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Boston Coastal Storm Risk Management Study: Probabilistic and Numerical Coastal Storm Hazards Analysis for Storm Surge and Waves

Draft Report

Madison Yawn, T. Chris Massey, Luke A. Aucoin, Sydney
Crisanti, and Norberto Nadal-Caraballo

July 2026





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Draft report

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Abstract

The U.S. Army Corps of Engineers is currently engaged in the Boston Coastal Storm Risk Management Study. One of the phases of this study is focused on numerically modeling and deriving statistical annual exceedance frequencies for water level and wave responses to storm conditions for the entire coastline of Boston, Massachusetts, and possible changes due to coastal storm risk management projects being added. This technical report details the development of inputs and application of the Coastal Storm Modeling System (CSTORM-MS) suite of models, Advanced Circulation (ADCIRC) and Steady State Wave (STWAVE), for this project. It presents efforts made to ensure valid modeling results for storm events impacting the city. Additionally, the report details the probabilistic coastal hazards analysis techniques for determining annual exceedance frequencies for water levels and waves.

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Preface

This study was conducted for the U.S. Army Corps of Engineers New England District under Project Number, “Boston Coastal Storm Risk Management Study.” The technical monitor was Ms. Lisa Winter (Senior Coastal Engineer), New England District (NAE).

The work was performed by the Coastal Processes Branch of the Flood and Storm Protection Division (CEERD-HF) along with the Harbors, Entrances, and Structures Branch of the Navigation Division (CEERD-HN), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Mr. Victor Gonzalez was branch chief; and Mr. David May was division chief. The deputy director of ERDC-CHL was Mr. Keith W. Flowers, and the director was Dr. Ty V. Wamsley.

Lt. Col. Joshua M. Haynes was commander of ERDC, and Dr. Elizabeth C. Fleming was the director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
Knots	0.5144444	meters per second
miles per hour	0.44704	meters per second
yards	0.9144	meters
miles	1.60934	kilometers
bars	100.0	kilopascals
atmosphere (standard)	101.325	kilopascals

1 Introduction

This report documents work completed by the U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center's Coastal and Hydraulics Laboratory (ERDC-CHL). This report details the development and validation of numerical modeling and descriptions of statistical methods for estimating water levels and wave heights in and around the city of Boston, Massachusetts, including potential impacts of future sea level rise.

1.1 Background

Sea level rise and other changing climate effects are some of the critical factors driving the inundation risks of Massachusetts' 47-mile coastline. Over the past century, Massachusetts has experienced a sea level rise of nearly one foot. This issue is particularly acute in Boston, largely because portions of the city are built on marshlands. Boston is the largest city in New England and the 23rd largest city in the United States, with a population of about 635,000. It is located onshore of the Atlantic Ocean, with a busy port, the largest in Massachusetts, and multiple historical and pertinent coastal neighborhoods including Charlestown, East Boston, Downtown and North End, South Boston, and Dorchester. To support the U.S. Army Corps of Engineers (USACE) New England District (NAE), this study sought to evaluate existing and future coastal storm risks by conducting a feasibility level analysis of storm induced water levels and wave conditions for existing and future conditions under both a without and with coastal storm risk management projects in the area.

A regional coastal hazards probabilistic analysis for storm induced surge and waves was conducted as part of the North Atlantic Coast Comprehensive Study (NACCS) (Cialone et al. 2015; Nadal-Caraballo et al. 2015). The NACCS study made use of 1,050 synthetic tropical cyclones (TCs), five (5) historical tropical events, and 100 historical extratropical cyclones (XCs) to characterize the storm climate for the entire North Atlantic coast (Nadal-Caraballo et al. 2015). A portion of the historical events served to validate and calibrate the high-fidelity numerical

modeling used to simulate the water's responses to storm events. The hydrodynamic modeling was conducted using the integrated Coastal Storm Modeling System (CSTORM-MS) (Massey et al. 2012), that included a third-generation deep water wave model, Wave Model (WAM) (Komen et al. 1994), the ADvanced CIRCulation (ADCIRC) (Westerink et al. 1992, Luetlich et al. 1992) for storm surge and circulation, and the Steady State Spectral WAVE (STWAVE) (Smith et al, 2001, Massey et al. 2011) for nearshore wave effects. The development of the modeling domains and subsequent calibration and validation of these numerical models is well documented in the NACCS modeling report (Cialone et al. 2015). Probabilistic statistical results of annual exceedance frequencies for water levels and wave conditions, (Nadal-Caraballo et al 2015), were computed at over 18,000 save point locations located along the north Atlantic coast at both offshore and inland locations.

The NACCS modeling suite and statistical results serve as a major starting point for this current study in the Boston area. Leveraging the calibrated and validated numerical modeling domains resolved sufficiently for large-scale regional studies allows for much less calibration and validation when updating the numerical models to have enhanced resolution in the project area needed to resolve sufficiently the proposed with-project features and other local missing features not required for a large regional study, such as jetties and breakwaters. Based on similar studies that leveraged the NACCS, the expectation is that the updated project scale modeling will perform as well as or better than the regional model in the areas that underwent updating and not significantly alter results away from the project area.

1.2 Objective(s)

The purpose of this analysis is to quantify impacts in terms of changes to storm surge and waves and the resulting hazards due to proposed changes from the Boston Coastal Storm Risk Management (CSRМ) project conditions as well as sea level rise impacts. This is achieved by leveraging the hydrodynamic modeling suite and the probabilistic coastal hazards analysis techniques from the NACCS.

1.3 Approach

Following the methods from the NACCS, the CSTORM modeling for this study was configured to use the deep-water wave model WAM, the unstructured ADCIRC model for water levels and circulation, and the STWAVE wave model to calculate nearshore wave responses to storm events. The ADCIRC and STWAVE models were run in coupled mode for more accuracy in capturing the dynamic nature of storm surge and waves. Updated ADCIRC meshes and STWAVE grids were created to add mesh resolution in the project area and include locations of project features as well as update the topographic and bathymetric dataset using available data. These updates to the model domains are primarily intended to allow for better representations of the geometry and features of the area and for direct comparisons between with and without-project comparisons.

For the initial phase of the study, two ADCIRC meshes describing existing conditions (without-project [WOP]) and future conditions (future without-project [FWOP]), were created by leveraging the existing NACCS mesh, an existing storm surge ADCIRC mesh constructed by the Woods Hole Group for the City of Boston (reference), as well as early footprint designs of with-project (WP) conditions to guide further mesh refinement. The meshes are designed to maintain similar resolution and element alignments between the different versions. This approach ensures that differences in the hydrodynamic model results can be attributed to the inclusion of the project design, rather than being significantly influenced by variations in mesh resolution or alignment.

Using these updated numerical models to simulate a select number of events from the NACCS storm suite allows for updating coastal hazards estimates described as annual exceedance frequencies (AEFs) for water levels and wave conditions for locations surrounding Boston under near-term and future sea level rise conditions in order to support evaluating design conditions for the CSRM projects. A reduced storm suite (RSS) of 60 synthetic TCs and 15 historical XCs was selected from the existing NACCS storm suite to use as representative storms for the project area to estimate water levels and wave heights. The RSS for this study also

included two (2) recent extratropical storms occurring in 2018, after the NACCS study was conducted, that had the highest recorded measured water levels at Boston, as recorded at a National Oceanic and Atmospheric Administration (NOAA) water level gauge at station 8443970. The statistical evaluation of the existing and future conditions was completed using the CHS Probabilistic Framework (CHS-PF), which employs the Joint Probability Method Aided by Metamodeling Prediction (JPM-AMP) (Yawn et al. 2024) for quantification of TC hazards. The extreme value analysis (EVA) of XC hazards in the CHS-PF is performed using the Storm Simulation (StormSim) Probabilistic Simulation Technique (PST; formerly known as the Stochastic Simulation Technique) (Yawn et al. 2024). The JPM requires that coastal storm hazards are evaluated by developing a joint probability model that links the atmospheric forcing parameters describing a synthetic TC to an associated storm response (i.e., storm surge) for that event. The results from the joint probability analysis define hazard curves, which express the magnitude of the storm response as a function of AEF. For quantifying these hazards, the CHS-PF leverages machine-learning techniques to apply Gaussian process metamodels (GPM) to support expanding the numerically modeled storm suite by several orders of magnitude for defining an augmented TC suite (ATCS). The GPM is trained on the hydrodynamic model simulations of the RSS and provides the ability to predict new storm responses for the ATCS while maintaining the accuracy of the original hydrodynamic model. Machine-learning techniques are an integral part of the CHS-PF, and the application of this framework to create hazard curves for with- and without-project conditions for the Boston project area is documented herein.

Hazard curves were developed for storm surge level (SSL), still water level (SWL; storm surge + astronomical tide), significant wave height (H_{mo}), and wave peak period (T_p) at more than 170,000-point locations surrounding the Boston study area. Using the methods documented in the Sections below, these hazard estimates reflect the combined cyclone (CC) impact from both TCs and XCs.

2 Storm Selection

A suite of 60 synthetic TCs was strategically selected from the original NACCS storm suite to simulate for characterizing the regional storm hazard (i.e. statistically significant range of water levels and wave conditions). The goal of the storm selection was to find the optimal combination of storms to be sampled out of the available TCs from the NACCS storm suite to obtain a reasonable estimation of the water level hazard. The number of storms sampled for the RSS was limited to 60 TCs and informed by previous studies where the Design of Experiments (DoE) approach had been applied (e.g., Melby et al. 2021). Due to the nature and progression of work within a CSRM study, the Feasibility phase is generally conducted with a smaller suite of storms (USACE 2021; 2024) in comparison to the Pre-construction, Engineering, and Design (PED) phase (Melby et al. 2021). The number of storms selected is study dependent and often ranges between 20 and 80 events for Feasibility studies.

The storm selection process was performed using the DoE approach (Taflanidis et al. 2017; Zhang et al. 2018), in which the RSS hazard curves are compared to available benchmark hazards curves at a given number of specific locations or save points. The difference between the RSS hazard curve and benchmark curve is minimized by initially sampling a small subset of TCs, and then iteratively adding additional TCs (e.g., 5 by 5) until the difference between the two curves is significantly reduced or becomes negligible.

Through an inter-agency agreement with the Federal Emergency Management Agency (FEMA) initiated in 2022, the CHS-North Atlantic (CHS-NA) study was recently conducted to leverage existing data from the NACCS to update coastal hazards data for the region from Virginia to Maine. The development of this dataset included applying the CHS-PF methodology using the JPM-AMP approach (Yawn et al. 2024), and the discrete storm weights (DSWs) (storms/yr) associated with the NACCS synthetic TCs were updated to account for storm climatology data from 1938-2022. For the CHS-NA study, the updated TC hazard curves were derived by training a GPM on the CSTORM simulations for the NACCS initial TC suite (ITCS) of 1,050 synthetic TCs. This GPM was then applied

as an emulator to predict storm responses for an ATCS of more than 1.2 million storm events. The ATCS was developed by further discretizing the parameter space of the ITCS to create more combinations of the TC atmospheric forcing parameters. The updated CHS-NA hazard curves were applied as the benchmark curves supporting the TC selection for the Boston CSRM in an effort to use the most up-to-date hazard information available for the study area. The Boston RSS was sampled from the NACCS ITCS, so that the available wind and pressure fields could be used for simulating with- and without-project responses in the updated ADCIRC and STWAVE models applied for this study.

This study leveraged the CHS-NA SSL hazard curves developed using the CHS-PF as the benchmark hazards, which represent the non-tidal residual for the North Atlantic region. The following steps outline the DoE approach used for the selection of the TC RSS:

1. Identify a set of save points within the study area where the DoE optimization is to be performed.
 2. Develop or use existing TC benchmark hazard curves.
 3. Determine the number of TCs to be sampled.
 4. Develop new hazard curves for the RSS.
 5. Select the annual exceedance frequency (AEF) range at which the RSS and benchmark hazard curves will be compared. Differences can be computed along the entire hazard curve, segment of the hazard curve, or at specific AEFs (e.g., 0.02 to 0.002 storms/year, equivalent to 50 to 500 years).
 6. Calculate errors between the RSS and benchmark hazard curves at predetermined AEFs.
 7. Conduct an iterative optimization analysis, described in Melby et al. (2021), Appendix C, to evaluate the benefit of increased RSS size; (e.g., 5 by 5, from 10 to 25 TCs).
 8. Once the sought number of storms is reached (e.g., 25), in order to evaluate the overall RSS performance, the RSS selected through optimization indicated in Step 7 is compared to multiple RSS where TCs are sampled in a single batch.
 9. Complete storm selection by choosing the optimal RSS from Step 8.
-

This process was used to identify an RSS of 60 synthetic TCs that matched the SSL benchmark hazard curve using a sampling radius of 300 km (186.4 miles) from NACCS save point 1900. The storm selection process results in updated DSWs, which were applied in the JPM integration process to evaluate how well the RSS matched the SSL hazard at other points in the study area. This comparison illustrated highly favorable results when evaluating the selected storm events at neighboring point locations identified as areas of interest by NAE as illustrated in Figure 2-1 below. Additionally, the sensitivity to the number of storms selected was evaluated by also considering a subset of 40 and 80 events. By testing varying sizes of an RSS in the storm sampling methodology, it was observed that the 60-storm RSS applied for this study resulted in a reasonable estimation of the SSL hazard in the Boston area. This is also indicated by the favorable match between the RSS and benchmark hazard curves illustrated in Figure 2-1. Table 2-1 presents the list of storms along with corresponding storm IDs, central pressure deficits (Δp), radius of maximum wind (R_{max}), forward speed (V_t), and heading (θ). Figure 2-2 presents the selected storm tracks for the Boston area.

Figure 2.1. Evaluation of selected tropical cyclone (TC) events at save points of interest near Boston Harbor.

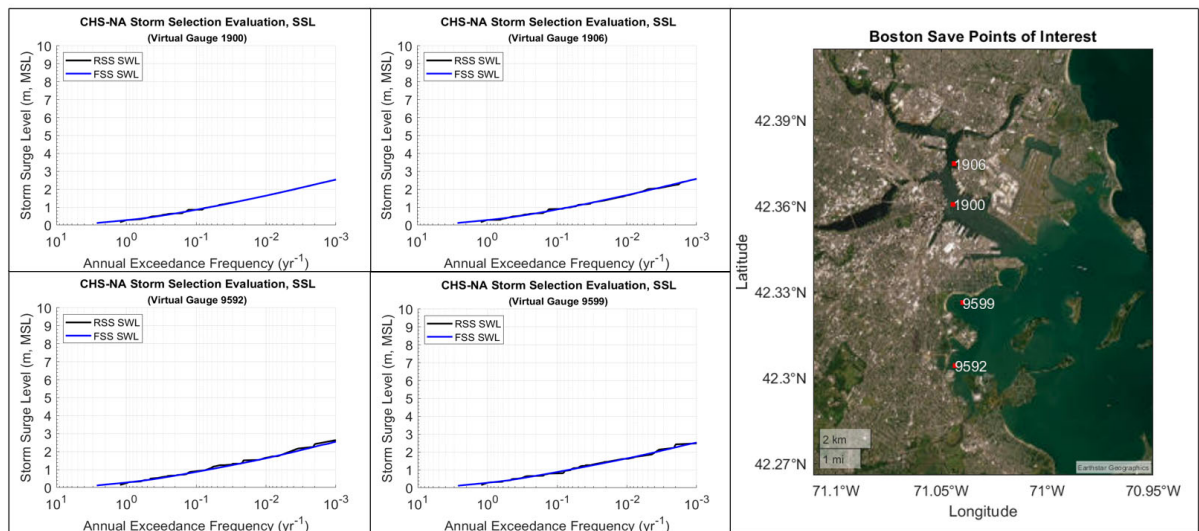


Figure 2.2. Storm tracks for selected storms (white) near Boston Harbor (red point).

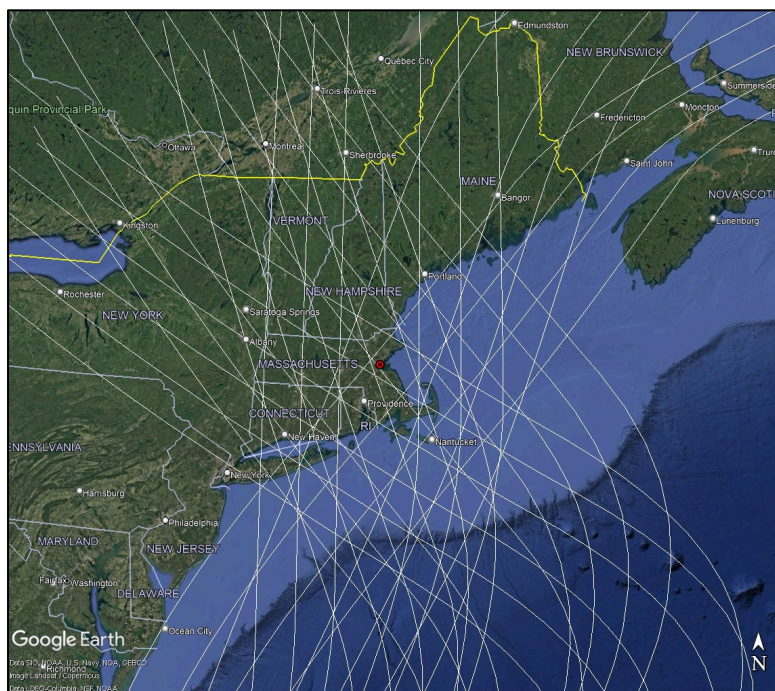


Table 2-1. Tropical cyclone (TC) parameters for selected storms.

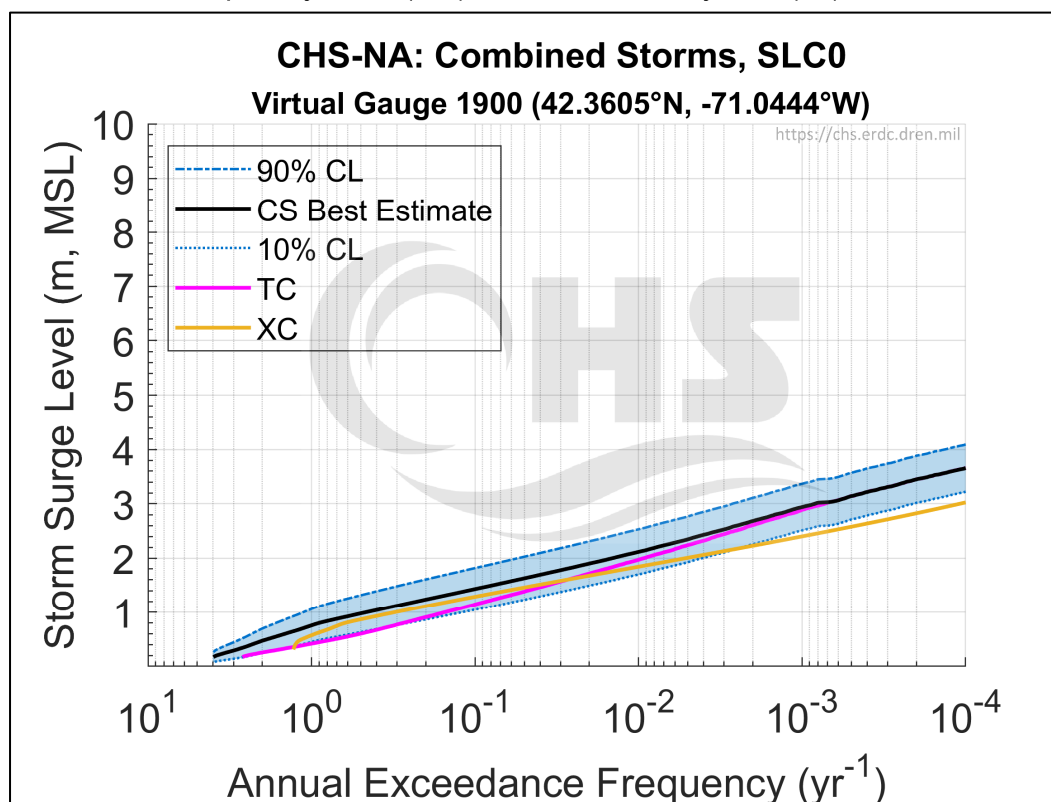
TC Count	TC ID	Master Track ID	θ (deg)	Δp (hPa)	R_{max} (km)	V_t (km/h)
1	372	12	-60	28	33.8	64
2	374	13	-60	68	76.5	56.1
3	381	14	-60	58	79.4	65.1
4	382	14	-60	48	48	57.7
5	385	15	-60	78	66.2	59.7
6	412	35	-40	48	67.5	54.7
7	413	35	-40	38	79.3	24.2
8	415	36	-40	78	45.6	25.4
9	421	37	-40	78	82.4	58.7
10	455	58	-20	48	28.8	64.1
11	457	59	-20	88	58.5	33.8
12	460	59	-20	58	67.7	66.1
13	463	60	-20	88	66.7	56.3
14	488	77	0	38	25	56.2
15	489	77	0	33	61	54.2

TC Count	TC ID	Master Track ID	θ (deg)	Δp (hPa)	R_{max} (km)	V_t (km/h)
16	498	78	0	43	80.2	49.8
17	502	79	0	78	82	47.3
18	691	16	-60	48	74.6	66.4
19	696	17	-60	48	88.8	33.2
20	734	39	-40	68	51.2	49
21	736	39	-40	48	86	31.4
22	740	40	-40	58	77.2	35.1
23	741	40	-40	48	49.8	62.2
24	743	40	-40	28	93.1	67.6
25	748	41	-40	28	34.6	39.7
26	752	42	-40	38	96.5	34
27	756	43	-40	48	77.7	63.8
28	757	43	-40	38	94	30.2
29	789	61	-20	78	51.6	35.6
30	790	61	-20	68	76.2	65.7
31	791	61	-20	58	154.3	53.9
32	793	61	-20	38	35.7	64.1
33	794	62	-20	78	48.7	36.9
34	796	62	-20	58	78.7	64.9
35	798	62	-20	38	39.7	66
36	800	63	-20	68	102.9	57.2
37	848	81	0	48	86.2	51.8
38	849	81	0	43	74	73.2
39	853	82	0	68	63.5	50.8
40	862	83	0	68	71.8	59.7
41	868	83	0	38	71.7	38.2
42	929	90	20	48	56.9	54.2
43	945	92	20	58	52.4	50.4
44	946	92	20	53	50	45
45	949	92	20	38	86.8	60.7
46	958	93	20	38	50.6	17.1
47	960	93	20	28	48.1	53.1
48	961	94	20	68	100.2	38.3
49	963	94	20	58	59.2	46.8

TC Count	TC ID	Master Track ID	θ (deg)	Δp (hPa)	R_{max} (km)	V_t (km/h)
50	964	94	20	53	151	52.6
51	965	94	20	48	63.7	58.6
52	969	94	20	28	93.6	49.1
53	1002	113	40	53	68.5	82.9
54	1003	113	40	48	58.2	52.3
55	1007	114	40	73	57.8	50.6
56	1016	115	40	73	54.6	22.9
57	1023	115	40	38	56.5	47.6
58	1030	116	40	48	104.4	58.4
59	1034	117	40	73	88.3	27
60	1035	117	40	68	156.5	44.6

Given that waves and water levels are influenced by both TCs and XCs within the North Atlantic, a reduced set of XCs were also identified for this study with the intent of capturing wave and water level hazards at the save points of interest. The NACCS storm suite included 100 XCs (Nadal-Caraballo et al. 2015) that were identified using the Composite Storm Suite (CSS) methodology developed by Nadal-Caraballo et al. (2012). These storm events are generally weaker and produce smaller storm surges, which means that they are most influential to the high frequency hazard space as illustrated in Figure 2-3. Using the CSS methodology, the NACCS storm suite identified an optimal set of 100 XC events that accurately reflected the hazards at 23 water level gauges from Virginia to Maine, including the Boston, MA, gauge. Although XCs occur more frequently than TCs within the study area, the CSS methodology effectively captures an optimal set of events that represents the high-frequency probability space without requiring hundreds of storm events to be simulated in the hydrodynamic models. It is important to note that the difference in the number of TC versus XC events considered in the NACCS storm suite is primarily a reflection of the discretization of TC parameters required for the joint distribution model applied within the JPM.

Figure 2.3. Storm surge level (SSL) hazard curve illustrating influence of the TCs and extratropical cyclones (XCs) on the combined cyclone (CC) hazard.



The XC storm selection for the Boston CSRM relied on available SSL hazard data at save point 1900 given that this location had the most significant influence from XC storms when compared to the other save points of interest in Figure 2-1. For each of the 100 XCs within the NACCS storm suite, an AEF value was assigned to the peak storm surge response for each of the 100 NACCS XC storm events at save point 1900 by interpolating its frequency from the XC hazard curve. This was done to evaluate how well the peak storm responses covered the range of AEFs given that the XC hazard curve was developed using EVA methods. The interpolation resulted in selecting 15 storm events that covered the SSL hazard from approximately 1 to 10^{-2} yr⁻¹. In addition, two more recent XC events that are not included within the original NACCS storm suite were included as part of this study, since they were significant events with respect to historical water level observations in the Boston Harbor. The 17 selected XC events applied for this study are documented in Table 2-2.

Table 2-2. Peak dates of selected XC storm events.

Count	NACCS XC ID	Year	Month	Day
1	29	1972	12	16
2	60	1992	12	11
3	39	1978	12	25
4	6	1947	3	3
5	96	2010	10	15
6	64	1993	12	21
7	13	1960	2	19
8	8	1952	3	11
9	7	1950	11	25
10	52	1985	11	5
11	28	1972	11	9
12	37	1978	2	7
13	2	1940	2	15
14	62	1993	3	14
15	24	1971	3	4
16	201*	2017	12	31
17	202*	2018	2	26

*Not part of original NACCS study

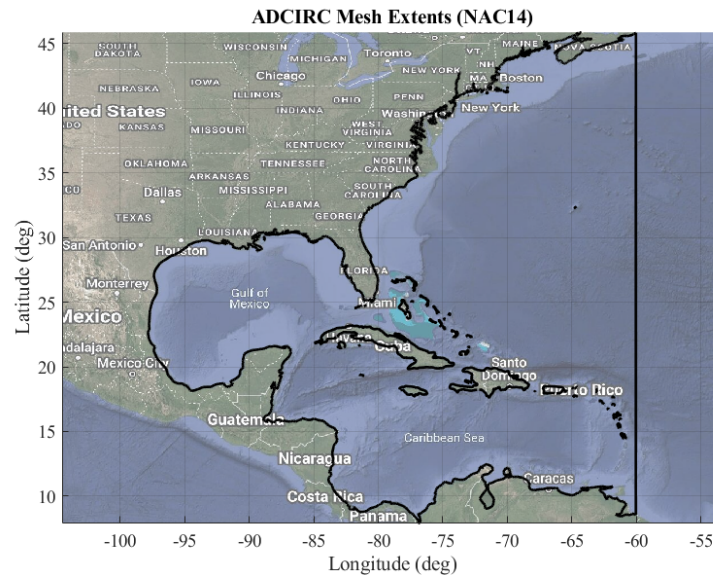
3 ADCIRC Model Mesh and Nodal Attribute Development

A new ADCIRC model mesh and a new ADCIRC nodal attribute file were developed by leveraging aspects of different existing meshes for this project to conduct high-resolution surge and wave modeling for historical baseline and future storm conditions. This chapter provides details about the development of the ADCIRC model mesh.

The ADCIRC model is a finite-element-based hydrodynamic free surface circulation model (Westerink et al. 1992, Luetlich et al. 1992). ADCIRC is a computational model using a continuous Galerkin finite element method with linear polynomials to solve a variation of the depth integrated shallow water equations. It employs highly flexible, unstructured meshes composed of nodes and triangular elements that tessellate the entire computation domain. These nodes are specified by their longitude, latitude, and topographic/bathymetric depth values. To solve the depth-integrated shallow-water equations, ADCIRC incorporates inputs such as wind velocity vectors, atmospheric surface pressure, tidal forcing conditions, river inflow fluxes, and wave radiation stress gradients (provided by a coupled-wave model). The model assumes water is incompressible and has hydrostatic pressure conditions. It outputs depth-averaged water height and currents at each node for specified time intervals during the simulation. Additionally, ADCIRC features a robust algorithm for wetting and drying, allowing water to inundate normally dry areas and recede naturally, as well as allowing normally wet areas to dry when water moves out.

3.1 Mesh Development

Figure 3.1: Spatial extents for the NAC14 ADCIRC mesh. .



The well-validated and calibrated mesh from the NACCS was leveraged for this study, herein referred to as NAC14. This mesh provided regional scale accuracy for the entire north Atlantic coast area, including Boston. The extent of the NAC14 mesh can be seen in Figure 3.1. A mesh provided by the Woods Hole Group (WHG) was developed specifically for storm surge studies in the Boston area (WHG, 2022). This mesh will be referred to throughout as the WHG mesh and it was also used as a source mesh in the high-resolution areas of Boston. The NAC14 mesh has approximately 6 million elements and 3 million nodes, whereas the WHG has approximately 1.5 million elements and 800,000 nodes. Figure 3.2 shows color contour maps of mesh resolution, element sizes, in the greater study area for both the NAC14 and WHG meshes. The different inland extents of the two meshes are evident from this figure as is the fact that the far offshore resolutions are comparable. Further, the WHG resolution in the Boston area is on the order of 30 meters compared to the NAC14 mesh which is on the order of 150 meters. As a comparative example, the relative element sizes and resolutions around the Boston Logan airport are shown in Figure 3.3 for both the WHG and the NAC14 meshes. The WHG mesh is approximately 6-8 times finer in resolution in the Boston area than the NAC14 mesh. Figure shows the boundary extents of the NAC14 and WHG meshes. The NAC14 mesh extents go further inland than the WHG mesh.

Figure 3.2 Color contour maps showing mesh resolution for the NAC14 mesh vs the WHG mesh.

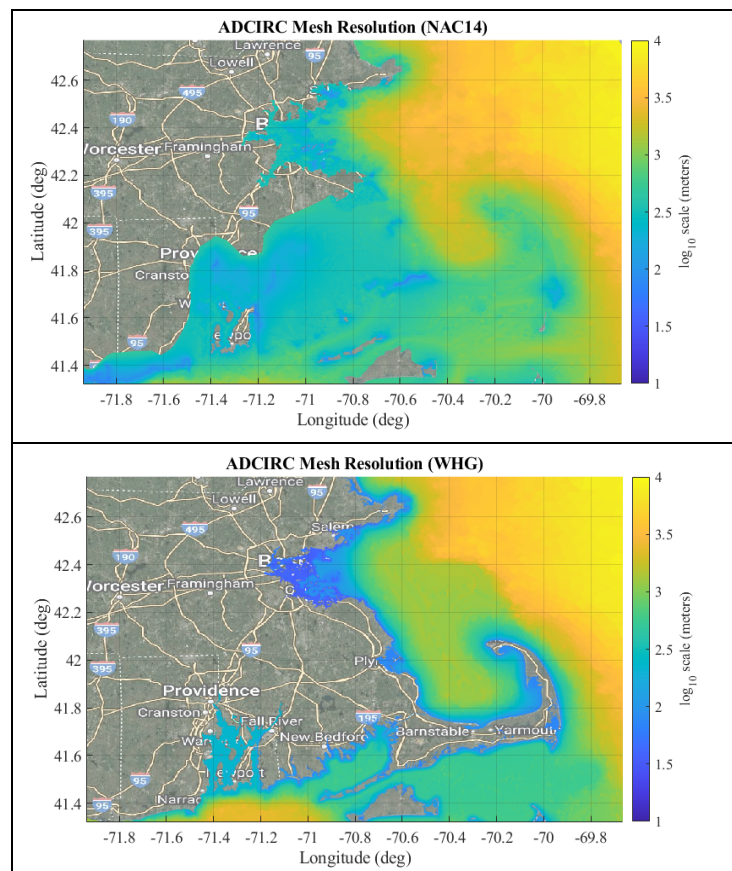


Figure 3.3: Comparing element resolution near the Boston Logan International Airport in the WHG mesh (left) and NACCS mesh (right).

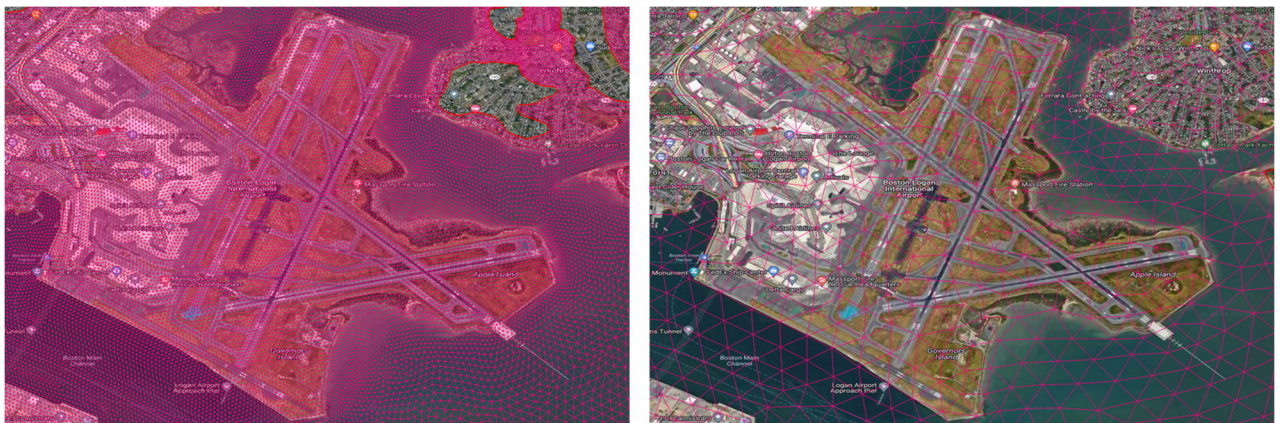
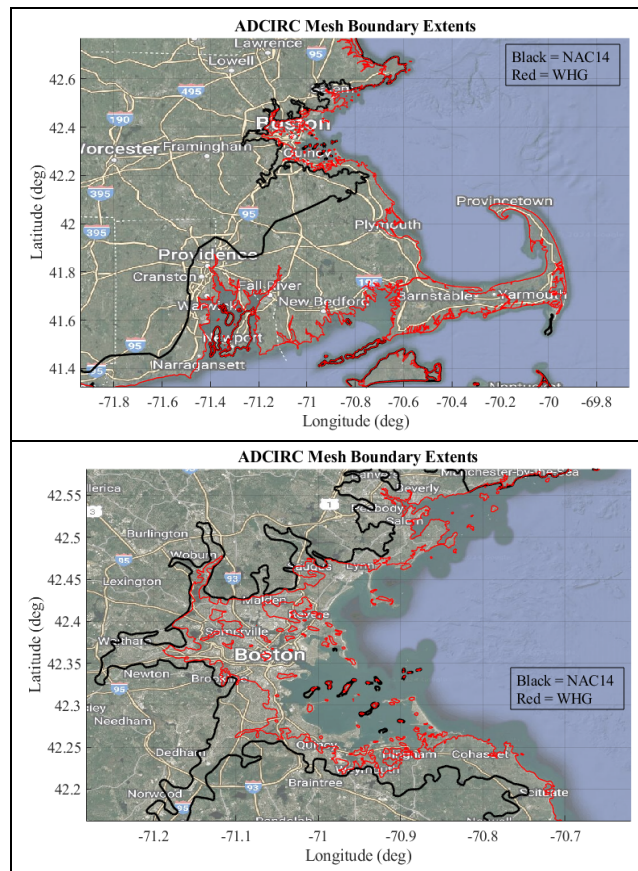


Figure 3.4: WHG group mesh extents (red) compared to the NAC14 mesh extents (black)



For this study, meshes, WP, WOP, and FWOP, were produced by first merging the WHG mesh in the Boston area into the NAC14 mesh. The newly combined mesh was further refined and modified in the project area to enhance resolution and adjust element edges to accurately represent with-project conditions. Using this approach allows the individual WP, WOP, and FWOP meshes to have nearly identical element structures, alignment, and resolution in the project areas. This uniformity ensures that any discrepancies in the solutions can be attributed to project alterations rather than differences in mesh quality or resolution. Details about merging the NAC14 and WHG mesh as well as refinements for project conditions are expanded upon next.

The WHG had several island cutouts over inland areas, as seen in Figure 3.5, which were devoid of elements. Due to their overlap with significant residential areas, the island cutouts were meshed in, in the updated WP, WOP, and FWOP meshes.

Figure 3.5: WHG mesh extents zoomed into the Boston Area, showing the many inland holes or “islands” in the mesh.

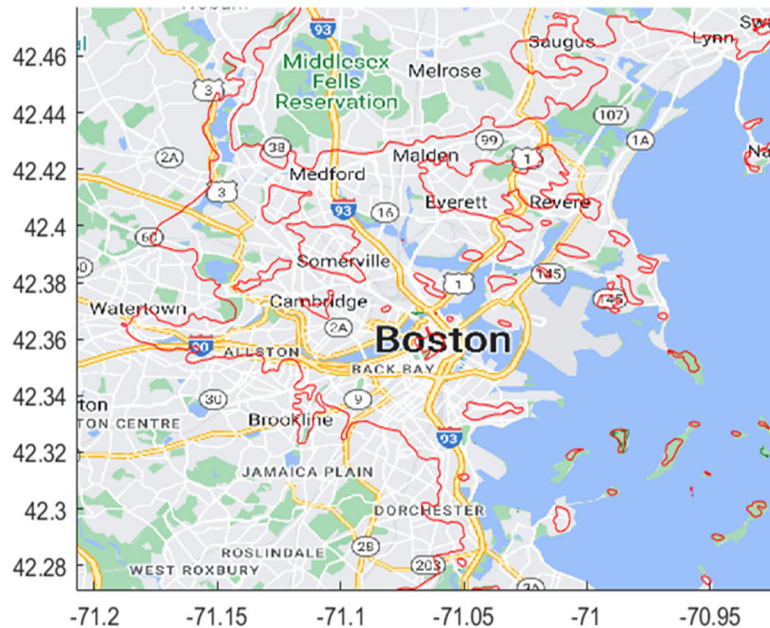
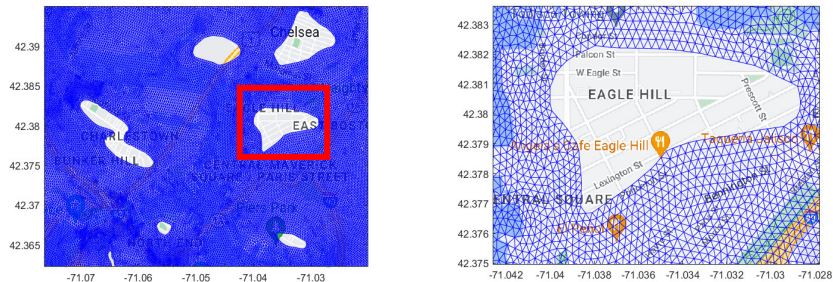
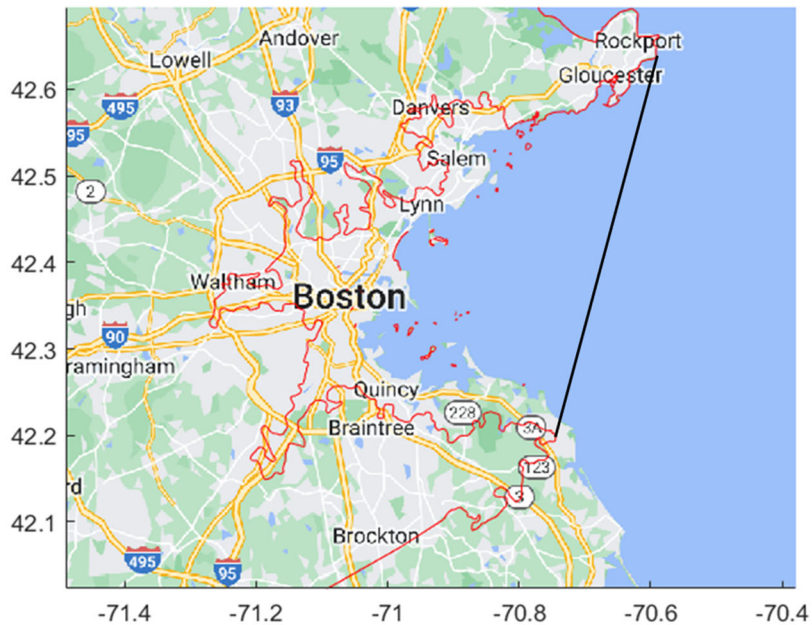


Figure 3.6: Example of the cutout islands overland, zoomed out (right), and zoomed into the red box (left)



The WHG mesh was extended to match the inland extents of that of the NAC14 mesh in the immediate Boston area and the inland holes were filled in. The mesh was then clipped outside the project area, along the offshore area shown as a black line in Figure 3.7. This clipped mesh was then merged with the NAC14 mesh, keeping the NAC14 elements away from the clipped area of the WHG mesh in the Boston. To address differences in resolution and misalignment of elements, a buffer region along the black line in Figure 3.7 was re-meshed and edited by hand.

Figure 3.7: A zoomed out perspective of Boston, where the black line demonstrates where the updated WHG mesh was clipped.



The next step in the mesh updates was to add in the potential WP conditions as well as features for future conditions, such as shipping channel deepening and widening.

Figure 3.8: Mapping structures in the FWOP mesh (left) and WP mesh (right)

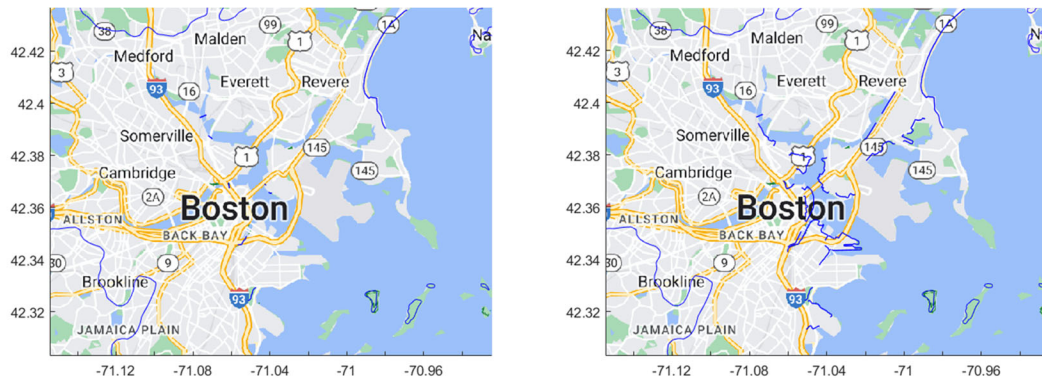
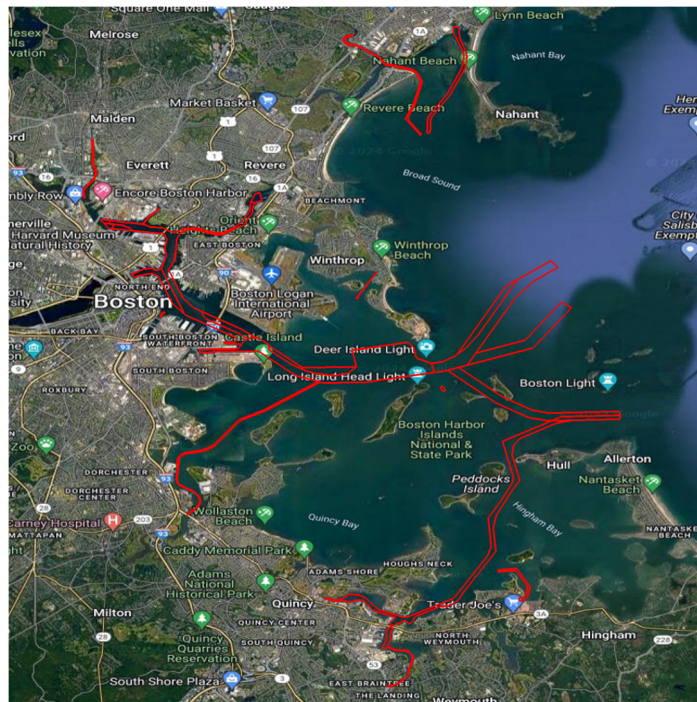


Figure 3.9: Example of Structure that was altered and connected in the WP mesh (A13,Ryan Playground)



The WHG mesh lacked future and current storm control structures, such as levees and floodwalls. Each of these structures were inserted into the FWOP and WP meshes and put in at approximately 30 meters. Locations of the structures can be seen in Figure 3.8. In areas where the structures were less than 30 meters apart, or connected by an area of land that was of a higher elevation, structures were extended and connected, as seen in Figure 3.9.

