output from WAM and the (described above) Hurricane Irene wind fields. Morphic interpolation (Smith and Smith, 2002) of the directional spectra was used along the boundary of both STWAVE grids to supply spectral energy inputs to the models, and both models used wave breaking. Independent STWAVE simulations with a static water elevation were run from August 27 to August 30, 2011 to include 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 numerous sources to obtain the most accurate bathymetry possible (see Cialone et al. 2015, 2017 for model development discussion and details).

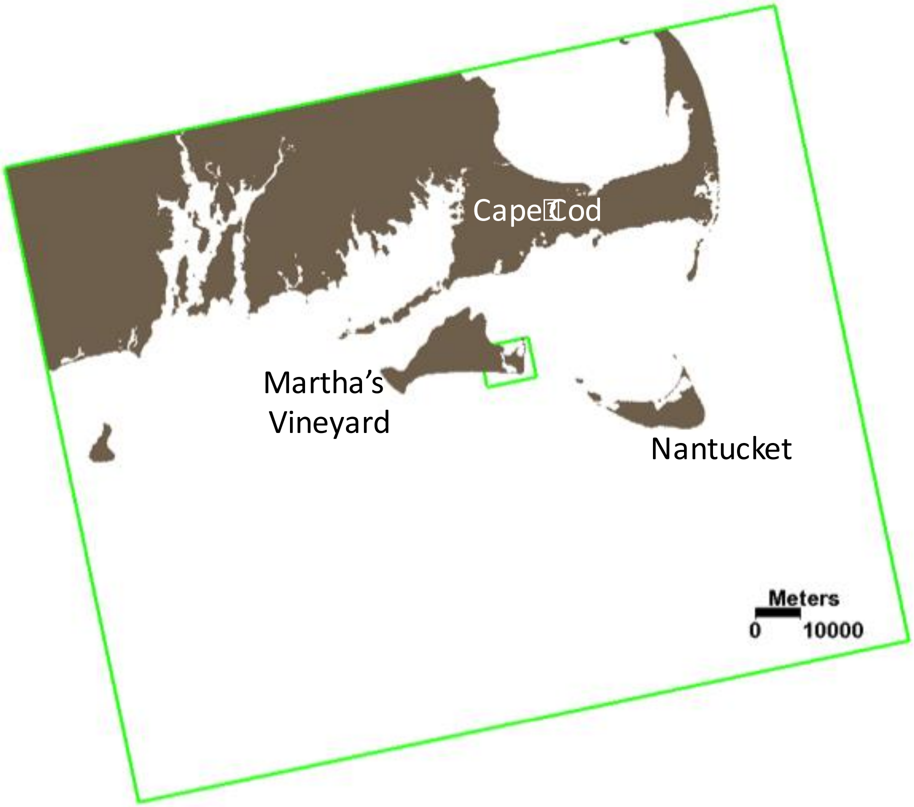


**Figure 7:** The Southern Massachusetts grid (SMA) (outer green box) and the higher-spatial resolution Katama Bay grid (KB) (inner green box) used for STWAVE.

Bathymetry for the high-resolution Katama Bay (KB) grid was obtained from surveys conducted with GPS- and sonar-equipped small boats combined with a 10-m resolution digital elevation model produced by NOAA in 2008 (Orescanin et al. 2016). The Katama Bay grid resolves the smaller-scale bathymetric contours of the bay and offshore region, particularly in the vicinity of the inlet and ebb shoal, in contrast to the lower-resolution SMA grid (Figure 8). Prior to coupling, both nested (Smith and Smith 2002) and un-nested STWAVE model runs conducted for the Hurricane Irene time period using the high-resolution grid were stable. For the large-scale, un-nested-grid case, there were no waves specified on the southern boundary, with waves generated within the grid using the OWI Hurricane Irene wind field. When using the nested grids, waves on the boundaries of the inner, high-resolution grid were provided by the spectral output from the SMA grid.

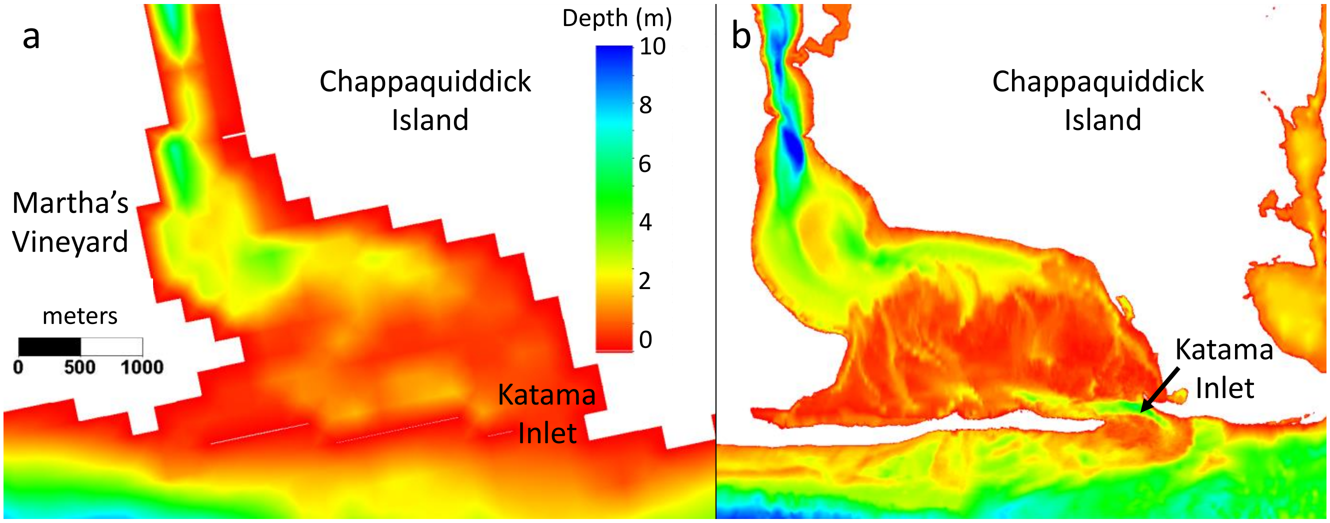


**Figure 8:** Contours of bathymetry (color and scale bars are in (a)) for a) the 200 by 200 m coarse SMA STWAVE grid and b) the 10 by 10 m fine Katama Bay (KB) STWAVE grid.

## 2.4 CIRCULATION MODEL

### 2.4.1 Model Description

The two-dimensional variant of the Advanced Circulation model (ADCIRC) is a depth-averaged model for ocean circulation based on 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). ADCIRC is an unstructured finite-element model, and thus the resolution can be varied across the domain to resolve complex bathymetry and associated processes in areas of interest, while minimizing computational cost by relaxing the resolution in areas where the bathymetry varies more slowly.

### 2.4.2 Model Setup and Domain

Two ADCIRC meshes of differing resolution were used (Figure 9). The coarser mesh was taken from the NACCS (Cialone et al., 2015; 2017). The finer mesh was developed by merging the Katama Bay mesh (Orescanin et al. 2016) with the NACCS mesh to achieve the resolution required near the coast and within the bay, while simultaneously including the large, basin-scale effects crucial to model storm surge accurately (Blain et al. 1994), here called the KB-ADCIRC mesh. The NACCS mesh treats the southern shoreline of Martha's Vineyard (Figures 1, 3) as a hard, no normal-flow boundary (Figure 9a), whereas the high-resolution KB-

ADCIRC mesh allows water to overtop the low-elevation Norton Point (Figure 1, 3b) and to enter Katama Bay through Katama Inlet (Figure 9b). Tidal forcing was applied to both meshes at the open ocean boundaries near 60 degrees west longitude. Consistent with the STWAVE grids, meteorological forcing was applied from Oceanweather Hurricane Irene wind and pressure fields. The ADCIRC simulations 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 to August 30, 2011. The Courant-limited time step for ADCIRC model runs was 0.5 seconds. A constant water level adjustment (the "sea surface height above geoid" parameter in ADCIRC) was set to the NACCS value of 0.111 meters to represent baroclinic and steric effects not accounted for in the ADCIRC model (Cialone et al. 2015). Values for spatially varying bottom friction, horizontal eddy viscosity, and primitive equation weighting of the continuity equation were the same as those in the NACCS study (Cialone et al. 2015).  Manning's n was set to the NACCS values, except for the areas in the higher-resolution area of the ADCIRC mesh, where the Manning's n values were reset to those used in a previous study (Orescanin et al. 2016).  Additional ADCIRC model input parameters include a nonlinear bottom friction with finite amplitude terms and a lower limit of bottom friction (FFACTOR) of 0.003, nonlinear advection terms in space and time, a 2.0-day ramp period using the hyperbolic tangent ramping function, a wetting and drying threshold depth of 0.10 meters, and a minimum wetting velocity of 0.10 m/s.