Figure 3.10: Navigation Channel outline (red) overlaid on a map of the city of Boston

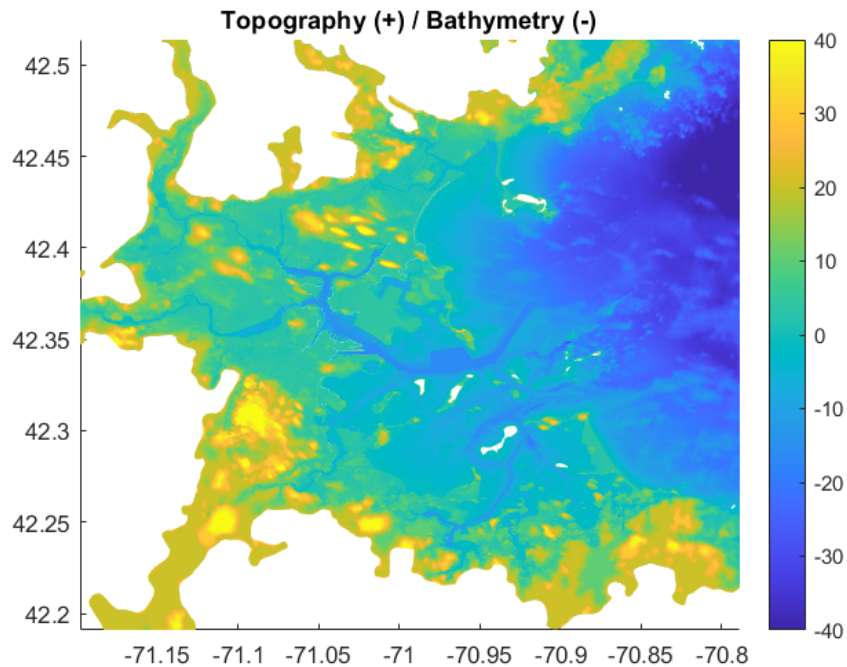


There were approximately 20 navigation channels, as seen in Figure 3.10, that were not included in the WHG mesh. These were inserted using the Engineering With Nature Modeling Toolkit in the Surfacewater Modeling System (SMS), at varying resolutions, in both WP and FWOP, tailored to match the resolutions of the surrounding areas, thereby ensuring the stability of the model. The topography and bathymetry were altered to include their depths.

3.2 Topography and Bathymetry

The base topography and bathymetry utilized in the updated mesh was that taken from the NACCS ADCIRC mesh. Then for the greater Boston area, that data was superseded by using data from the WHG mesh. However, due to several cutouts, like those pictured in Figure 3.6, some topographic data was missing. This topography was subsequently updated using the 10-meter resolution data from the USGS (Andrews, 2018).

Figure 3.11: Topography and Bathymetry in the Area of Interest, where the y-axis is longitude (degrees), and the x-axis is latitude (degrees). The color bar ranges from -40 to 40 meters relative to NAVD88.

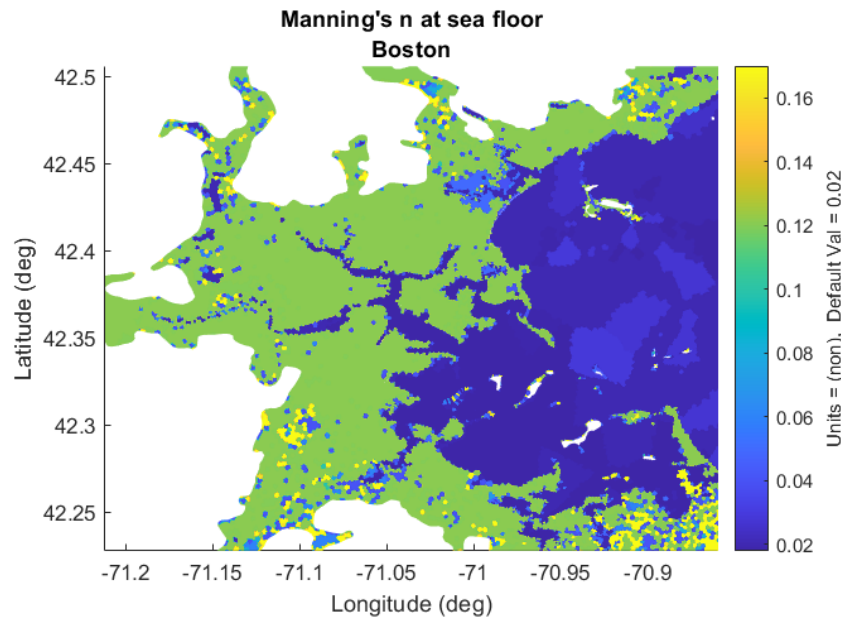


3.3 Nodal Attribute Settings

A set of additional ADCIRC model parameter settings defined for each point in the mesh, known as nodal attributes, were utilized for the NACCS and carried over to this Boston CSRM. Information on the nodal attributes used can be found in the NACCS Coastal Storm Model Simulations: Waves and Water level report (Cialone et al. 2015). For this study, the Manning's n values were updated to account for the enhanced resolution in the Boston area.

3.3.1 Manning's n Coefficient

Figure 3.12: Manning's n values over the Boston Metropolitan Area

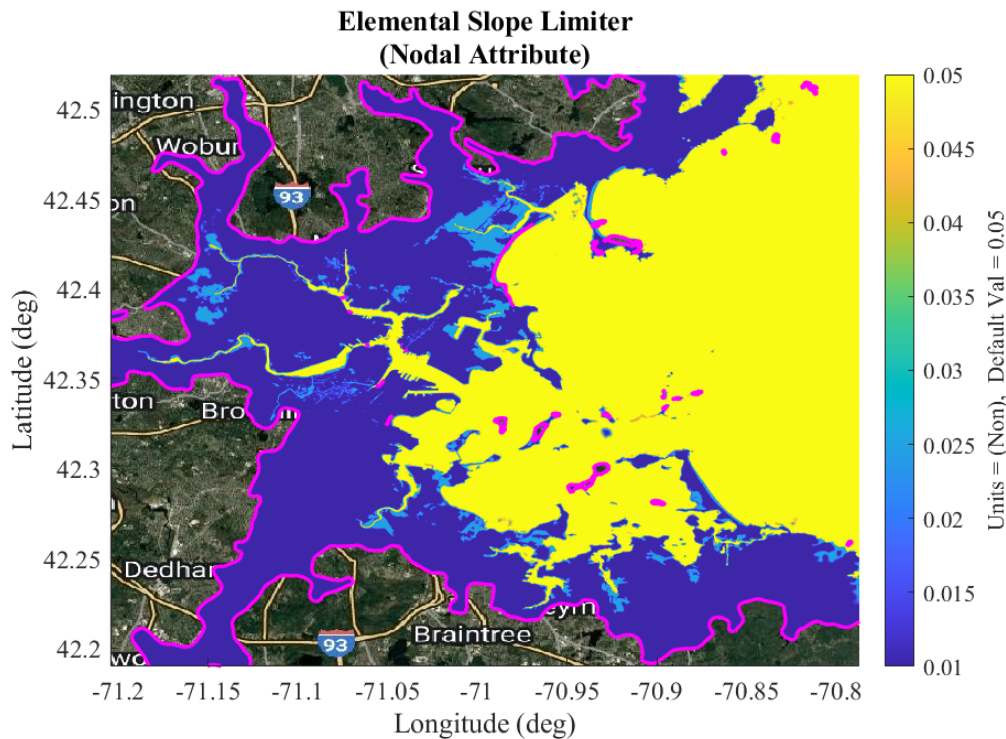


When implemented in ADCIRC, Manning's n values at each mesh node are converted to a quadratic friction coefficient that is used by the model to calculate the bottom friction for each time step of a simulation, values for the area of interest can be seen in Figure 3.12. The dataset used to update Manning's n values was the USGS National Land Cover Database (NLCD) (Dewitz 2021), land cover data for the entirety of North America at a 30-m resolution.

To allow for more numerical model stability, particularly considering the smaller mesh elements, the ADCIRC nodal attribute known as the elemental slope limiter, herein abbreviated as ESL, was incorporated for use. Within ADCIRC the ESL is used to limit the upper magnitude of the slope of the water surface elevation solution across an element. The ESL values are allowed to be spatially varying and are assigned at each ADCIRC node and the elemental values are constructed using the nodes making up the element. At each ADCIRC model time step, wet elements only have their water surface elevation solution examined to ensure that the slope of the computed solution does not exceed the ESL value for that element. If the slope exceeds the ESL value, then the water surface elevation solution

is adjusted to lower the slope of the solution. This adjustment is done by averaging the solution around the element, from neighboring wet elements only. Thus, at a wet-dry front, the use of the ESL itself will not induce dry elements to become wet. The ESL is intended to be a form of artificial numerical diffusion which adds stability to the solution process without significantly altering the overall solution itself. The ESL only limits a solution when its slope exceeds the ESL value set for an element and is checked for each model time step, so that it is only used when required during the model run time, as compared to once turned always on. For this study the ESL value was by default set to 0.05 in deep water and a value of 0.01 set for areas of the mesh that are initially land. Then shallow water areas in the project area with small element sizes were set to 0.02. These values are rather conservative so that ESL is used sparingly and only in the areas most likely to become unstable, e.g. overland areas where the wetting and drying algorithm is actively being used and where newly wet elements have thin layers of water and still receive strong forcing values from large magnitude winds. Figure 3.13 shows the ESL in the project area.

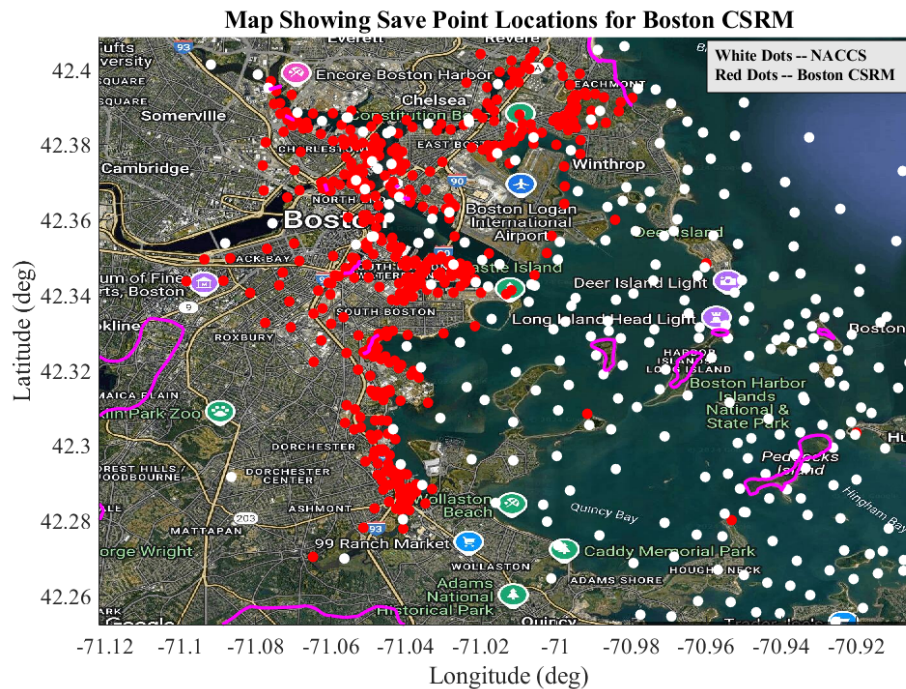
Figure 3.13 Map showing values of the ADCIRC nodal attribute, elemental slope limiter, in the Boston area.



3.4 Model and Statistics Save Point Locations

The NACCS study contains 18,977 save point locations located along the coastline of the North Atlantic, where numerical model output was recorded, and statistical analysis was performed. The save points were located both in normally wet locations and normally dry locations, with many points selected coincident to or in the vicinity of known USACE projects. For this present study, all NACCS save point locations were retained and 440 new locations were added in the Boston area. These new points were placed around the proposed with-project design locations as well as other key locations within the city. Figure 3.14 shows the save point locations in the Boston area, with white dots showing NACCS points and red dots showing the new Boston save points.

Figure 3.14 Map showing locations of save points from the NACCS and the Boston CSRM.



Model data and statistical data are also being recorded at the ADCIRC nodes for this project.

3.5 River Boundaries and Flux Forcing Values

The same fourteen rivers included in the NAC14 ADCIRC mesh from the NACCS were included in the updated meshes. As a reminder from the NACCS modeling report (Cialone et al 2015), most of these rivers had USGS gages (with mean daily flow rates) located either at upstream dam locations or at the head of tide with sufficient periods of record available for analysis (data began in the 1930s and 1940s for most gages). However, the Raritan and Passaic Rivers required NAN personnel to translate flow from a known gage measurement/location to the model boundary location through data manipulation. The production discharge for tropical storms for each river was computed as the maximum value between the 90th percentile and a discharge equal to the mean plus one standard deviation. On average, the production discharge of each river is close to three times the mean discharge as can be observed in Table 3-1. This method was

utilized to create reasonable inflows that would result in somewhat conservative water levels.

Table 3-1 River flow rates used in the NACCS for 14 major rivers.

River	Mean Flow (cms)	Production Flow (cms)	Maximum Flow (cms)
Brandywine River	70	255	405
Chester Creek	20	57	163
Connecticut	802	1954	6400
Delaware	829	2209	7900
James	589	1982	8382
Mattaponi	36	85	283
Pamunkey	93	311	708
Potomac	993	3794	9458
Rappahannock	228	736	2384
Schuylkill	358	934	2645
Susquehanna	2043	7617	31715
Hudson	570	1444	4474
Passaic	76	283	615
Raritan	221	651	1969

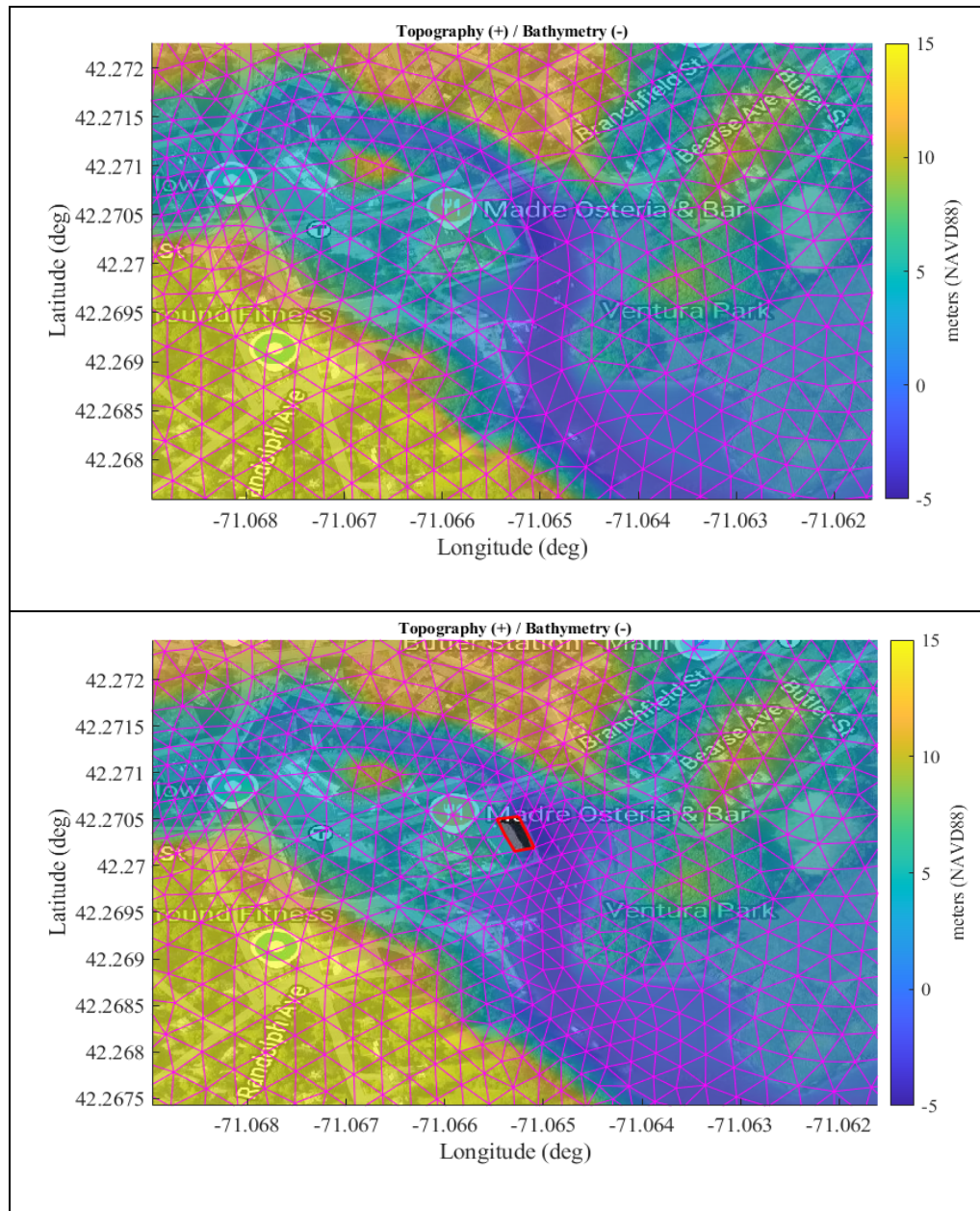
To assess possible impacts to total water levels in the Neponset River watershed area south of Boston, river flow rates for the Neponset River were also added into the interior of the ADCIRC mesh just below the Neponset River Waterfall (Walter Baker Dam) near Adam Street in Dorchester/Milton, MA, see Figure 3.15. River flows for the Charles River and Mystic River were not included in the forcing as these rivers are controlled by dams. The dams are included in the ADCIRC model as weir-pair boundary conditions. Testing was performed for eight (8) of the synthetic tropical storm events using a river flow rate of 105.6 cms (approximately 3730 cfs). This testing required special updating to the ADCIRC mesh with additional resolution in the river area where the flows were inserted. Figure 3.16 shows the topography and bathymetry contours along with the mesh element edges, as magenta lines, for the FWOP mesh (top), in the Neponset River area near Baker Dam and the updated FWOP

mesh (bottom) to allow for river flux forcing, at the river side of the red boxed area. Results from this testing are given in Section 7 of this report.

Figure 3.15 Map from Google Earth showing the general location of the Neponset River between Baker Dam and Interstate 93.



Figure 3.16 Maps showing the ADCIRC mesh topography and bathymetry values as well as element edges as magenta lines for the FWOP (top) and the FWOP updated to include Neponset River flows (bottom).



4 STWAVE Model Setup Parameters

STWAVE (STeady-state WAVE) is a phase-averaged spectral wave model for nearshore wave generation, propagation, transformation, and dissipation (Smith et al. 2001, Smith 2007, Massey et al. 2011). STWAVE numerically solves the steady-state conservation of spectral wave action equation. Source and sink mechanisms include surf-zone wave breaking, wind input, wave-wave interaction, white capping, and bottom friction.

STWAVE is formulated on a Cartesian grid, with the x-axis typically oriented in the cross-shore direction (I) and the y-axis oriented alongshore (J), parallel with the shoreline. Angles are measured counterclockwise from the grid's x-axis.

In the NACCS, 10 STWAVE domains were used to cover the entire north Atlantic coastline, see Figure 3.17. All but two domains used a 200-m grid spacing resolution, the Chesapeake domain used 125-m and the Washington DC domain used a 100-m resolution. Summary details of those grids are given in Table 3-2.

Table 3-2 NACCS STWAVE model domain specifications.

Grid	Projection	Grid Origin (x,y) (m)	Azimuth (deg)	Resolution (m)	Number of Cells	
					I	J
Northern Maine (NME)	UTM 19	682704.7, 4899673.0	110.7	200.0	392	682
Central Maine (CME)	UTM 19	568406.9, 4857172.5	112.0	200.0	427	720
Southern Maine (SME)	UTM 19	482432.8, 4800937.9	133.0	200.0	439	717
Eastern Massachusetts (EMA)	UTM 19	450200.0, 4724100.0	180.0	200.0	638	670
Southern Massachusetts (SMA)	UTM 19	465575.3, 4518084.4	101.9	200.0	733	887
Long Island (LID)	UTM 18	802679.3, 4544326.0	117.9	200.0	453	986
North New Jersey (NNJ)	UTM 18	689660.5, 4494212.9	150.2	200.0	569	593
Central New Jersey (CNJ)	UTM 18	642056.1, 4413284.8	153.1	200.0	468	596
Chesapeake Bay (CPB)	UTM 18	581350.8, 4339880.0	159.8	125.0	1687	2653
Washington D.C. (WDC)	UTM 18	348428.2, 4313375.1	159.9	100.0	377	837

For the present study, only three domains were kept from the NACCS, the Southern Maine (SME), the Southern Massachusetts (SMA) and the Eastern Massachusetts (EMA), see Figure 3.18. The other domains were located far enough away from the project area that their nearshore wave conditions do not have any contributions to the water levels and wave conditions in the Boston area. The EMA domain from the NACCS was updated to extend its inland boundary further westward in order to allow for wave conditions to cover the newly refined areas within the ADCIRC mesh. The EMA domain was further updated by refining its resolution to use 125-m grid spacing instead of 200-m, updated its topography and bathymetry values taken from the FWOP ADCIRC mesh, and updated Manning's n frictional values taken from the FWOP ADCIRC nodal attribute file. The ocean boundary was left intact in order to use the same boundary spectral energy conditions as those used in the NACCS. The new STWAVE domain name is EMA125FWOP, see Figure 3.19 for a close-up view of the extended area beyond the original EMA domain inland boundary. Table 3-3 provides the STWAVE model domain grid particulars for each of the three domains, EMA125FWOP, SMA, and SME used in this study.

Figure 3.17 Map showing the boundaries and locations of the 10 STWAVE domains used in NACCS.

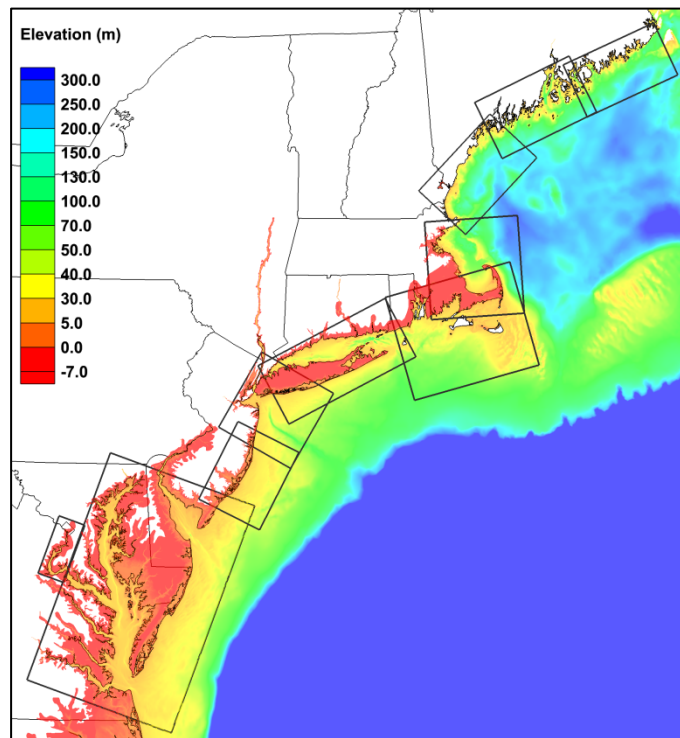


Figure 3.18 Map showing the location of the STWAVE domains, SME, SMA, EMA, and EMA125FWOP.

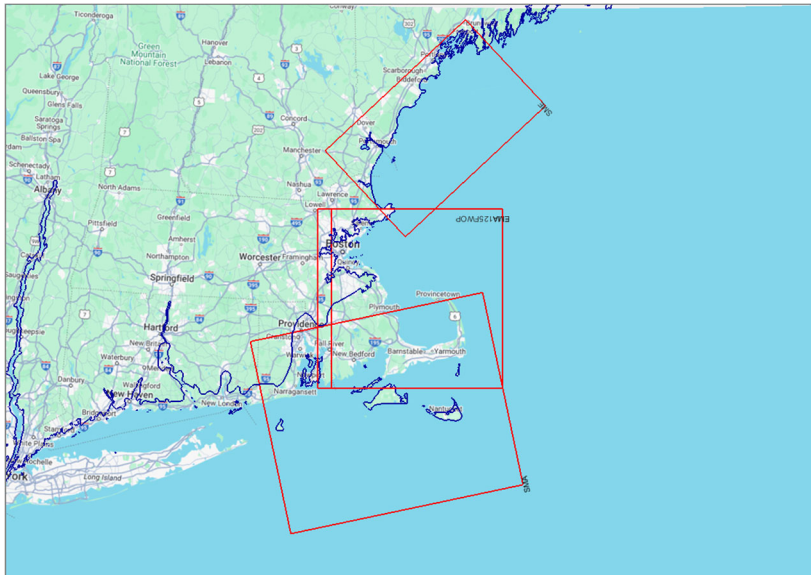


Figure 3.19 Map showing a close-up view of the EMA and EMA125FWOP STWAVE domain extents in the Boston area.

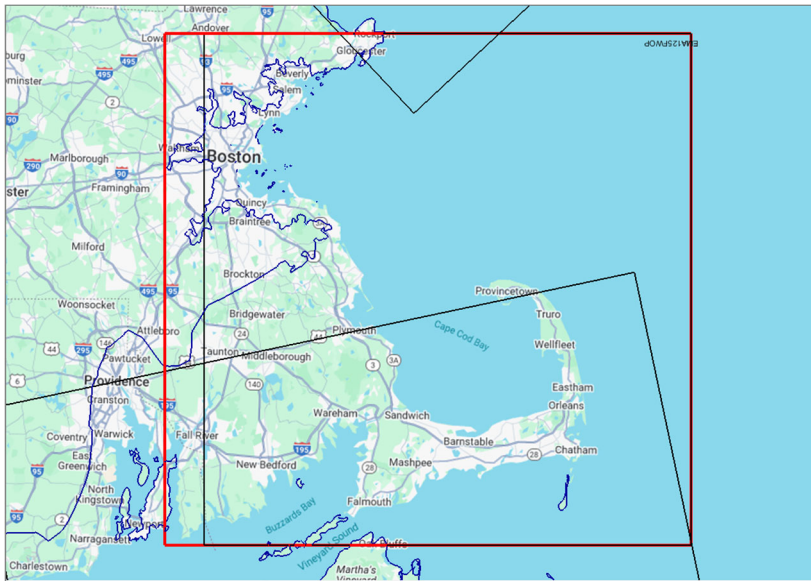


Table 3-3 STWAVE model domain specifications for Boston CSRM.

Grid	Projection	Grid Origin (x,y) (m)	Azimuth (deg)	Resolution (m)	Number of Cells	
					I	J
Southern Maine (SME)	UTM 19	482432.8, 4800937.9	133.0	200.0	439	717
Eastern Massachusetts FWOP (EMA125FWOP)	UTM 19	450200.0, 4724100.0	180.0	125.0	1104	1072
Southern Massachusetts (SMA)	UTM 19	465575.3, 4518084.4	101.9	200.0	733	887

5 Limited Revalidation Results

A comparison of the water surface elevation data for the 17 historical extratropical events was performed using the NOAA Tides and Currents gauge data at Boston, MA station ID: 8443970 versus the CSTORM coupled ADCIRC+STWAVE model results. This is the only gauge in the immediate project area that had measured water level data. Time series plots of water surface elevation are provided for two storms, extratropical storm number 13 in Figure 5.1 and extratropical storm number 202 in Figure 5.2. Plots of all 17 XC storm water levels are provided in Appendix 1. The model agrees very well with measured data phasing and with magnitudes. Table 5-1 provides a comparison of the maximum water surface elevations at this gauge for all 17 XC events. The maximum difference between measured and modeled is 1.1 ft (0.35 m), the minimum difference is nearly zero feet (0.01 m), and the average difference over all 17 storms is 0.5 ft (0.16 m). This maximum and mean errors of 1.1 ft and 0.5 ft respectively, are within the range of the average error for water levels from the NACCS, which was about 1 ft (Cialone et al. 2015).

As was the case in the NACCS, there is no nearshore wave measurement data in the Boston, MA area. As such and due to the similarity of the STWAVE setups between the NACCS and this study, accuracy levels of wave results will be assumed comparable.

Figure 5.1 Time series of water surface elevation at the Boston, MA NOAA Station ID 8443970 for historical extra-tropical storm 13 (February 1960).

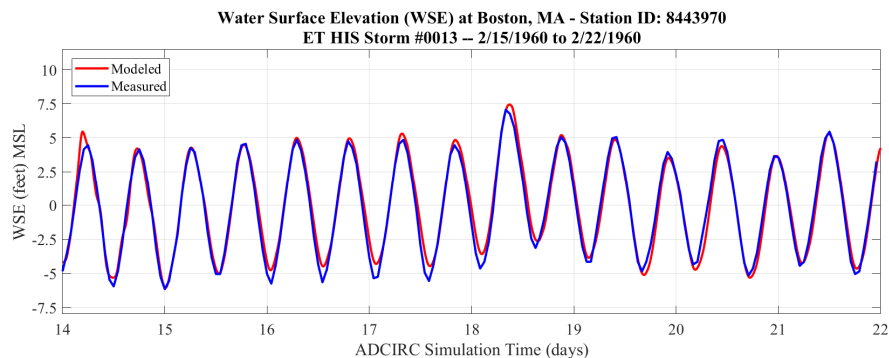


Figure 5.2 Time series of water surface elevation at the Boston, MA NOAA Station ID 8443970 for historical extra-tropical storm 202 (February-March 2018).

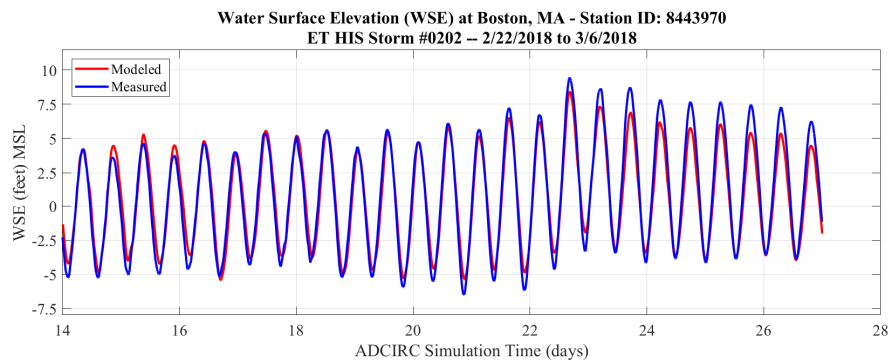


Table 5-1 Comparison of modeled vs measured maximum water level data at NOAA station 8443970 (Boston, MA) for 17 historical extra-tropical events.

Storm #	Date Begin	Date End	Measured (ft) MSL	Modeled (ft) MSL	abs(diff) (ft)
2	2/11/1940	2/17/1940	6.2	6.1	0.1
6	2/27/1947	3/7/1947	6.7	6.8	0.1
7	11/21/1950	11/29/1950	6.3	6.8	0.4
8	3/7/1952	3/15/1952	5.1	5.3	0.2
13	2/15/1960	2/23/1960	7.1	7.4	0.4
24	2/28/1971	3/8/1971	6.5	6.9	0.4
28	11/5/1972	11/13/1972	6.3	5.7	0.5
29	12/12/1972	12/20/1972	6.7	6.9	0.3
37	2/3/1978	2/11/1978	9.8	9.9	0.0
39	12/21/1978	12/29/1978	6.3	7.3	1.0
52	11/1/1985	11/9/1985	5.2	5.4	0.3
60	12/7/1992	12/15/1992	8.8	8.1	0.7
62	3/10/1993	3/18/1993	7.2	6.7	0.5
64	12/17/1993	12/25/1993	6.0	5.0	0.9
96	10/11/2010	10/19/2010	6.7	5.8	0.9
201	12/27/2017	1/9/2018	10.0	8.8	1.1
202	2/22/2018	3/7/2018	9.5	8.4	1.1

6 Simulation Results for Maximum Water Surface Elevations

This section presents results from two historical extratropical storm events and three synthetic tropical storm events. The results show maximum water surface elevations for each storm event as two-dimensional color contour plots. Results are presented for two sea level conditions (SLCo, and SLC1) as well as for results using tides and those without tides included. Similar plots are included for all the storm events in Appendix 2 through Appendix 5.

Historical Extratropical Storms:

Maximum water surface elevation results for historical XC storm 37 and 202 are presented in Figure 6.1 and Figure 6.2. For each figure, four panels of results are shown, upper left shows results for SLCo and no tides, upper right shows SLC1 and no tides, lower left shows SLCo including historical tides, and lower right shows SLC1 and includes the historical tide date range.

For XC storm 37, results are shown in Figure 6.1 where the inclusion of tides significantly increases the overall water levels by about 4 feet for both SLCo and SLC1. Under the SLC1 case the inclusion of tides also significantly expands the overall inundation extents as compared to the SLCo case.

Figure 6.1 Maps of maximum water surface elevation for historical extratropical storm number 37.

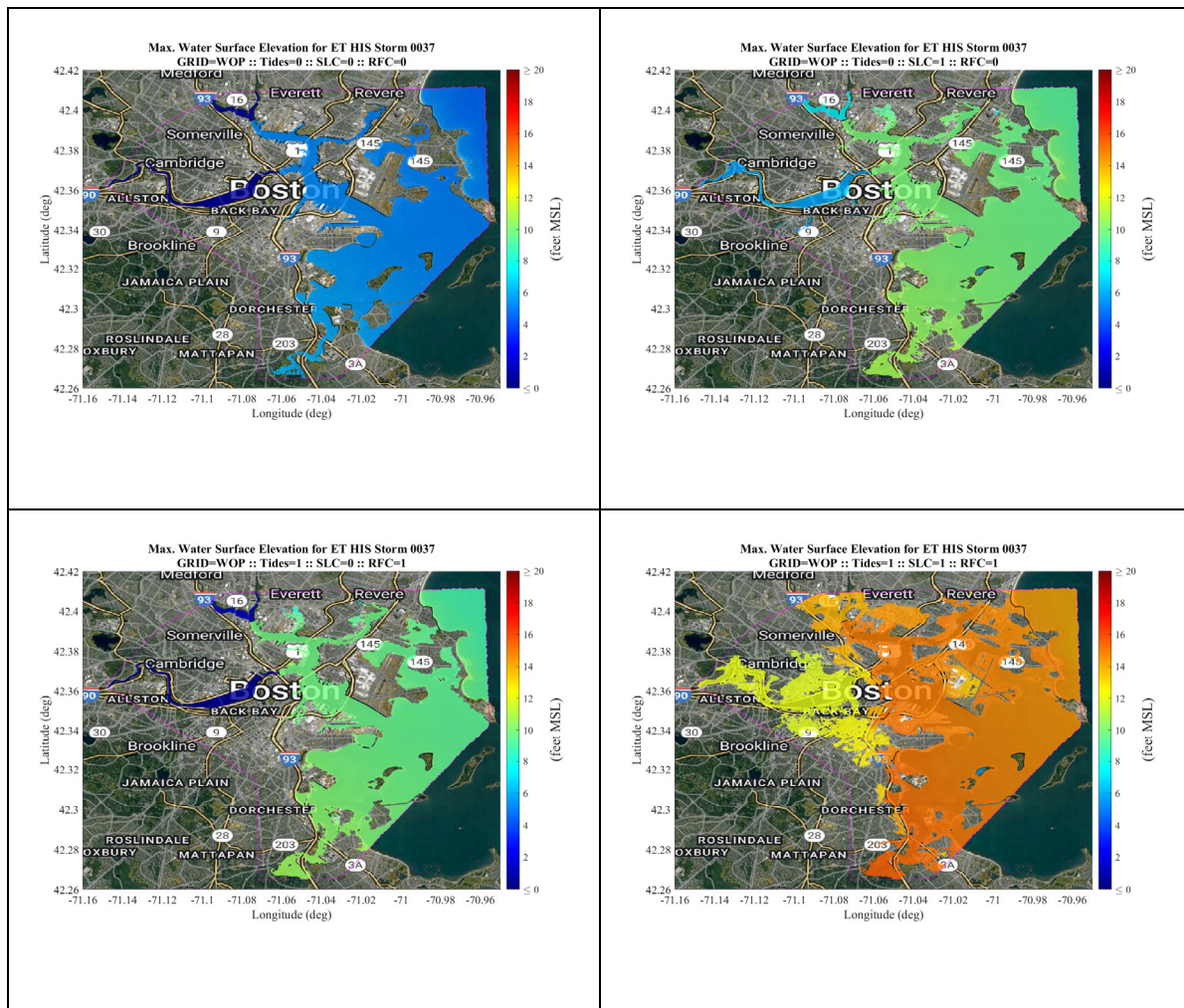
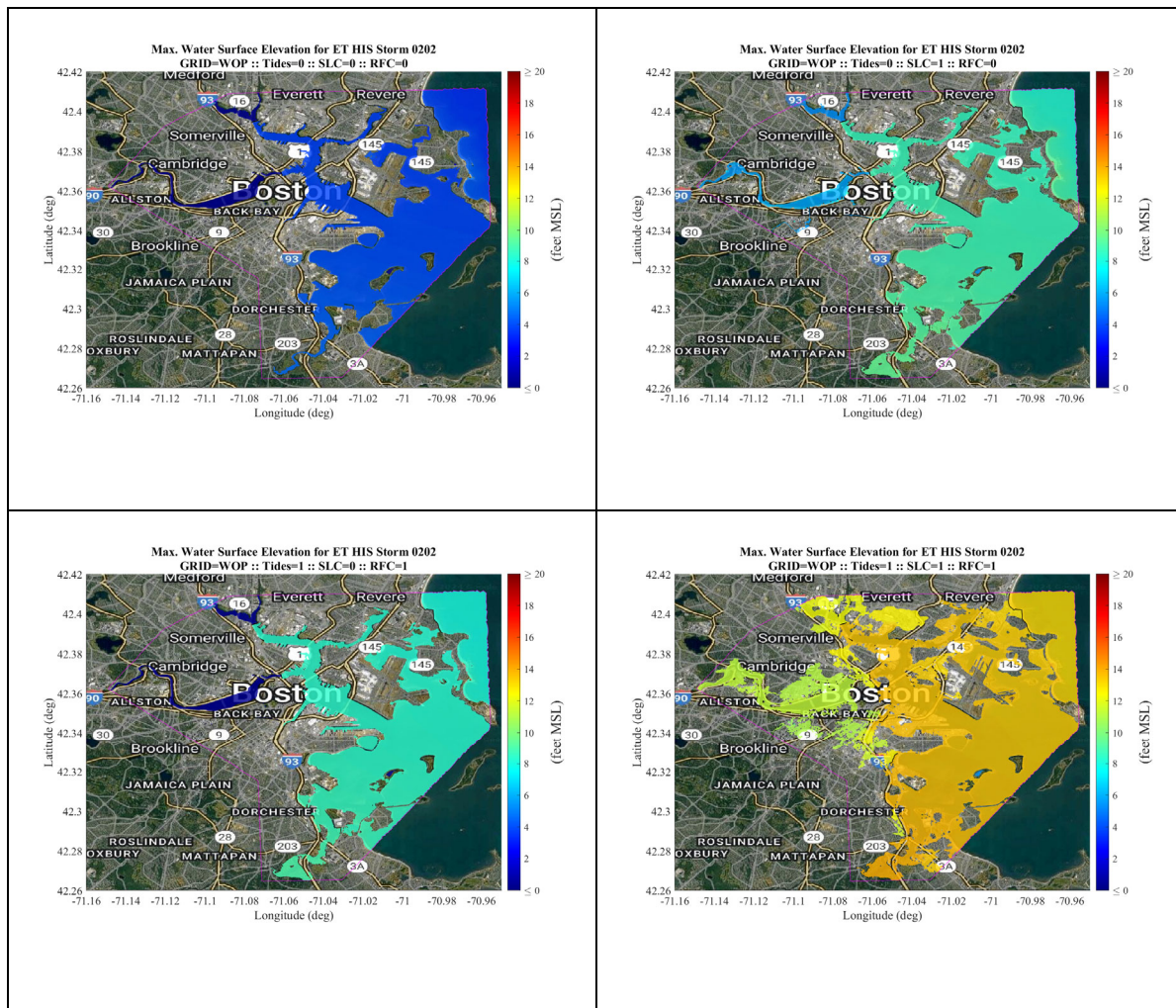


Figure 6.2 shows four panels of maximum water surface elevation results for historical XC storm 202. Again, it is seen that inclusion of tides increases the overall water elevations and expands the inundation areas. The SLC1 condition under with tides conditions, shows significantly more inundation than the SLC0 with tides case.

Figure 6.2 Maps of maximum water surface elevation for historical extratropical storm number 202.



Synthetic Tropical Storms

Figure 6.3, Figure 6.4, and Figure 6.5 show four panel plots of maximum water surface elevations for synthetic tropical storm numbers 385, 794, and 1016. In the four panels the upper left shows results for SLC₀ and no tides, upper right shows SLC₁ and no tides, lower left shows SLC₀ including a random tide date range, and lower right shows SLC₁ and includes the same random tide date range as used in the SLC₀ case. These storms were selected to show sample results for a high storm surge case, storm 385, a medium level of storm surge, storm 794, and a relatively low

storm surge in storm 1016. In all cases, inclusion of additional sea level rise, going from SLC0 to SLC1, increases the overall water levels, nearly linearly along the open coast and larger bay areas, however nonlinear increases and changes are evident in the nearshore and inundated areas where the coastline is complex and or where wetland areas occur. Similarly, the inclusion of the random tide as part of the simulation also increases the water levels and the overall inundation extents. The inclusion of tides under SLC1 results in the largest surges and most inundated areas.

Figure 6.3 Maps of maximum water surface elevation for synthetic tropical storm number 385.

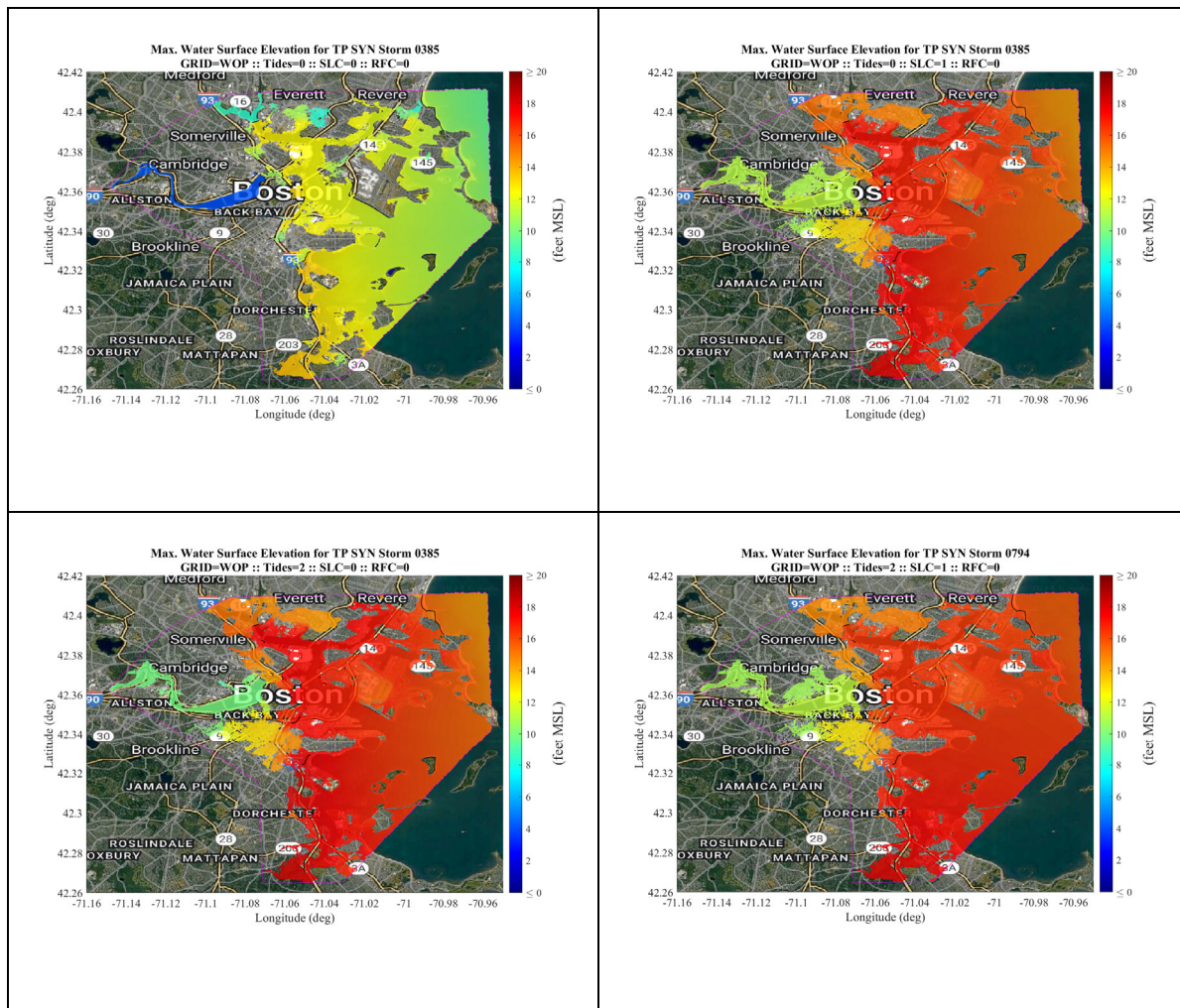


Figure 6.4 Maps of maximum water surface elevation for synthetic tropical storm number 794.