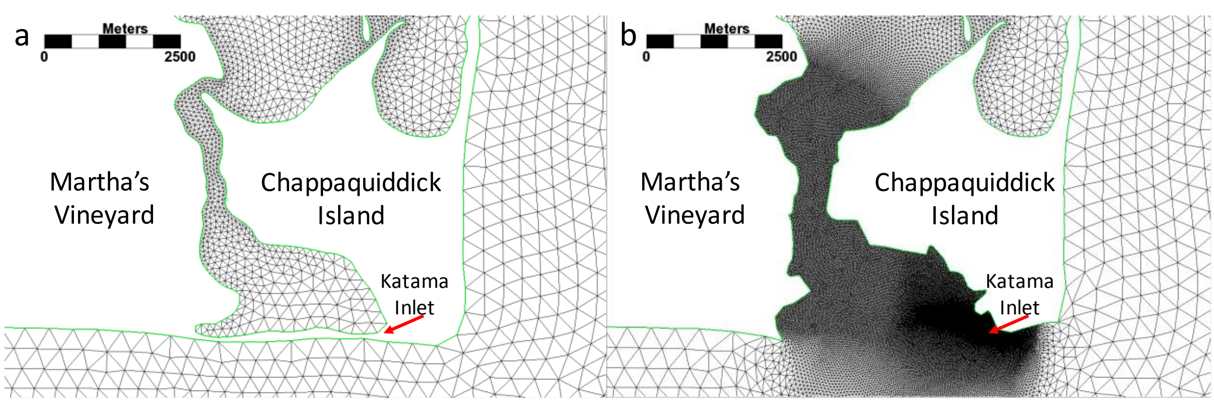


**Figure 9:** a) The NACCS mesh and b) the NACCS and Katama merged ADCIRC mesh.

## 2.5 MODEL COUPLING

To simulate surge levels, wind waves, currents, and the interactions among them, ADCIRC and STWAVE were two-way coupled in water level and wave-radiation stresses 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 to receive wave radiation-stress gradients during run time at every STWAVE snap (every 30 minutes). With this coupling, wind blowing over inundated regions during high surge events will generate waves. Both ADCIRC and STWAVE were run in their parallel computing modes by partitioning the domain to utilize high-performance computing resources at 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. The three models compared here are the (1) NACCS coarse resolution coupled model (NACCS), (2) the high resolution ADCIRC-only model (KB-ADCIRC), and (3) the high resolution coupled model (KB-CSTORM).

# 3 RESULTS AND DISCUSSION

## 3.1 OBSERVATIONAL DATA

To assess the accuracy of the models, comparisons were made with observations during Hurricane Irene in Katama Bay. Water elevation was estimated with bottom-mounted pressure sensors (sampled at 2 Hz) along the north-south axis of the bay (yellow circles, Stations 01-03, Figure 1). Station 01, the northern most station is near the transition from the bay to Vineyard Sound through Edgartown Channel. Station 02 is the farthest from any land boundary interaction and characterizes Katama Bay. Station 03 is close to Katama Inlet, near the transition from the Atlantic Ocean to Katama Bay. More details of the observations can be found in Orescanin et al. 2014. Model results also were output at 10 additional locations within the bay, as well as on the ebb shoal (Station 04) to simulate conditions outside of the bay.

## 3.2 MODEL EVALUATION

### 3.2.1 Error Statistics

As is seen in many storm surge modeling efforts (Orton et al. 2012; Sun et al. 2013), modeled water-elevation levels were less than observed, with the maximum under prediction during peak surge (Figure 2c and d). Water level is predicted more accurately by the models that use high spatial-resolution meshes (KB-ADCIRC and KB-CSTORM) than by the lower resolution NACCS model (Figure 2 and Table 1). The high-resolution model (KB-ADCIRC and KB-CSTORM) predictions of the timing of the peak storm surge are more accurate than the NACCS predictions, which tend to lag the observed peak surge (Figure 2). The coupled KB-CSTORM has somewhat lower errors than KB-ADCIRC at the center (Figure 2d, Station 02) and southern side (Figure 2e, Station 03) of the bay, particularly during the 12-hour period of peak storm surge (Figure 2 and Table 1 column 4). The 12-hour period was selected to represent the shortest duration of peak storm and provides an end-member estimate of reduction of error (the RMSE will be bounded by the typical conditions and peak storm duration). The reduction in error percentage by coupling with the wave model is small during calm conditions, but increases during the peak surge period, suggesting that both bottom topography and waves are important to modeling hydrodynamics near inlets.

Table 1. Root mean square error between modeled and observed water levels for the total duration time series (column 3) and for the 12-hour window centered on the time of the peak surge (Storm Duration, column 4).

| **Station** | **Model** | **Total Timeseries RMSE (m)** | **Storm Duration RMSE (m)** |
|---|---|---|---|
| **01** | **NACCS** | 0.18 | 0.27 |
| | **KB-ADCIRC** | 0.18 | 0.30 |
| | **KB-CSTORM** | 0.17 | 0.24 |
| **02** | **NACCS** | 0.16 | 0.31 |
| | **KB-ADCIRC** | 0.15 | 0.28 |
| | **KB-CSTORM** | 0.13 | 0.19 |
| **03** | **NACCS** | 0.22 | 0.33 |
| | **KB-ADCIRC** | 0.08 | 0.16 |
| | **KB-CSTORM** | 0.10 | 0.19 |
| **Average** | **NACCS** | 0.19 | 0.30 |
| | **KB-ADCIRC** | 0.14 | 0.25 |
| | **KB-CSTORM** | 0.13 | 0.21 |

Table 2. Error reduction relative to the low-spatial resolution NACCS results. Reduction is defined as (RMSE_NACCS-RMSE_KBXX)/RMSE_NACCS * 100% from the Average values (bottom rows in Table 1).

| **Model** | **Total Timeseries Error Reduction (%)** | **Storm Duration Error Reduction (%)** |
|---|---|---|
| **KB-ADCIRC** | 26.3 | 16.7 |
| **KB-CSTORM** | 31.6 | 30.0 |

### 3.2.2 Spatial Comparisons

#### *3.2.2.1 Resolution Effects*

Increasing spatial resolution leads to more accurate modeled values. However, another explanation for the difference in accuracy between the NACCS and the high-resolution runs is that during NACCS mesh development, the southern shoreline (Norton Point, Figures 1, 3a) is made into a hard no-normal-flow boundary. The result is that NACCS does not allow flow through Katama Inlet nor the overtopping of the beach that occurred during Hurricane Irene. The lack of inlet currents and of overtopping can explain many of the flow-pattern differences between the high-resolution models and the NACCS. The NACCS does not allow Atlantic water to enter Katama Bay from the south, and thus the simulated circulation (Figure 10a, NACCS) and water levels (Figure 2, NACCS) in the bay are owing to wind stress and to water entering or exiting through Edgartown Channel to the north, in contrast with the high-resolution models (Figures 5, 6b, KB-CSTORM) and with the observations during peak surge conditions. In addition, the high-resolution models indicate a narrow coastal jet with magnitudes over 2.0 m/s along the southern coast that is not apparent in the lower-resolution simulations. Currents also are amplified within the Bay and Edgartown Channel relative to those simulated with NACCS (compare Figures 10b and c with Figure 10a), indicating a net northward circulation, consistent with previous results (Orescanin et al., 2014). Comparing the effects of resolution and waves on velocity during peak surge suggests not only increased northward flow through Katama Bay for

KB-ADCIRC (Figure 10b) and KB-CSTORM (Figure 10c), but also an enhanced coastal current during KB-CSTORM compared with KB-ADCIRC, suggesting the influence of waves is to concentrate flows along the coast.

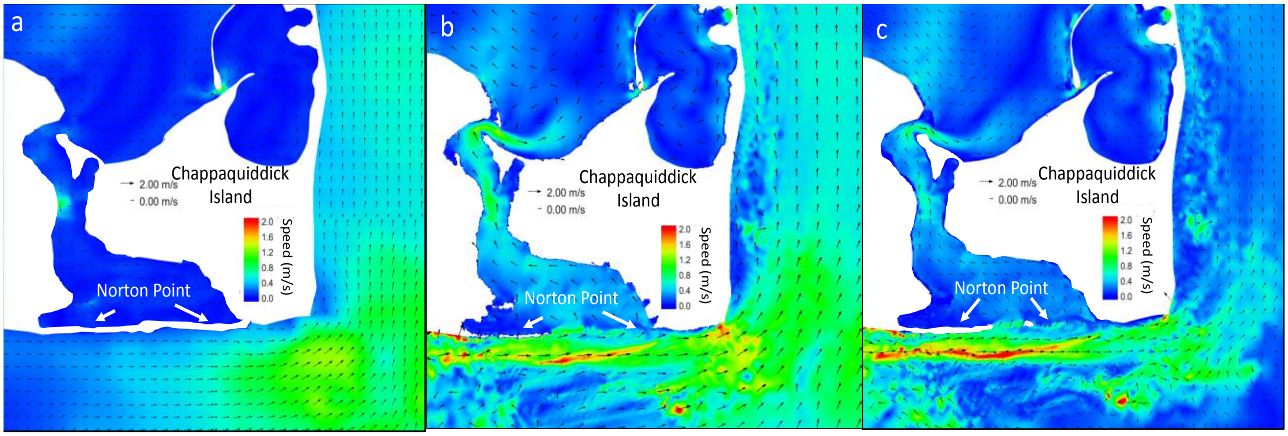


**Figure 10:** Contours of current speed (color bars are inset) and vectors (point in direction of the current with length proportional to speed, scale left of and above the color bars) for a) NACCS b) KB-ADCIRC and c) KB-CSTORM during peak surge. Norton Point is indicated by arrows.

During the peak surge the NACCS model tends to have higher water levels on the southern shoreline than either of the high-resolution models (Figure 2f). The ~0.3 m increase in NACCS modeled water level suggests that the high-resolution bathymetry that includes the relatively small Katama Inlet may have a relatively large effect on shoreline water levels. In addition, the predicted increase in surge on the southern shore simulated by the low-resolution model with no inlet suggests a possibility of enhanced overtopping along Norton Point when the inlet is closed, consistent with the observation that Katama Inlet opens during extreme surge events.