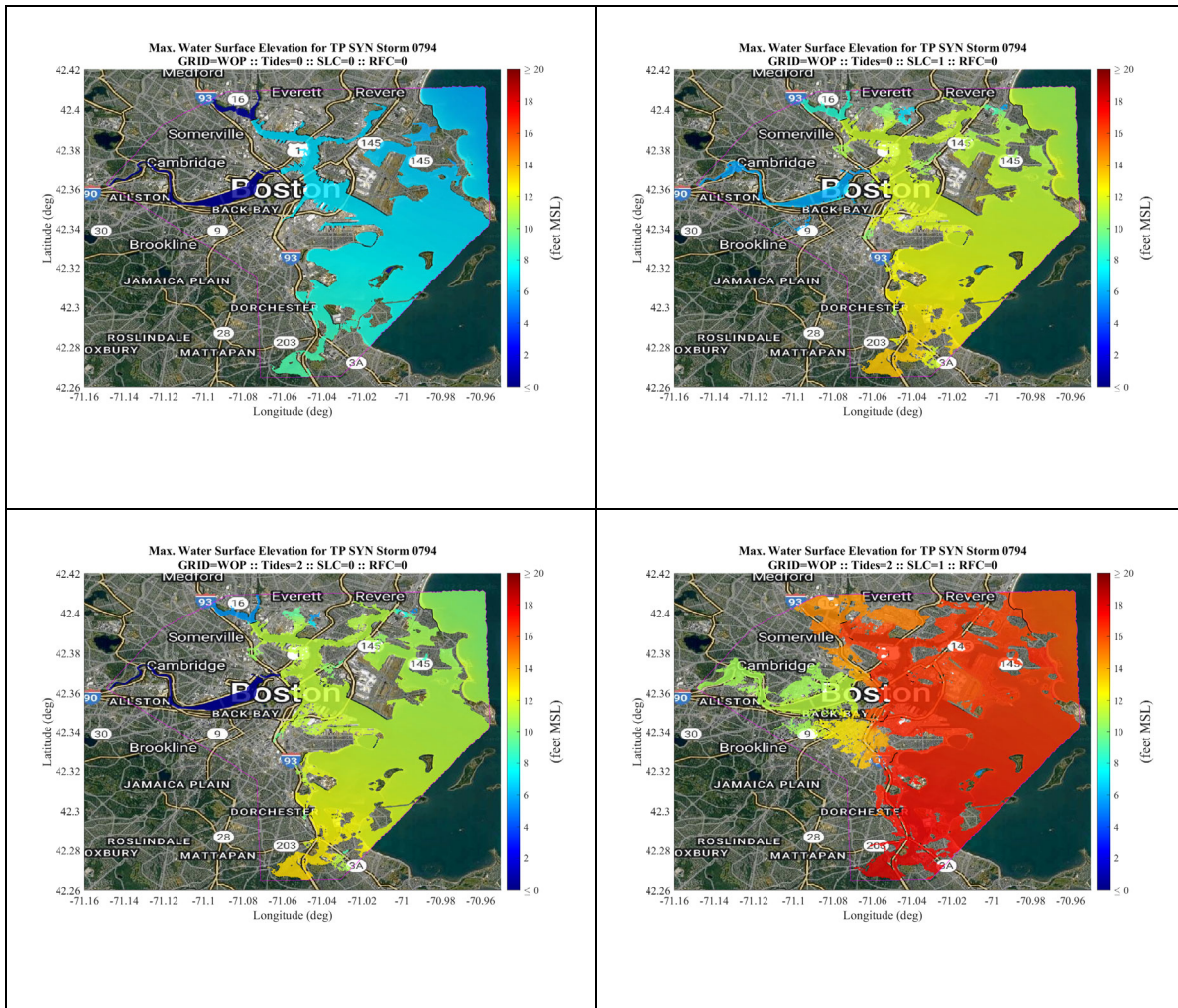
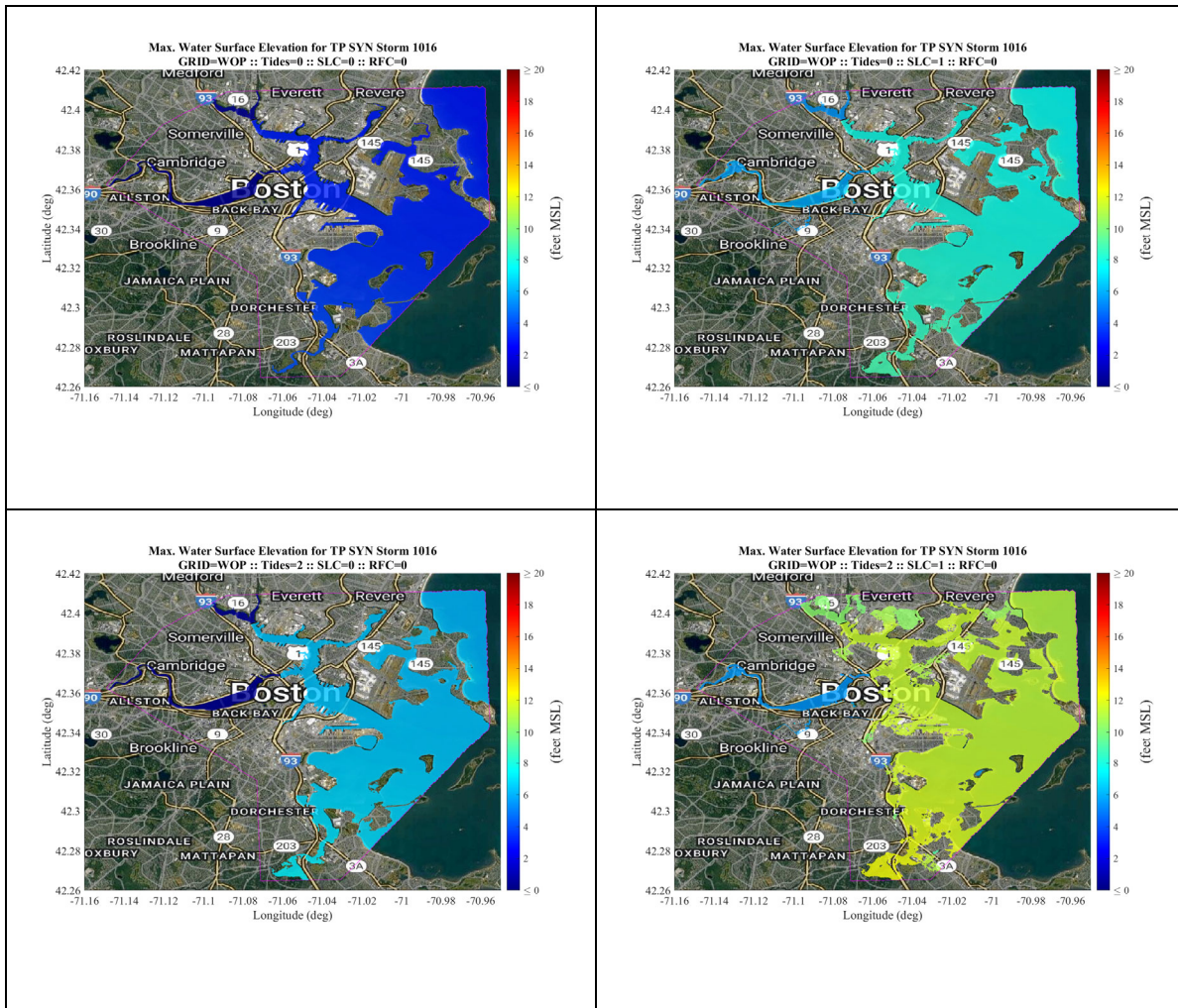


Figure 6.5 Maps of maximum water surface elevation for synthetic tropical storm number 1016.

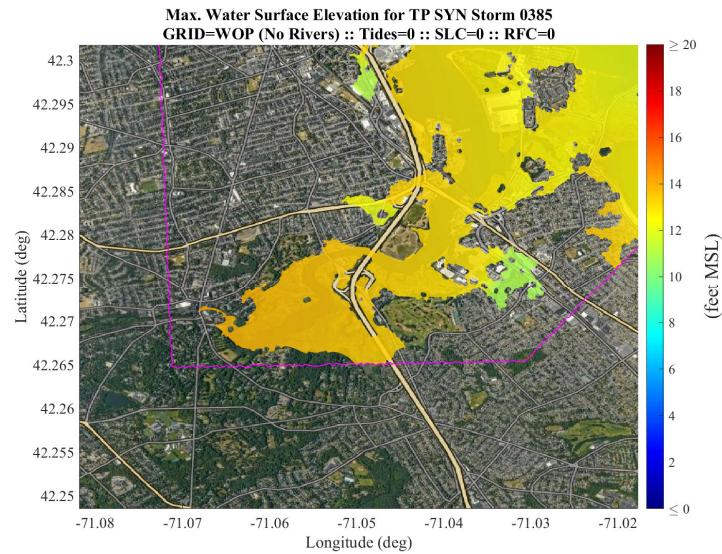


See Appendix 6 through Appendix 9 for images of maximum water surface elevations for all 60 synthetic TC events, with and without tides, and both SLC₀ and SLC₁.

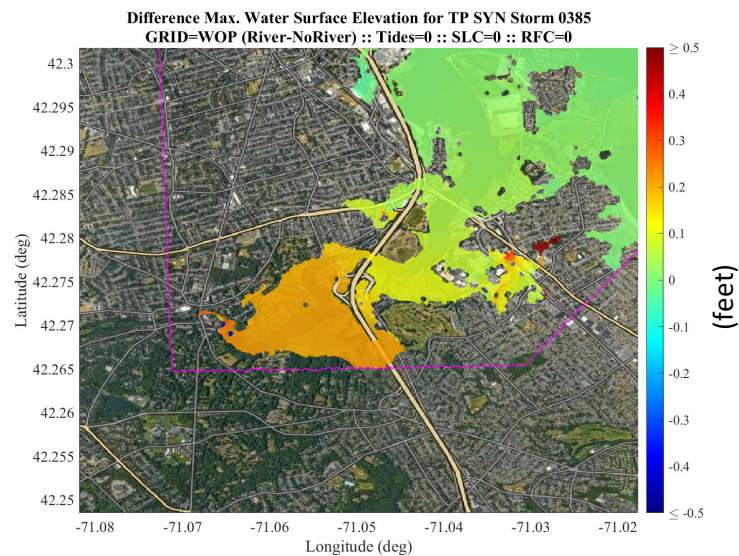
7 Sensitivity Testing of Inclusion of Neponset River Inflows on Modeled Coastal Maximum Water Surface Inundation

A limited set of simulations were performed to test the sensitivity of inundation levels to the inclusion of river flows at the Baker Dam on the Neponset River. A flow of 3,730 cubic feet per second (CFS) (105.62 CMS) was input into the ADCIRC mesh as a constant flow rate for the Neponset River and used during test simulations for six tropical synthetic storms, storms 385, 421, 488, 734, 789 and 1007, that had varying degrees of inundation extents and levels under without Neponset River flows. The simulations were run without tides for both SLC0 and SLC1 conditions. Figure 7.1, Figure 7.2, and Figure 7.3 show representative color contour maps of three of the storms, showing maximum water surface inundation for simulations without river flows in parts (a) and then differences in maximum water surface inundation values compared to simulations that included riverine flows. The majority of the changes to inundation were confined mostly to the area of the river between Baker Dam and I-93 with the changes occurring mainly in increased water heights and not so much in inundation extents. The changes in heights were on the order of 0.2 feet to around 0.8 feet. Storm 385 also shows a change in inundation extent and heights between I-93 and the Newport Avenue Extension Road and just beyond. The increase in extents are a few blocks, so not very extensive and again the inundation depths in that area for that storm say increases on the order of 0.2 to 0.6 feet. Based on this limited number of runs, the inclusion of river flows into Neponset River appear to have a spatially localized impact on storm surge inundation extents and changes to inundation heights by less than 0.5 feet in the majority of the areas where it changes at all. The inclusion of the riverine inflows does not appear to have a negative impact on the ADCIRC model stability and as such could be included for future modeling work.

Figure 7.1 Color contour maps of (a) maximum water surface elevation for tropical storm 385 without riverine inflows in the Neponset River and (b) difference in maximum water surface elevation between with riverine and without riverine flows.

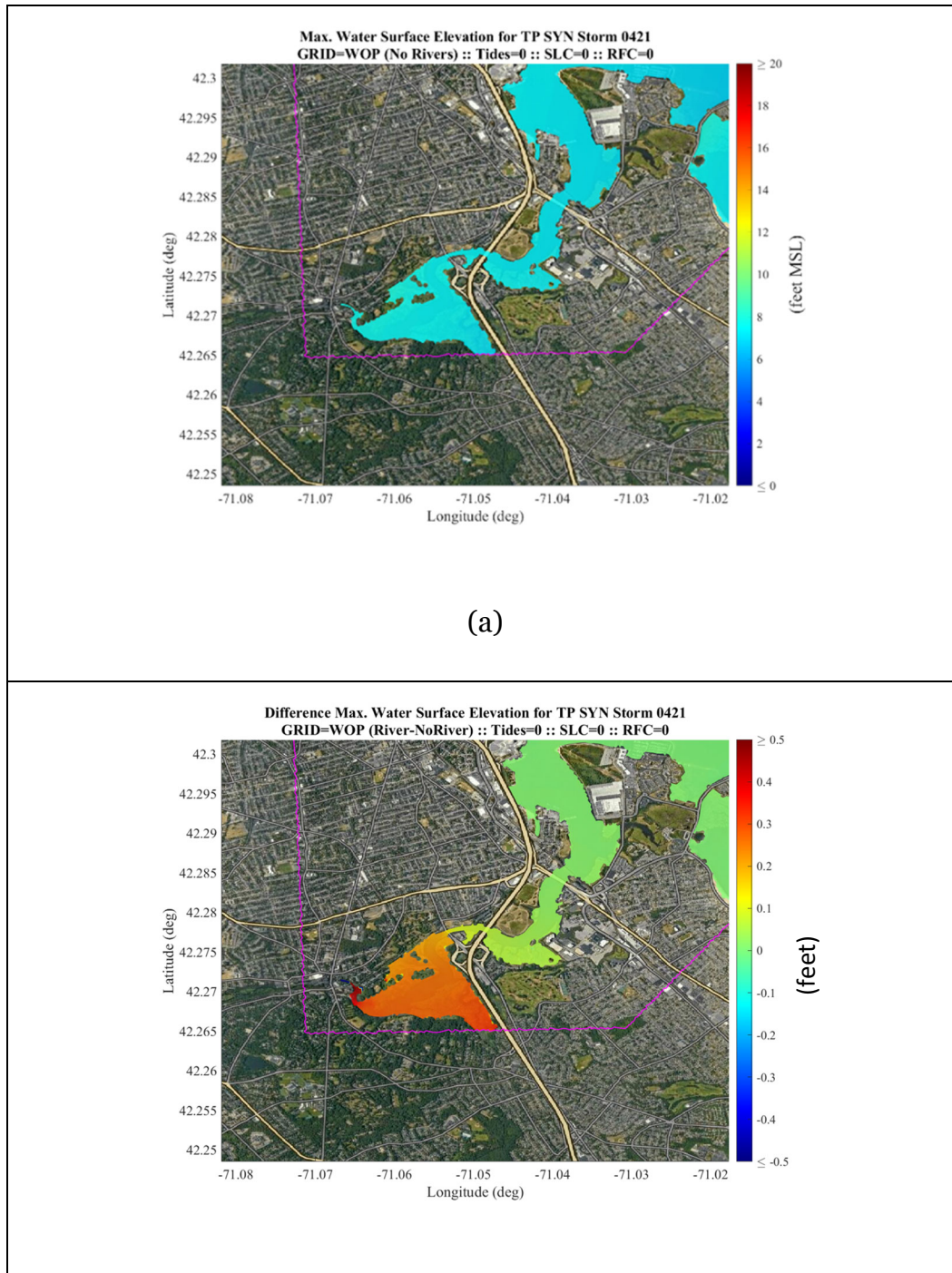


(a)



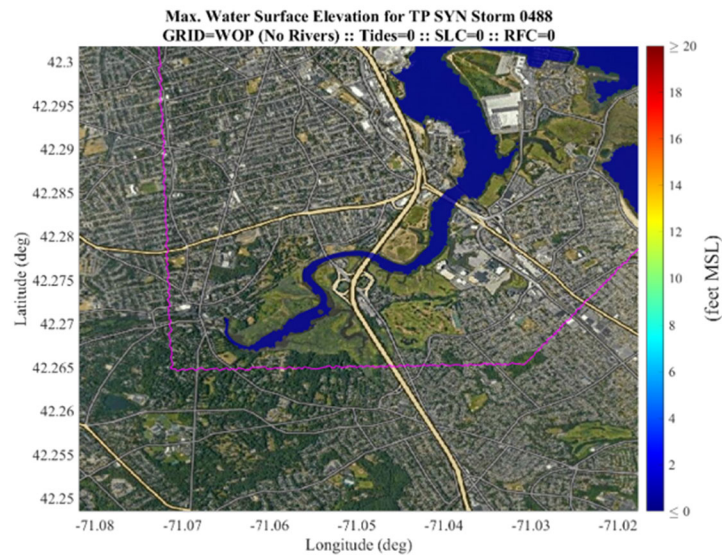
(b)

Figure 7.2 Color contour maps of (a) maximum water surface elevation for tropical storm 421 without riverine inflows in the Neponset River and (b) difference in maximum water surface elevation between with riverine and without riverine flows

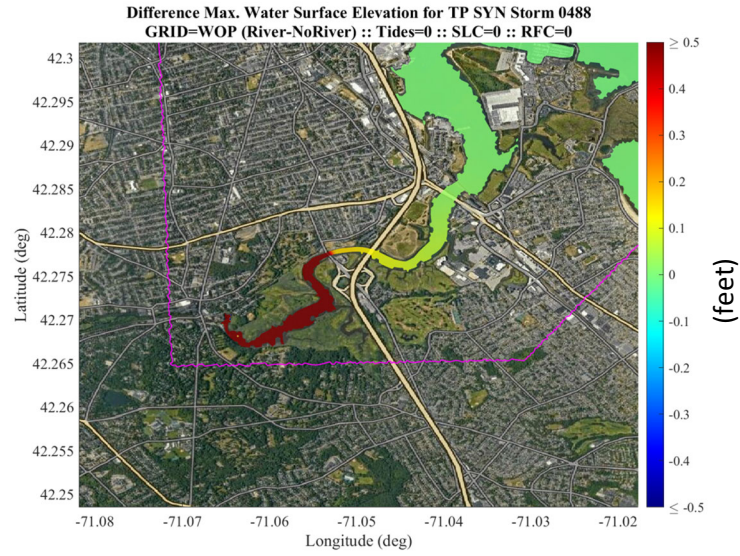


(b)

Figure 7.3 Color contour maps of (a) maximum water surface elevation for tropical storm 488 without riverine inflows in the Neponset River and (b) difference in maximum water surface elevation between with riverine and without riverine flows



(a)



(b)

8 Water Level and Wave Hazards

In the Boston Coastal Storm Risk Management (CSRM) Study, reduced storm suites (RSSs) of 60 tropical cyclones (TCs) and 17 extratropical cyclones (XCs) were simulated to determine the change in water level and wave hazards for the various with-project (WP) and without-project (WOP) conditions under consideration, while leveraging data from the existing North Atlantic Coastal Comprehensive Study (NACCS; henceforth denoted as the Coastal Hazards System-North Atlantic or CHS-NA study) (Nadal-Caraballo et al. 2015; Cialone et al. 2015) results. However, relying solely on the RSS to develop the hazard curves for the project area would result in increased uncertainty due to the limited number of storm simulations applied in the statistical analyses. To resolve this issue, the CHS-Probabilistic Framework (CHS-PF) methodology relied on Gaussian process metamodeling (GPM) and regression techniques to support the estimation of hazards for the CSRM without-project (WOP) conditions. The CHS-PF has recently been applied in other regional-scale and CSRM studies to support the quantification of coastal storm-induced hazards, including the South Atlantic Coastal Study (SACS) (Nadal-Caraballo et al. 2022) and the Upper Barataria Basin CSRM (Yawn et al. 2024). The following sections give an overview of how the data and metamodels developed as part of the CHS-NA study were leveraged here in conjunction with the CSRM WOP storm simulations to quantify hazards for the project domain.

8.1 CHS-PF Overview

Through an inter-agency agreement with the Federal Emergency Management Agency (FEMA) initiated in 2022, the CHS-NA study was recently conducted to leverage existing data from the NACCS to update and improve the resolution of coastal hazards data using the computational grid nodes of the ADCIRC model. This work for the CHS-NA study was subsequently applied here to enable quantification of updated WOP and WP hazards considering two sea level scenarios at the ADCIRC nodes near the Boston CSRM study area.

8.1.1 Tropical Cyclone (TC) Hazards

As part of the CHS-PF methodology for quantifying TC-induced coastal hazards for the CHS-NA study, the development of an ATCS is implemented to increase the coverage of the TC parameter and probability spaces for a given study area. The goal of developing this augmented storm suite is to improve the resolution of the storm responses and associated DSWs as a means of developing robust hazard curves without requiring the additional computational burden of simulating more storms in the hydrodynamic models, such as the ADCIRC and STWAVE models. For this study, the parameter space of the CHS-NA ITCS of 1050 storms was expanded to establish an ATCS of over 1.2 million TCs. Each of the storms within the ATCS was then assigned a DSW representing the probability of each event with units of storm/year. These DSWs were computed by developing marginal distributions of the TC atmospheric forcing parameters based on historical TC observation data from the National Hurricane Center's Hurricane Data 2nd generation (HURDAT2) database during the period of 1938-2021 (Landsea and Franklin 2013; <https://www.aoml.noaa.gov/hrd/hurdat/hurdat2.html>). These marginal distributions were then linked using a meta-Gaussian copula to compute the joint probability of the TC parameters defining a given storm in the ATCS, which is a necessary component of computing the DSWs as documented in Nadal-Caraballo et al. (2022). GPMs were trained on the NACCS storm surge and significant wave height responses of the ITCS, and these GPMs were subsequently applied to predict storm responses for the ATCS at 1.8 million nodes while maintaining the accuracy of the original ADCIRC and STWAVE models. The GPM predictions are a function of the TC primary parameters (i.e., L_o , Δp , R_{max} , V_t , θ). The ATCS responses and DSWs were then applied as the input for the JPM integration, which resulted in the development of hazard curves describing SWL, SSL, H_{mo} , and T_p as a function of AEF and magnitude.

8.1.2 Extratropical Cyclone (XC) Hazards

For the quantification of XC-induced coastal hazards, the CHS-PF relies on the EVA of historical storms. Due to the inability to parametrically represent the atmospheric forcing of XCs in the same manner as TCs, the current GPM-based approaches are unsuitable for the probabilistic

analysis of this storm population. As part of the NACCS, 100 XCs were identified from historical records and simulated using ADCIRC and STWAVE (Nadal-Caraballo et al. 2015), similar to the simulation of TCs. The EVA of XC hazards in the CHS-PF is performed using the StormSim-Probabilistic Simulation Technique (PST). The PST was developed to fit a generalized Pareto distribution (GPD) (Pickands 1975) to define the low-frequency tails of the hazard curve. PST utilizes observations or simulations from extreme storm events in the form of a partial duration series (PDS) to simulate multiple sequences or life cycles of storm activity and their corresponding responses. The GPD was selected according to extreme value theory for the analysis of PDS of extreme events (Coles 2001). The PST also employs a mean residual life (MRL) automated threshold detection method (Langousis et al. 2016) for objective selection of the GPD threshold parameter. The algorithm for the MRL method is as follows:

1. The PDS dataset, X , is sorted in ascending order and used as the initial set of values for the threshold θ .
2. For a given θ , a sample u is defined containing all values in X above the threshold ($X > \theta$). The arithmetic mean (ε) of these excesses is then computed for the sample:

$$\varepsilon = \frac{1}{n} \sum_{i=1}^n (u_i - \theta); i = 1, 2, \dots, n \quad (7-1)$$

where n is the sample size.

3. Assuming that the excesses are independent, a weight (ω) is also computed for the sample:

$$\omega = \frac{N-j}{\text{Var}(u-\theta)}, \quad (7-2)$$

in which N is the size of dataset X , and j is the rank of each value in the set of θ . Langousis et al. (2016) suggested repeating this step for up to $j = N - 10$ values of θ , to ensure a minimum sample size of $n = 10$ excesses for the computation of ε .

4. Next, a linear regression model is fitted to a subsample of the set (θ, ε) using the weighted least squares method and the weighted mean square error (WMSE) is computed as:

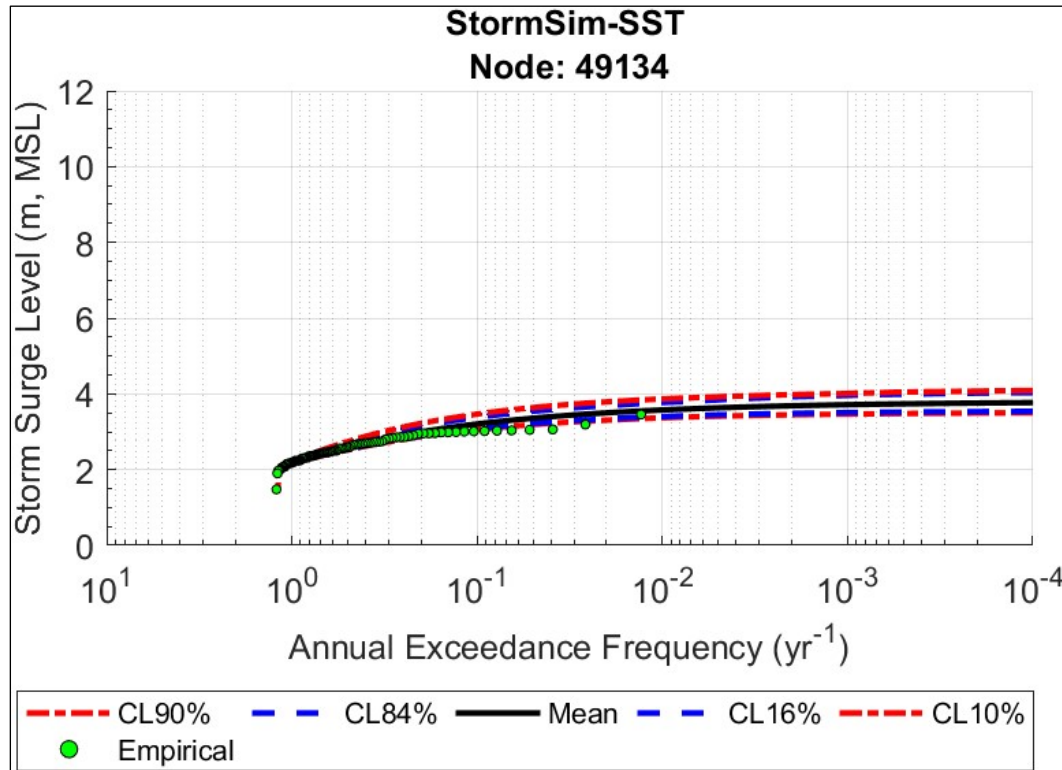
$$WMSE = \frac{1}{N_\theta} \sum_{i=1}^{N_\theta} \omega_i (\varepsilon_{p,i} - \varepsilon_i); i = 1, 2, \dots, N_\theta, \quad (7-3)$$

in which ε_p is the predicted excess, and N_θ is the subsample size. Langousis et al. (2016) suggested repeating this step for up to $j = N - 20$ subsamples of θ to ensure minimum sample size of $N_\theta = 10$ excesses for the linear fit.

5. The end result of this process is a third set of pairs $(\theta, WMSE)$ from which the threshold with minimum WMSE is selected as the parameter of the GPD.

The simulation results for surge and H_{mo} for each sea level change (SLC) condition simulated for the XCs were applied as input to the PST to characterize the SWL, SSL, and H_{mo} hazards produced by XCs within the study region. Below is a plot that illustrates the results of PST at a particular location, with the GPD best fit (black line) and confidence limits (blue and red lines) estimating the hazard at AEF values outside of the frequency range of the empirical (i.e., simulated) SSL data.

Figure 8.1. Illustration of StormSim-PST results at Boston CSRM node 49134 for surge, WOP. The empirical data (green dots) is plotted at Weibull plotting positions for comparison with the GPD-fitted hazard (black line) produced by the tool.



8.1.3 Combined Cyclone (CC) Hazards

The combined cyclone (CC) curves synthesize the probabilities and responses from the TCs and XCs into final hazard curve results. The probabilities of these two storm populations are combined, assuming independence, as follows:

$$P(CC) = P(TC) + P(XC) \quad (7-4)$$

where: $P(CC)$ = combined probability of a given response due to both TCs and XCs; $P(TC)$ = probability of a given response due to TCs; $P(XC)$ = probability of a given response due to XCs.

In the CHS-PF, the magnitude and frequency of T_p is characterized as a marginal probability distribution while preserving the physical dependence between T_p and H_{mo} through a conditional probability

distribution. In this approach, the T_p - H_{mo} relationship at each point location was modeled using a two-parameter power function (Chun and Suh 2018) with the form:

$$T_p = \alpha(H_{mo}^\beta) \quad (7-5)$$

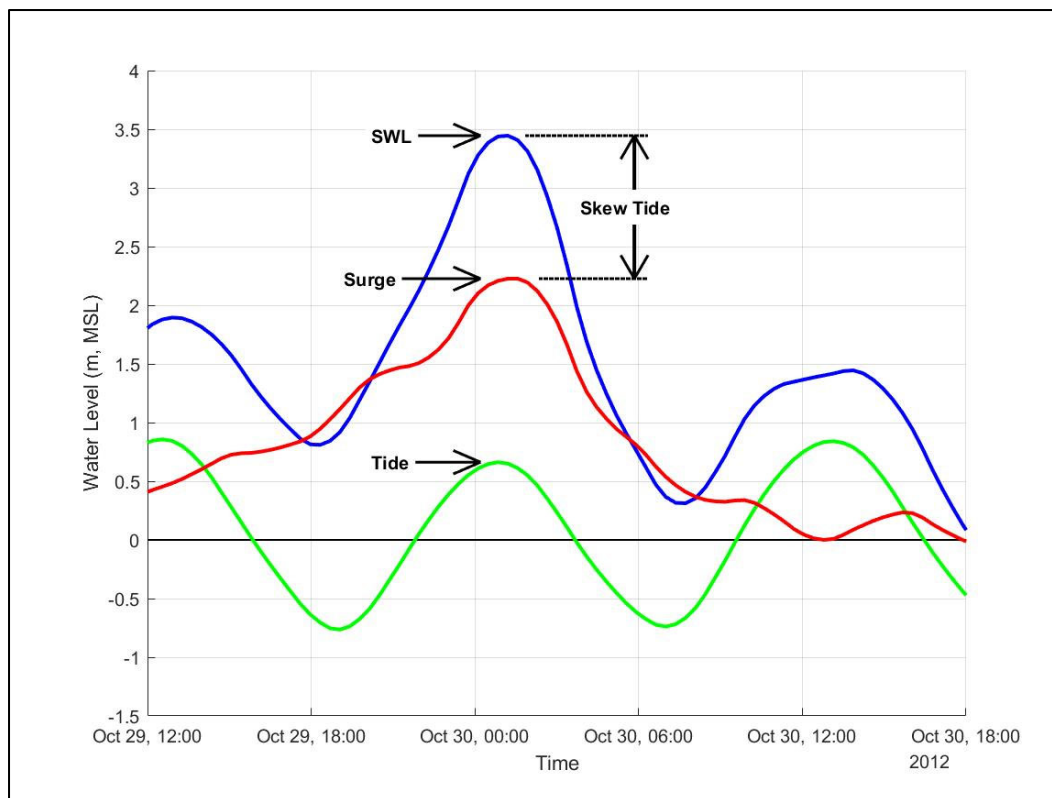
where coefficients α and β were estimated in this study with the least absolute residual robust linear least-squares fitting method. The power function was evaluated on the H_{mo} hazard curves to estimate the TC, XC, and CC hazards for T_p .

The T_p and H_{mo} hazard curves computed within the JPM and StormSim-PST processes are “marginal” hazards, since at any fixed AEF value, these hazards coincide with the SWL hazard when the correlation between SWL and H_{mo} is equal to 1. To properly compute the hazards when the correlation between SWL and H_{mo} is not 1, “conditional” hazard curves for T_p and H_{mo} are estimated where the H_{mo} is derived from a conditional probability distribution, that is, $P(H_{mo}|SWL)$. Nadal-Caraballo et al. (2022) expounds on the methodology of using the hydrodynamic results to fit the conditional distributions and then estimate the conditional hazard curves.

8.1.4 Astronomical Tides

The GPM methodology is capable of accurately and efficiently predicting the storm surge and wave responses for tens or hundreds of thousands of TCs, beyond those simulated in ADCIRC and STWAVE. The astronomical tide is a stochastic process that is uncorrelated to the TC parameters, and the current version of the GPM cannot replicate the behavior of the tides. As a result, tides must be added to the GPM predictions as a post-process by estimating the skew tide ($tide_{sk}$). The $tide_{sk}$ is computed as the difference between the with-tide (SLCo, Tides 2) and without-tide (SLC o, Tides o) surge response as simulated by ADCIRC. As shown in Figure 8.2, the $tide_{sk}$ is intended to capture the non-linear interaction between storm surge and the astronomical tide.

Figure 8.2. Idealized example of water level components.



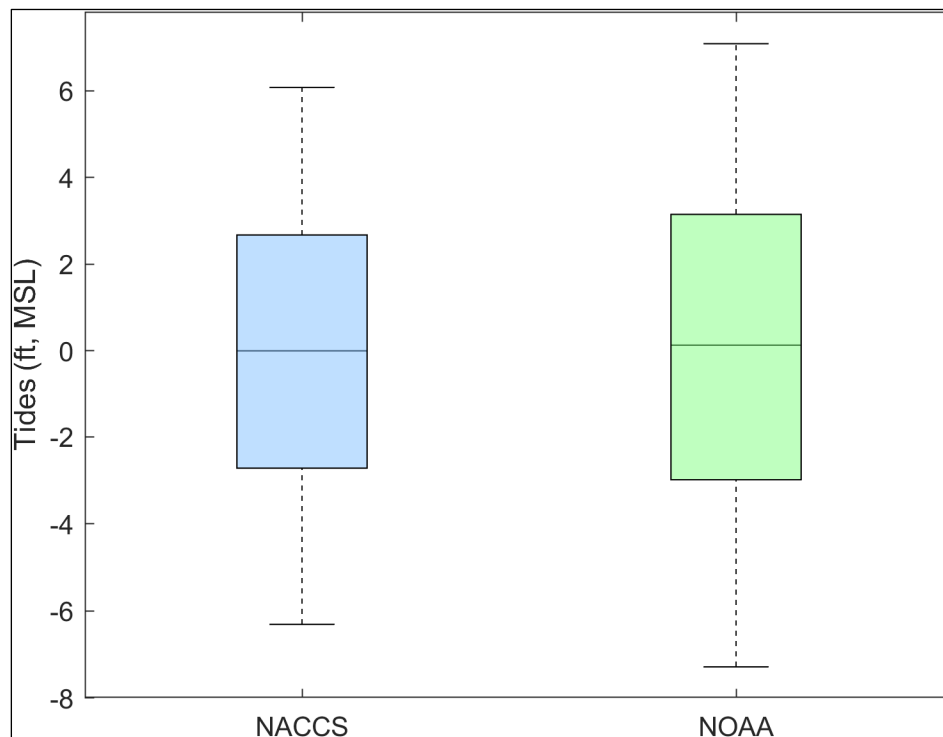
The following steps summarize the process of accounting for astronomical tides in the TC SWL hazard curves through the *tide_{sk}*:

1. Use the GPM to simulate the surge-only responses for the 1.2 million storms in the ATCS. Note that the surge-only predictions include wave effects, such as wave setup, but exclude tides.
2. To account for the tides, compute the difference between the with-tide and without-tide scenarios for storms simulated in ADCIRC. The remaining value is the *tide_{sk}*, which results from the random interaction between storm surge and astronomical tides and tends to be negatively correlated with the surge.
3. Fit a cubic regression model to the *tide_{sk}* and storm surge pairs at each of the nodes.
4. Predict a random *tide_{sk}* for each storm in the ATCS using the regression model.

5. Superimpose the predicted $tide_{sk}$ on the storm surge responses estimated for the ATCS for developing the SWL hazard curves.

This approach for incorporating the tide into the hazard curves is also applied for the TC H_{mo} responses to appropriately account for non-linear effects on the wave hazards. A similar approach is applied for estimating the $tide_{sk}$ associated with the SWL and H_{mo} responses when computing the XC hazards as further discussed in Section 7.4. While the $tide_{sk}$ methodology for the TCs is meant to reconstruct the tidal influence for the synthetic storms, the $tide_{sk}$ methods for the XCs cover most of the observed tidal record from 1937-2014. Figure 7-3 illustrates how the tidal record during the 100 NACCS XCs at savepoint 9584 covers the majority of the XC tidal range at the NOAA Tides and Currents gauge 8443970 (Boston, MA).

Figure 8.3. A boxplot comparison of the tidal values from the 100 NACCS XC runs (blue box) and the predicted tides at NOAA station 8443970 (green box). The NOAA data only includes hourly tidal timeseries during the XC season (October - April) from the period of record 1937-2014.



The interquartile range (IQR) of the tides simulated from the NACCS XCs covers about 88% of the IQR of the tides predicted during the XC season at the NOAA station 8443970.

8.1.5 Error Estimation

As part of the JPM, estimating error is an important step to identify differences in observed versus modeled processes and to support model calibration. The estimation of bias (systematic error) and uncertainty (spread) associated with the meteorological and hydrodynamic numerical modeling was completed for the NACCS study by simulating historical TCs and comparing the predicted responses to observed high water marks. The bias and uncertainty can be estimated in terms of absolute and relative components. The validation storms considered for the NACCS numerical models were Hurricanes Sandy, Irene, Isabel, Josephine, and Gloria (Cialone et al. 2015). In the JPM approach, it has been typically assumed that the error is unbiased, and the uncertainty has been addressed by using an error term within the JPM integral. Bias correction is required before the JPM integration if non-negligible bias is identified in the assessment of model error. Generally, errors in water level and wave hazards are evaluated by comparing the validation storm simulation results to observations. Given that a validation effort including the simulation of historical storm events was not completed for this study, the CHS-NA bias and uncertainty values were leveraged for developing evaluating uncertainty within the Boston CSRM domain.

To estimate water level hazards, the numerical modeling bias and uncertainty associated with the ADCIRC and PBL models were computed using a spatially-varying approach to estimate the error on a point-specific basis. As a result, 2D surfaces of the bias and uncertainty were estimated to support the quantification of the water level hazards for the updated CHS-NA hazard curves. However, limited observation data was available to support the estimation of bias for the wave model meaning that only a global uncertainty was computed for the waves.

8.1.5.1 Bias Estimation and Correction

Following the CHS-PF methods outlined in Yawn et al. (2024), the absolute and relative components of the bias can be combined to limit either overestimation or underestimation of the uncertainty as:

$$\mu_c = \frac{\mu_{a_{Total}}}{\|\mu_{a_{Total}}\|} \frac{1}{\sqrt{\frac{1}{\mu_{a_{Total}}^2} + \frac{1}{(\mu_{r_{Total}} \cdot \tau)^2}}}, \quad (7-6)$$

where μ_c = total combined bias (m); $\mu_{a_{Total}}$ = total absolute model bias (m); $\mu_{r_{Total}}$ = total relative model bias (m/m). Note that differently from Equation (6-1b), a non-dimensional factor $\frac{\mu_{a_{Total}}}{\|\mu_{a_{Total}}\|}$ is incorporated into Equation (6-2) to retain the sign of the bias, which is necessary for the bias correction before estimating uncertainty.

Here the “total” nomenclature represents the combination of multiple sources of the error, such as the ADCIRC and planetary boundary layer (PBL) models, which is necessary for estimating error associated with water levels. However, for the wave responses, only the wave model is accounted for in these error approximations.

This dimensional bias is referred to as the weighted absolute form of the bias (μ_a) and is defined as follows:

$$\mu_a = \frac{\sum_{i=1}^N w_i (\varepsilon_a)_i}{\sum_{i=1}^N w_i} = \frac{\sum_{i=1}^N w_i (\tau_{sim} - \tau_{obs})_i}{\sum_{i=1}^N w_i}, \quad (7-7)$$

where $(\varepsilon_a)_i$ = absolute model error (meters); $(\tau_{sim} - \tau_{obs})_i$ = simulated storm response (meters) minus observed response (meters); w_i = weight assigned to each error value i based on the GKF Equation ; N = is the number of simulation-observation pairs considered in model validation. For this application of the GKF equation, d_i was computed as the distance from a virtual gauge (VG) to each validation data point. A positive bias indicates overprediction of the observations by the numerical model, whereas a negative bias represents underprediction of the observations.

Bias that varies as a function of hydrodynamic response magnitude is considered to be a weighted relative bias (μ_r). This form of bias is estimated by normalizing each simulated-observed difference by the simulated value:

$$\mu_r = \frac{\sum_{i=1}^N w_i (\varepsilon_r / \tau_{sim})_i}{\sum_{i=1}^N w_i} = \frac{\sum_{i=1}^N w_i [(\tau_{sim} - \tau_{obs}) / \tau_{sim}]_i}{\sum_{i=1}^N w_i}, \quad (7-8)$$

where ε_r = relative model error (meters/meters). In the CHS-PF, both the geospatial bias and uncertainty are estimated by applying a Gaussian kernel surface (GKS). The GKS method takes advantage of the available validation information to characterize the local variability of numerical model biases within the study area. Evidence-based correction of these biases, even when considering a small subset of storms, is crucial to avoid underestimation of coastal hazards and risk. The data assimilation approach utilized to perform bias correction minimizes the potential for overcorrection in relation to the development of the storm response hazard curves.

This method results in 2D surfaces of the relative and absolute forms of bias and uncertainty for the study area. These quantities' relative and absolute forms are later combined to create 2D surfaces of total bias and uncertainty, respectively. The GKS approach was applied to create 2D surfaces of the biases introduced by the ADCIRC and PBL models covering all VGs considered in this study. In this approach, weights are assigned to each validation data point. From the perspective of each VG, the weights in Equations (7-7) and (7-8) were assigned to the validation data points based on their distance from the VG.