#### *3.2.2.2 Coupling Effects*

Error statistics show that the coupling of STWAVE and ADCIRC in KB-CSTORM improves prediction performance compared with using ADCIRC alone (KB-ADCIRC), especially on the southern shore and within Katama Bay. For example, during the peak storm surge, KB-CSTORM includes wave-driven setup, and predicts significantly (up to 0.3 m) higher water elevations in the southern part of Katama Bay and in the surf zone directly to the south than are predicted by KB-ADCIRC (Figure 11). In addition, the overall higher water levels within Katama Bay predicted by KB-CSTORM during peak surge indicates waves are contributing to an overall elevation change within the bay, consistent with previous results for single-inlet systems (Malhadas et al., 2009; Olabarrietta et al., 2011). Although the more common moderate wave forcing may not increase the bay water levels (Orescanin et al., 2014), during surge events not all wave-driven momentum flux entering the bay through Katama Inlet can be radiated out of the bay through Edgartown Channel, resulting in an overall bay setup that is common in single-inlet systems.

Currents simulated by the higher-resolution KB-ADCIRC and KB-CSTORM models have tidal fluctuations throughout the Bay in contrast to the weaker (and non-tidal) velocities predicted by the coarser NACCS model (not shown). KB-ADCIRC and KB-CSTORM velocities are nearly identical during calm wave conditions, but deviate during Irene, with KB-CSTORM predicting a reduced ebb current (to zero flow) during the peak of the storm, consistent with the breaking-wave-driven currents observed at Katama Inlet (Orescanin, et al, 2014).

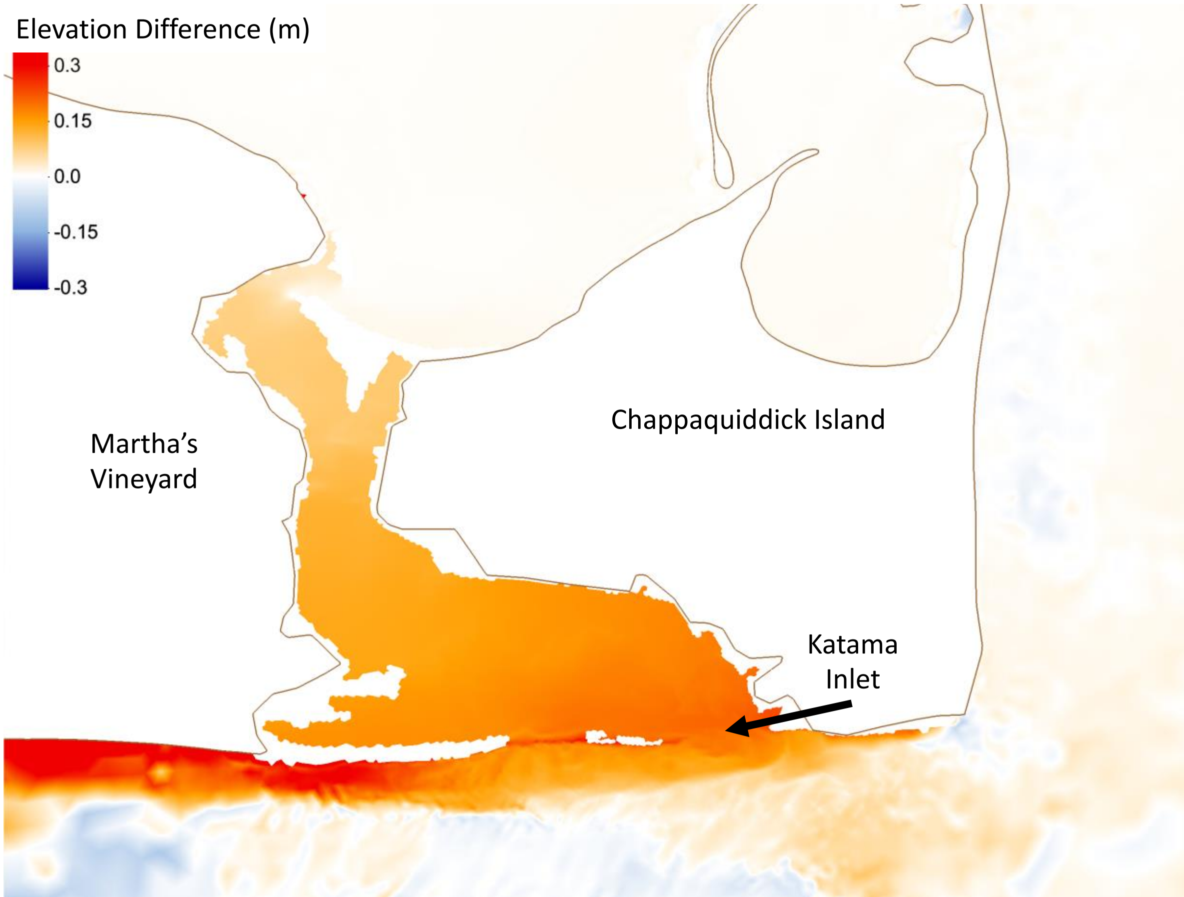


**Figure 11:** Contours (color bar in the upper left) of water elevation difference between KB-CSTORM and KB-ADCIRC model runs during peak storm surge.

At some locations, KB-CSTORM predicts much larger (> 1 m) significant wave heights than NACCS predicts, especially near the shore (Figure 12). Both models predicted ~0.5 m wave height in the center of the bay (Figure 1, Station 02) during the peak of the storm, in contrast to the observed ~0.2 m wave height (not shown). On the ebb shoal (Figure 1, Station 04, just offshore off the mouth of Katama Inlet) NACCS predicts much smaller wave heights than KB-CSTORM predicts (Figure 12). There were no observations on the ebb shoal, but comparisons of model predictions with observations of waves in 12 m depth, a few km south of the ebb shoal (Martha's Vineyard Coastal Observatory, https://www.whoi.edu/mvco, not shown) suggest the modeled wave heights are similar to those observed (up to 5 m significant wave height) before and after the peak of the storm (the MVCO sensor did not operate for a few hours during the peak of the storm). The KB-CSTORM model predicts ~3 m wave heights on the ebb shoal during the peak of the storm, whereas the NACCS model predicts 1.5 m wave heights The underprediction of wave heights by NACCS (red colors near the ebb shoal, Figure 12) may be related to the low-resolution bathymetry or to the lack of two-way coupling with the wave model.

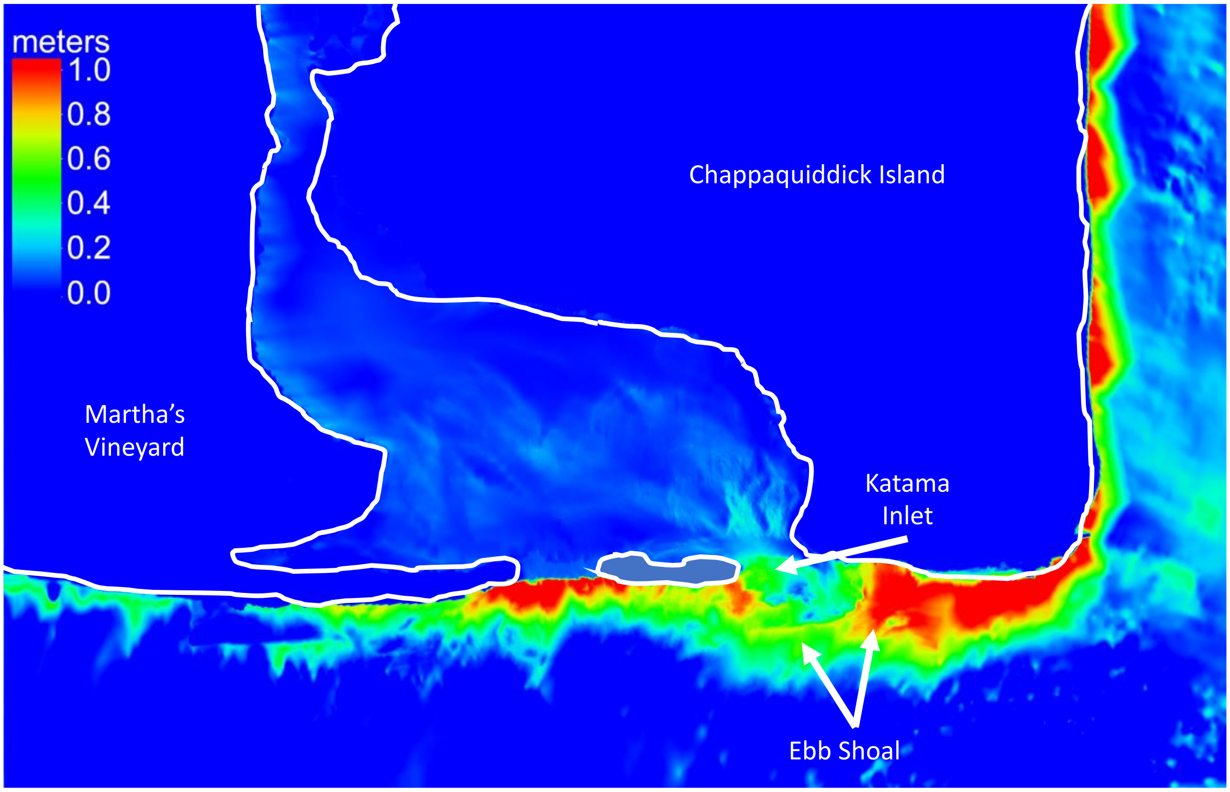


**Figure 12:** Contours (color bar in upper left) of wave height difference between KB-CSTORM and NACCS model runs during peak storm surge.

# 4 CONCLUSIONS

Comparisons of simulations with observations in the Katama Bay system prior to and during Hurricane Irene indicate that the coupling of wave (STWAVE) with circulation (ADCIRC) models in addition to using high resolution bathymetry (KB-CSTORM) results in better predictions of wave heights and water levels during Hurricane Irene than predicted with the lower resolution (KB-NACCS) or with the high resolution, no wave (KB-ADCIRC) models. These results suggest that both high spatial resolution of small (< 400 m) tidal inlets and wave coupling are required for accurate surge prediction. During the peak surge of Hurricane Irene, errors in water level elevations were 30% lower using KB-CSTORM than using NACCS. The improved model predictions primarily are owing to resolving the inlet and nearby shorelines in the KB-CSTORM model, whereas the low-spatial resolution NACCS does not include the inlet nor does it allow overwash of the sand barrier separating Katama Bay from the ocean. An artifact of the low-resolution bathymetry is higher water levels and smaller currents along the shoreline than predicted by KB-CSTORM, which could lead to inaccurate predictions of sediment transport and morphological change.

Prior studies during moderate wave conditions show that water driven into Katama Bay by breaking-wave-induced momentum flux leaves the bay through Edgartown Channel, and thus bay water levels do not increase. In contrast, during extreme events (e.g., Hurricane Irene), model simulations suggest the flux through Edgartown Channel is insufficient to balance the breaking-wave-induced increased flows into Katama Bay through Katama Inlet, resulting in an increased water elevation in the bay. The increased water levels within the bay during storms can result in relatively large waves that could erode the banks and flood surrounding marshes.

**Acknowledgements:**

We thank Levi Gorrell and the PVLAB field crew for deploying, maintaining, and recovering sensors in sometimes less-than-ideal conditions. Thanks to MVCO for wave height and wind velocity time series. Funding was provided by a Vannevar Bush Faculty Fellowship (OUSD(R&E)), Sea Grant, NSF, and ONR.

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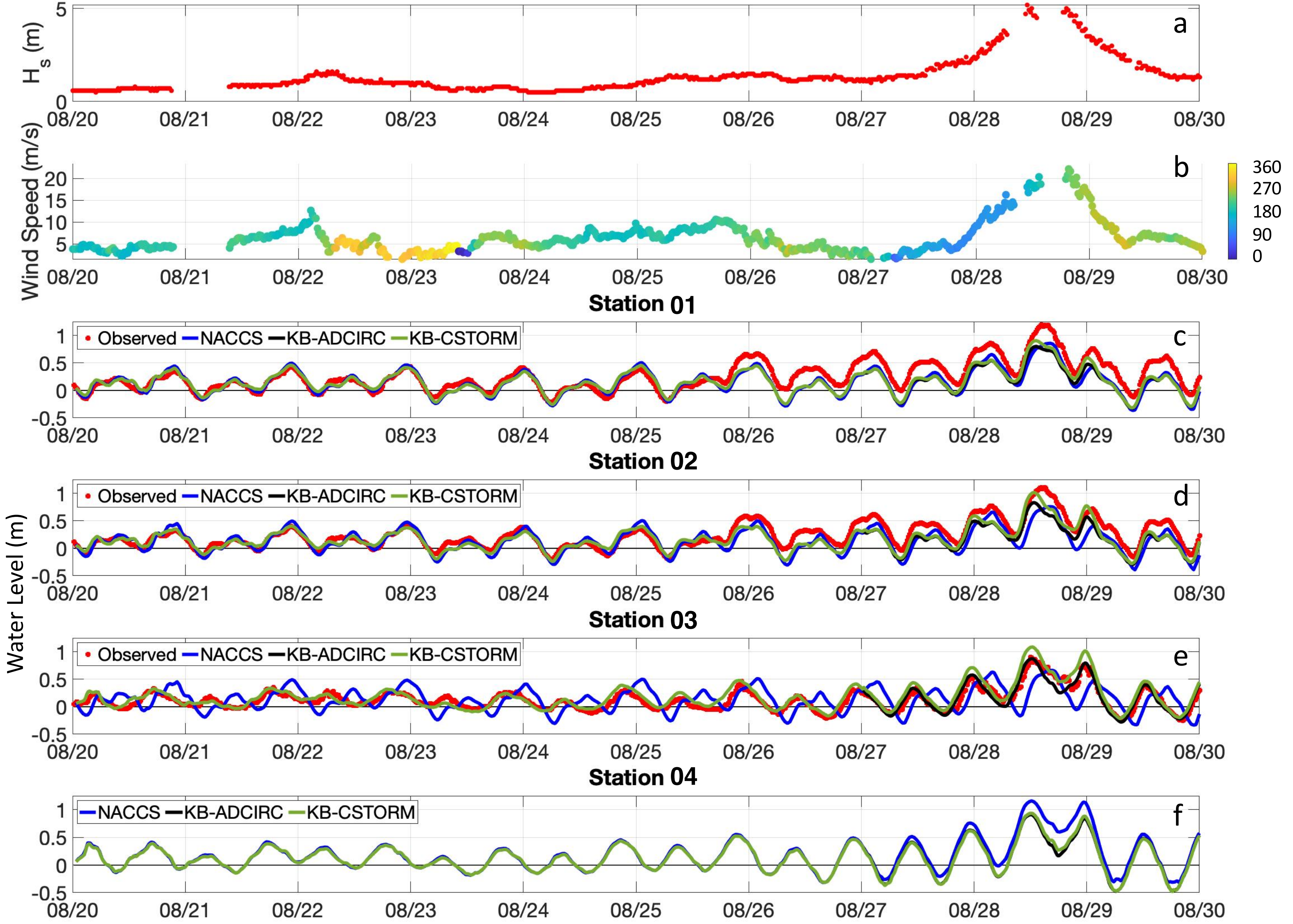
Figure 1




a
Boston
Cape Cod
Martha's
Vineyard
Nantucket
b
2 km
Vineyard
Sound
01
Edgartown
Channel
Chappaquiddick
Island
Martha's
Vineyard
Katama
Bay
02
03
Norton Point
04
Katama
Inlet
Atlantic Ocean

Figure 2





a
b
c
d
e
f
$H_s$ (m)
Wind Speed (m/s)
Water Level (m)
Station 01
Station 02
Station 03
Station 04
Observed
NACCS
KB-ADCIRC
KB-CSTORM
360
270
180
90
0
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30

Figure 3



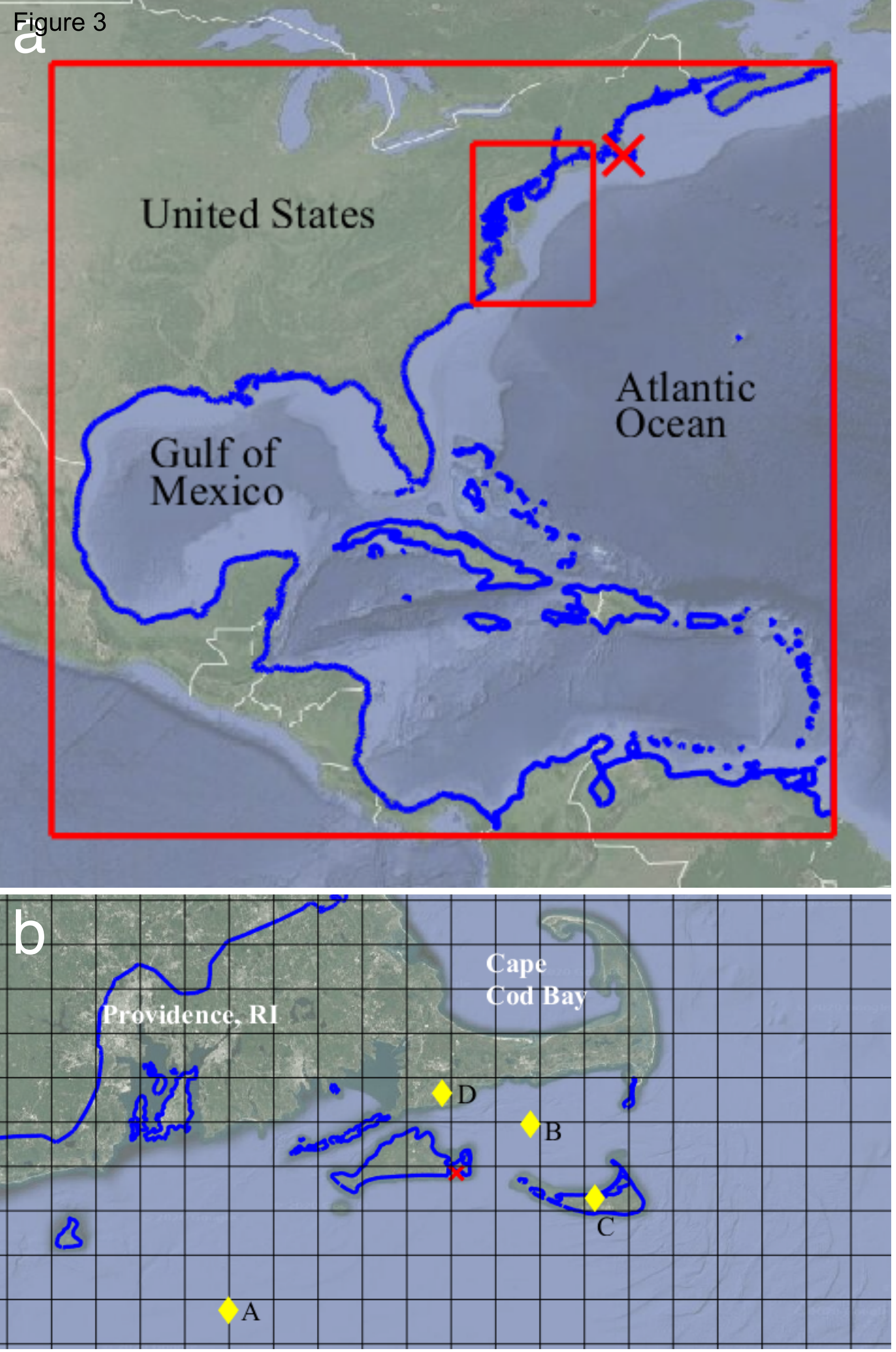

a
United States
Atlantic
Ocean
Gulf of
Mexico
b
Cape
Cod Bay
Providence, RI
D
B
C
A