The GKS method for bias leads to the generation of four 2D bias surfaces: (1) ADCIRC absolute bias, (2) ADCIRC relative bias, (3) PBL absolute bias, and (4) PBL relative bias. The next step in this process is to aggregate the absolute forms of the ADCIRC and PBL biases and, separately, aggregate the relative forms of these model biases, resulting in two new quantities: total absolute model bias and total relative model bias. The same workflow is also later implemented for estimating geospatial uncertainty. The total absolute bias and total relative model bias are computed for each node as the summation of individual model biases (e.g., ADCIRC, PBL):

$$\mu_{aTotal} = \mu_{a_1} + \mu_{a_2} + \dots + \mu_{a_n} \quad (7-9a)$$

$$\mu_{rTotal} = \mu_{r_1} + \mu_{r_2} + \dots + \mu_{r_n}, \quad (7-9b)$$

where μ_{aTotal} = total absolute model bias (meters) and μ_{rTotal} = total relative model bias (meters/meters).

8.1.5.2 Uncertainty Quantification

Similarly, the uncertainty can be estimated based on separate relative and absolute components using:

$$\sigma_c = \frac{1}{\sqrt{\frac{1}{\sigma_{aTotal}^2} + \frac{1}{(\sigma_{rTotal} \cdot \tau)^2}}}, \quad (7-10)$$

where: σ_c = total combined uncertainty (m); σ_{aTotal} = total absolute model uncertainty (m); σ_{rTotal} = total relative model uncertainty (m/m); and τ = storm response (e.g., SWL, H_{mo}).

Numerical model uncertainty is estimated based on three assumptions routinely made in JPM-based studies: (1) the uncertainty terms are independent; (2) their effects can be combined by addition, and (3) the aggregated uncertainties can be represented as a Gaussian distribution with a mean of zero. After quantifying and correcting any bias, two forms of model uncertainty are evaluated: (1) absolute, which retains the dimensions of the hydrodynamic responses and (2) relative, which is a non-dimensional quantity.

The weighted absolute form of the uncertainty (σ_a) and the relative form (σ_r) are estimated through the following equations:

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^n w_i (\varepsilon_a)_i^2}{(n-1) \sum_{i=1}^n w_i}} = \sqrt{\frac{\sum_{i=1}^n w_i (\tau_{sim} - \tau_{obs})_i^2}{(n-1) \sum_{i=1}^n w_i}} \quad (7-11)$$

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^N w_i (\varepsilon_a / \tau_{sim})_i^2}{\frac{(N-1)}{N} \sum_{i=1}^N w_i}} = \sqrt{\frac{\sum_{i=1}^n w_i [(\tau_{sim} - \tau_{obs}) / \tau_{sim}]_i^2}{\frac{(N-1)}{N} \sum_{i=1}^N w_i}} \quad (7-12)$$

The application of the GKS method also results in the generation of four 2D uncertainty surfaces for storm surge: (1) ADCIRC absolute uncertainty; (2) ADCIRC relative uncertainty; (3) PBL absolute uncertainty; and (4) PBL relative uncertainty. The next step in this process is to aggregate the absolute forms of the ADCIRC and PBL uncertainties and, separately, aggregate the relative forms of these model uncertainties. Similar to the case of bias, this approach results in two new quantities: total absolute model uncertainty and total relative model uncertainty. The total absolute and relative uncertainties for each node are estimated as the summation of individual numerical model uncertainties:

$$\sigma_{a_{Total}} = \sqrt{(\sigma_{a_1})^2 + (\sigma_{a_2})^2 + \dots + (\sigma_{a_n})^2} \quad (7-13a)$$

$$\sigma_{r_{Total}} = \sqrt{(\sigma_{r_1})^2 + (\sigma_{r_2})^2 + \dots + (\sigma_{r_n})^2} \quad (7-13b)$$

where: $\sigma_{a_{Total}}$ = total absolute model uncertainty (m) and $\sigma_{r_{Total}}$ = total relative model uncertainty (m/m). The $\sigma_{a_{Total}}$ and $\sigma_{r_{Total}}$ are then input into Equation 7-10 to estimate a total combined uncertainty (σ_c) for each VG in the CHS-SA study area.

In the case of H_{mo} , only a global uncertainty value is estimated. The absolute (σ_a) and relative (σ_r) forms of the STWAVE uncertainty are determined as follows:

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^N (\varepsilon_a)_i^2}{N-1}} = \sqrt{\frac{\sum_{i=1}^N (\tau_{sim} - \tau_{obs})_i^2}{N-1}} \quad (7-14)$$

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^N (\varepsilon_a / \tau_{sim})_i^2}{N-1}} = \sqrt{\frac{\sum_{i=1}^N [(\tau_{sim} - \tau_{obs}) / \tau_{sim}]_i^2}{N-1}}. \quad (7-15)$$

By taking the average σ_a and σ_r across all validation points i , the uncertainties are input into Equation 7-10 to estimate the global STWAVE uncertainty used to compute the CLs for the H_{mo} hazard curves.

8.2 CSRM Hazard Curve Development

As mentioned previously, relying solely on the RSS developed for this study to construct the Boston CSRM hazard results would result in uncertainties due to the limited number of storms supporting the analysis. Therefore, metamodeling and regression techniques are useful tools for informing relationships between the CHS-NA and Boston storm simulations to understand how the various WOP conditions will influence the updated hazard curves. This study leveraged the CHS-NA GPMs while employing additional regression techniques to support the analysis of the WOP conditions at each node within the Boston CSRM study area. Methods regarding the use of metamodeling and regression techniques, which had been used in previous CSRM studies, were evaluated, compared, and implemented within the CHS-PF to incorporate the CSRM simulations and ultimately compute the TC, XC, and CC hazard curves for WOP conditions across the Boston domain. Different methods were applied to quantify TC versus XC hazard curves as part of the Boston CSRM, which are documented in the following section.

For the TCs, the methodology for constructing the SWL CSRM hazard curves, regardless of project conditions or SLC scenario, can be generalized in the following five-step procedure:

1. Employ the CHS-NA storm surge GPM to compute the storm responses for the approximately 1.2 M storms in the CHS-NA ATCS.
2. Apply a delta GPM to estimate the differences in storm surge due to the specific CSRM project condition and SLC scenario. Add the differences to the CHS-NA ATCS responses to compute the Boston CSRM surge for the ATCS.
3. Bias correct the CSRM responses. For the SWL and H_{mo} responses, linearly superimpose the astronomical tide using the same approaches employed in the CHS-NA (Section 7.1.4).
4. Develop the TC hazard curves using the JPM integration methodology.

The methodology for constructing the same hazard curves for the XCs, regardless of project conditions or SLC scenario, can be generalized in the four steps below:

1. Apply delta Gaussian process regression (GPR) models to estimate the difference in storm surge due to the specific CSRM project condition and SLC scenario. Add the differences to the CHS-NA XC responses to compute the Boston CSRM storm surge level.
2. Apply delta GPR models to estimate the difference in still water level due to the specific CSRM project condition and SLC scenario. Add the differences to the CHS-NA XC responses to compute the Boston CSRM still water level.
3. Using the Boston SSL and SWL responses as inputs, fit the skew tide models using the approaches employed in the CHS-NA.
4. Develop the XC hazard curves using the StormSim-PST methodology.

Several of these steps in creating the TC and XC hazard curves are elaborated upon in the proceeding sections.

8.3 Delta Metamodel Training for the Tropical Cyclones (TCs)

A GPM was trained to reconstruct delta (Δ) values, that is, the point-by-point differences in the responses between the Boston CSRM simulations and the original CHS-NA results for the 60-TC RSS. For the SSL data, two sets of deltas were computed by subtracting the response values of the CHS-NA storms from the corresponding CSRM responses at the 60 storm simulations. The deltas are denoted using the equations below:

$$\Delta_{SSL,WOP,slc0} = SSL_{CSRM,WOP,slc0} - SSL_{CHL-NA,WOP,slc0} \quad (7-16)$$

$$\Delta_{SSL,WOP,slc1} = SSL_{CSRM,WOP,slc1} - SSL_{CHL-NA,WOP,slc1} \quad (7-17)$$

The delta metamodels were trained where the output arrays were the delta matrices for SLC0 and SLC1, respectively, and the input array was the TC atmospheric forcing storm parameters for the 60 CRSM simulations. These parameters include central pressure deficit, translational speed, heading, and radius of maximum wind. The GPMs were implemented to compute the slc0 and slc1 storm responses for the approximately 1.2 M storms in the CHS-NA ATCS where the output represented SSL specific to the Boston CSRM WOP conditions. For estimating the SWL and H_{mo} hazards, the skew tides were estimated for the Boston CSRM ATCS data

and then linearly superimposed upon the storm responses data prior to the JPM integration.

8.4 Delta Reconstruction with Gaussian Process Regression Models

GPR Models were trained to reconstruct delta (Δ) values, that is, the point-by-point differences in the responses between the CSRM simulations and the original CHS-NA results for the 17-XC RSS. For the SSL and SWL data, two sets of deltas were computed by subtracting the response values of the CHS-NA storms from the corresponding CSRM responses at the 17 storm simulations. The deltas are denoted by equations 7-18 through 7-21:

$$\Delta_{SSL,WOP,slc0} = SSL_{CSRM,WOP,slc0} - SSL_{CHL-NA,WOP,slc0} \quad (7-18)$$

$$\Delta_{SSL,WOP,slc1} = SSL_{CSRM,WOP,slc1} - SSL_{CHL-NA,WOP,slc1} \quad (7-19)$$

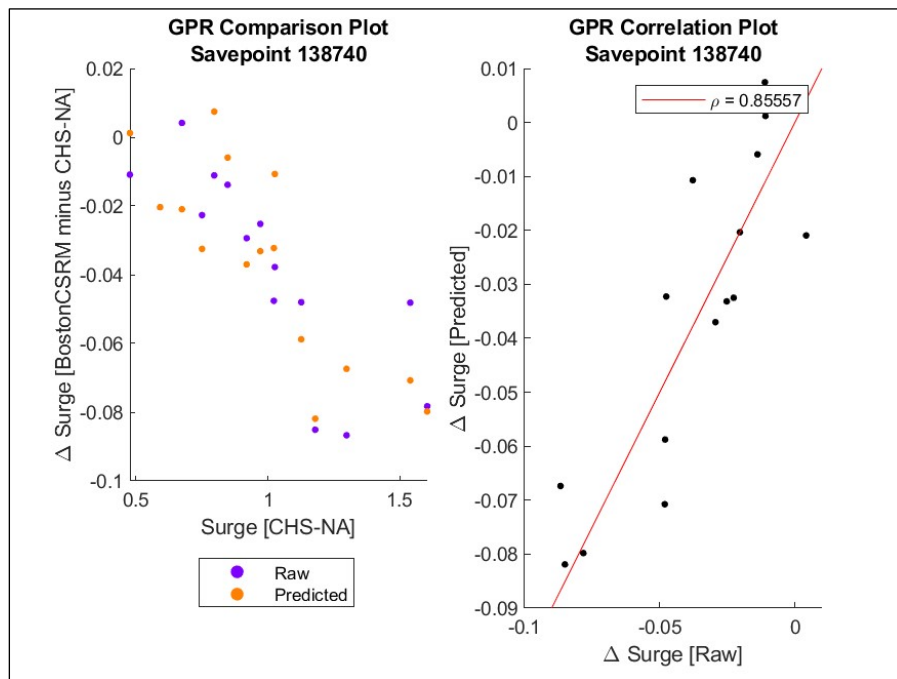
$$\Delta_{SWL,WOP,slc0} = SWL_{CSRM,WOP,slc0} - SWL_{CHL-NA,WOP,slc0} \quad (7-20)$$

$$\Delta_{SWL,WOP,slc1} = SWL_{CSRM,WOP,slc1} - SWL_{CHL-NA,WOP,slc1} \quad (7-21)$$

Four sets of regression models were developed where the response variable was the delta matrix and the predictor was the subtrahend of the delta, that is, either $SSL_{CHL-NA,WOP,slc}$ or $SWL_{CHL-NA,WOP,slc}$. The GPR model was chosen to fit the CHS-NA results to the deltas due to its advantages over simpler fits, such as linear regression. Namely, the non-parametric GPR model can capture more variability in a broader range of data than the dual-parameterized or slope-only linear regression, resulting in more accurate predictions of the response. The plot below demonstrates the robustness of the GPR fit at a node with high variability between the SSL and delta pairs (Figure 7-4).

Figure 8.4. The fitting of a GPR at location 138740 for surge and delta at the WOP condition. The subplot to the left compares the observed surge to both the delta

values observed from the CSRM results and the deltas predicted by the GPR model. The subplot to the right is a correlation plot between observed and predicted deltas.



For each set of deltas, a GPR model was trained with numerical optimization strategies (Rasmussen and Williams 2006) at each of the 173,364 nodes in the Boston CSRM study where there were at least 2 observations (e.g., 2 of the 17 storm simulations had valid response data for both the original CHS-NA and the CSRM simulations). Nodes where there were less than two data points were not kept in the analysis. Once the GPR regressions were established for each of the four delta cases (Equations 7-18 through 7-21), the delta values could be estimated given the responses produced by the 100 CHS-NA XCs. The CSRM realizations for all 100 CHS-NA XCs, for each variable and SLC condition, were estimated by subtracting the deltas from the CHS-NA responses. This new data was the input for the StormSim-PST procedure, which synthesized the data and the tidal models to compute the XC hazard curves for the Boston CSRM domain as follows:

1. A cubic regression model was fit with the $tide_{sk}$ computed as the difference between XC simulation results with-tides and without-tides. This approach enabled the tool to randomly include the effects of the

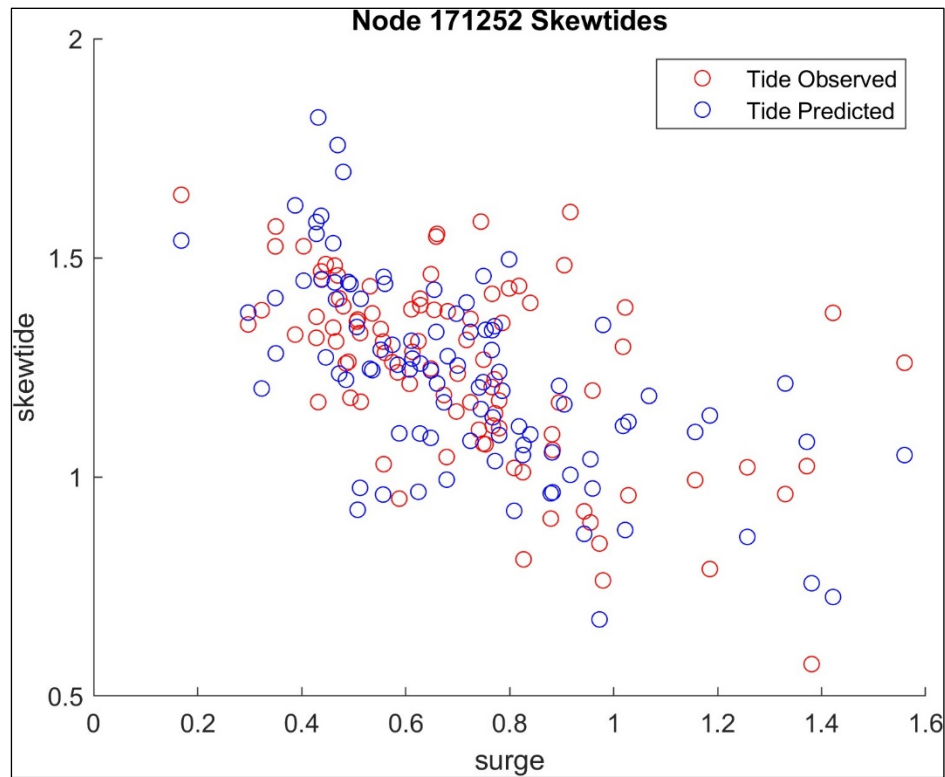
- $tide_{sk}$ by superimposing them in the POT dataset of XC responses without-tides.
2. By incorporating the regression model into the PST tool, a second set of POT values was provided for the replacement of the empirical distribution of peaks without-tides. This is usually done for simulation responses under the scenario of SLC 0, Tides 0, where simulation output is available with- and without-tides. The replacement of peak values with those including the effects of tides in the simulation allows for an equitable comparison of the peaks with the $tide_{sk}$.
 3. The PST processes the input using a bootstrap process of 1,000 iterations, in which both the $tide_{sk}$ and the SLC1 offset are also added to each random sample of the data.
 4. A GPD was fit to each random sample and the shape parameter values collected for assessment of the PST performance. Outlier shape parameter values result from the bootstrapping process. An outlier is considered here to be any value more than 3 standard deviations from the mean. To mitigate this situation, any outlier identified is replaced with the center value of the shape parameter.
 5. The tool estimated the threshold parameter of the GPD through the MRL methodology described in Section 6.4 of Yawn et al. (2024). This objective selection process considered different possible threshold values based on the input POT dataset. The hazard was estimated after selecting the threshold value and comparing the values. The criteria considered were the following:
 - a. Selection of a threshold that corresponds to the annual rate closest to two storms/yr.
 - b. Selection of the threshold parameter with the minimum weighted mean square error (WMSE; see Langousis et al. 2016).

For this study, the PST was executed with both threshold selection options, and the resulting hazard curves were compared at dozens of VGs. The threshold criterion that yields an annual rate closer to 2 storms/yr was selected for this study.

For the XCs, the 17-storm RSS for the Boston CSRM was deemed to have too few events for precise $tide_{sk}$ estimation. The CSRM realizations for all 100 CHS-NA XCs, as computed with the delta GPR models, was used in the place of the XC RSS, and $tide_{sk}$ was calculated for each storm. An

example of the cubic regression computed with the XC data is illustrated in Figure 7-5.

Figure 8.5. Illustration of skew tide reconstruction at Boston CSRM location 171252 for the XC, SLC0, WOP condition. The red circles indicate the surge and actual skew tide pairs computed from the ADCIRC simulations, while the blue circles indicate the pairs of surge and skew tide predicted from the fitted cubic regression model.



8.5 Hazard Quantification for the Boston CSRM

For this study, updated hazard curves were developed for present day and future conditions to describe wave and water levels as a function an AEF. An important part of estimating hazards is quantifying errors using confidence limits that bound the mean or best estimate (BE) curve. Using the bias estimates described in Section 7.1.5, it is standard practice to represent uncertainty as a Gaussian distribution process with mean zero (Resio et al. 2007; Toro 2008; FEMA 2012). Therefore, the storm responses were bias corrected prior to estimating the uncertainty as part of the CHS-NA, and confidence limit CL curves were computed using the following equation:

$$CL = \bar{\tau} + z\sigma_c, \quad (7-22)$$

where CL = confidence limit; $\bar{\tau}$ = mean value of a given TC response τ ; z = Z-score or number of standard deviations the CL is above $\bar{\tau}$; and σ_c = total combined model uncertainty associated with τ . This study considered CLs of 10%, 16%, 84%, and 90%. The spatial variation in the hazards is illuminated below in the 2D surface plots of the best-estimate SWL, H_{mo} , and T_p and hazards at the 0.01 (1/100 year) AEF.

Figure 8.6. SWL hazard at the 0.01 AEF for Combined Cyclones across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC0 condition.

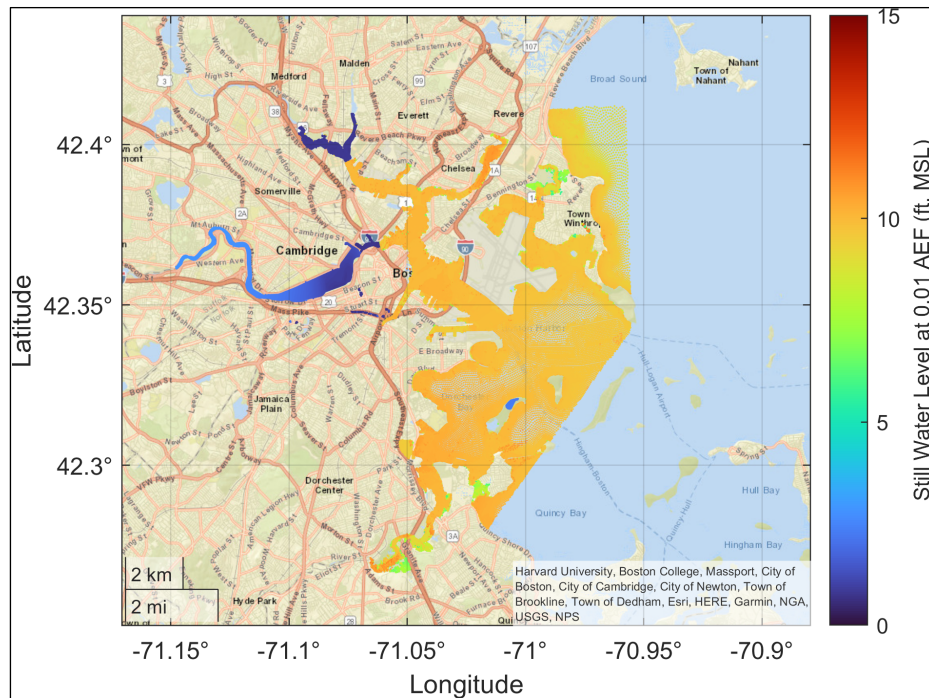


Figure 8.7. SWL hazard at the 0.01 AEF for Tropical Cyclones across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC0 condition.

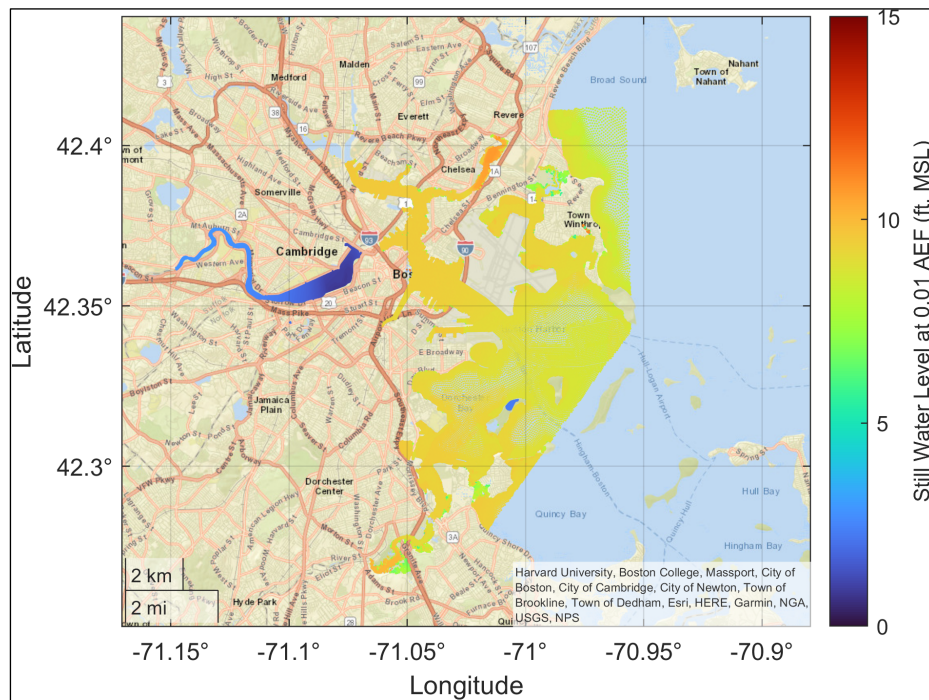


Figure 8.8. SWL hazard at the 0.01 AEF for Extratropical Cyclones across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC0 condition.

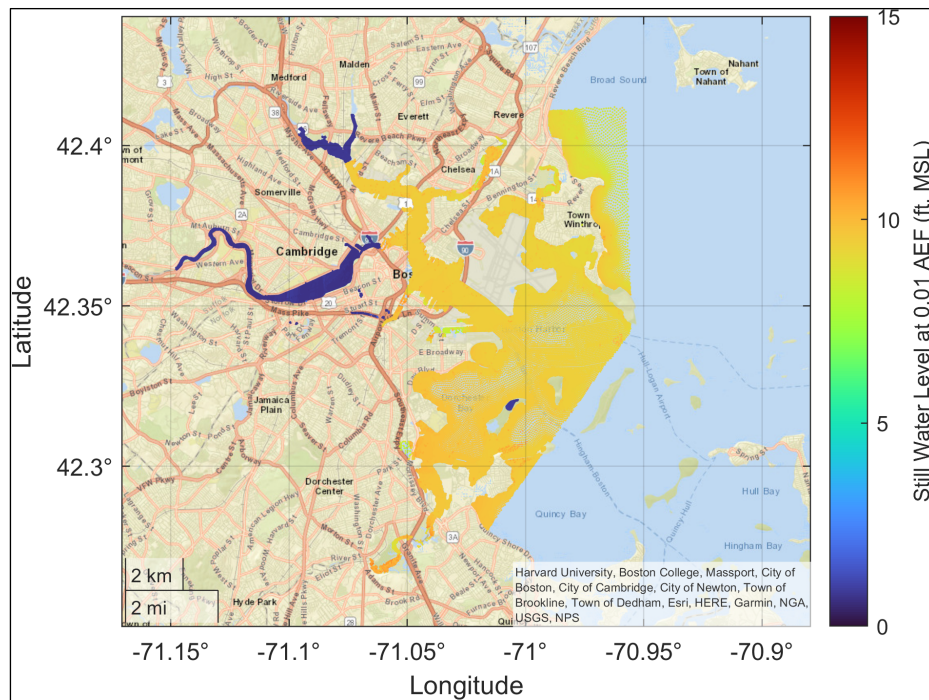


Figure 8.9. SWL hazard at the 0.01 AEF for Combined Cyclones across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC1 condition.

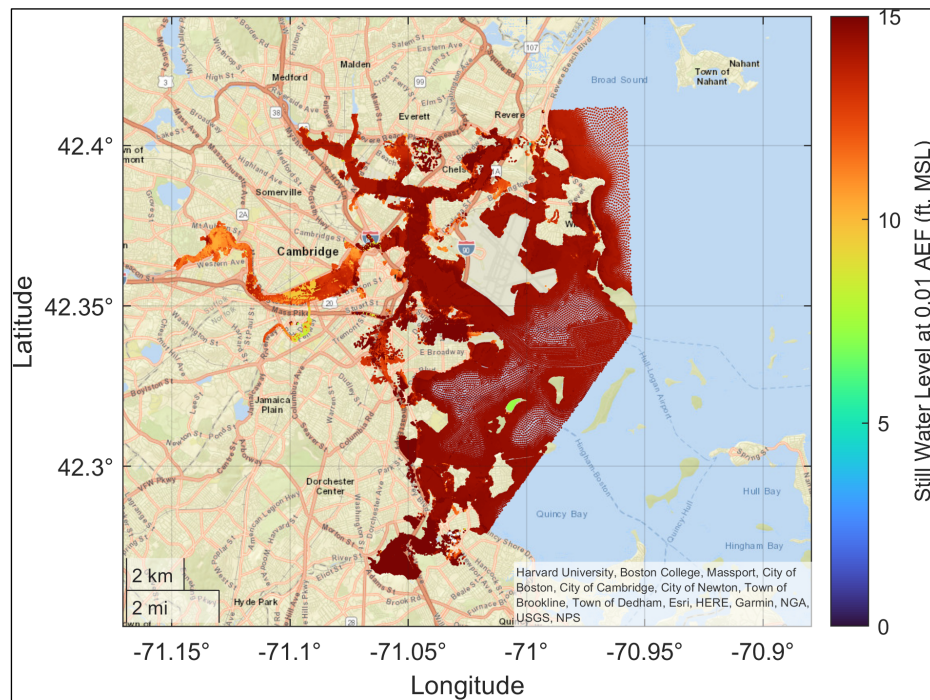


Figure 8.10. SWL hazard at the 0.01 AEF for Tropical Cyclones across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC1 condition.

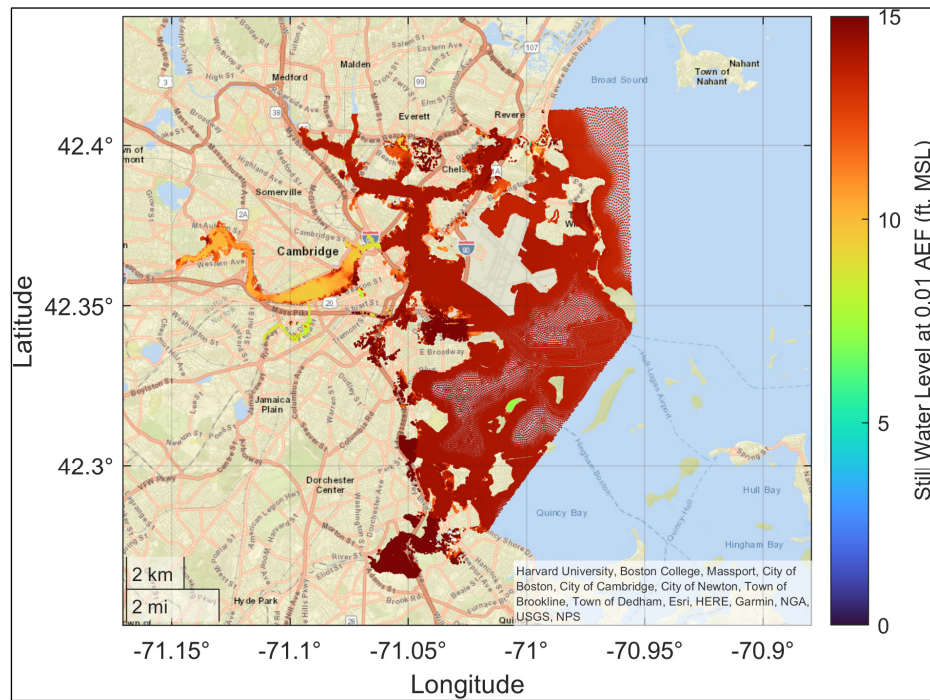


Figure 8.11. SWL hazard at the 0.01 AEF for Extratropical Cyclones across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC1 condition.

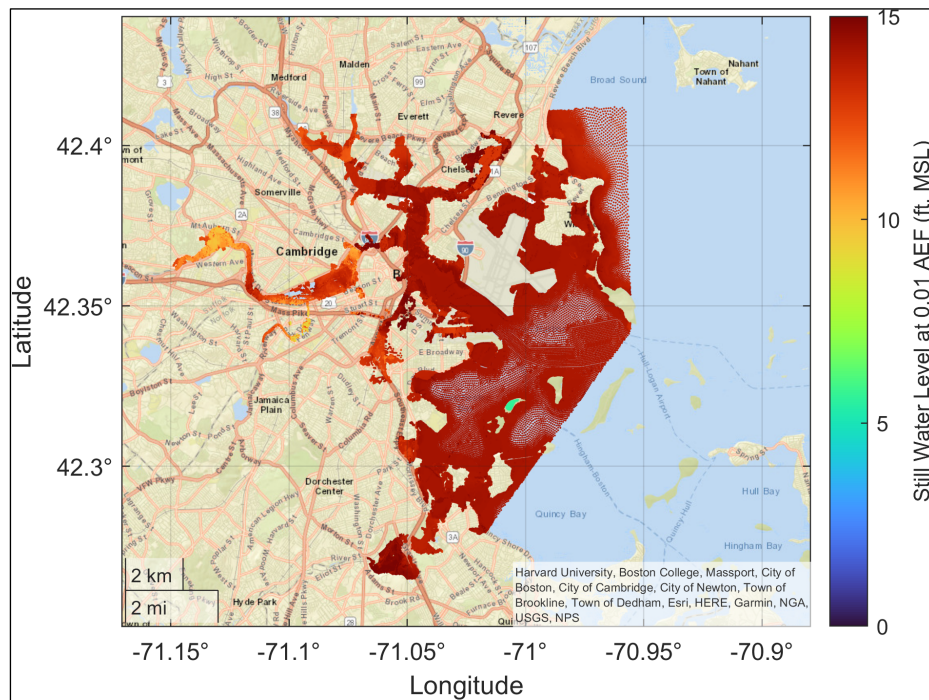


Figure 8.12. H_{m0} hazard at the 0.01 AEF for Combined Cyclones at save points across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC0 condition.

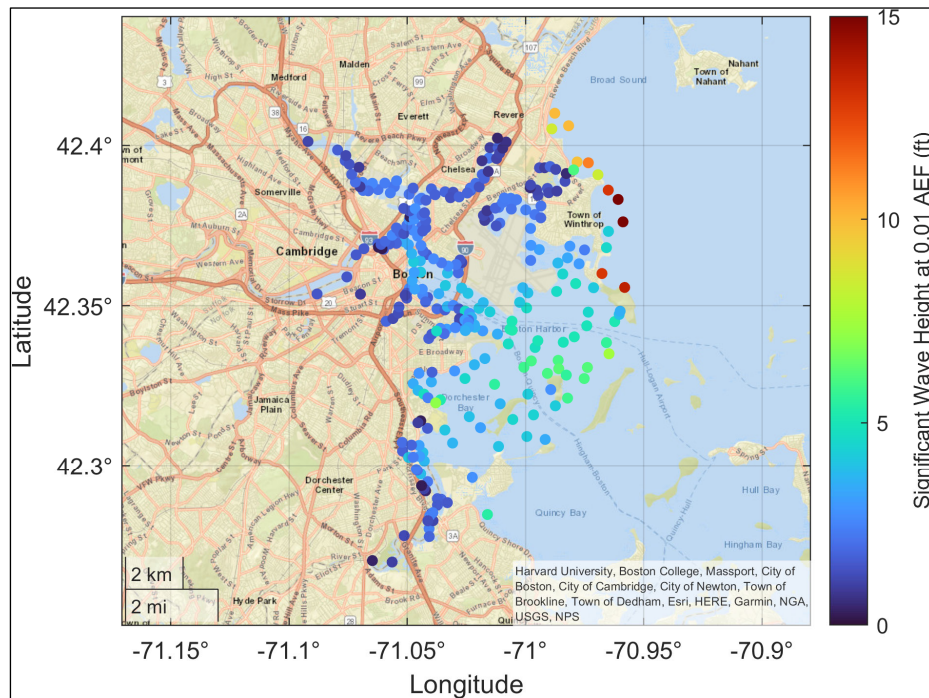


Figure 8.13. H_{m0} hazard at the 0.01 AEF for Combined Cyclones at save points across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC1 condition.

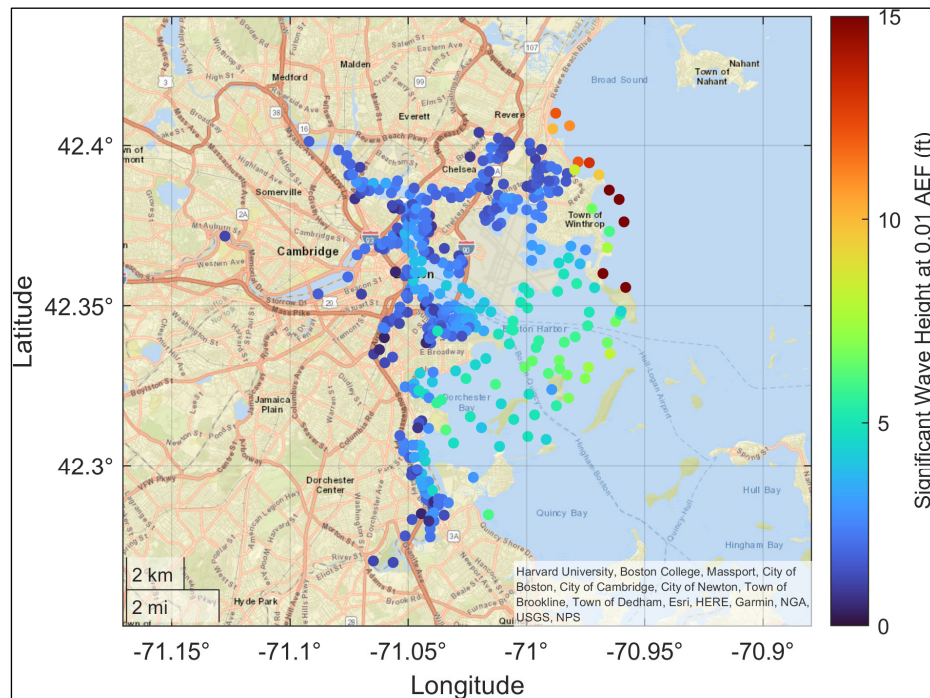


Figure 8.14. T_p hazard at the 0.01 AEF for Combined Cyclones at save points across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC0 condition.

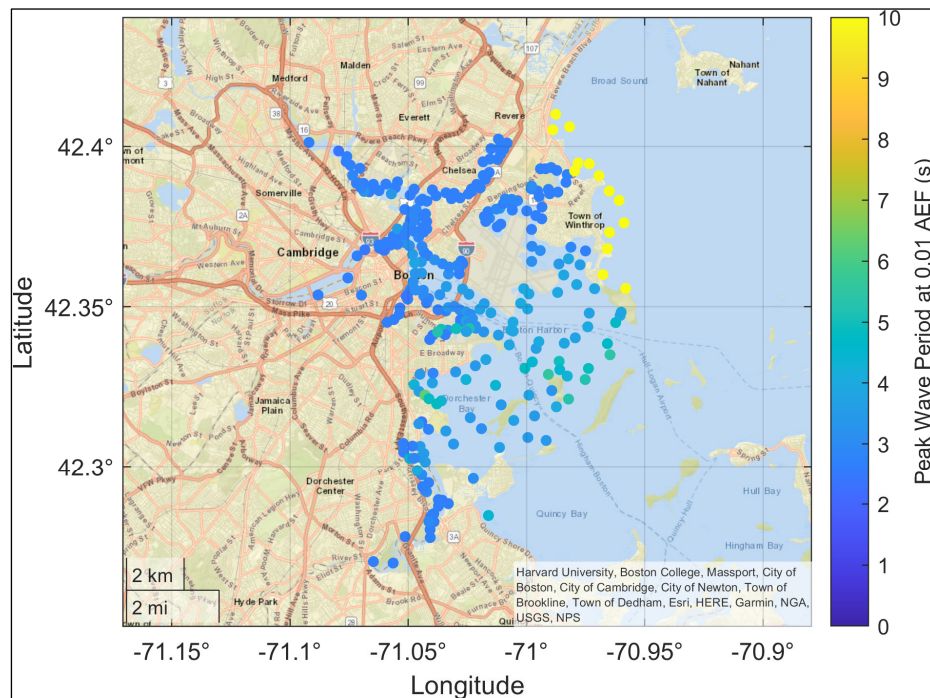
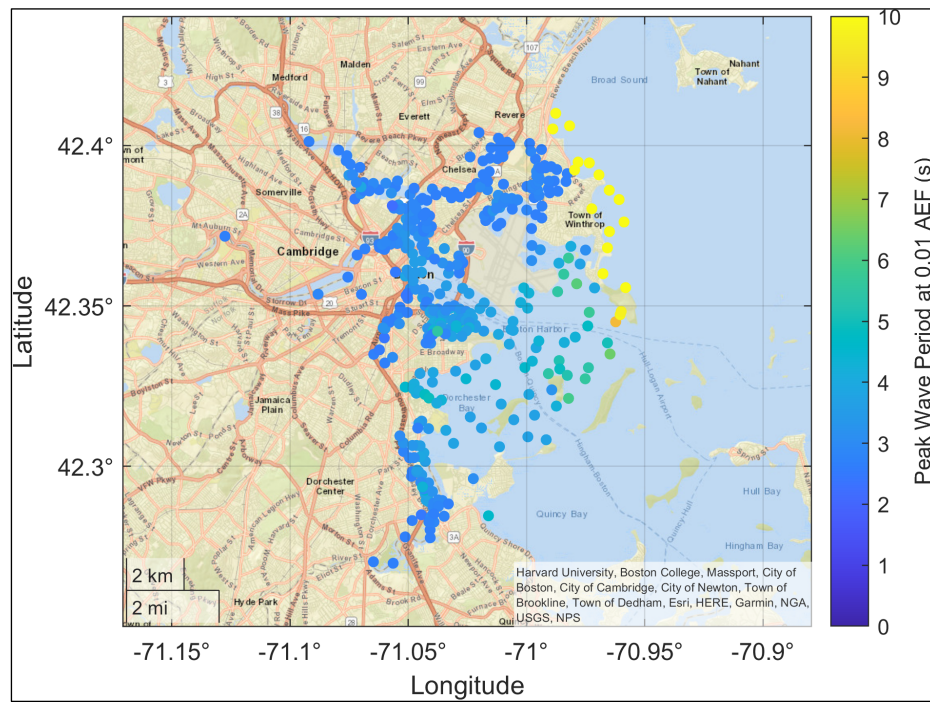


Figure 8.15. T_p hazard at the 0.01 AEF for Combined Cyclones at save points across the Boston CSRM domain. This hazard map corresponds to the WOP, SLC1 condition.



9 Conclusions

This report discusses the analysis conducted by the ERDC-CHL for the Boston CSRM study. Presented are the results for the initial numerical modeling for storm surge and waves along with the statistical calculations for without-project conditions only. With-project modeling and results have not been conducted at this point of the study. Details are presented on the setup of the ADCIRC and STWAVE model domains that leverage the NACCS. Details are provided on how representative storms were selected to represent the NACCS hazard curves for water levels in the Boston, MA area. As such 60 synthetic tropical storms (TC) were selected along with 17 historical extratropical storms (XC). A limited reexamination of the modeling calibration after performing mesh updates is presented for 17 historical extratropical events, which shows across the board good agreement with modeled versus measured water levels at the NOAA tides and currents gauge in Boston, MA. The average difference between measured and modeled maximum water levels for all 17 storms was 0.16 meters, just over one-half a foot. It is noted that only one gauge is available for the study area to make such comparisons. There are no nearshore wave measurements in the Boston, MA area in order to make comparisons with the model wave results. Thus, due to the similarity in the STWAVE model setups, the same order of accuracy is assumed for waves as those reported in the NACCS, which suffered from the same lack of nearshore wave measurement data. Modeling inputs for the Generation Two Coastal Risk Model (G2CRM) in the form of h5 files were also generated.