Figure 4

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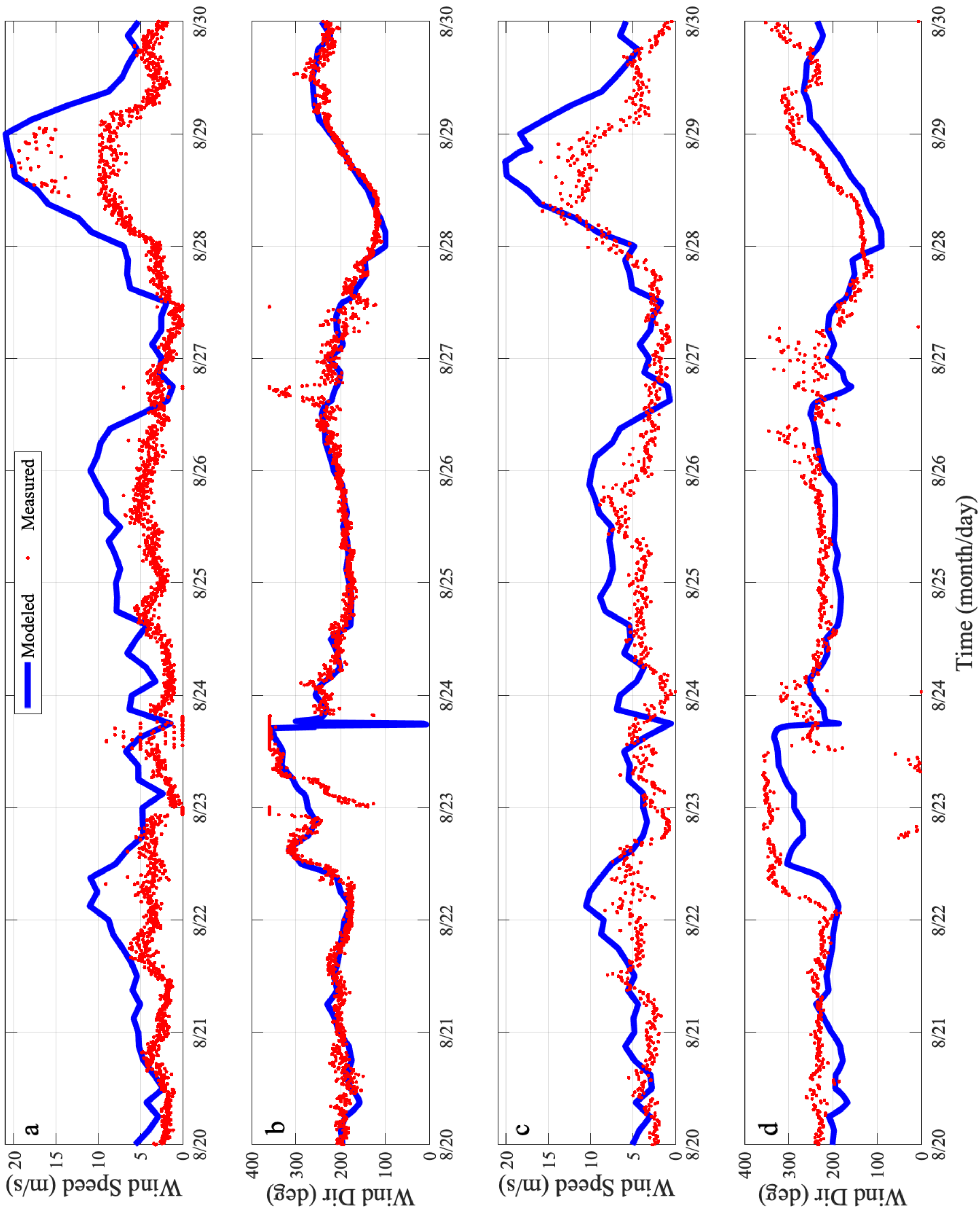


Figure 5

Click here to access/download;Figure;Figure5_NDBC44020.pdf

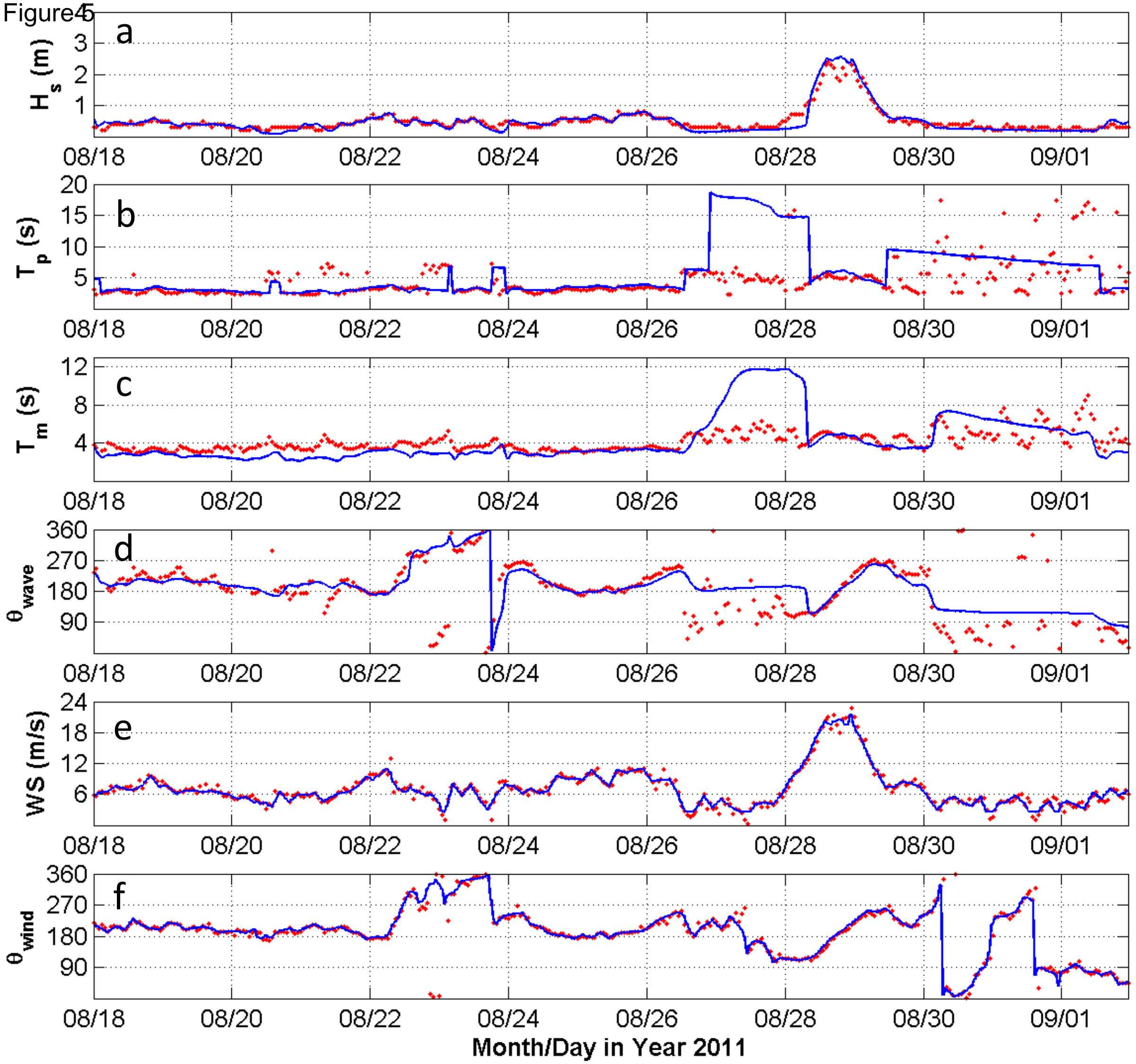


Figure 6



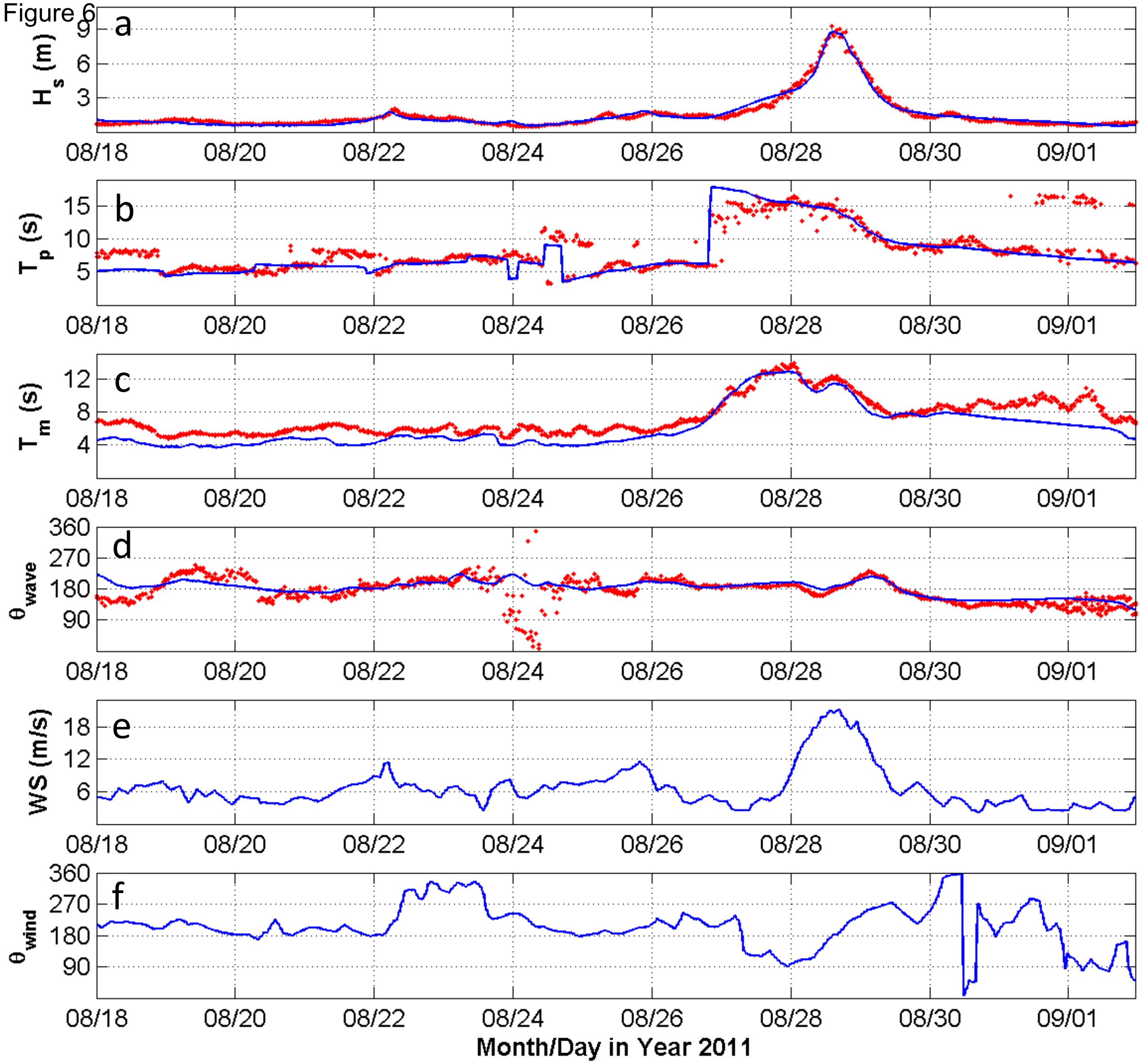

a
b
c
d
e
f
H_s (m)
T_p (s)
T_m (s)
θ_wave
WS (m/s)
θ_wind
08/18
08/20
08/22
08/24
08/26
08/28
08/30
09/01
Month/Day in Year 2011

Figure 7



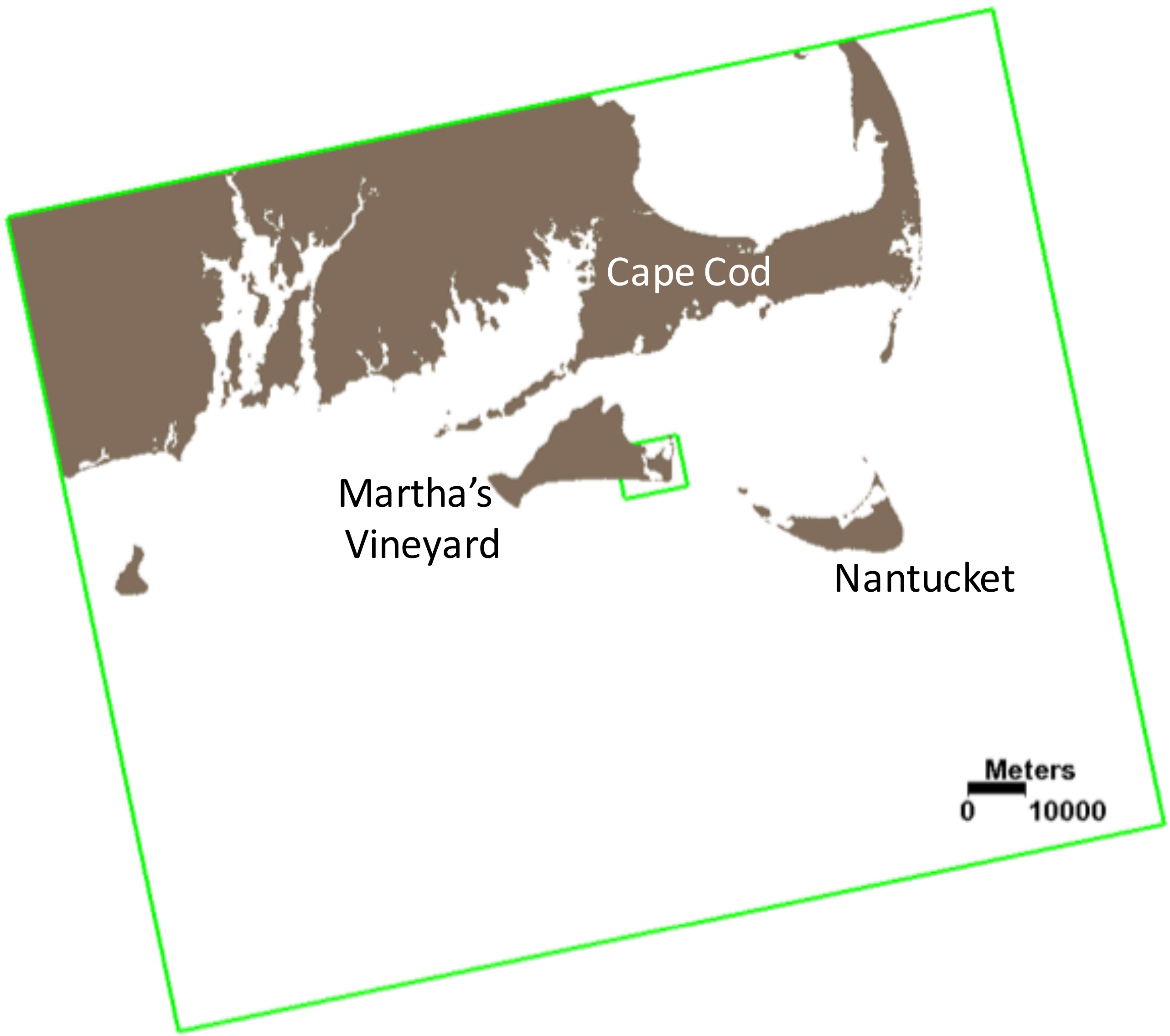
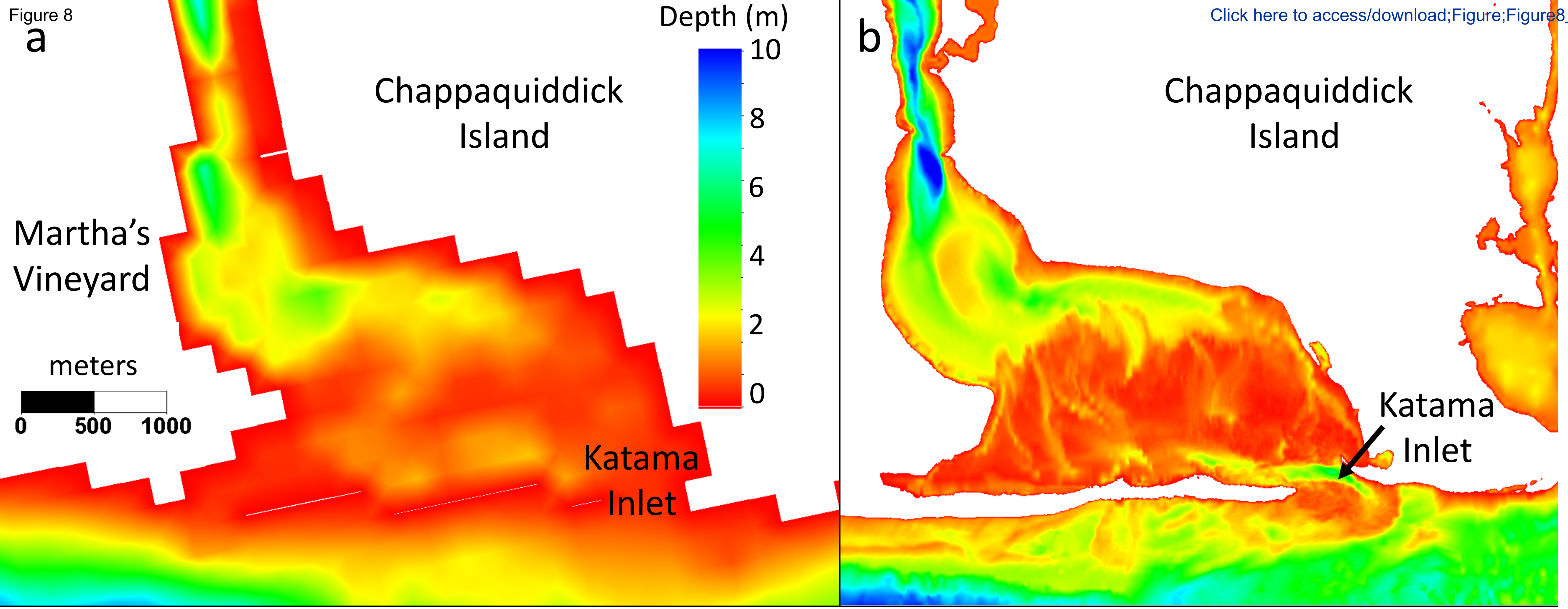


Figure 8





a
Depth (m)
10
8
6
4
2
0
Chappaquiddick Island
Martha's Vineyard
meters
0
500
1000
Katama Inlet
b
Chappaquiddick Island
Katama Inlet