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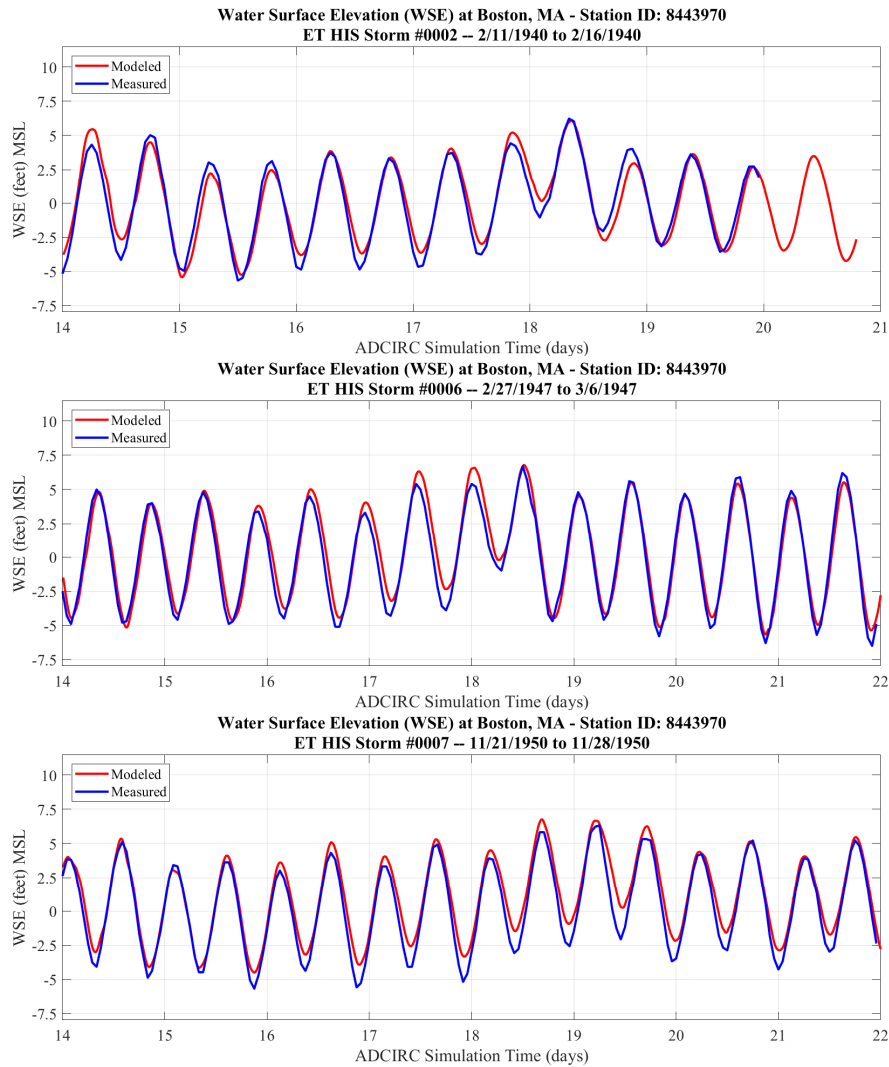
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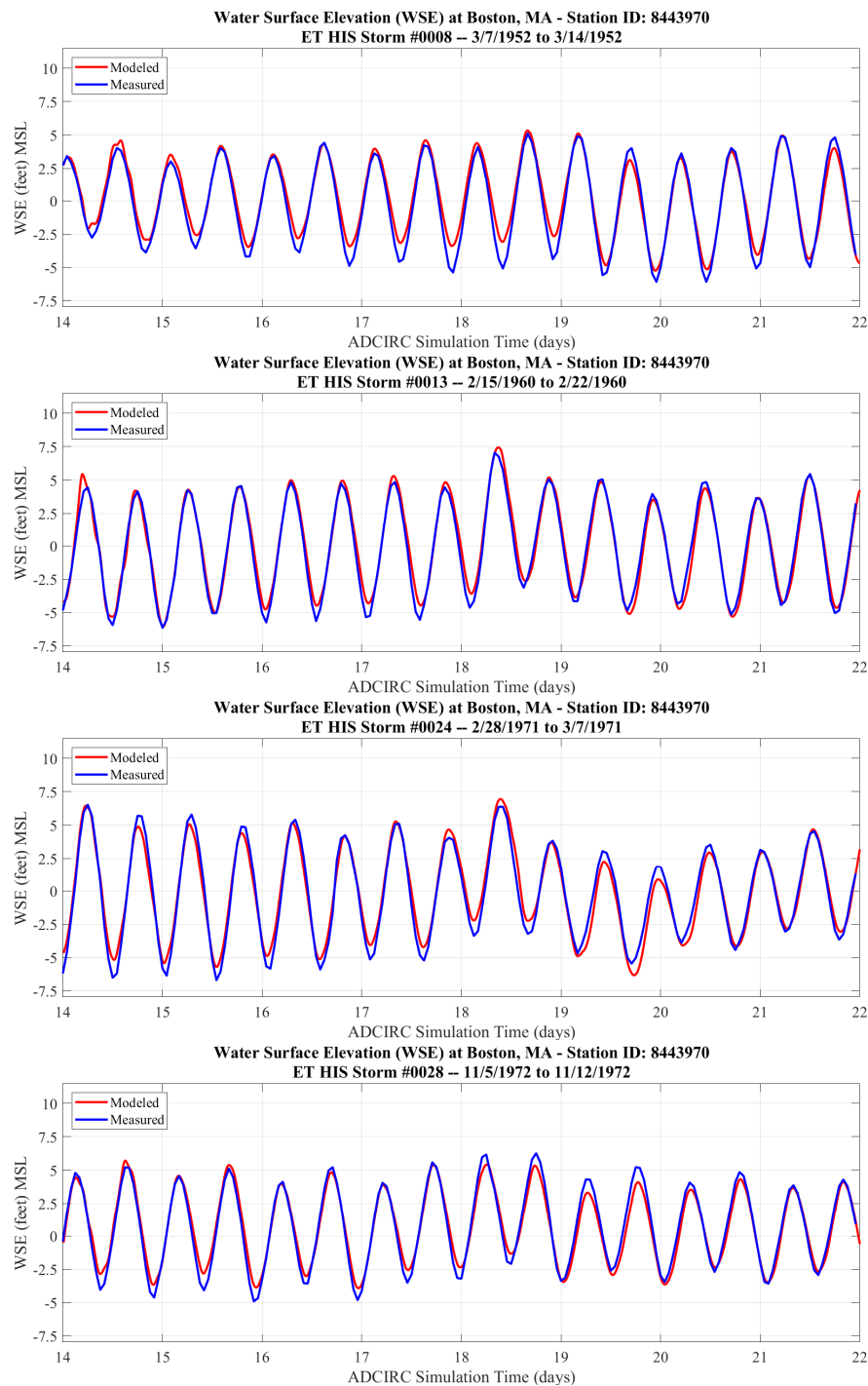
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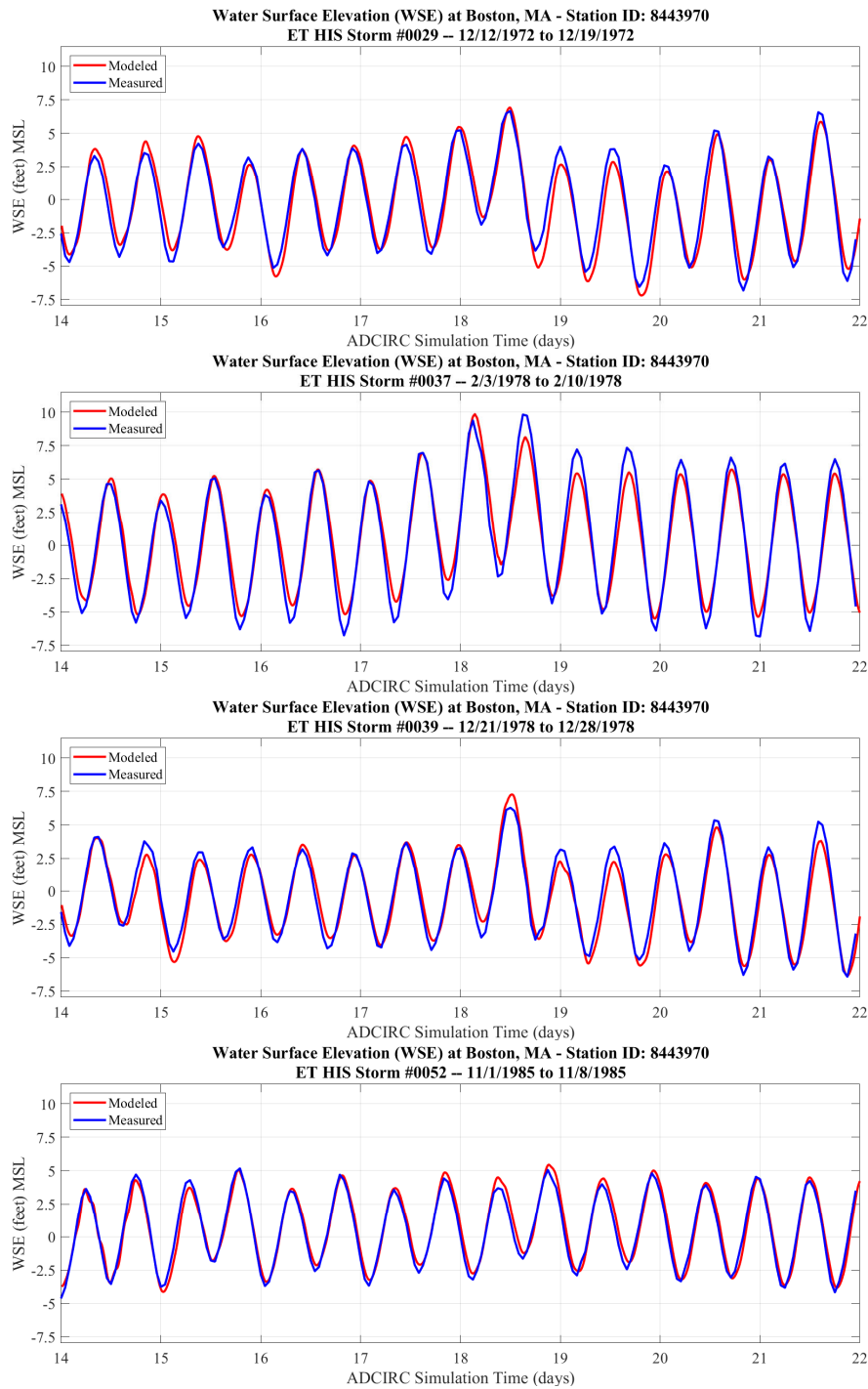
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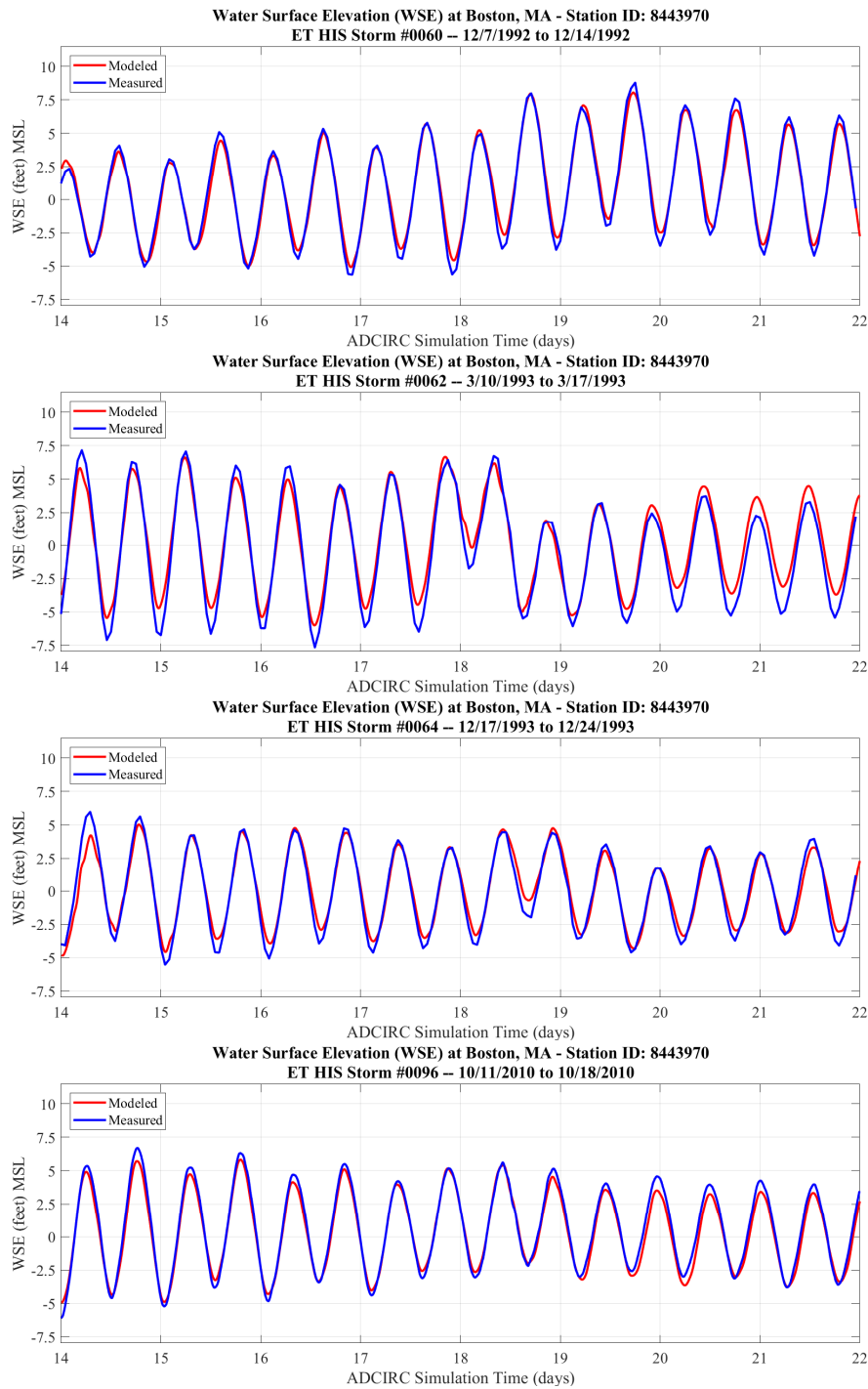
10 Appendix 1

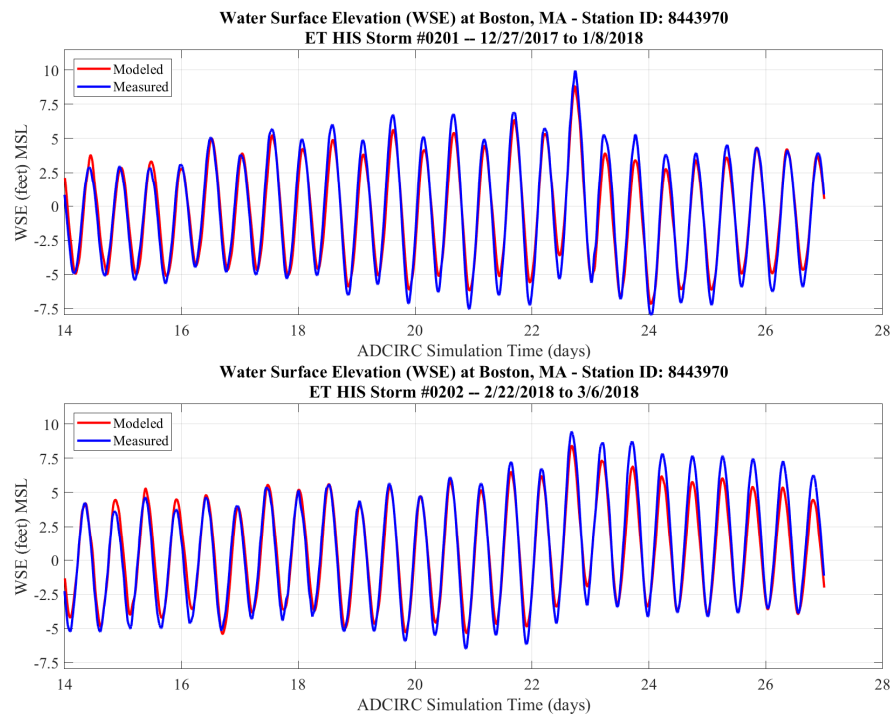
This appendix contains time series plots of water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results and measured data from NOAA tides and currents Boston, MA Station ID: 8443970 for all 17 historical extra-tropical events used in this study.





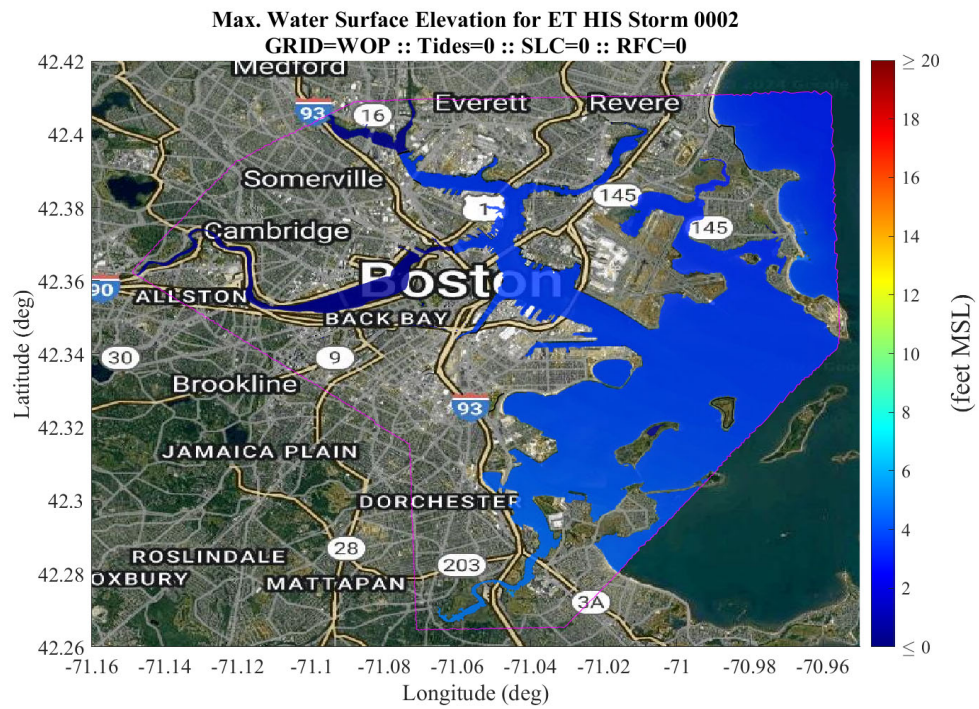


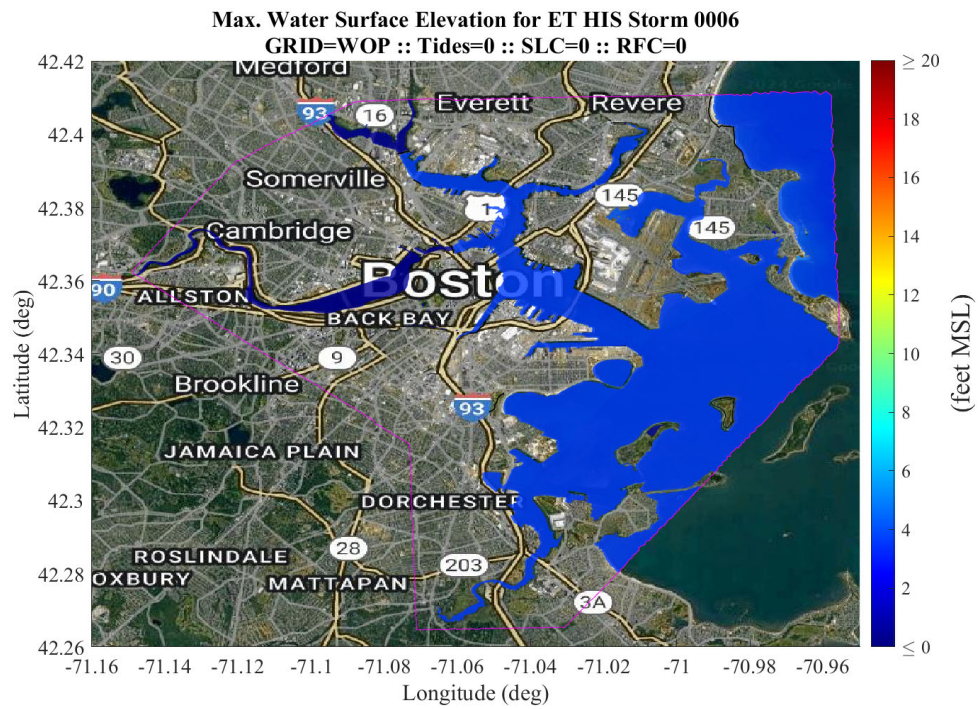


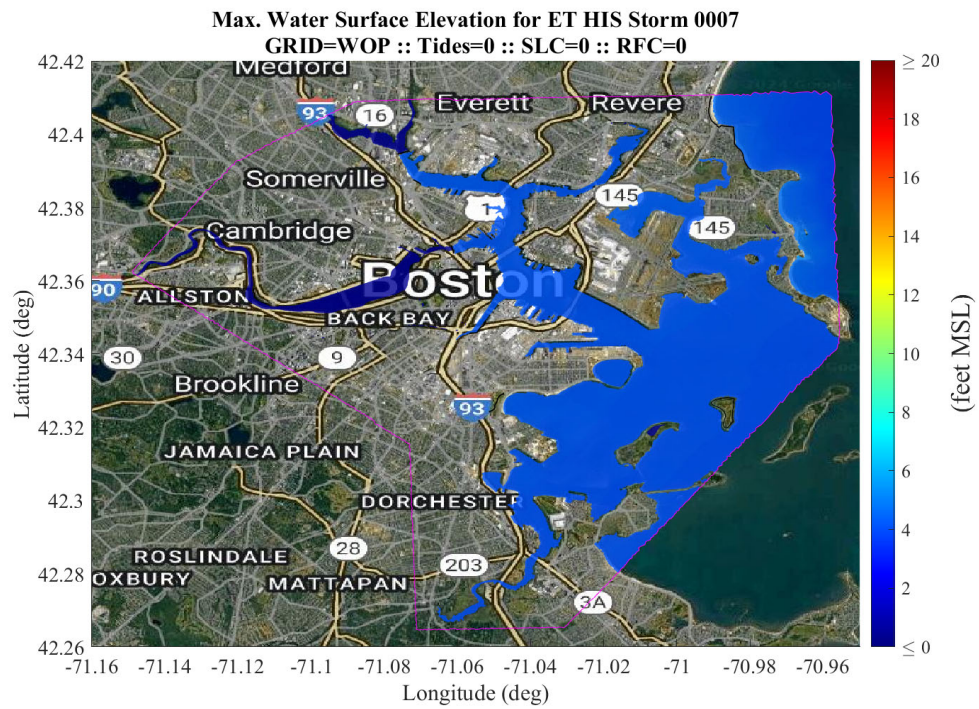


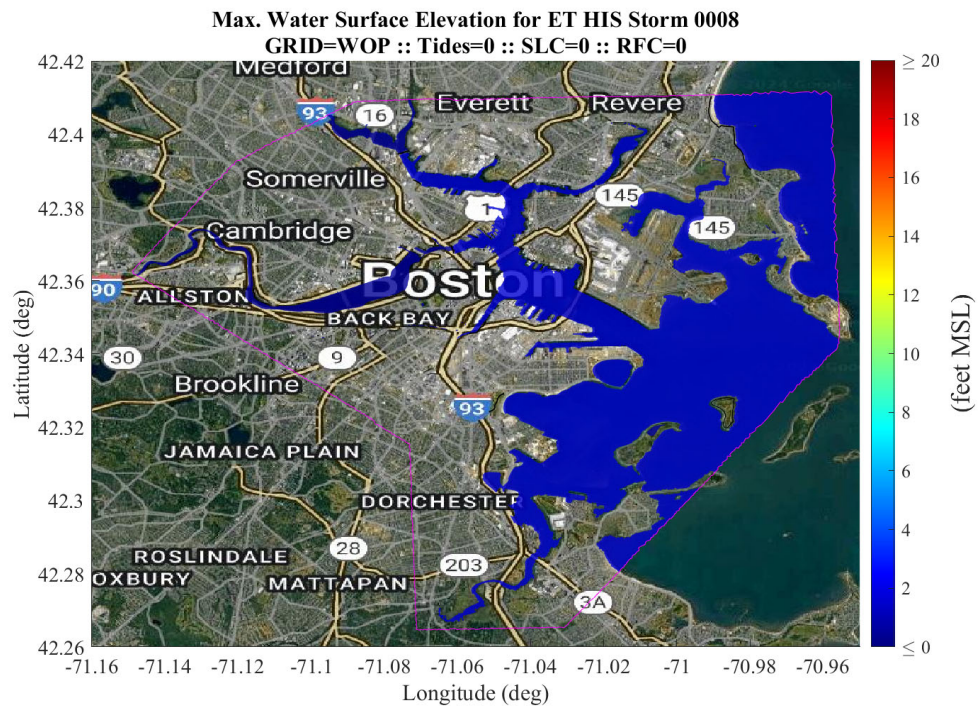
11 Appendix 2

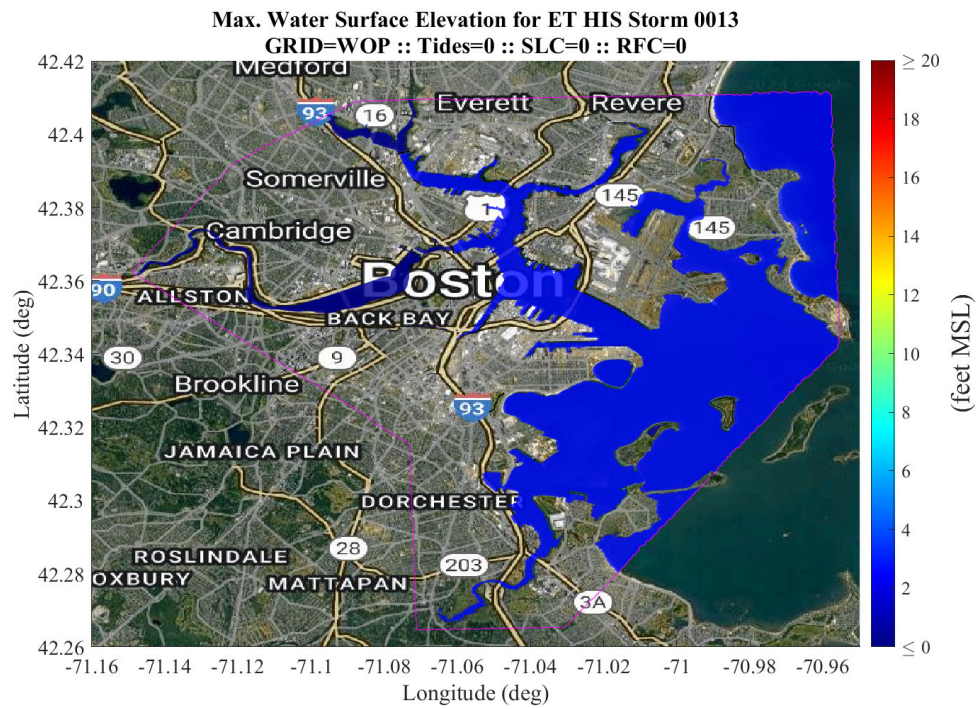
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 17 historical XC events for SLC0 and no tides.

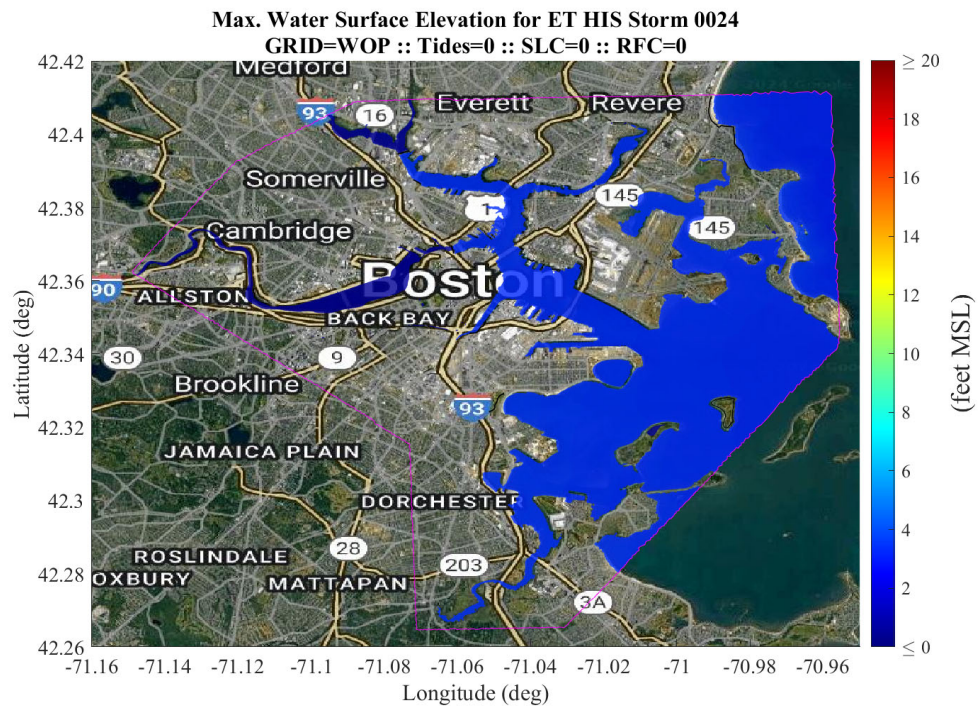


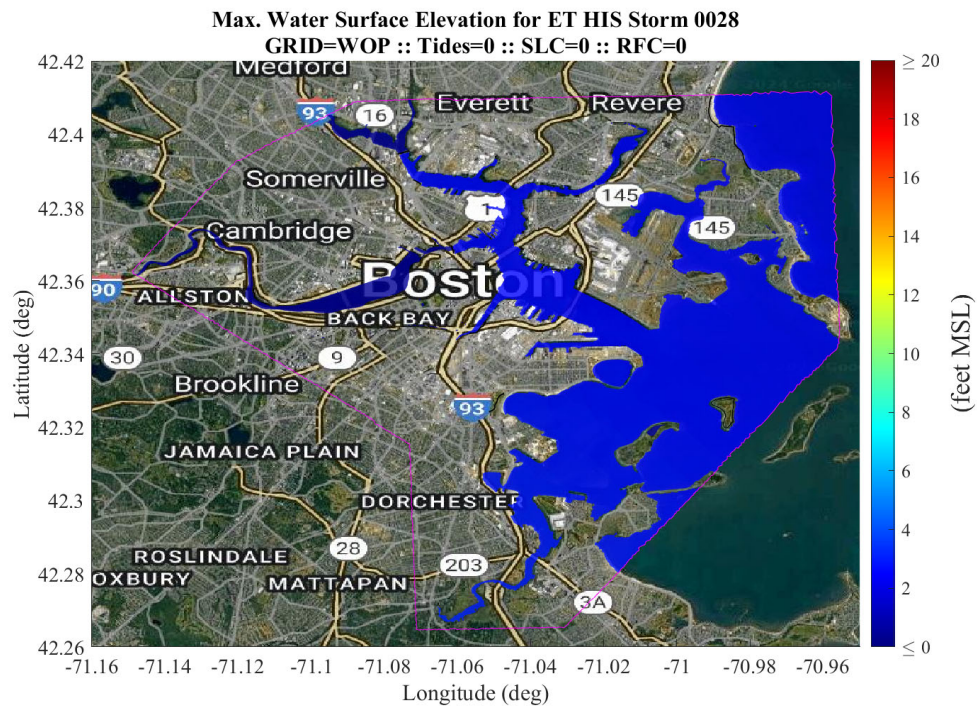


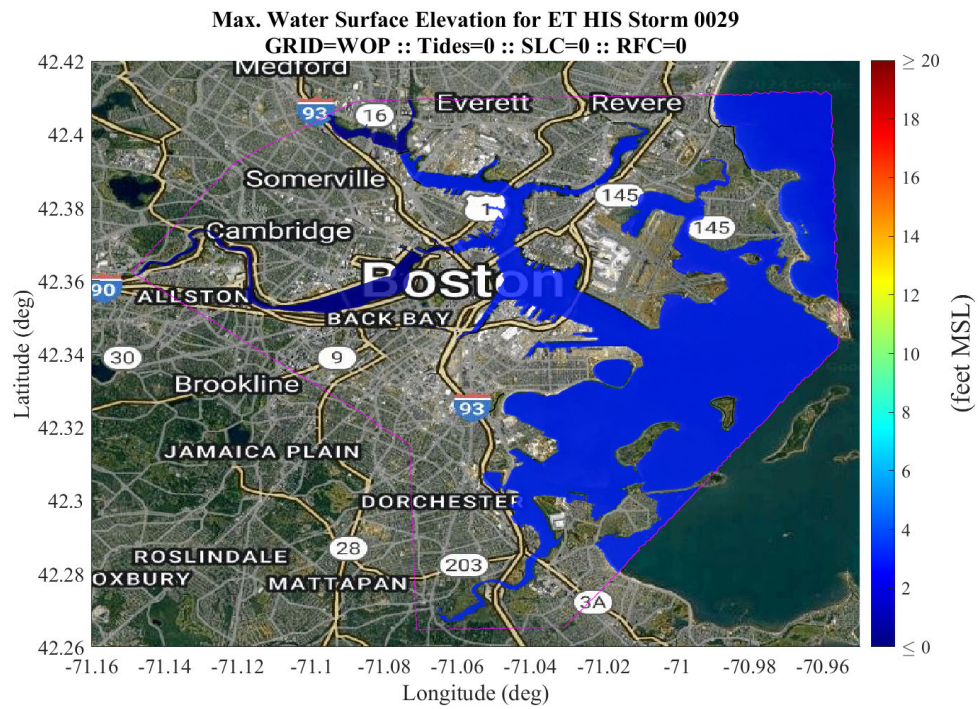


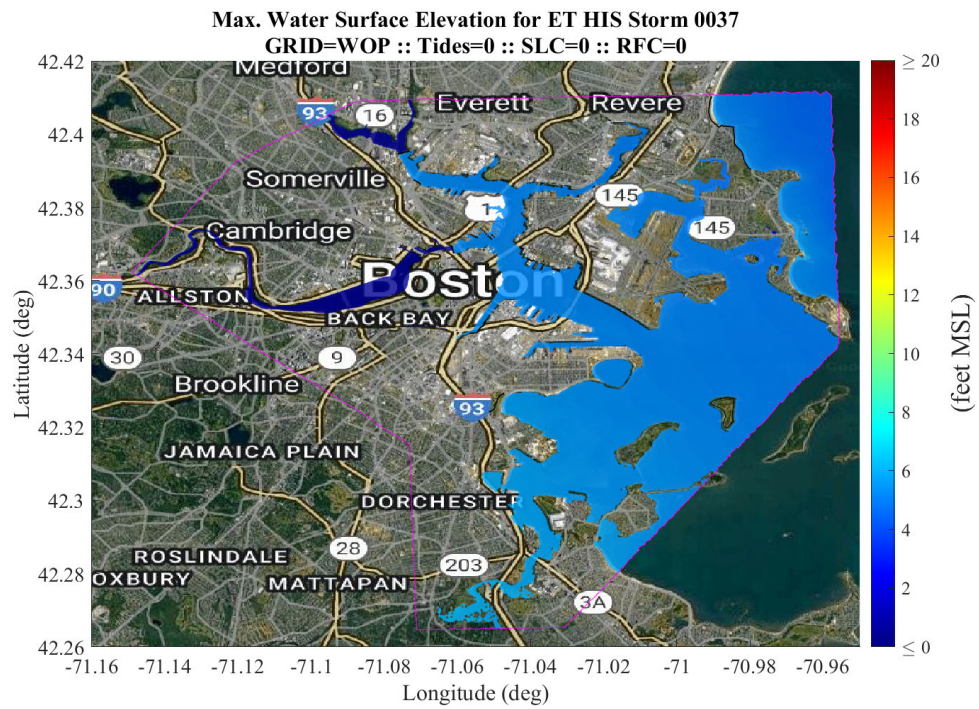


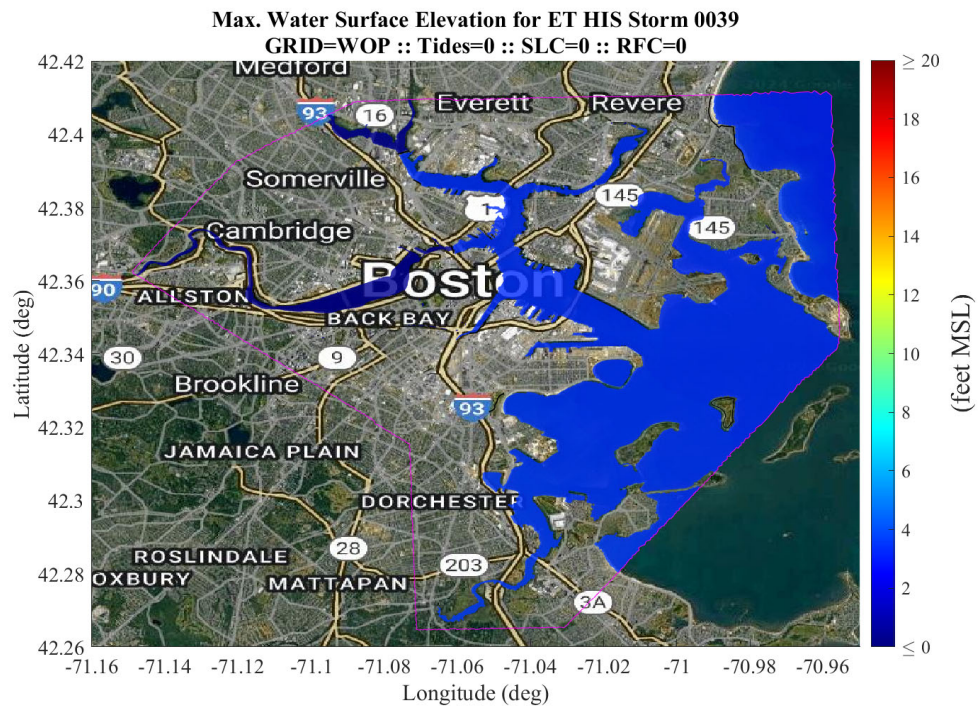


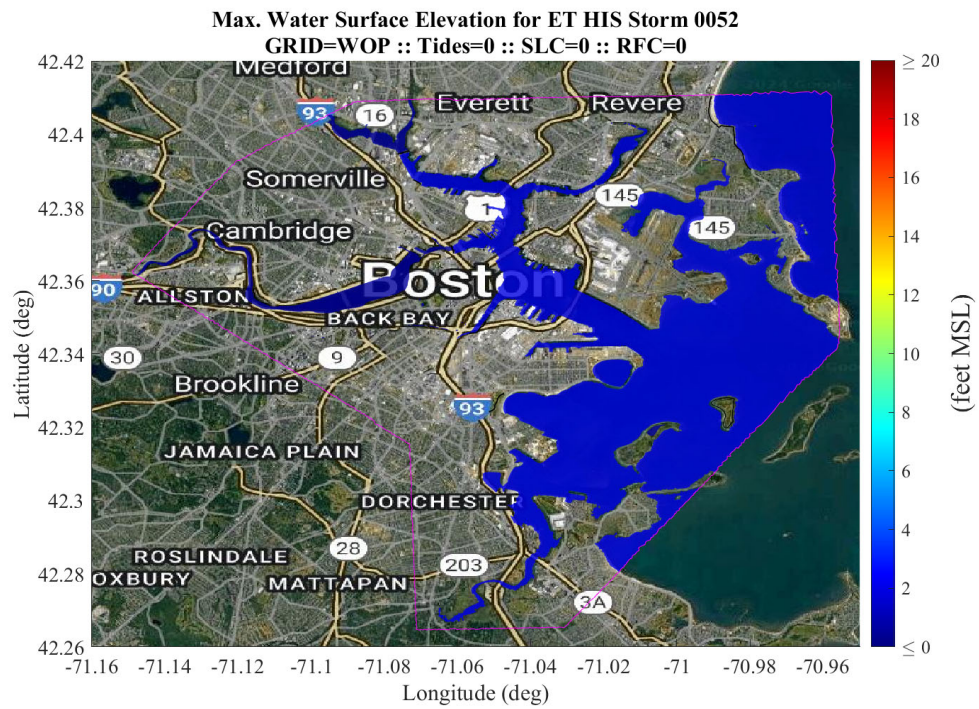


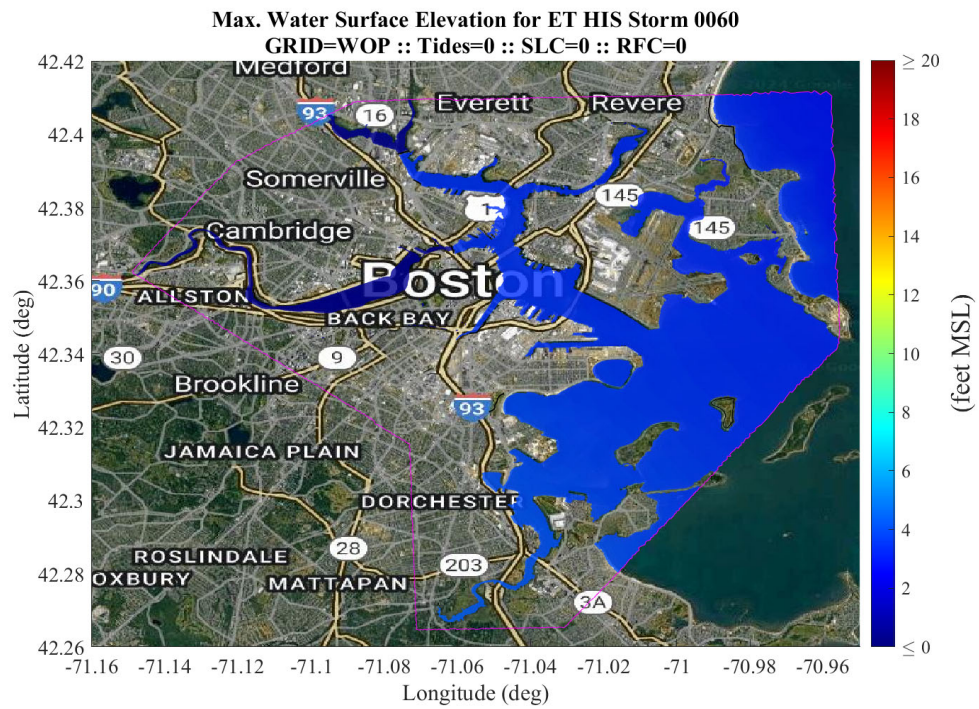


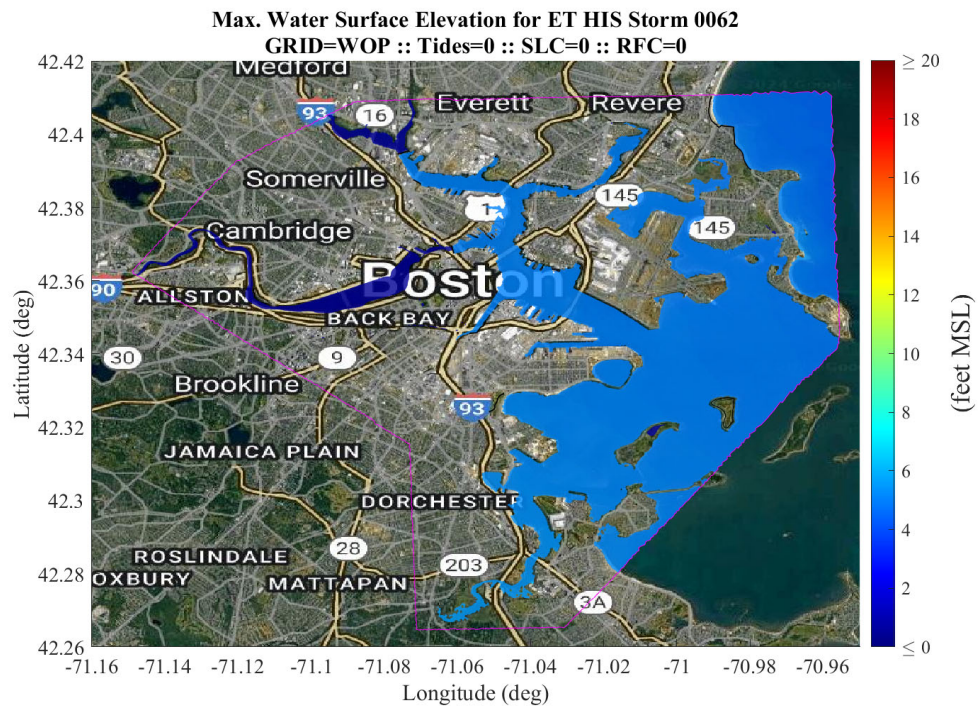


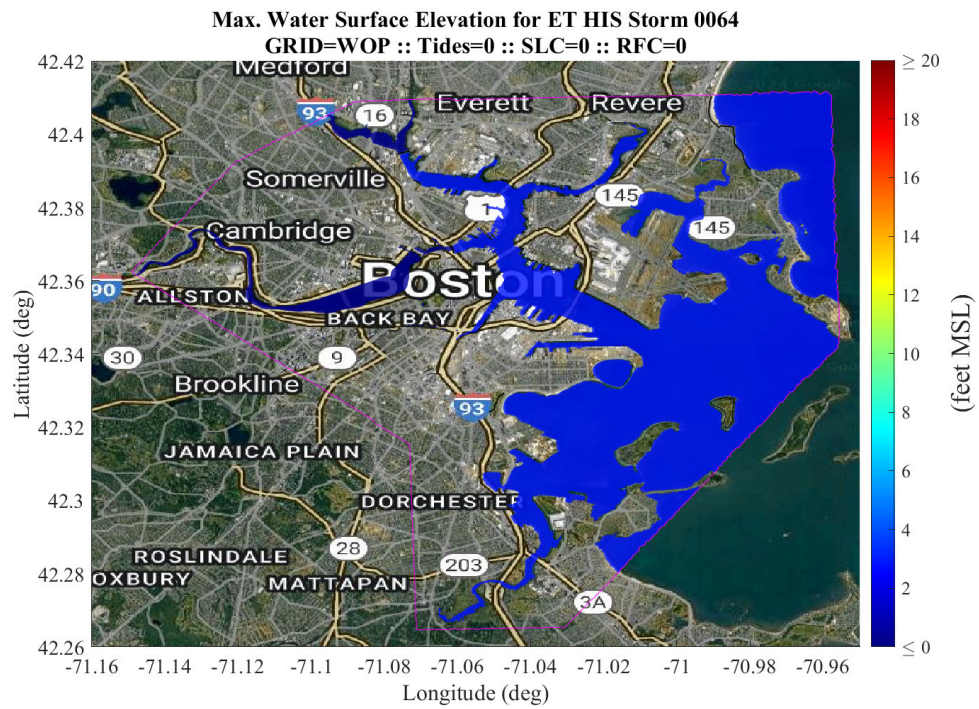


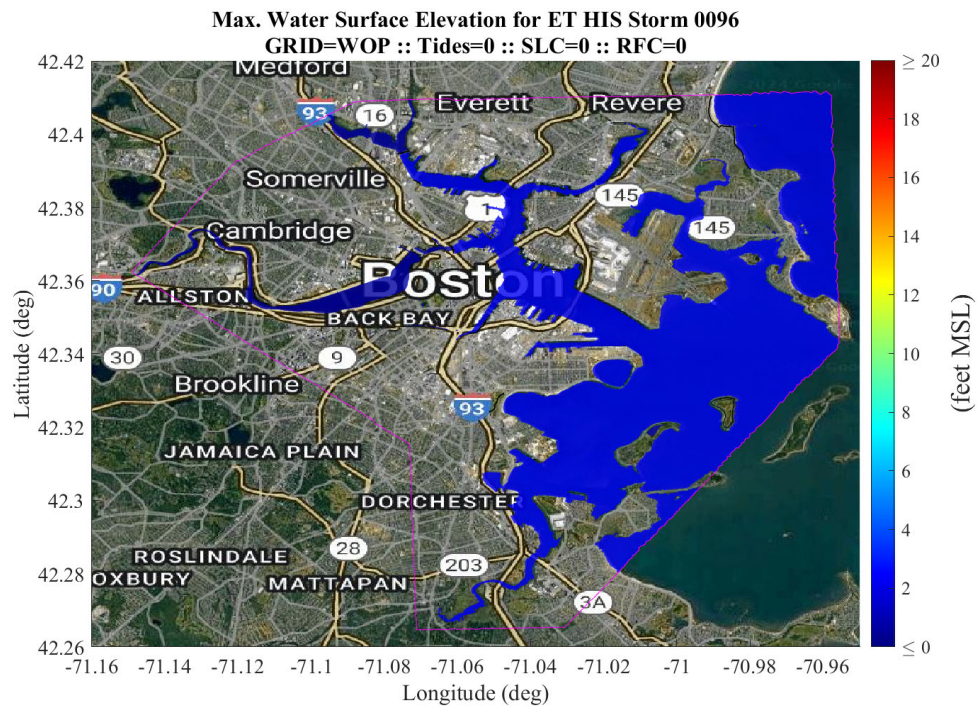


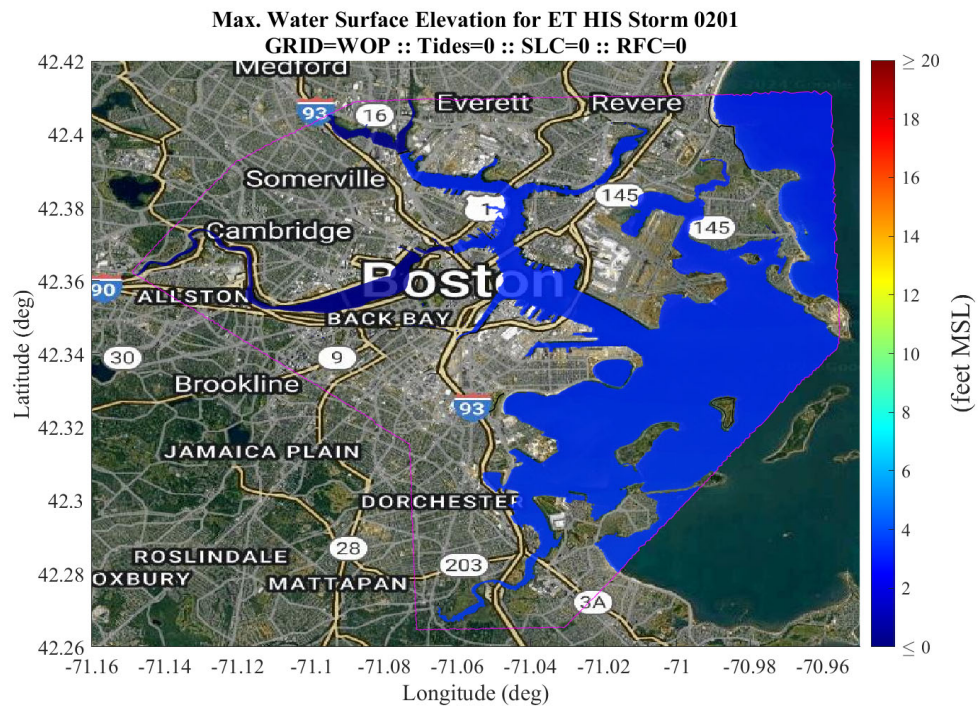


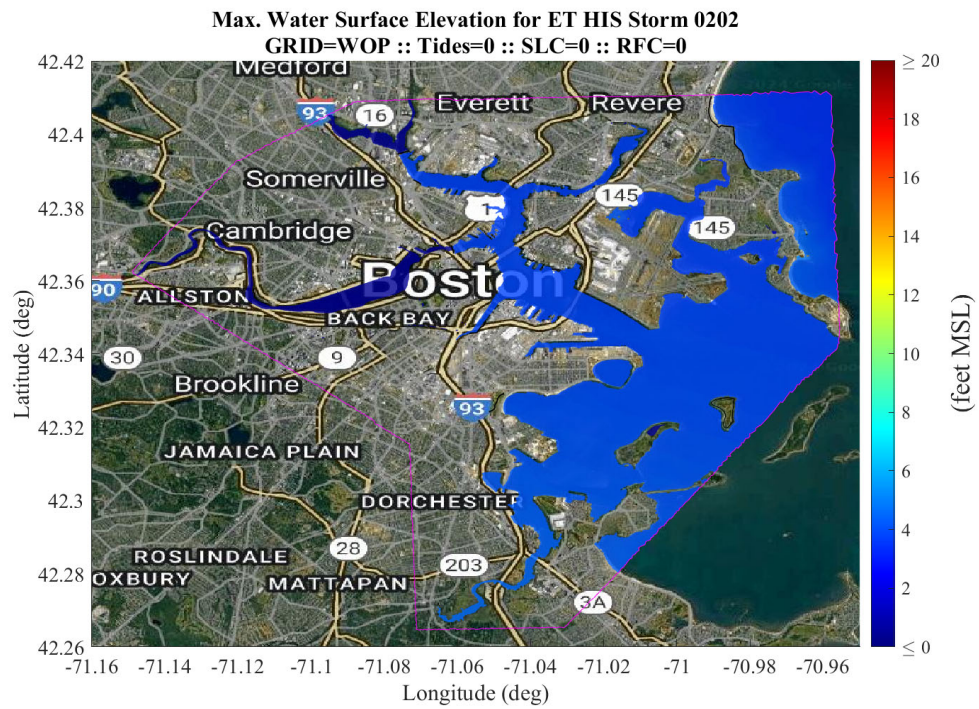






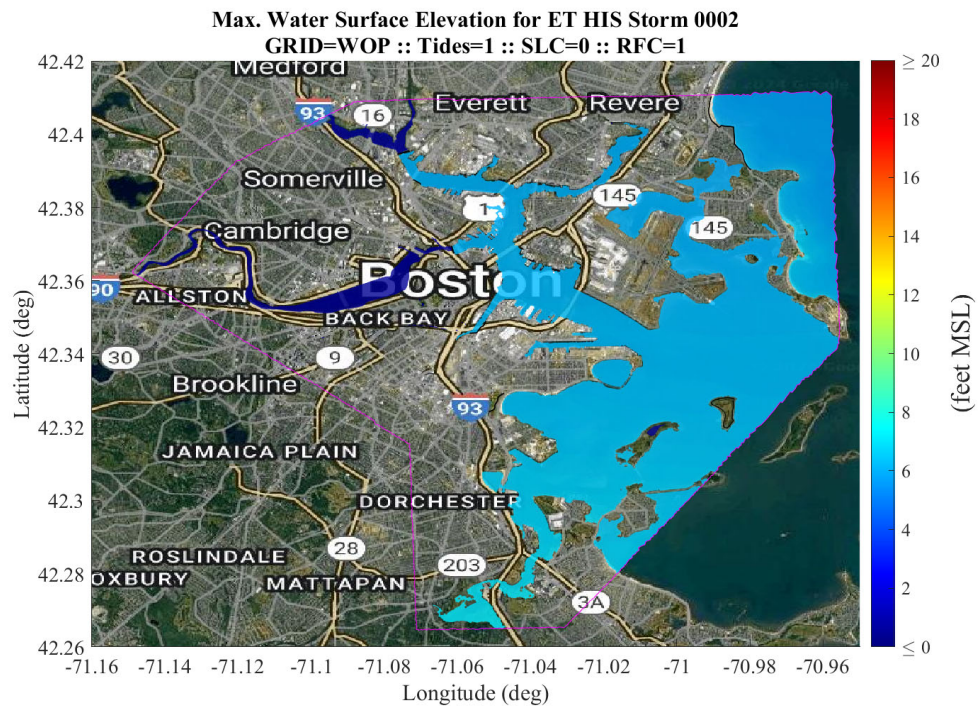


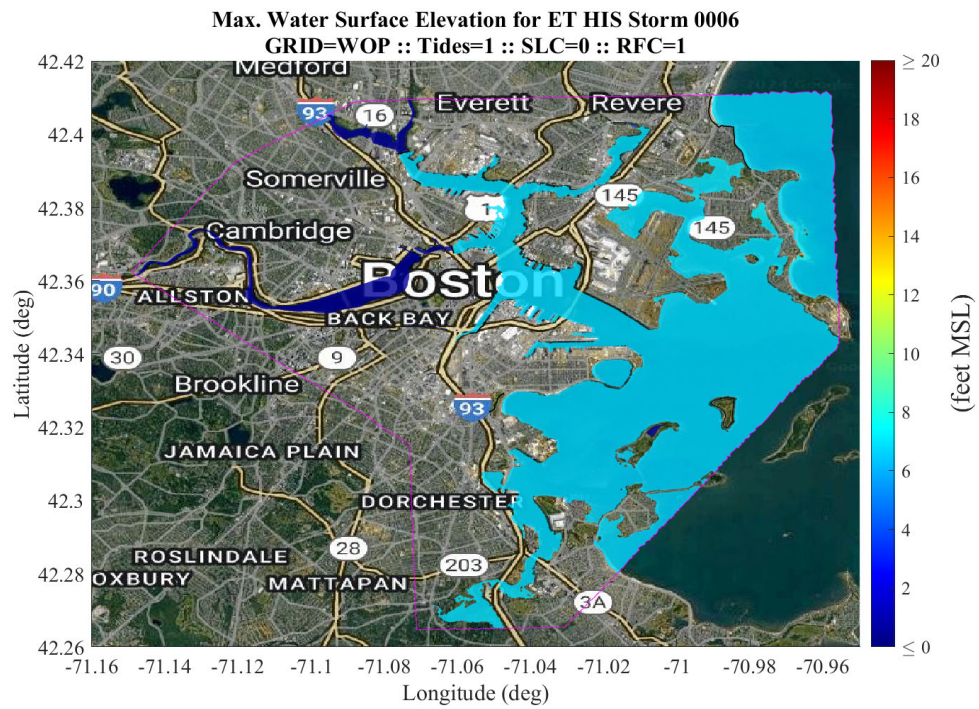


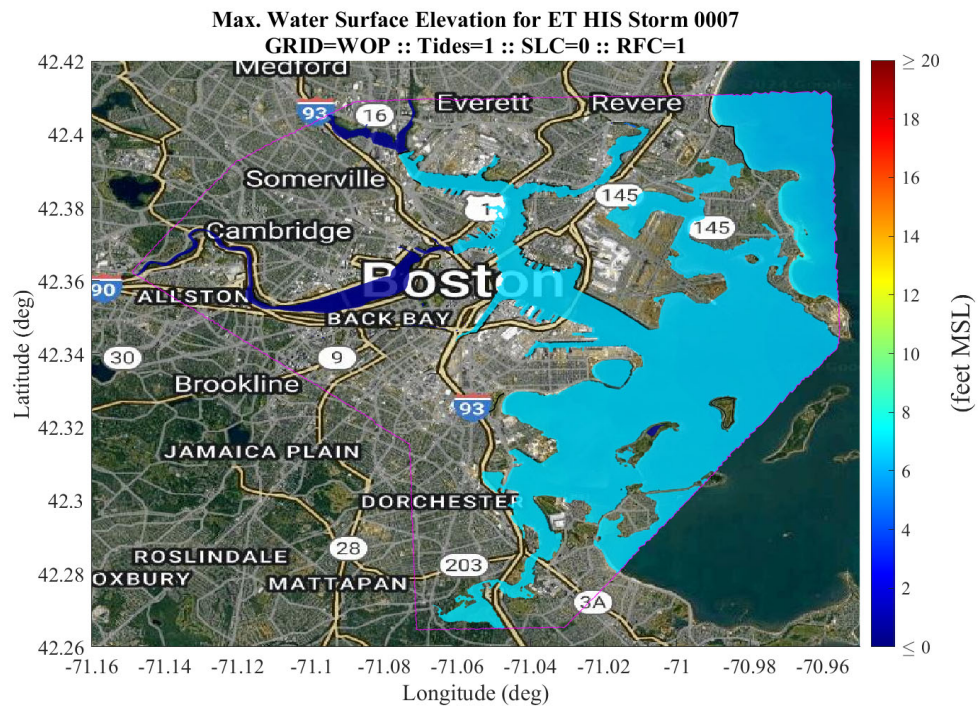


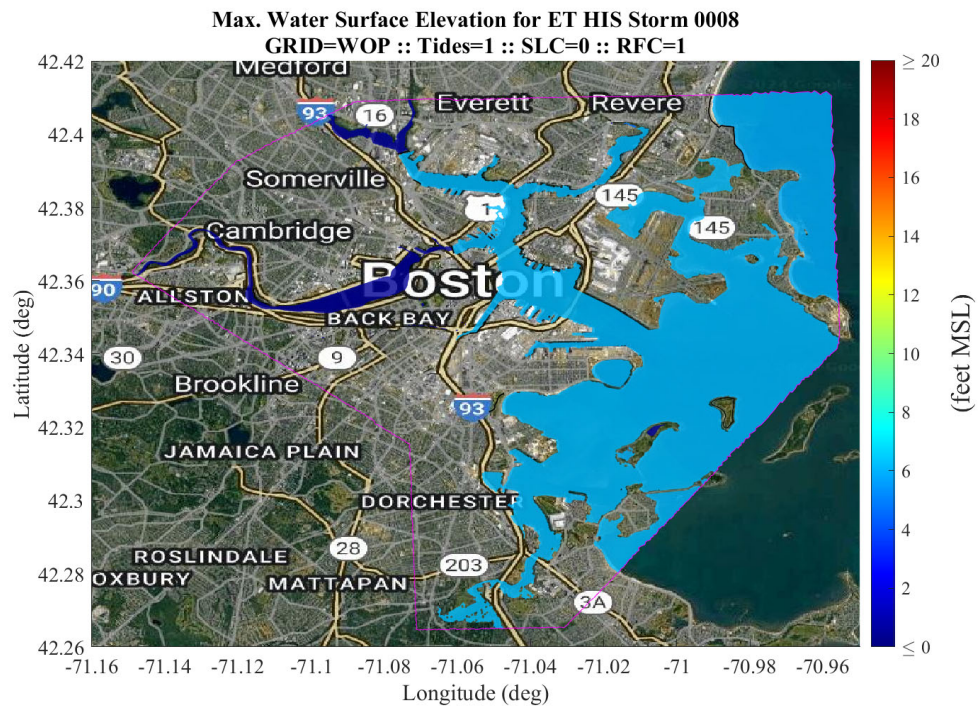
12 Appendix 3

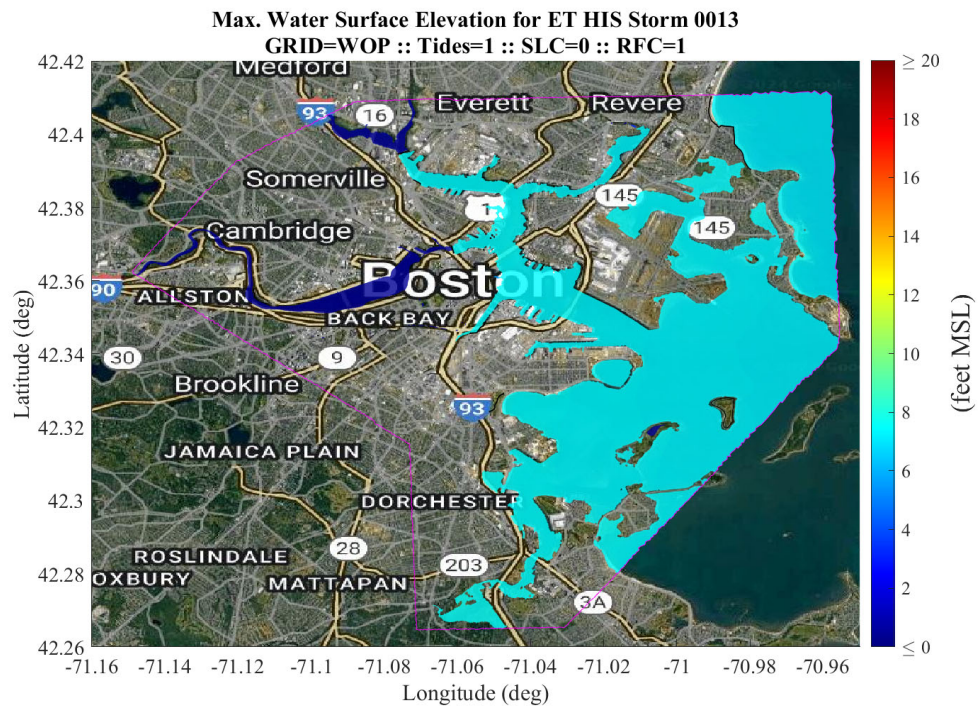
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 17 historical XC events for SLC0 and historical tides.