Figure 9



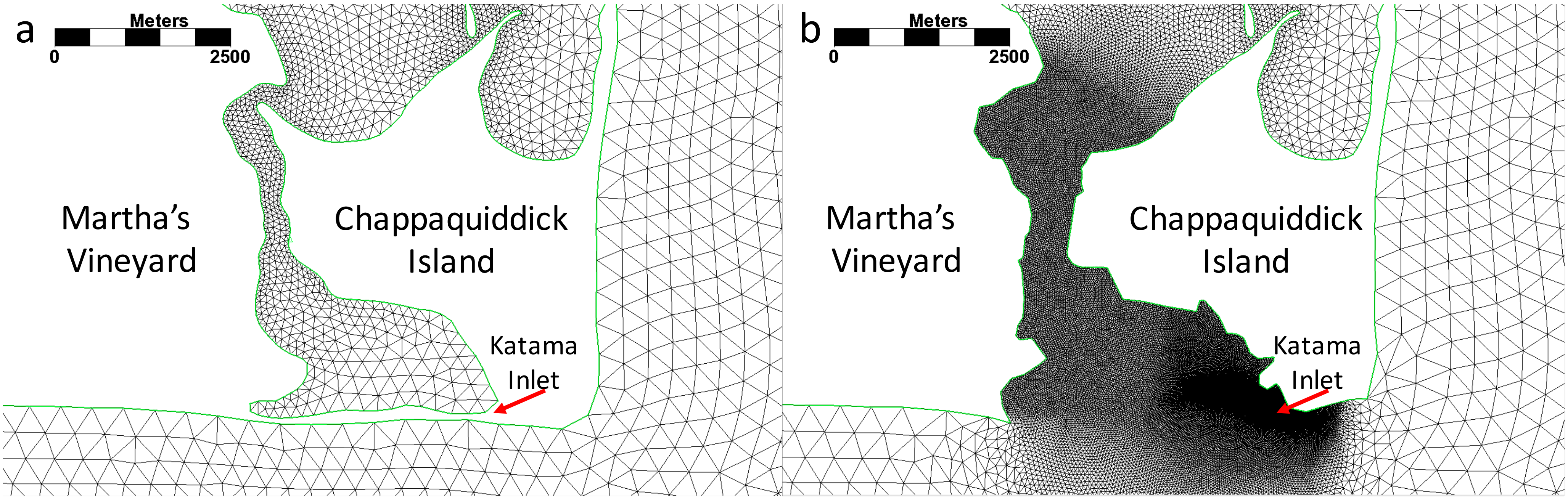

a
Meters
0
2500
Martha's Vineyard
Chappaquiddick Island
Katama Inlet
b
Meters
0
2500
Martha's Vineyard
Chappaquiddick Island
Katama Inlet

Figure 10



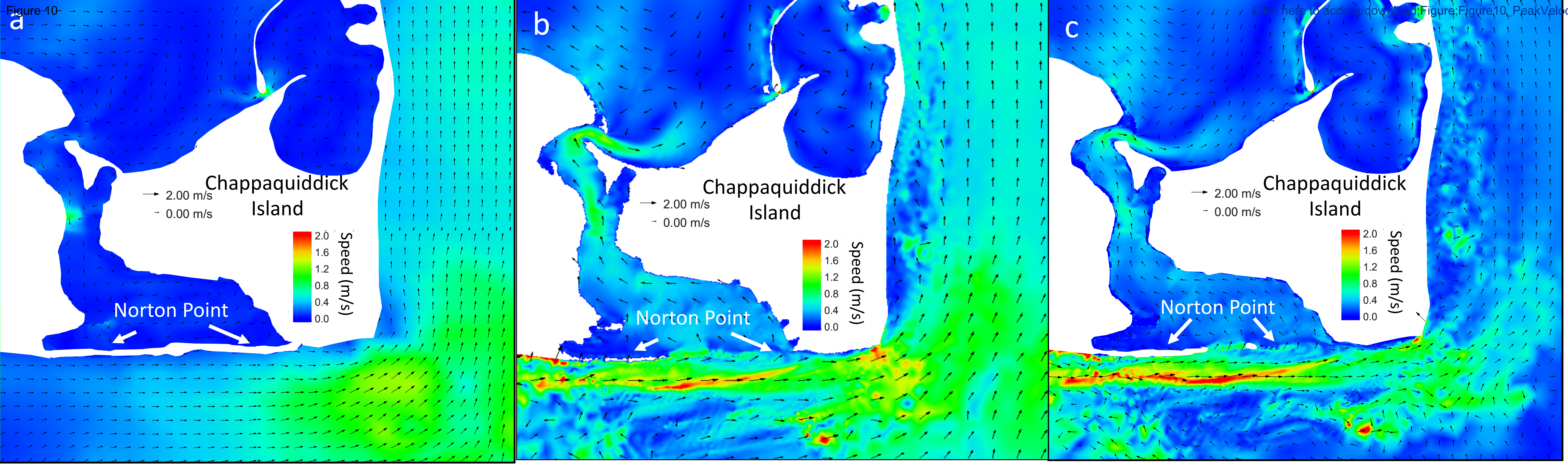

a
Chappaquiddick Island
2.00 m/s
0.00 m/s
Norton Point
Speed (m/s)
2.0
1.6
1.2
0.8
0.4
0.0
b
Chappaquiddick Island
2.00 m/s
0.00 m/s
Norton Point
Speed (m/s)
2.0
1.6
1.2
0.8
0.4
0.0
c
Chappaquiddick Island
2.00 m/s
0.00 m/s
Norton Point
Speed (m/s)
2.0
1.6
1.2
0.8
0.4
0.0

Figure 11



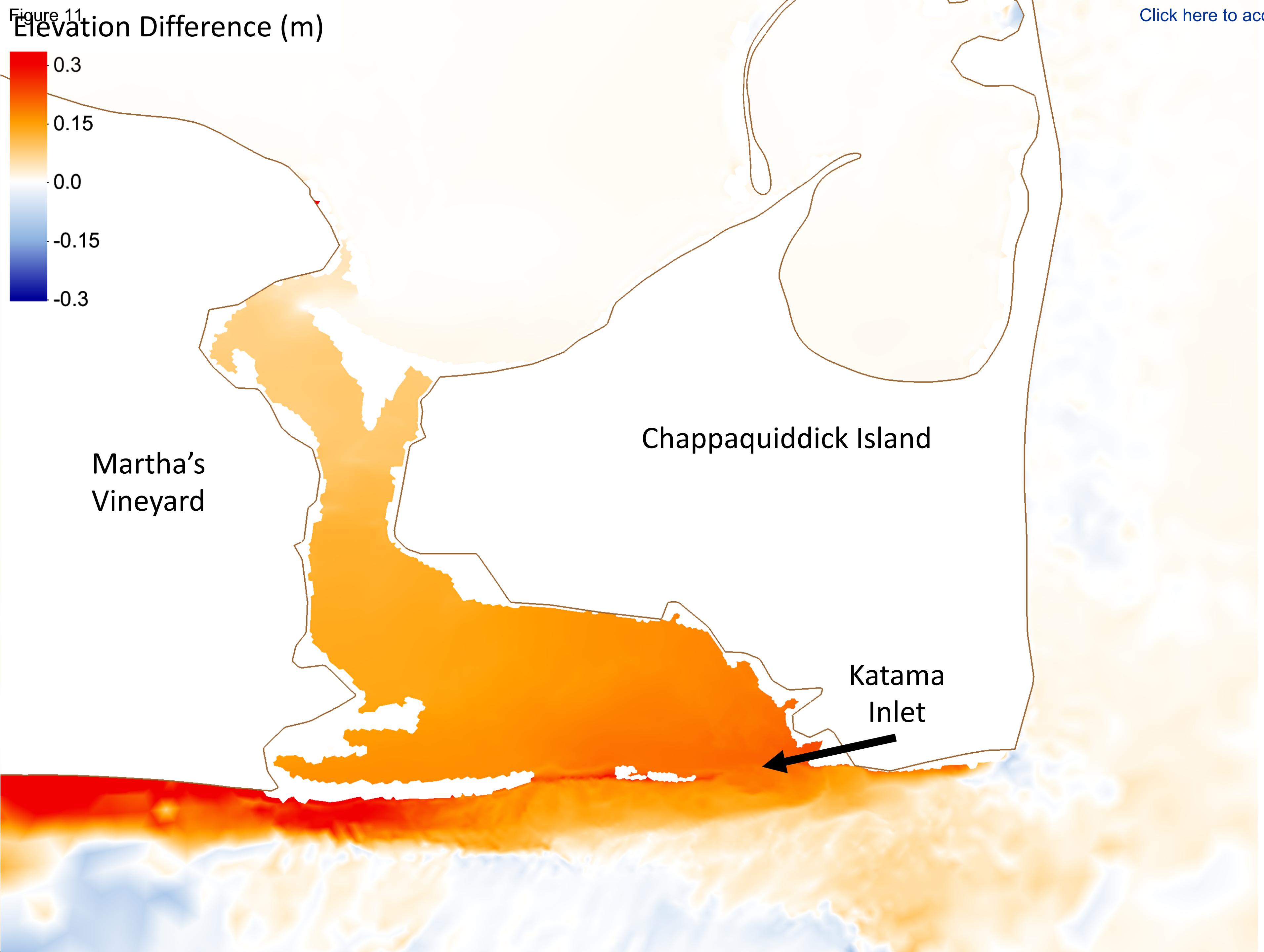
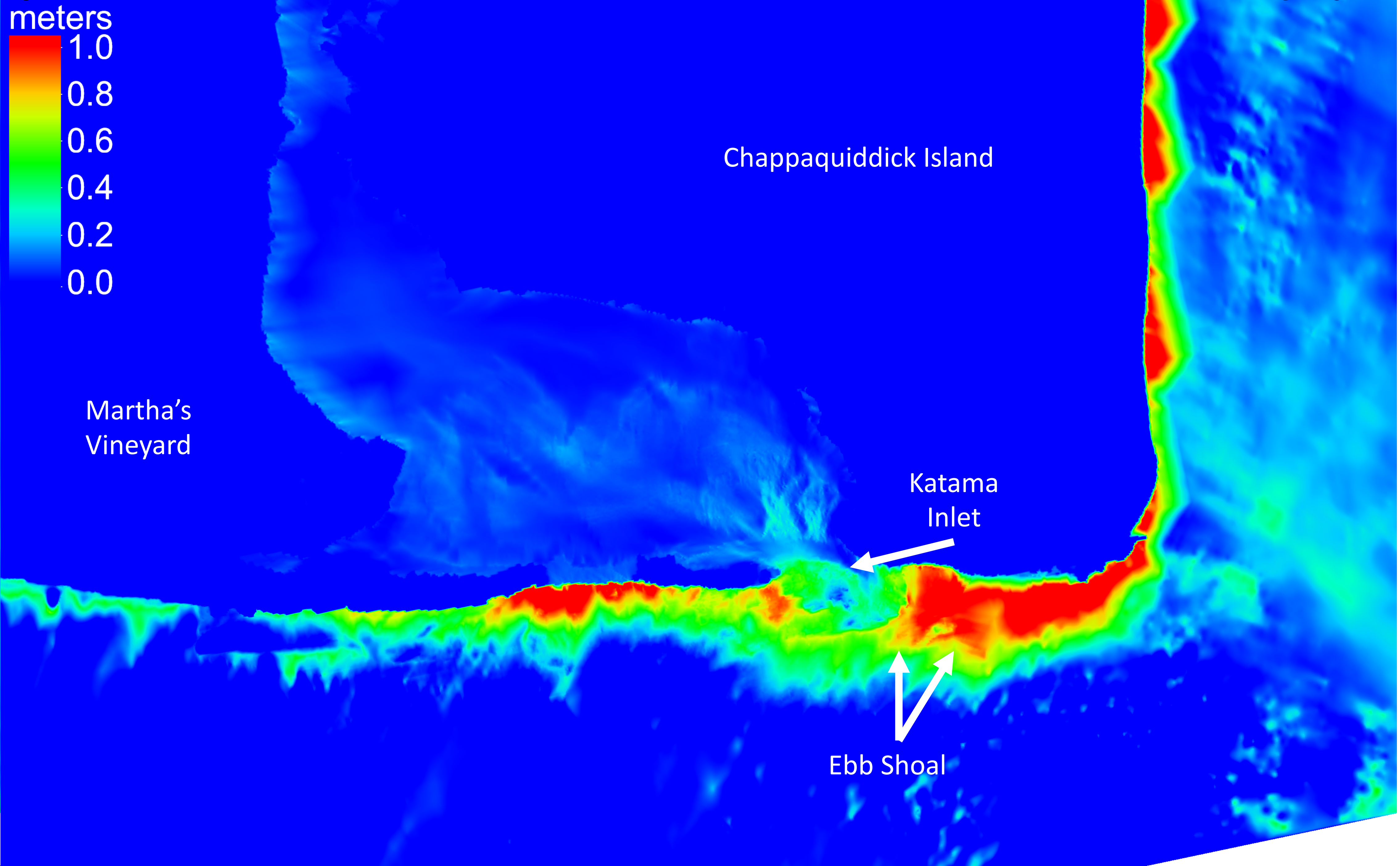