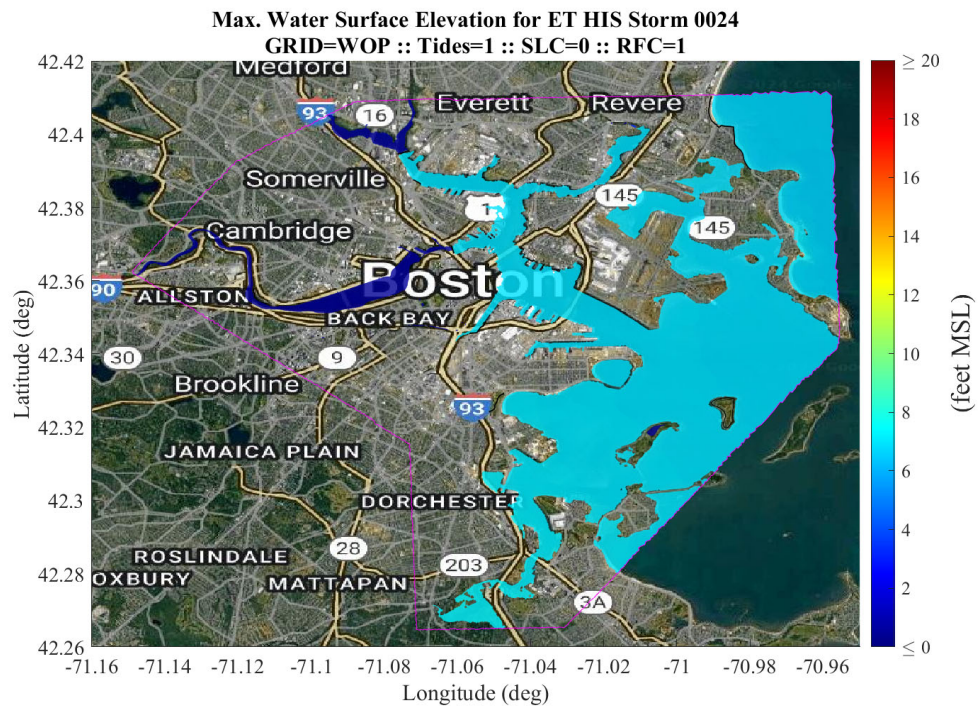


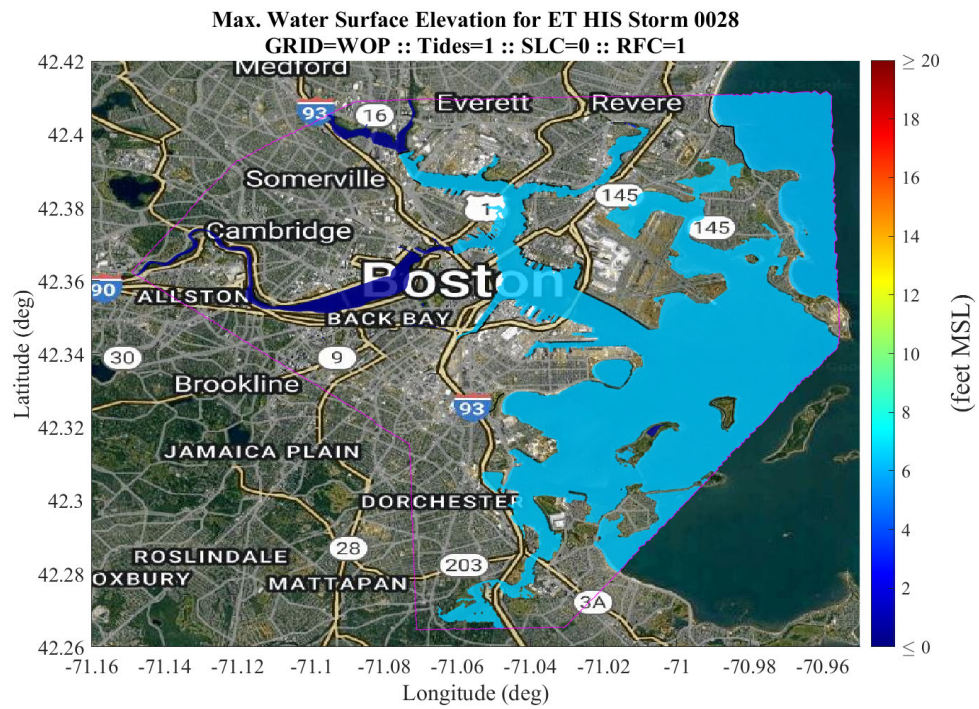


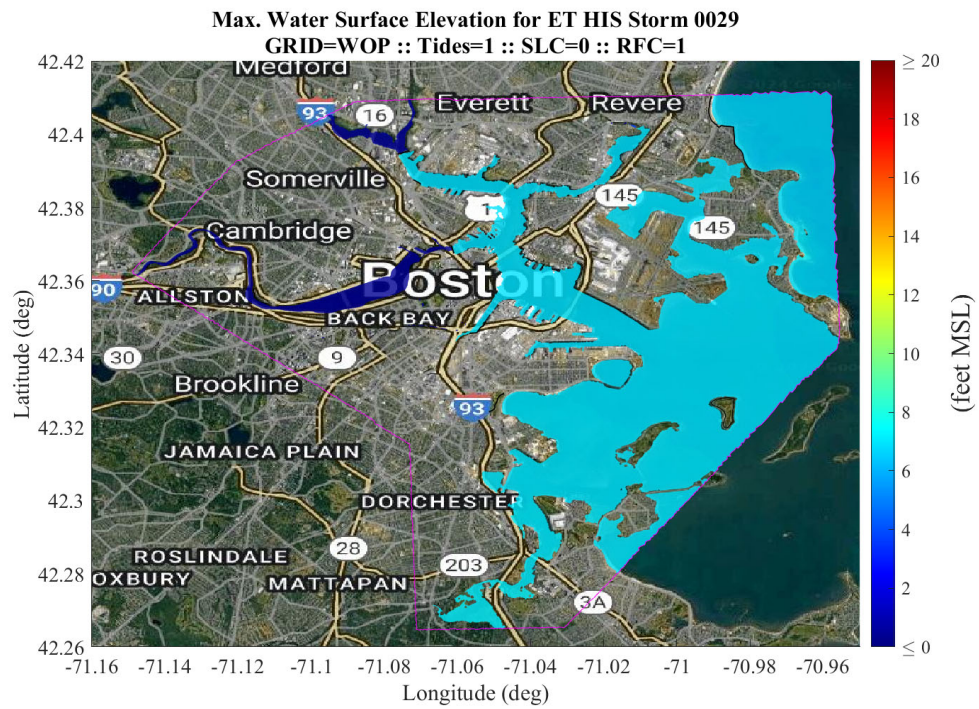


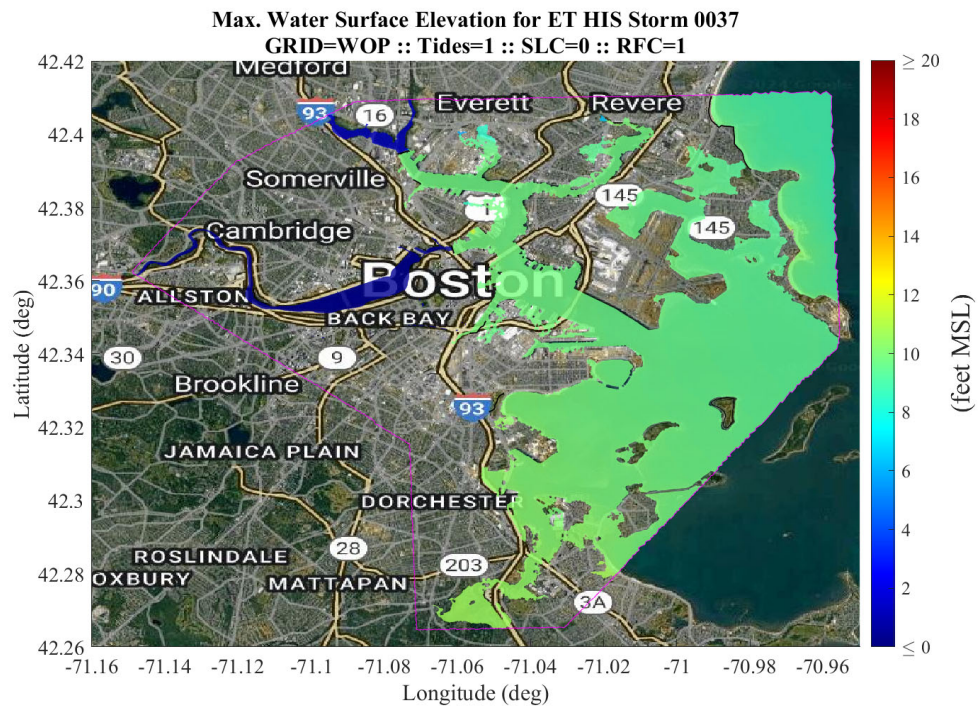


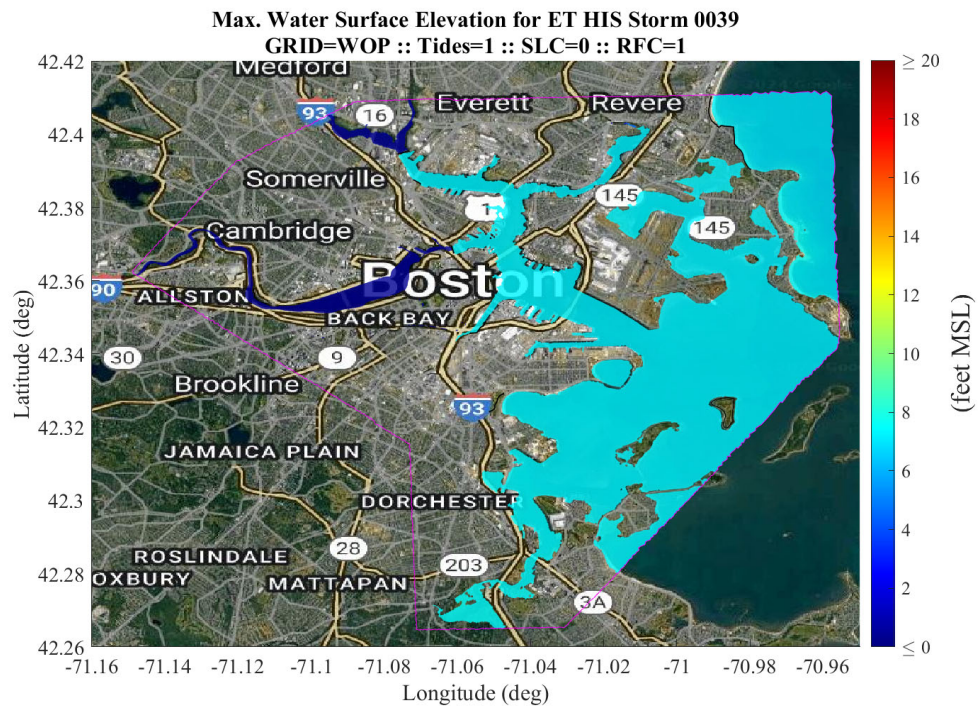


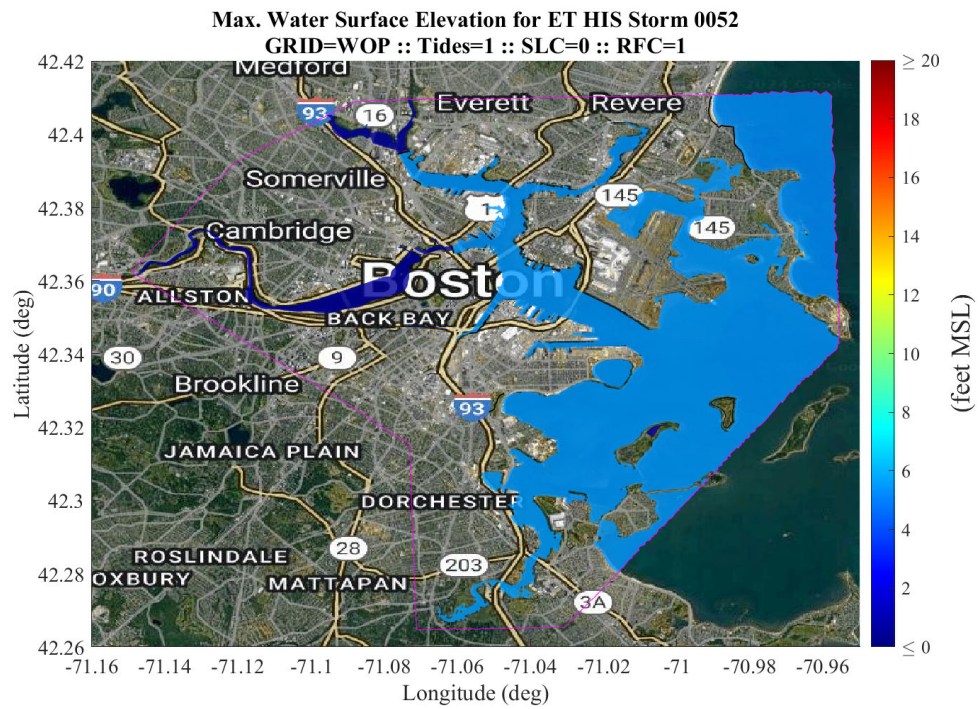


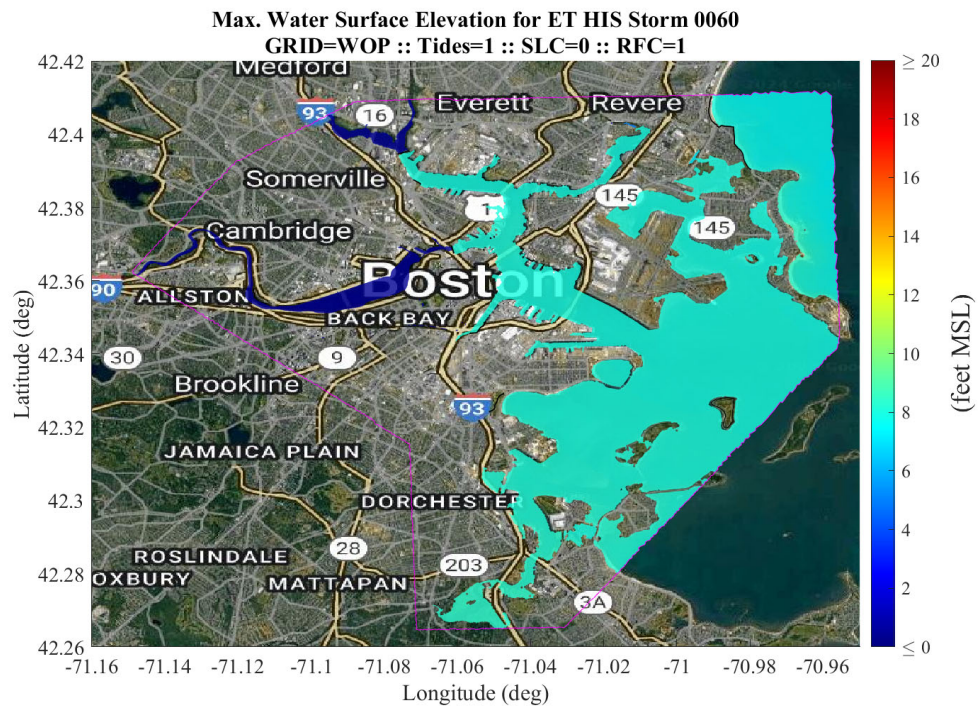


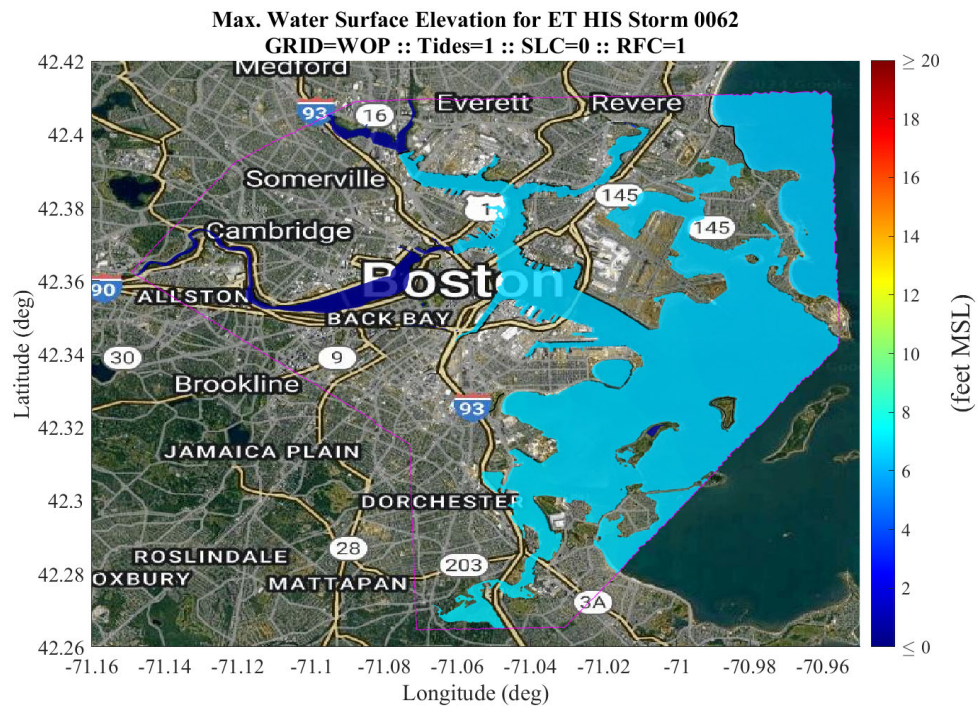


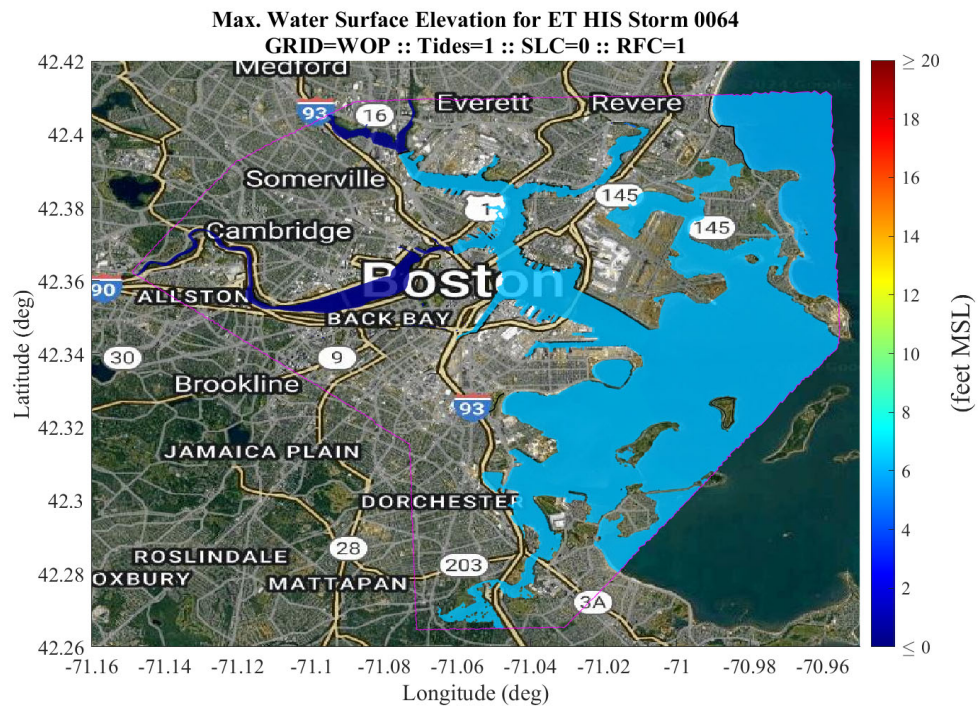


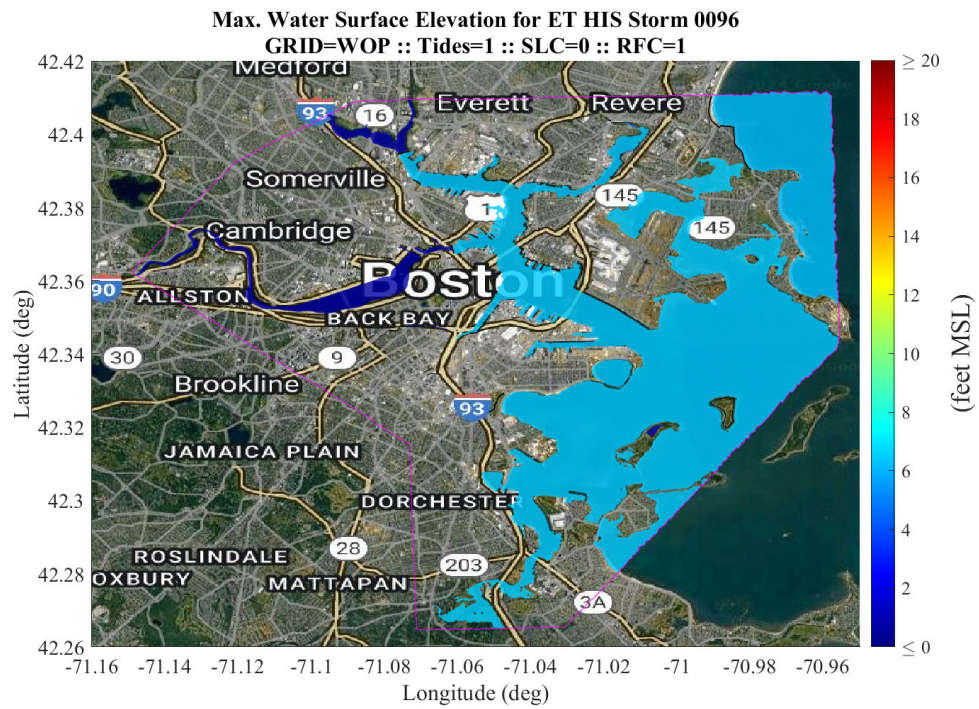


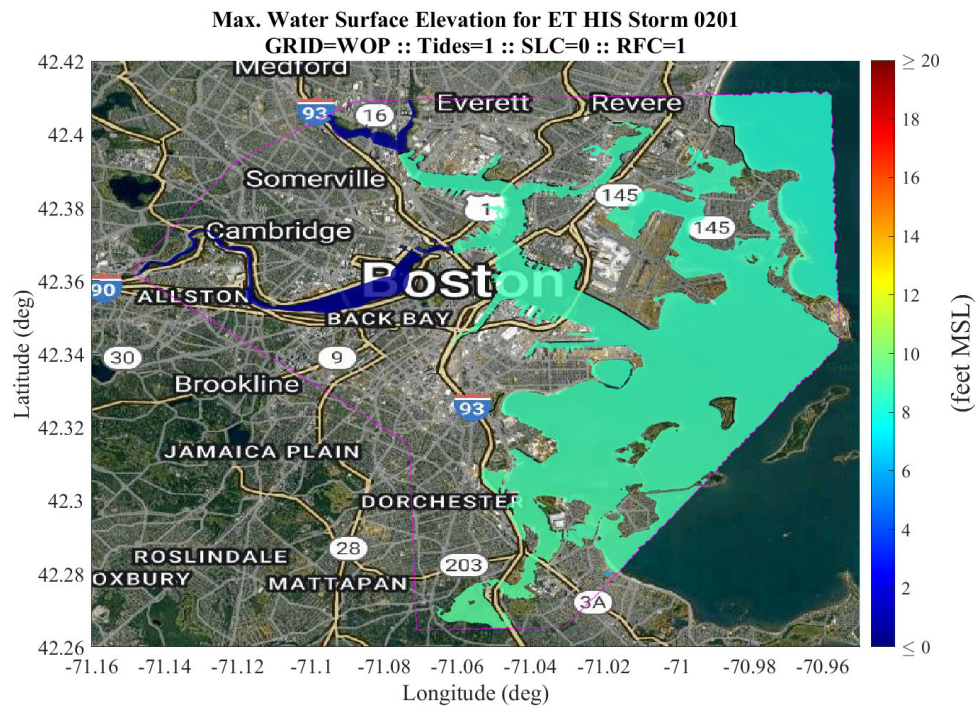


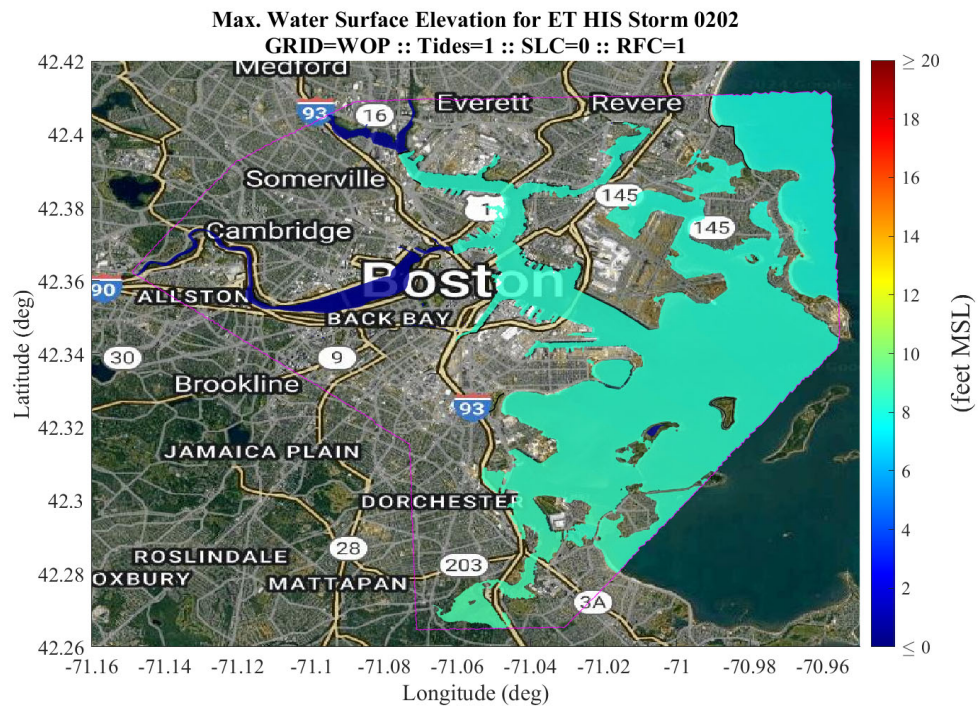






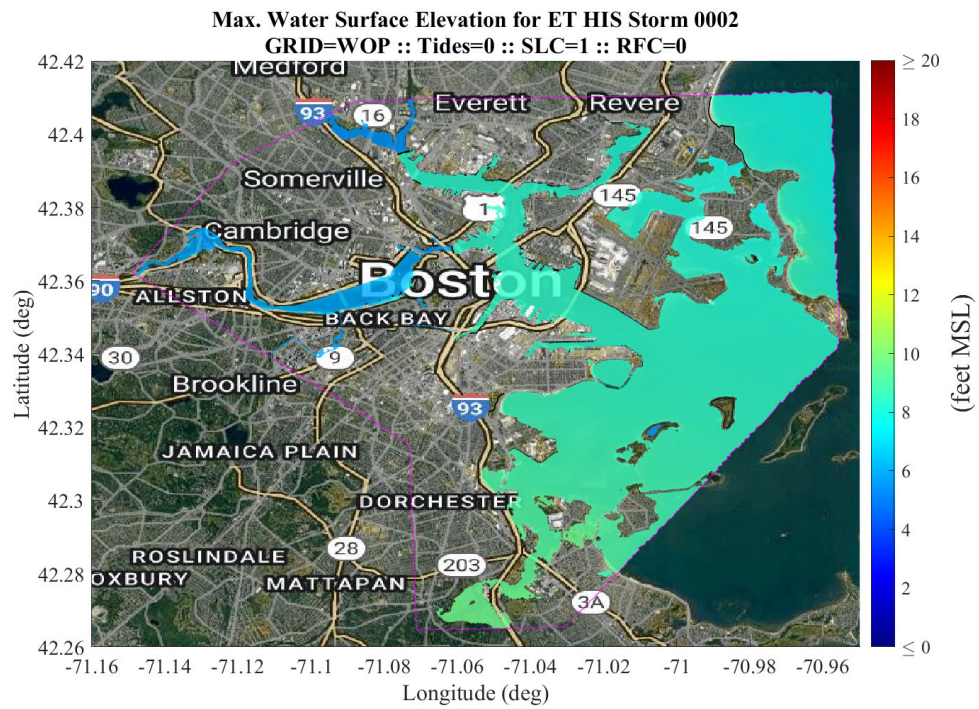


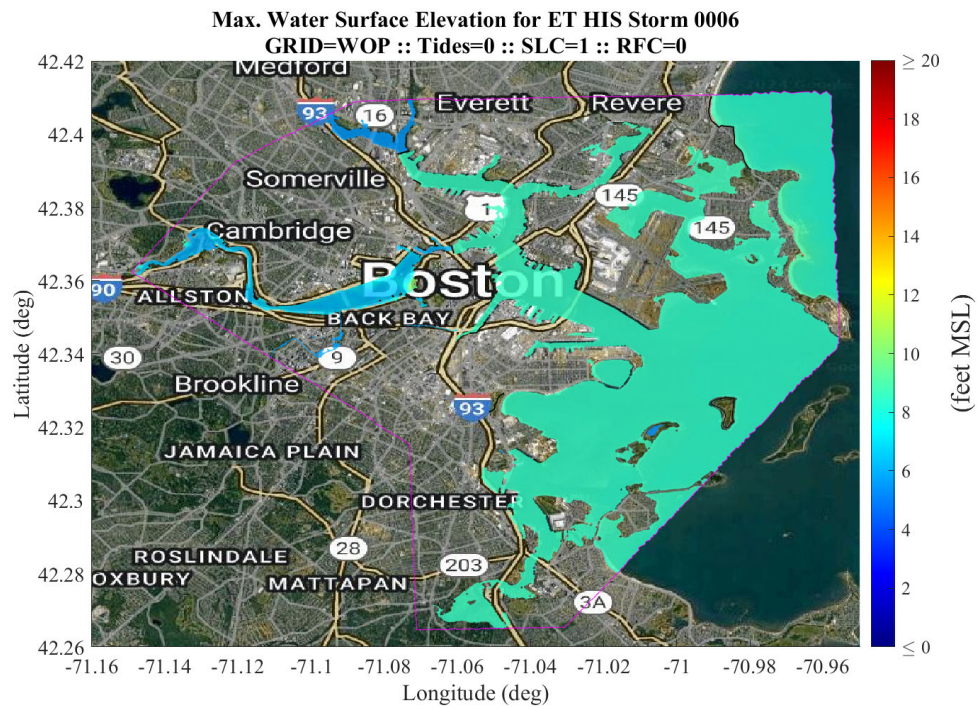


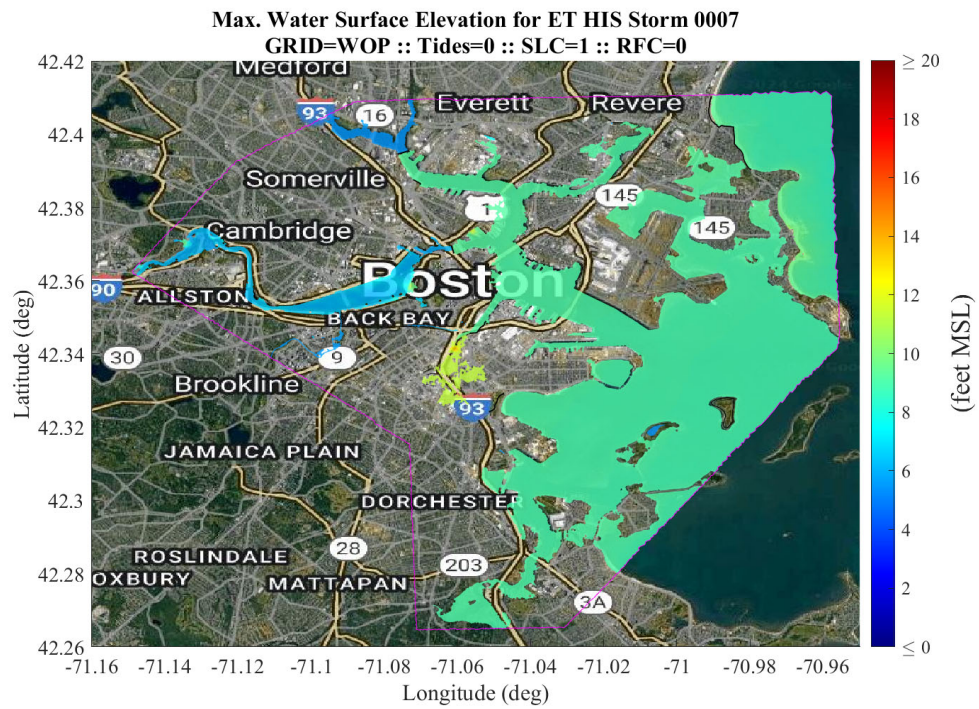


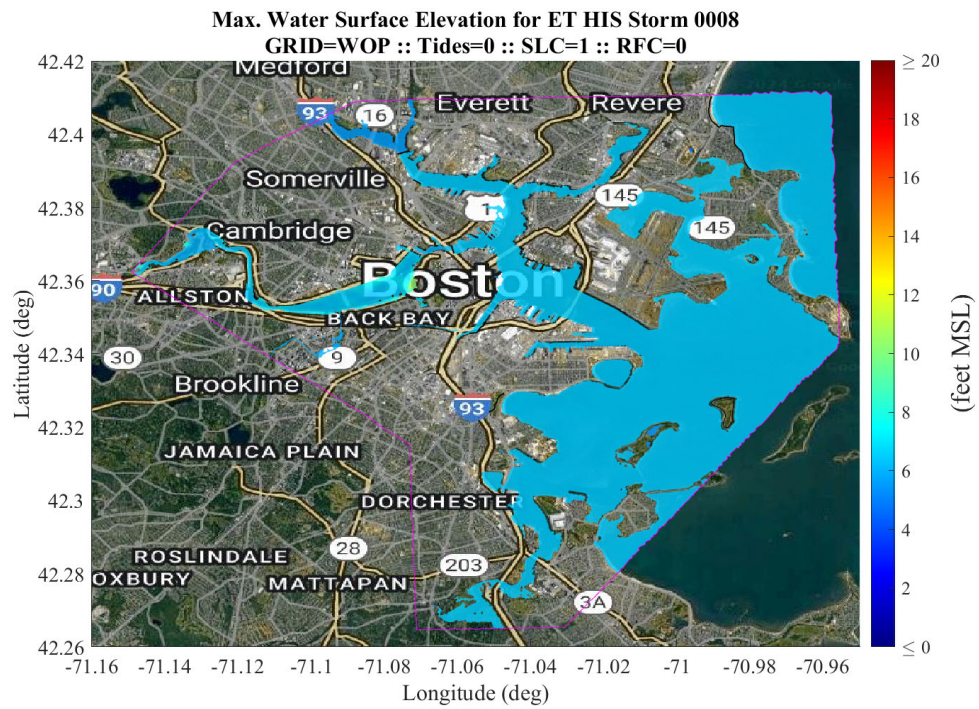
13 Appendix 4

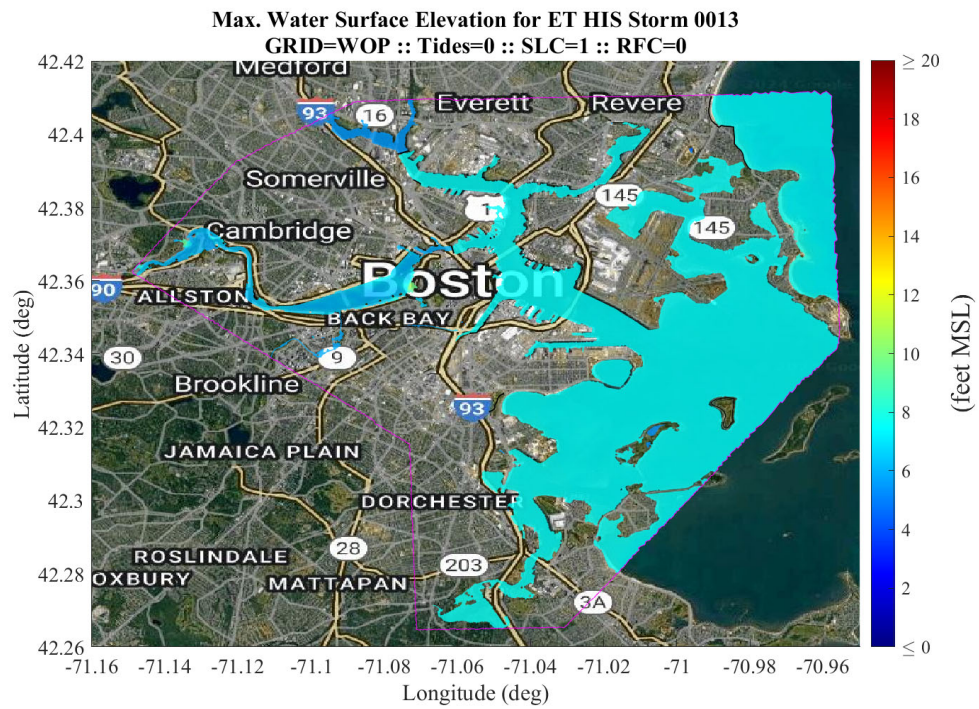
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 17 historical XC events for SLC1 and no tides.

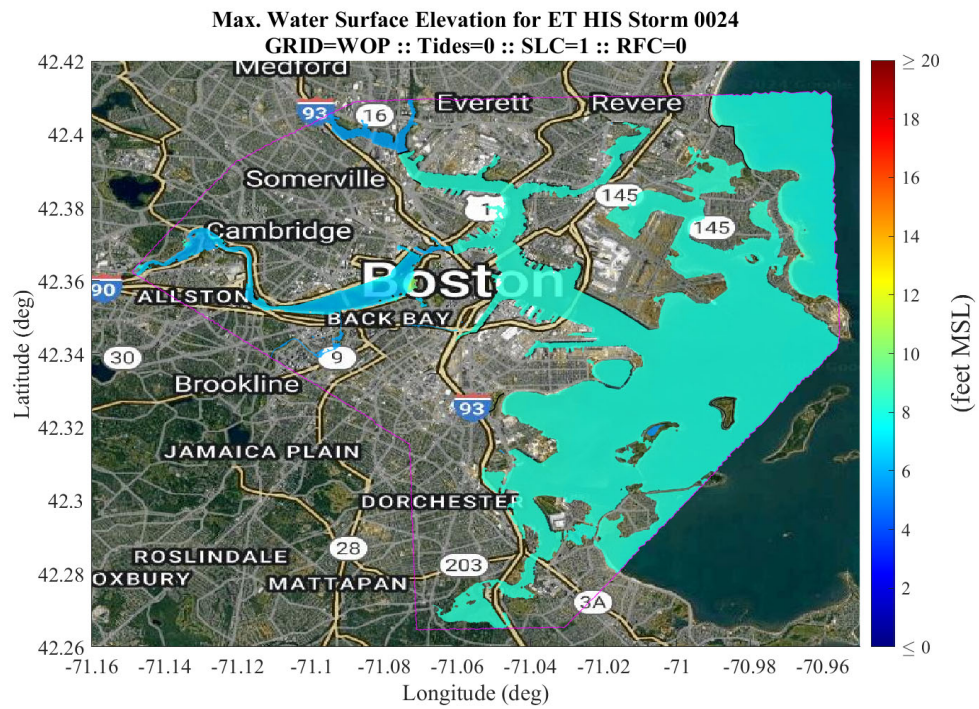


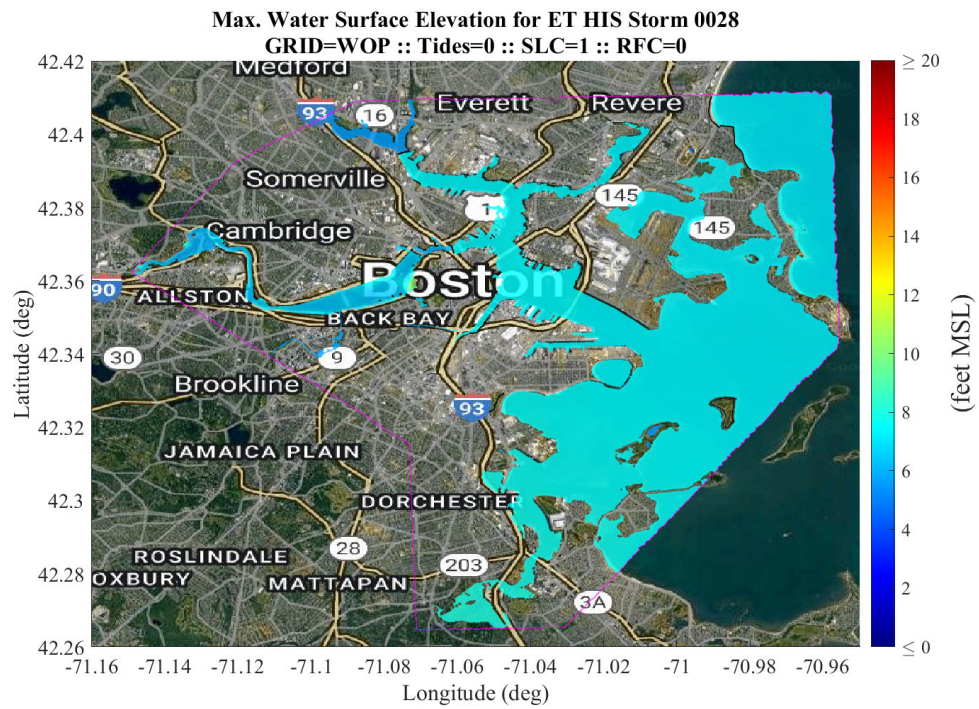


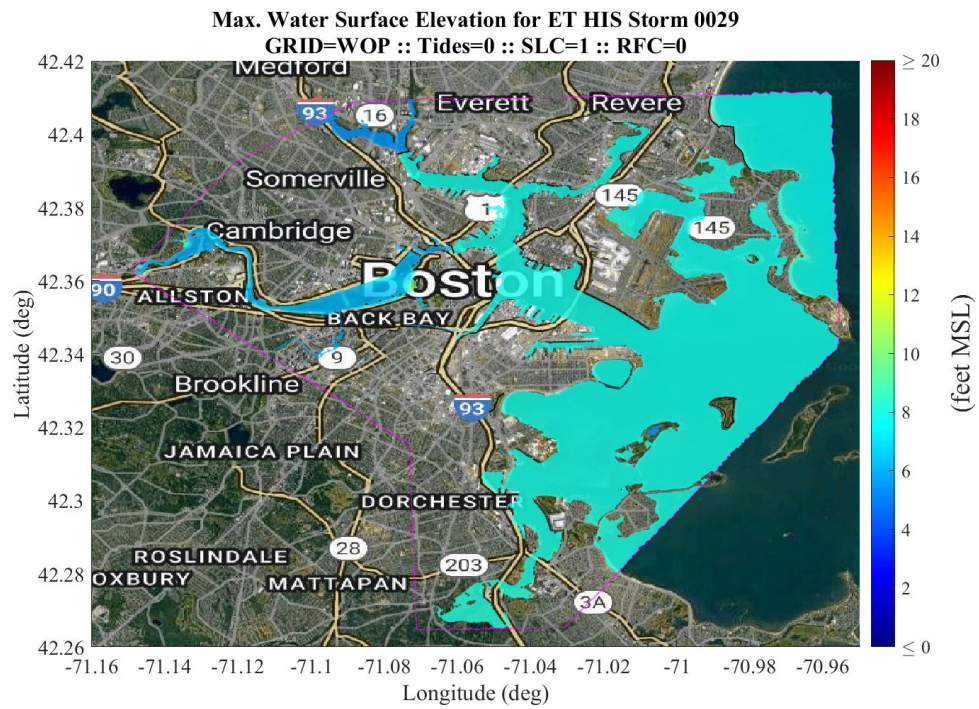


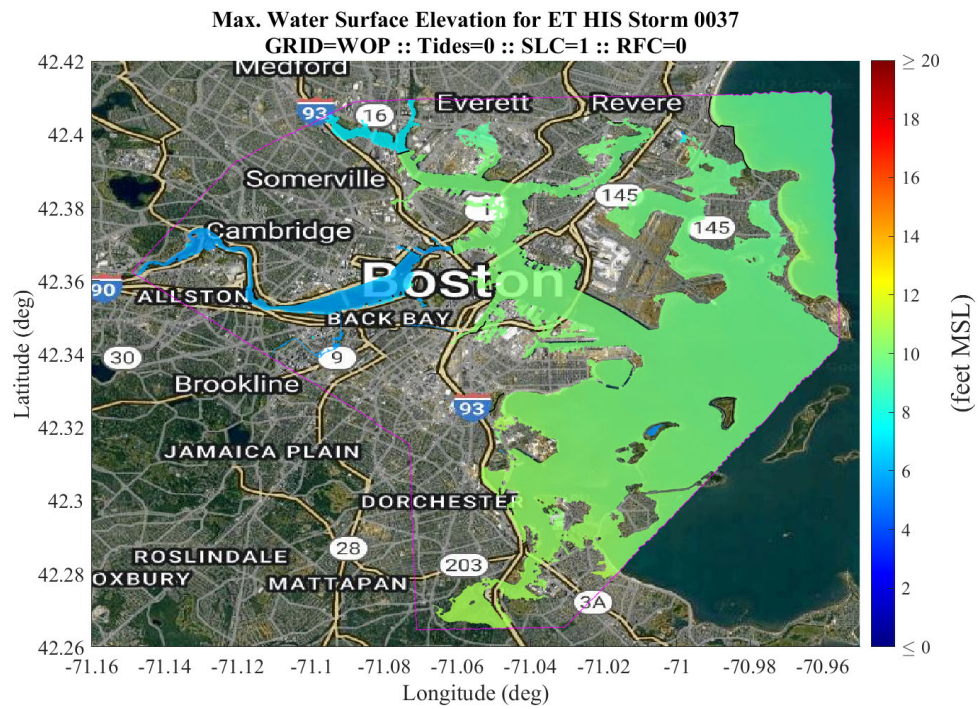


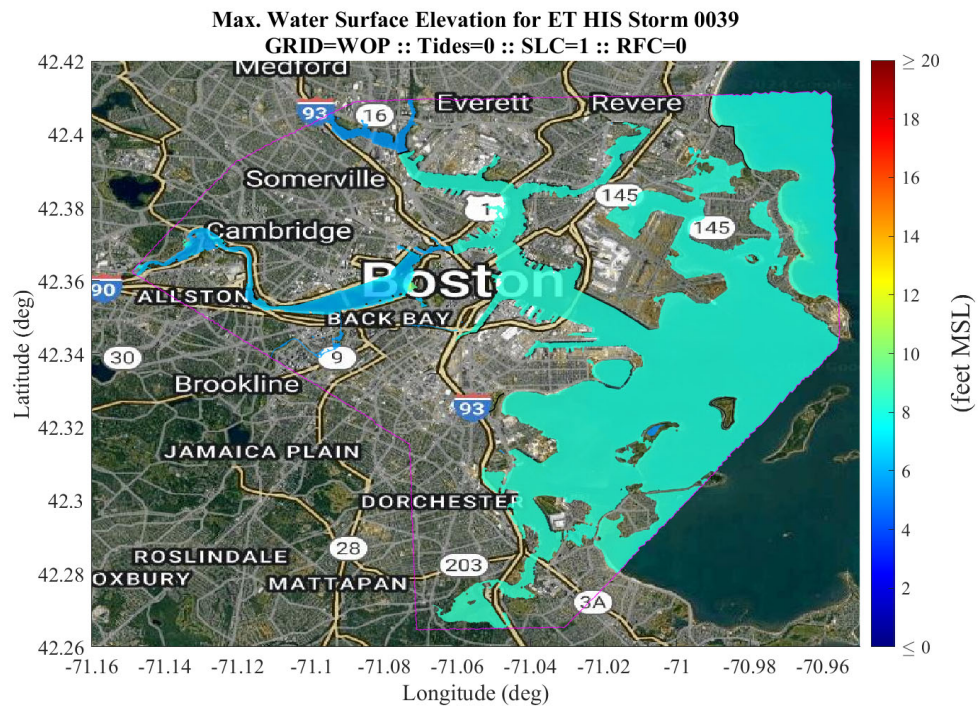


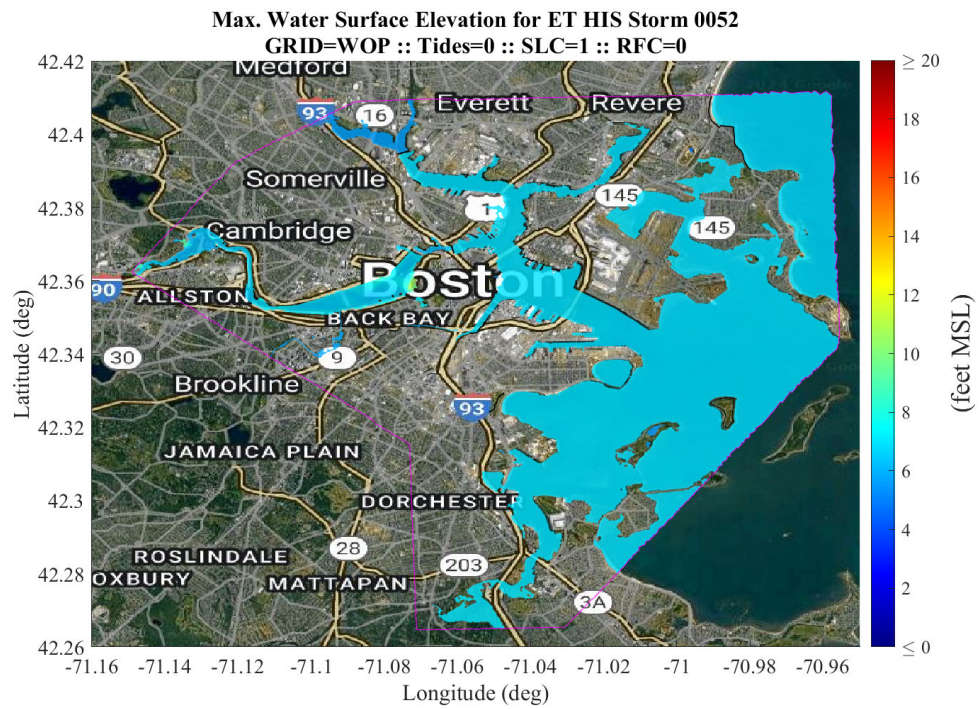


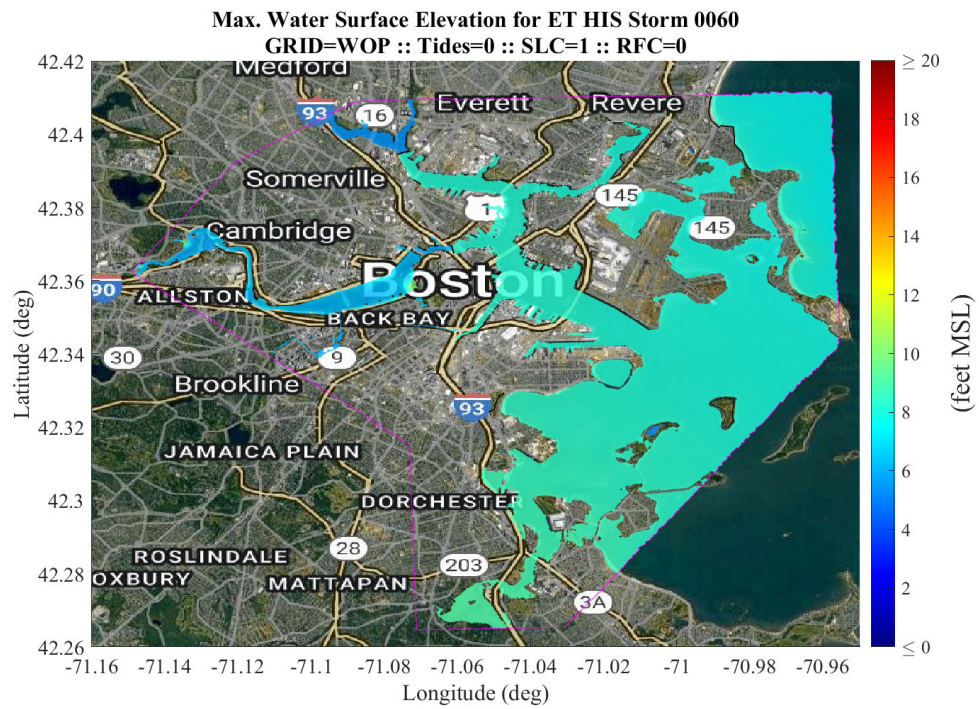


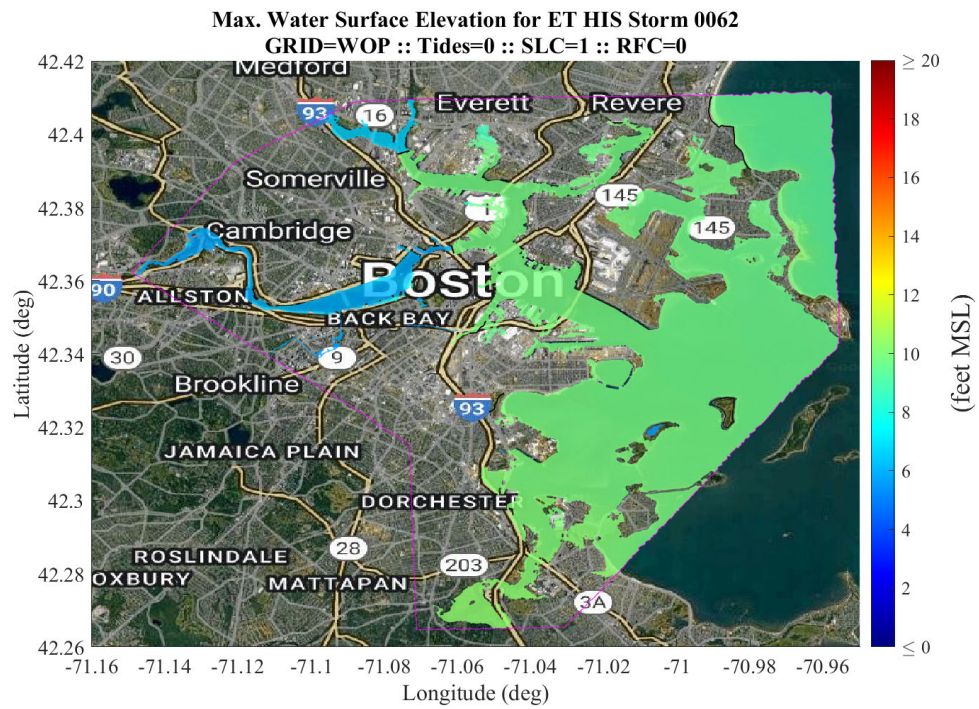


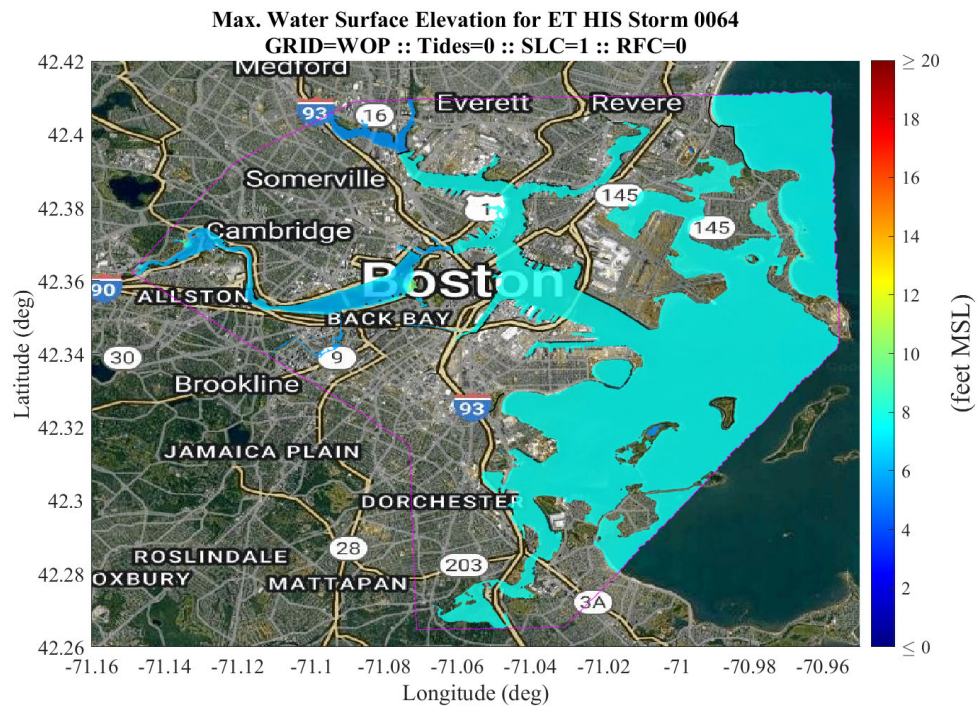


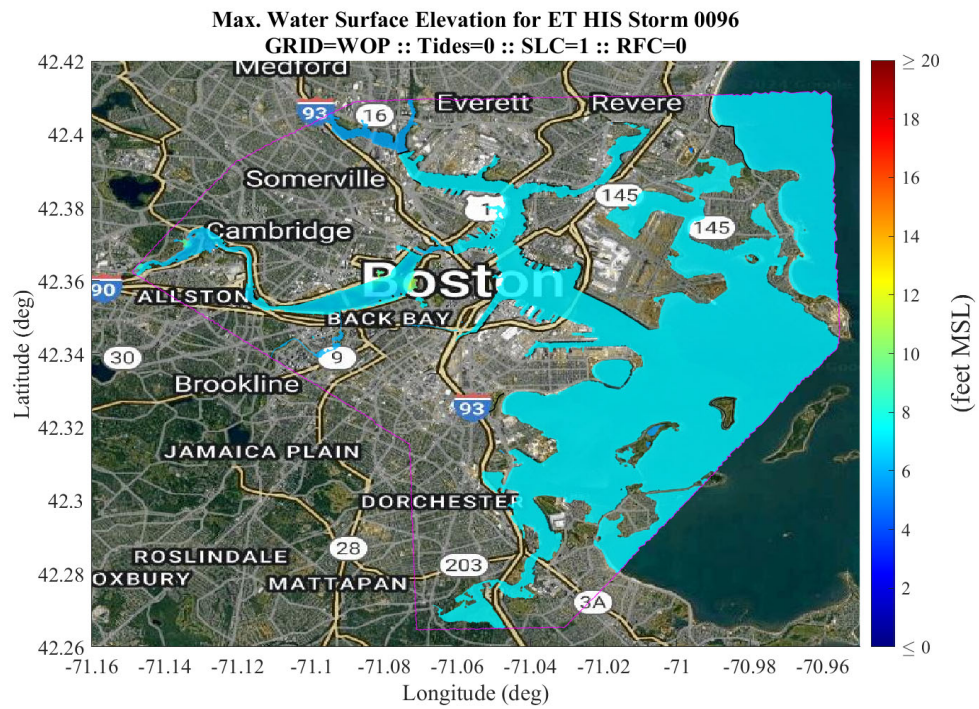


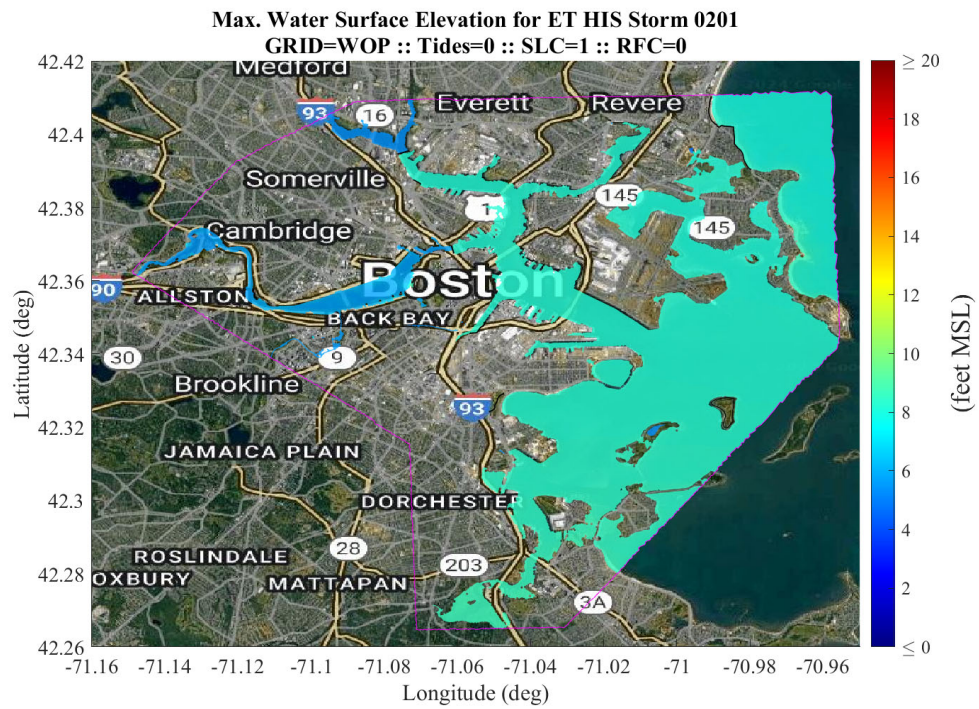


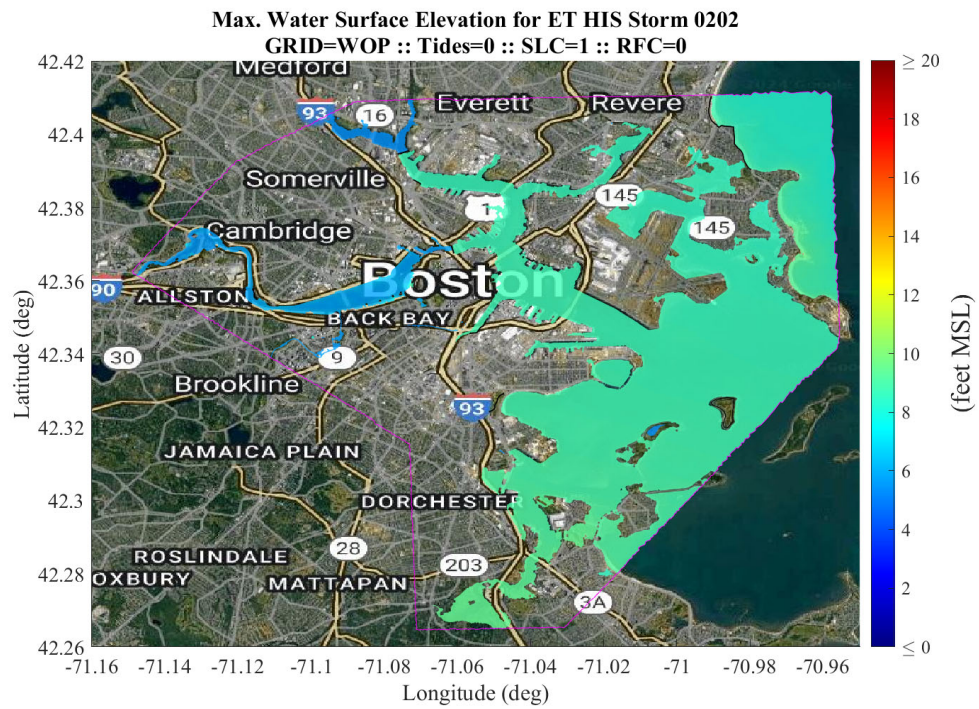






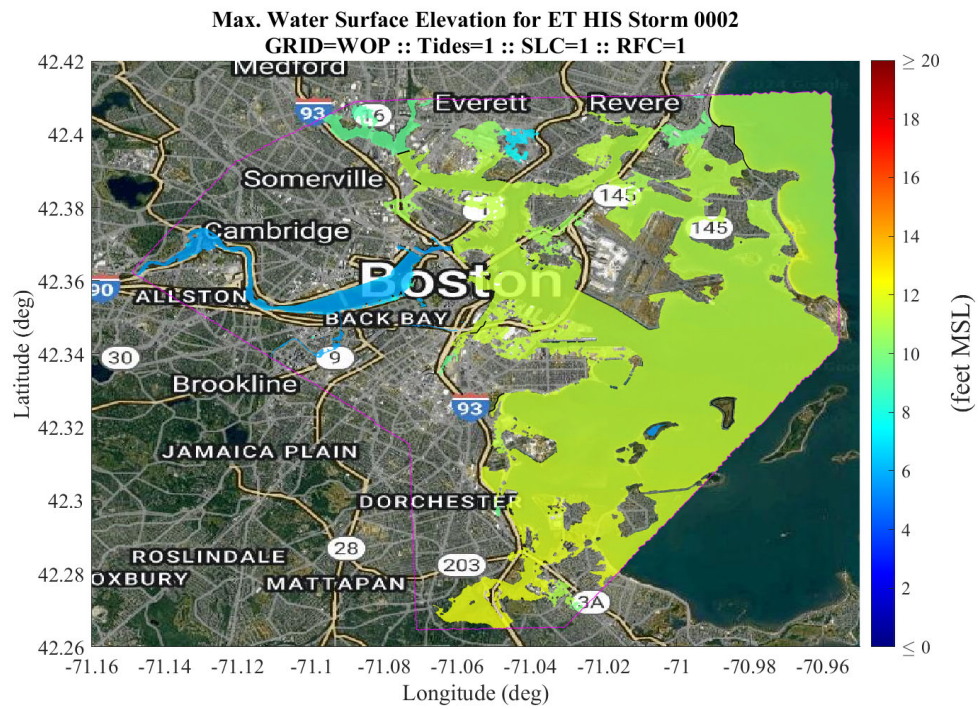


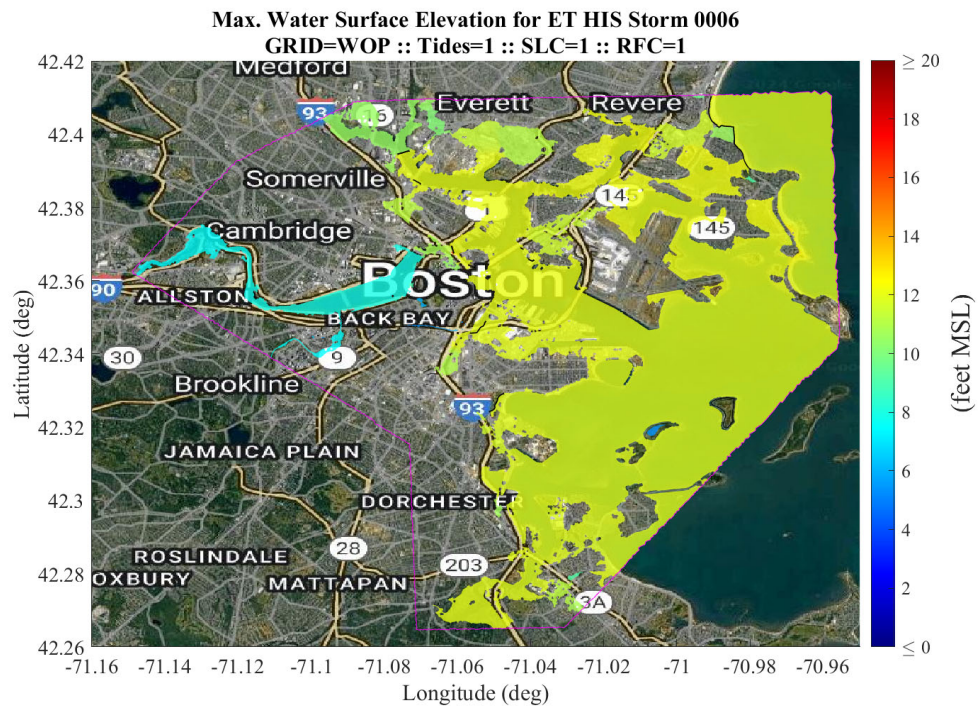


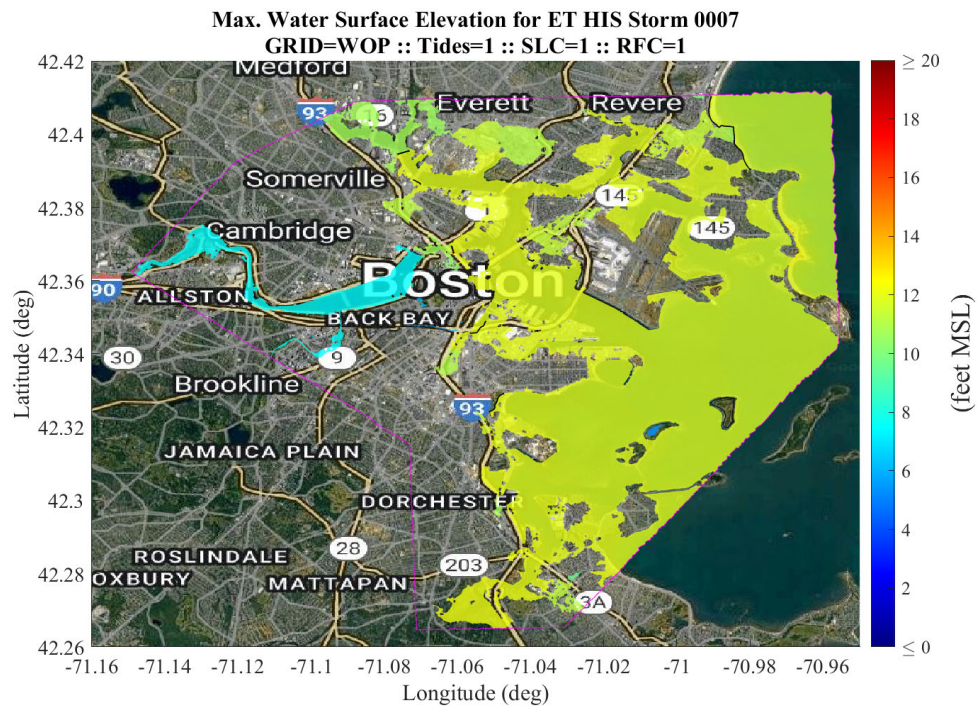


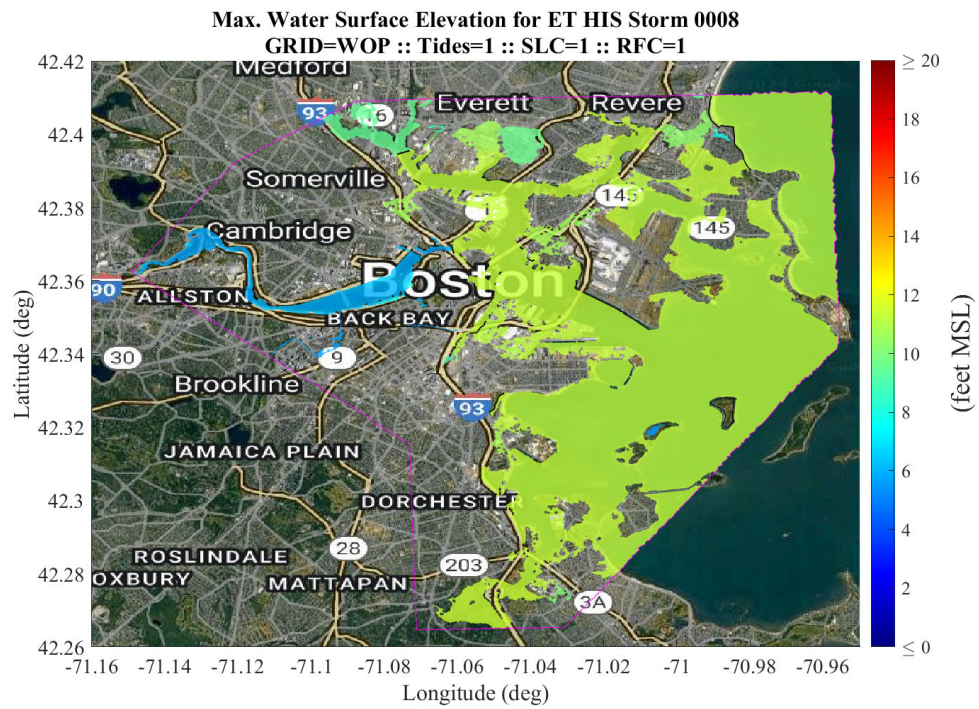
14 Appendix 5

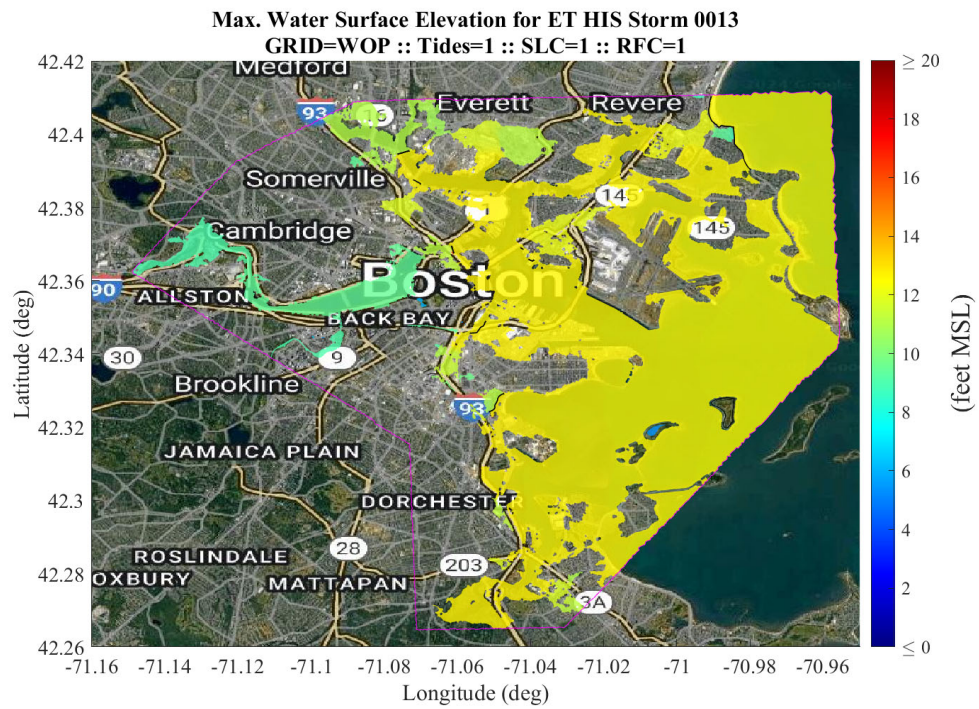
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 17 historical XC events for SLC1 and historical tides.