Elevation Difference (m)
0.3
0.15
0.0
-0.15
-0.3
Martha's Vineyard
Chappaquiddick Island
Katama Inlet

Figure 12




meters
1.0
0.8
0.6
0.4
0.2
0.0
Chappaquiddick Island
Martha's Vineyard
Katama Inlet
Ebb Shoal

May 25, 2020

To the Editor,

We thank the reviewers and editor for their helpful comments regarding our manuscript "Modeling Storm Surge in a Small Tidal Two-Inlet System". We have addressed all comments in the text. The largest change was in adding a description of the driving wind and wave models, resulting in new figures and an additional co-author, Robert E. Jensen. We believe the revised manuscript is improved and more thorough, in large part owing to the referees' suggestions.

Please provide us with any additional feedback. We look forward to hearing from you.

Sincerely,
Mara M. Orescanin

---

Detailed comments on our revision:

***Comments from Reviewer #1:***
*I would like to see how well the winds are represented in the domain. The figure below, which is a screenshot of the NDBC webpage, shows significant number of assets in the region that measured wind speed and direction. Any number of those stations could be used to document the accuracy of the wind field.*

We added a section detailing wind inputs and included several new figures showing observed and modeled wind speed and direction (Figures 4,5, and 6). We agree this helps strengthen the modeling description.

*In the above figure, there are also 3 NDBC buoys (44097, 44090, 44020) of which at least the latter two can be used to verify the accuracy of the wave model. This is especially critical considering the conclusion that coupling waves with circulation is important –which I agree with, as long as the waves are predicted correctly. Also, since Irene was such a large storm and travelled all the way up the Atlantic coast, there is the potential that significant energy in the swell may not have been captured by the domain size restriction of STWAVE.*

The new figures 5 and 6 show model-data comparisons of wave height, period, and direction, and wind speed and direction at two of the NOAA buoys.

*I do not expect the low resolution model to show significant coastal currents (Figure 6). A better comparison would be between the stand-alone high resolution ADCIRC result and the coupled system at the same resolution. This would also reveal the extent of the wave driven currents.*

Good suggestion. Figure 10 (used to be Figure 6) now also shows the currents for the high-resolution no wave model (KB-ADCIRC). This emphasizes the relative importance of wave forcing to the coastal enhanced current.

*Error reduction values of 16% for the uncoupled ADCIRC and 30% for the coupled system are based on a 12 hr window centered at the peak of the storm surge, based on the average of the three locations in the inlet. What would the values be if the time window was expanded to 24 hrs and 36 hrs?*

We prefer to retain the error calculation at 12 hours because it encompasses the peak surge. That is when waves become most important, and thus is of most interest here. As the length of the averaging window increases, the reduction in error approaches the error of the full time series.

*Looking at the observations in figure 2, it seems that the effect of the storm starts around the later part of Aug 27th with a moderate wind event that dies down just prior to that. There is a gradual increase in water level at station 01 and 02 starting between the 25th and 26th which is sustained all the way through the storm. Changing the time scale of the plot window (and analysis time) to start on or around the 25th would provide a better measure of how well the modeling system performs during the high wind event.*

We agree that starting Fig 2 on Aug 25 would focus the figure on the storm. However, we think it is important to display and discuss the pre-storm performance of the models, as well as their performance during the storm, as well as to place the high waves and strong winds during the passage of Hurricane Irene into perspective.

***Comments from Reviewer #2:*** *ADCRIC 2-D model will be significantly impact by the bottom roughness, and wonder if this is the reason for the simulation to be very sensitive to the bathymetry? In addition, can author elaborate a little bit towards the wave-current coupling. Overall, a nice job but I also suggest authors to review work from other study sites. For examples:*

We agree that bottom roughness is important, and thus instead of a universal roughness (via a single Manning's n) we used a spatially varying roughness near and inside the bay that was determined in a previous study (Orescanin et al. 2016) to provide the best model results compared with observations.

We have added more detail about the coupling of currents and waves.

*Kang, X., & Xia. M. (2020). The Study of the Hurricane-Induced Storm Surge and Bay-Ocean Exchange Using a Nesting Model. Estuaries and Coasts, DOI: 10.1007/s12237-020-00695-3*

*Mao, M., & Xia, M. (2018). Wave-current dynamics and interactions near the two inlets of a shallow lagoon-inlet-coastal ocean system under hurricane conditions. Ocean Modelling, 129, 124-144. doi: https://doi.org/10.1016/j.ocemod.2018.08.002*

*Mao, M., & Xia, M. (2016). Dynamics of wave-current-surge interactions in Lake Michigan: a model comparison. Ocean Modelling, 110, 1-20. doi: http://dx.doi.org/10.1016/j.ocemod.2016.12.007*

As suggested, in the Introduction we have cited 2 of these papers (thank you) that use different models.

***Comments from Reviewer #3:*** *First I will point out, to the authors and the editors, that I have reviewed a previous version of this paper that was submitted to different journal. Overall, I find that this submission is an improvement and hence my review is short.*

*I am not sure if this paper was submitted as a "research article", but it is short and I feel it is more like a "technical note". However, the application of these wave (STWAVE) and hydrodynamic (ADCIRC) models in different coupled and uncoupled modes to simulate flow in an ocean/inlet/bay/channel system yields interesting and important results. The paper covers the very interesting and difficult problem of resolving a small and dynamic system that is impacted during a strong storm event. Water level data from 3 pressure sensors deployed over a relatively small area are used to validate the model and understand the hydrodynamics during Hurricane Irene.*

*The paper lacks a description of all the model parameters. The wave model bathymetry and grid are described (L134-156), but the frequency resolution and other standard parameters are missing. Similarly for ADCIRC, the information needed for one to reproduce the model setup is missing. For example, L188-190 oddly lists parameter names but not the values. Adding the numbers here is an easy addition to the paper and is highly important. Alternatively, the values could be provided in a table.*

We have included all specifics of model details including values (or references to figures where model parameters are shown).

*More attention could also be given to revising the sentence structure, in making sure that each sentence conveys meaning. As examples, the section on 'Resolution Effects' is very confusing with L244 ("at least up to an upper convergence point") and very long sentences from L244-249 and from L250-255.*
*Overall I recommend minor revisions to give the authors the opportunity to add more detail about the model setup and improve the writing.*

We agree that some of our original sentences were long or confusing, and we have revised the offensive text as suggested.