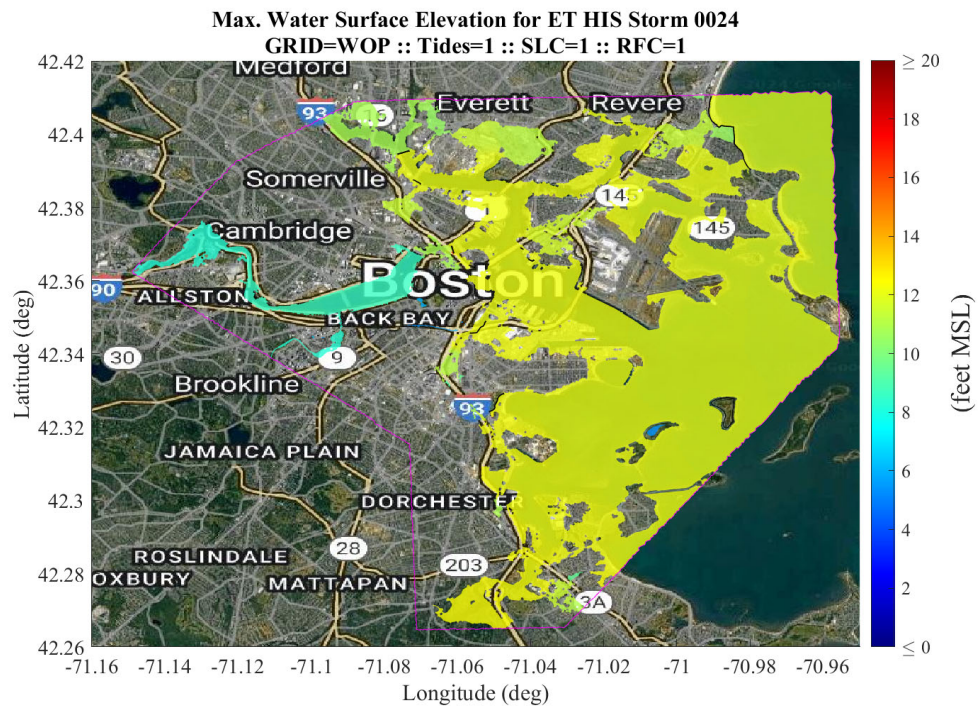


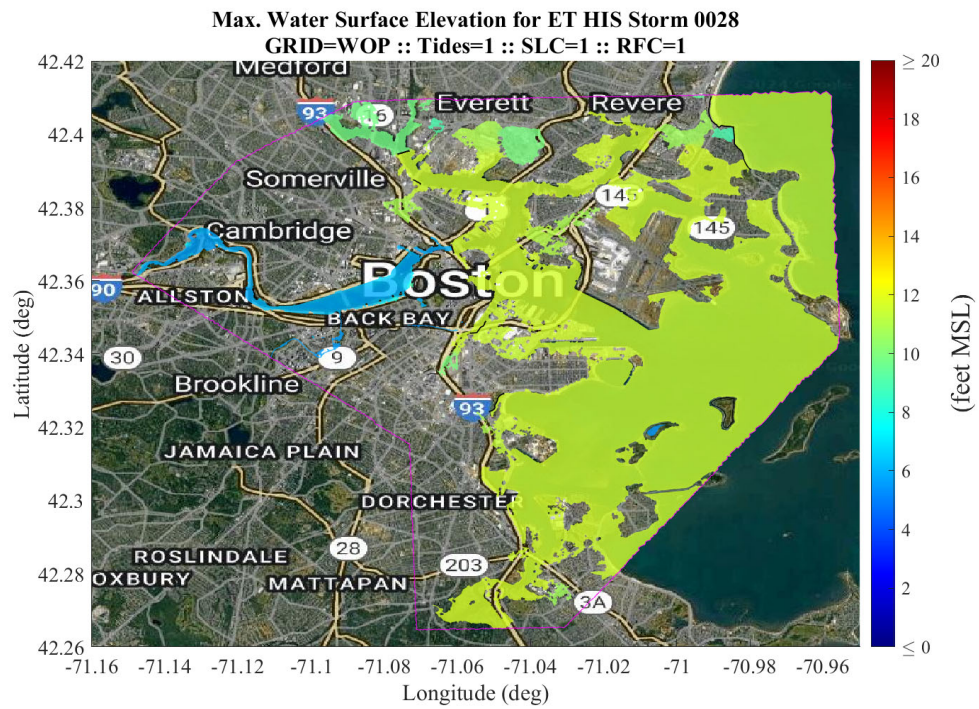


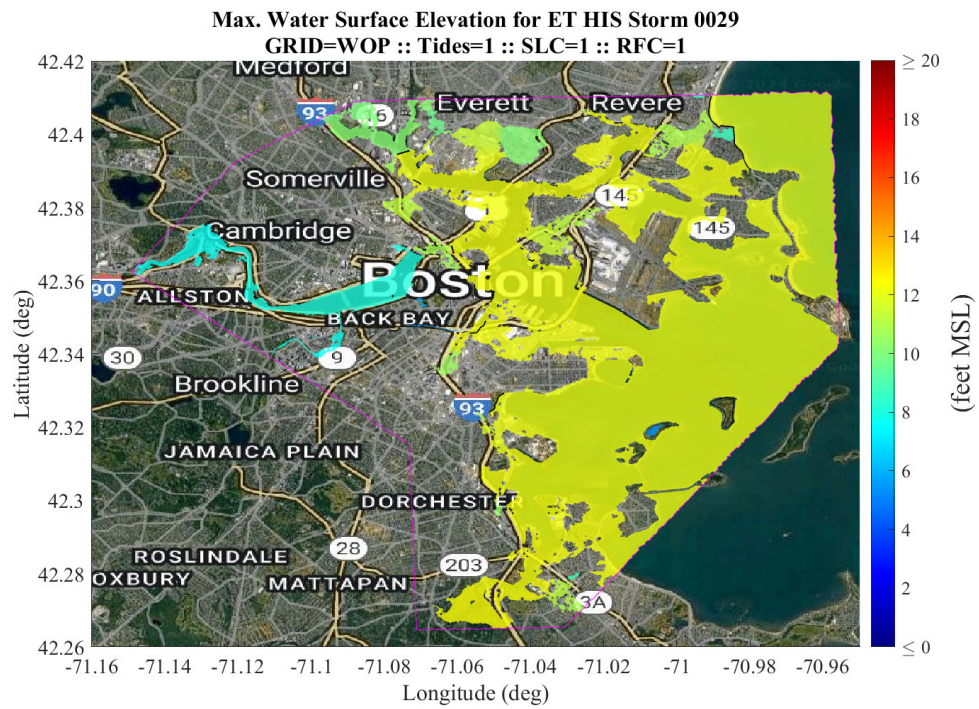


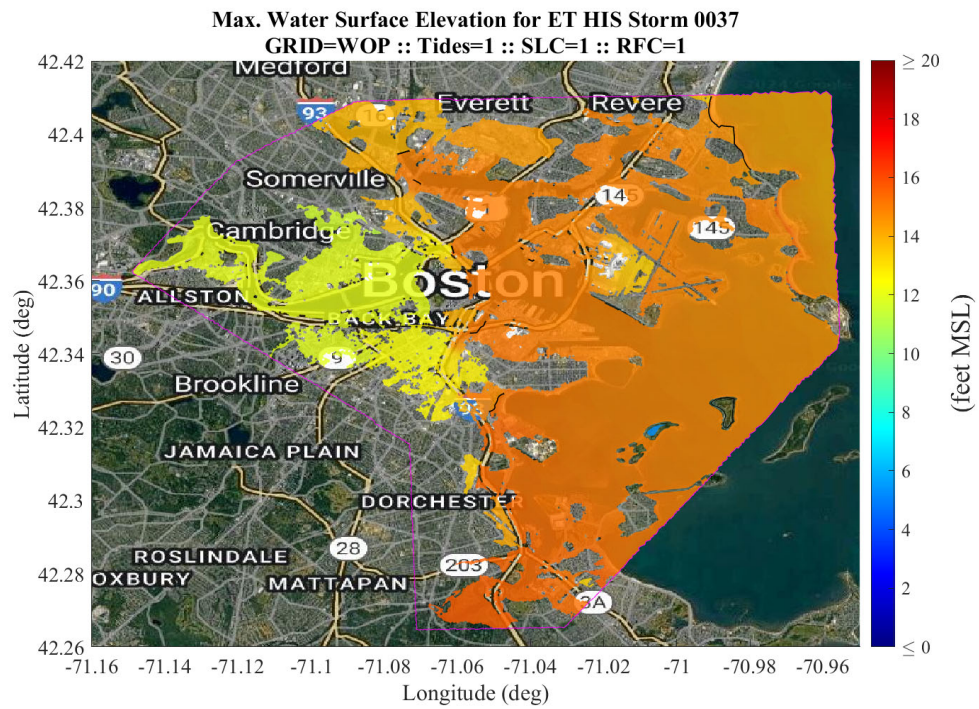


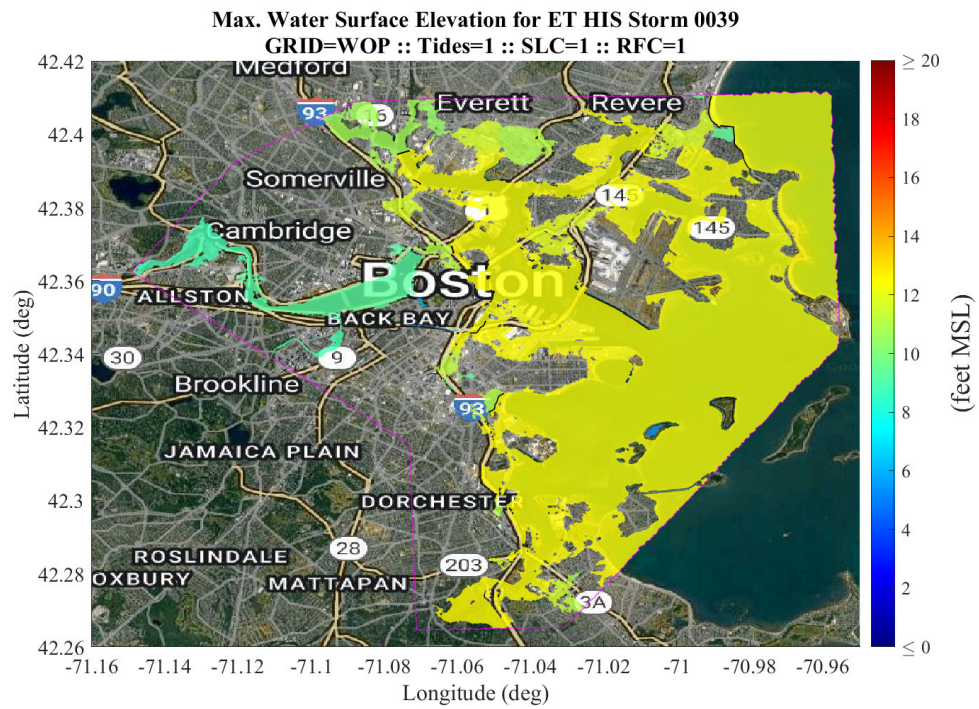


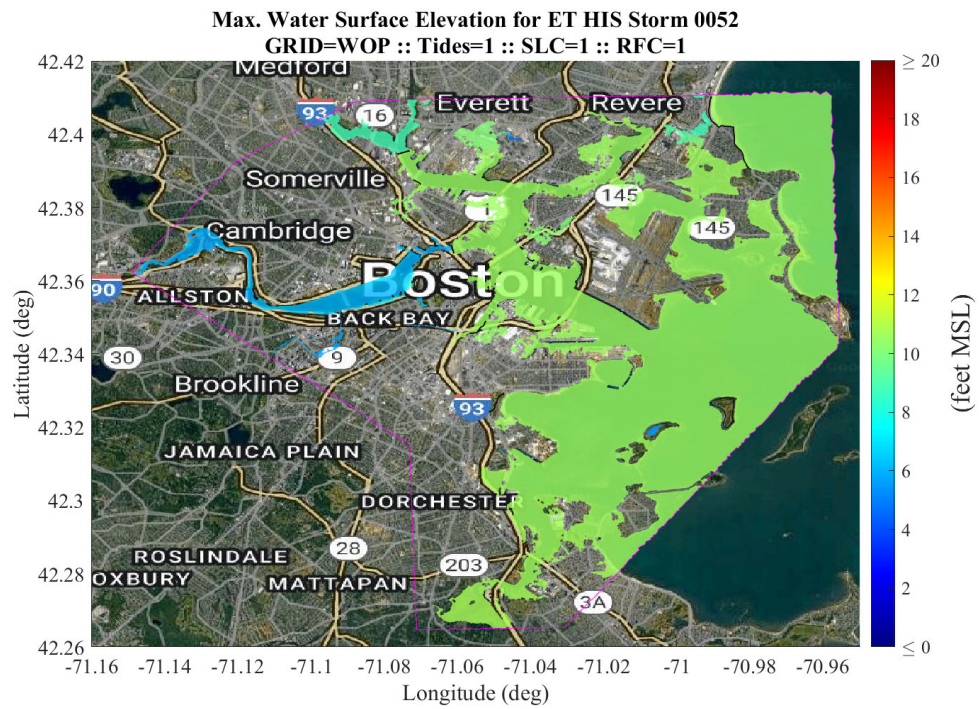


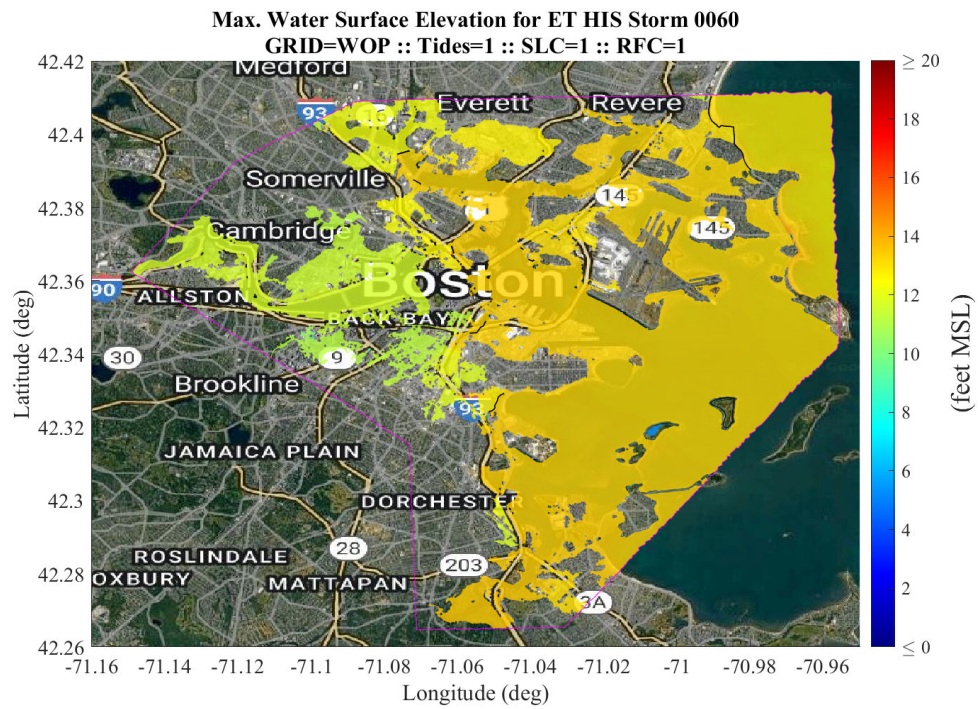


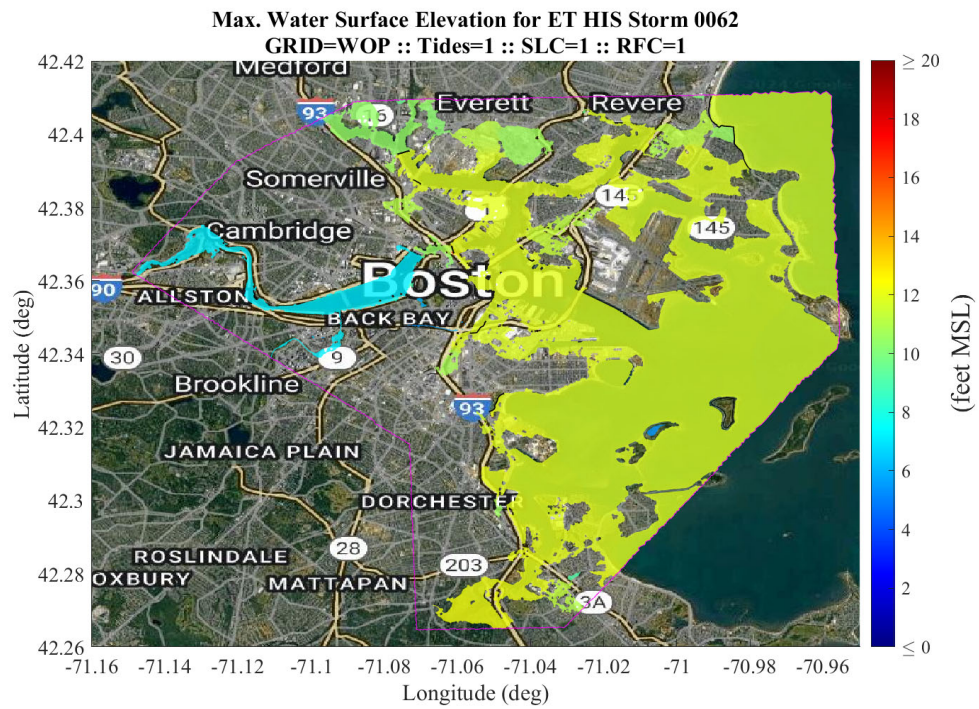


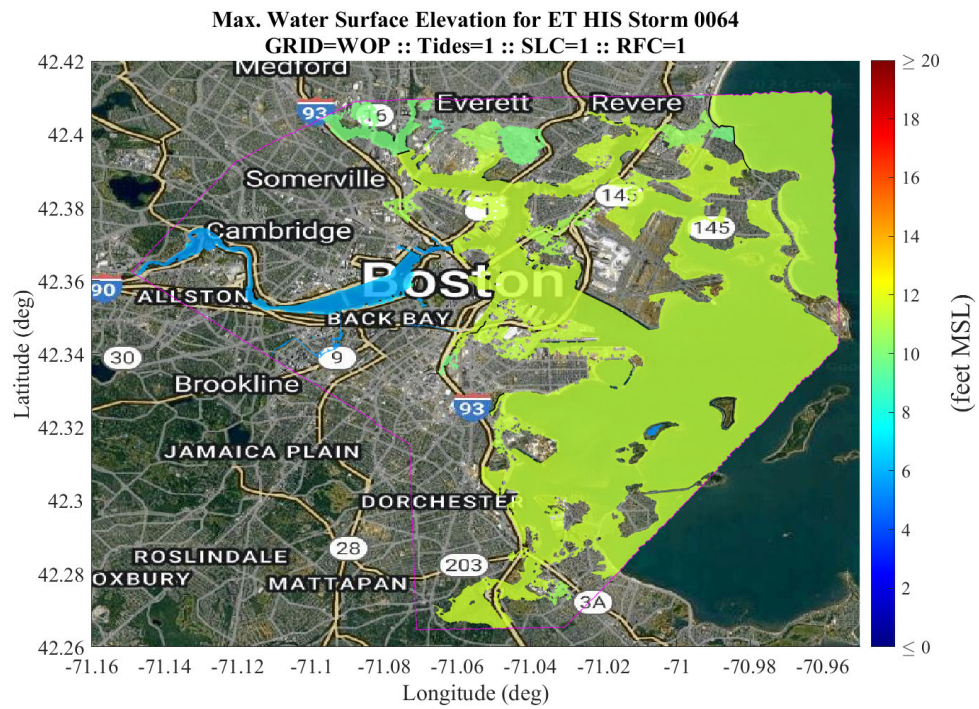


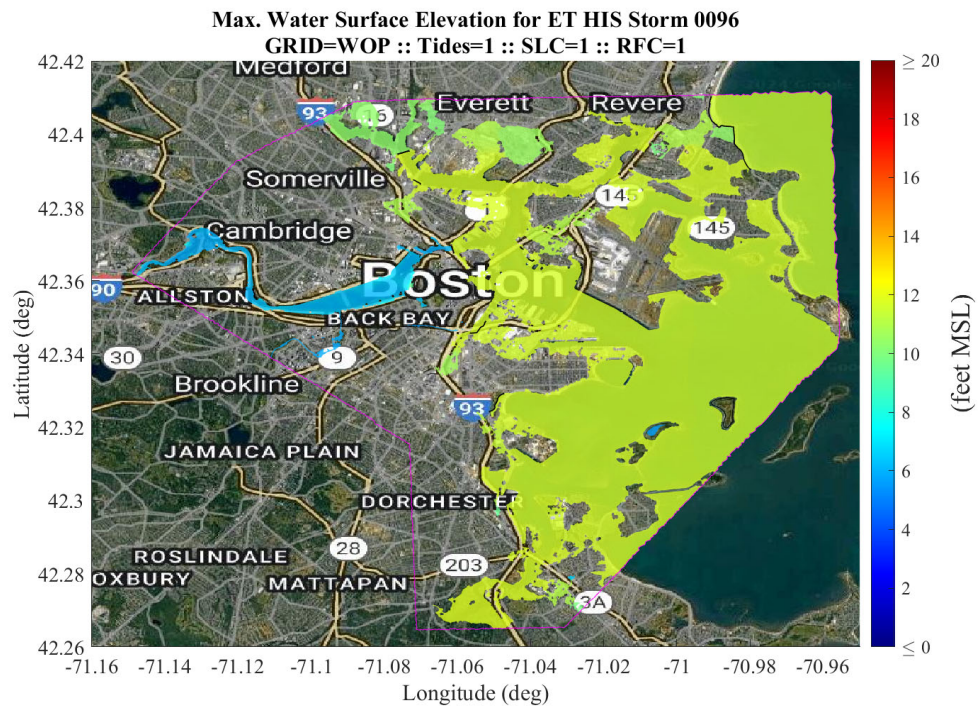


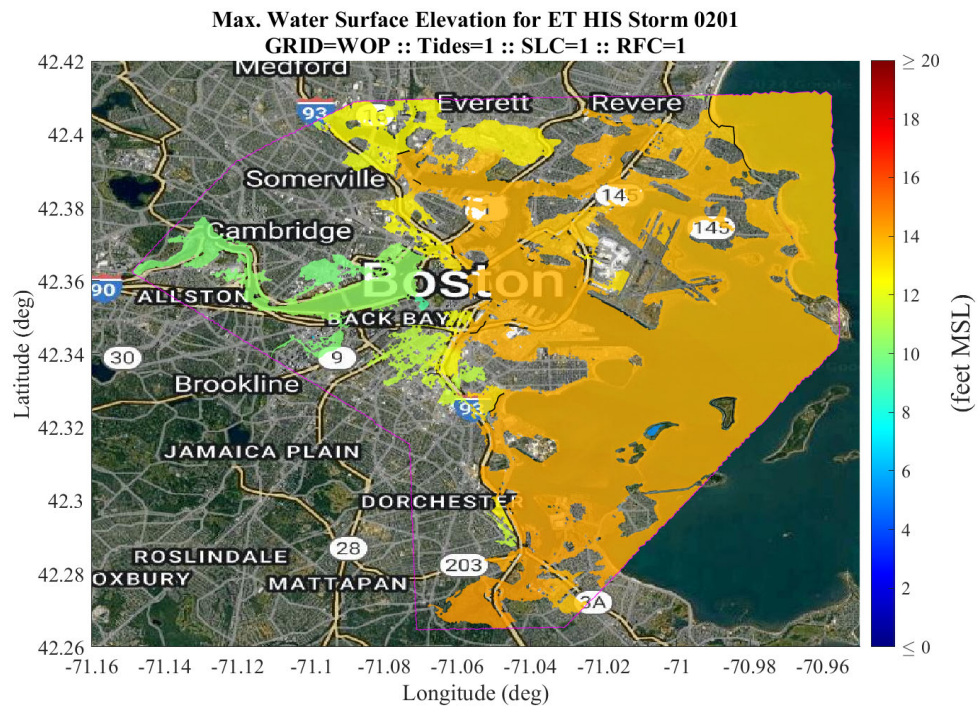


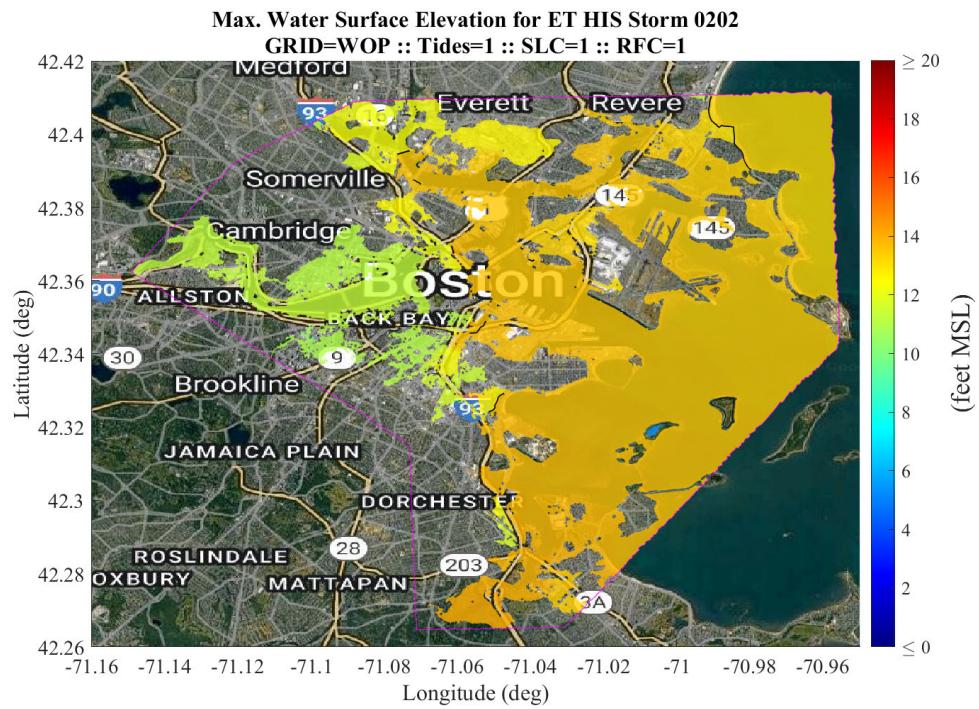






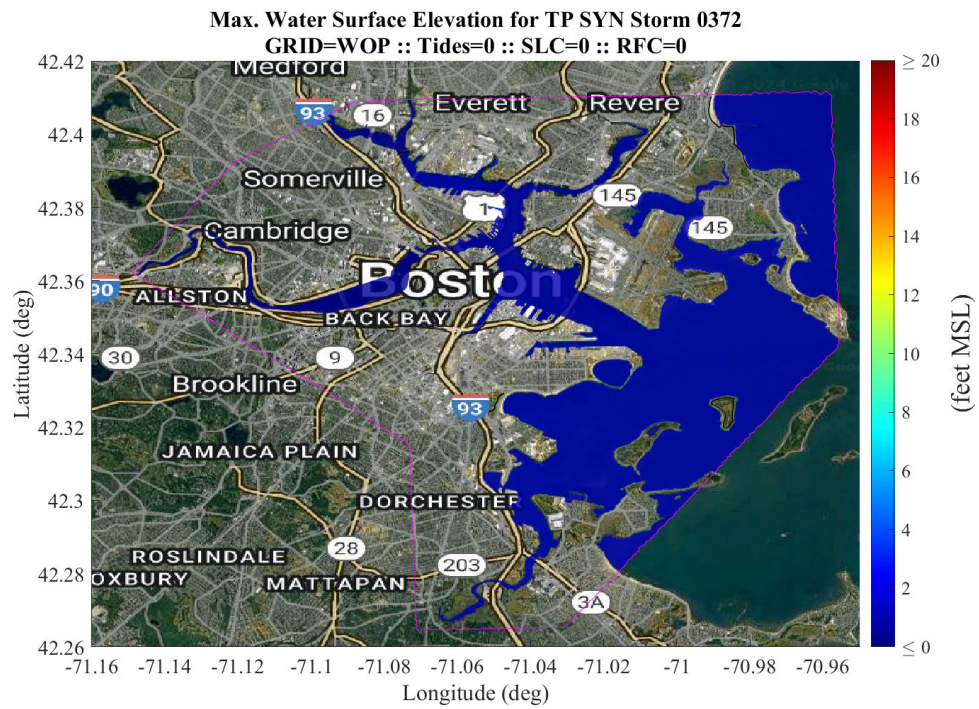


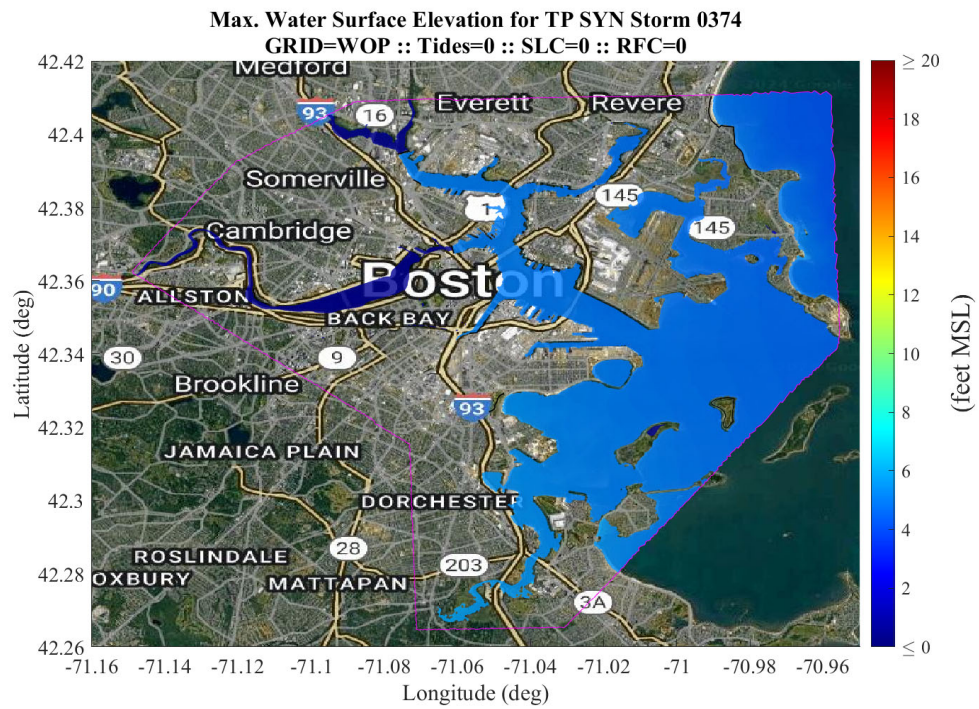


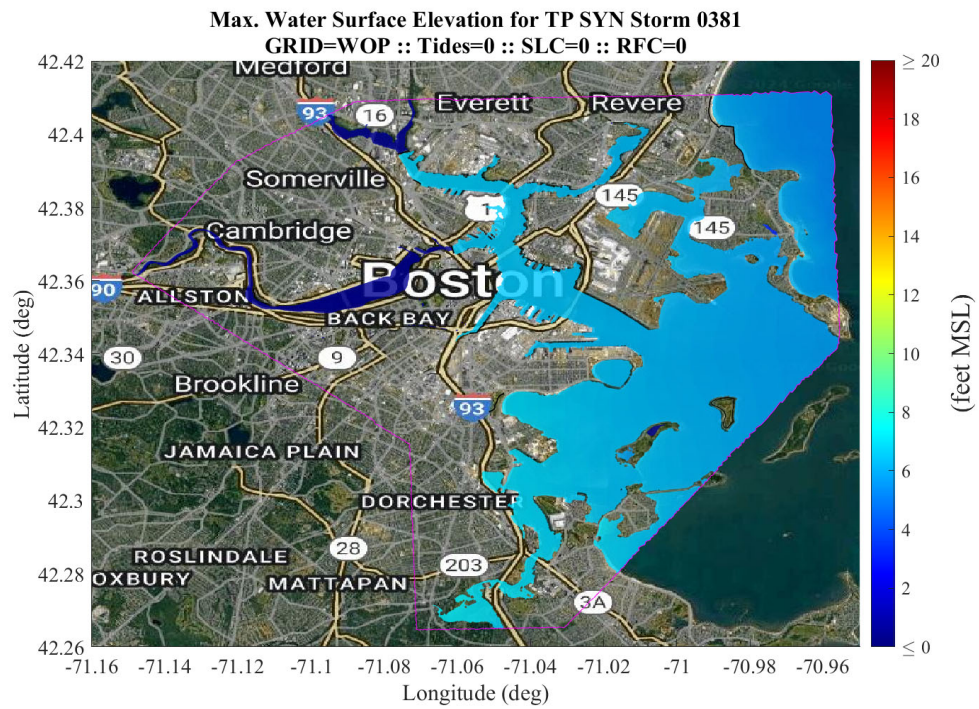


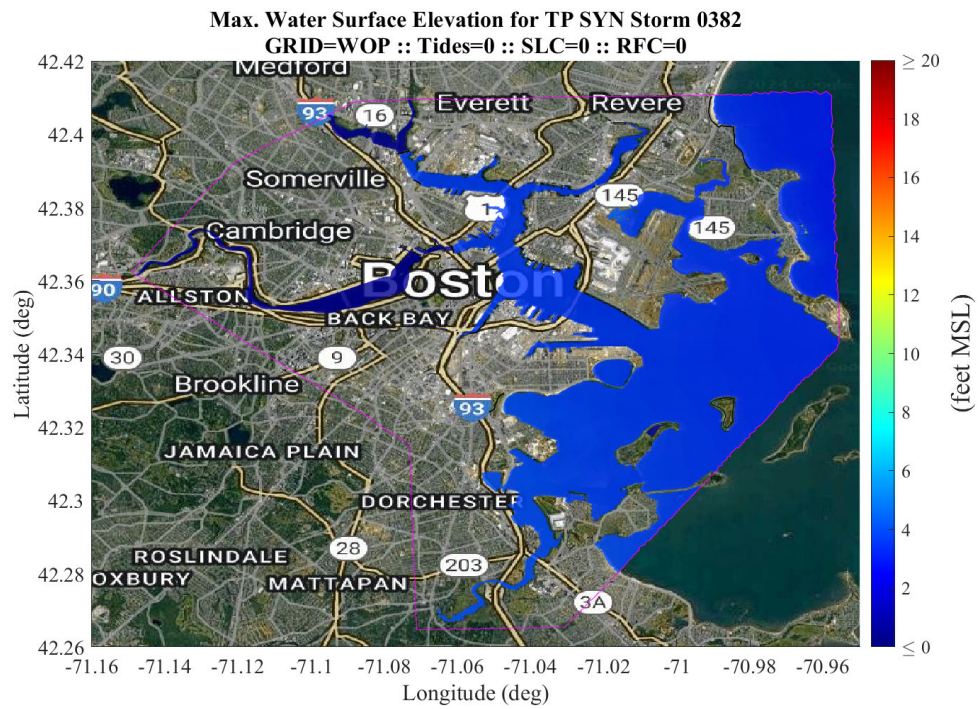
15 Appendix 6

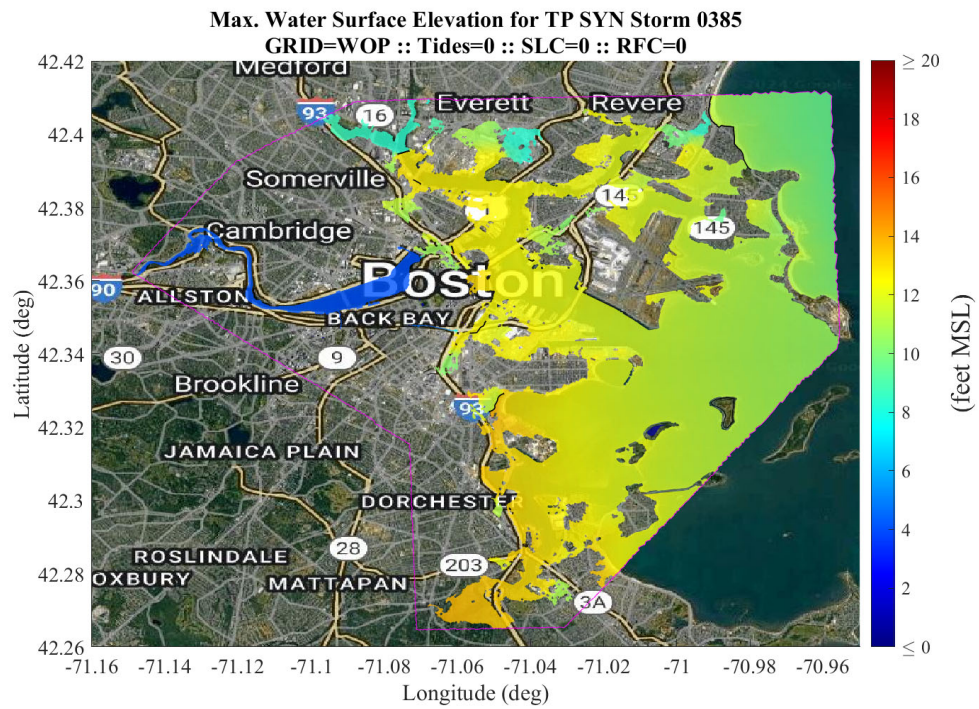
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 60 synthetic tropical cyclone TC events for SLC0 and no tides.

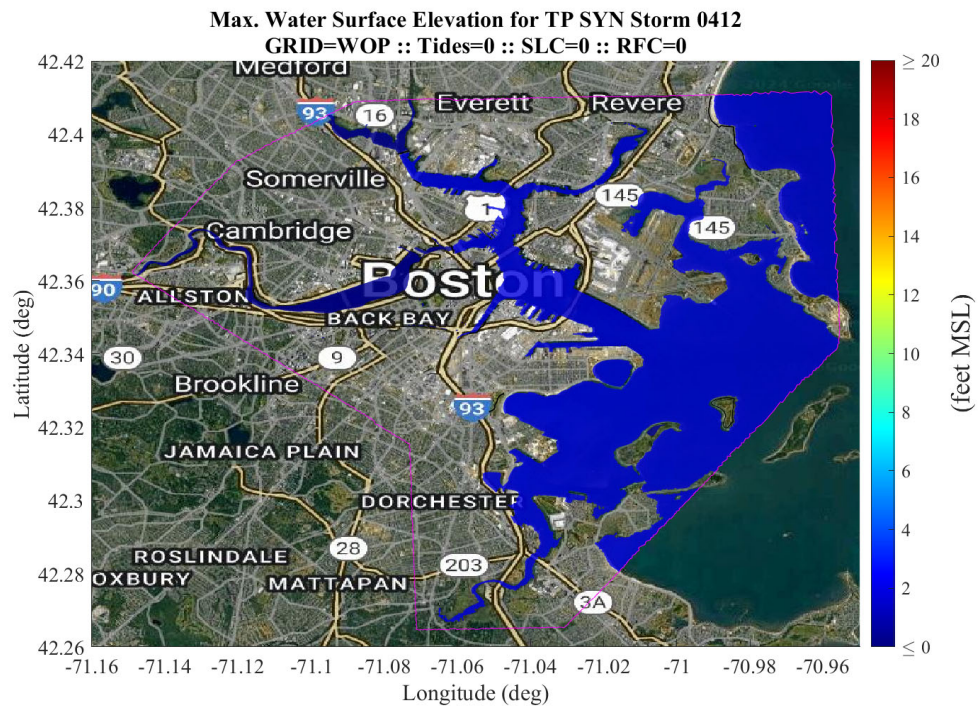


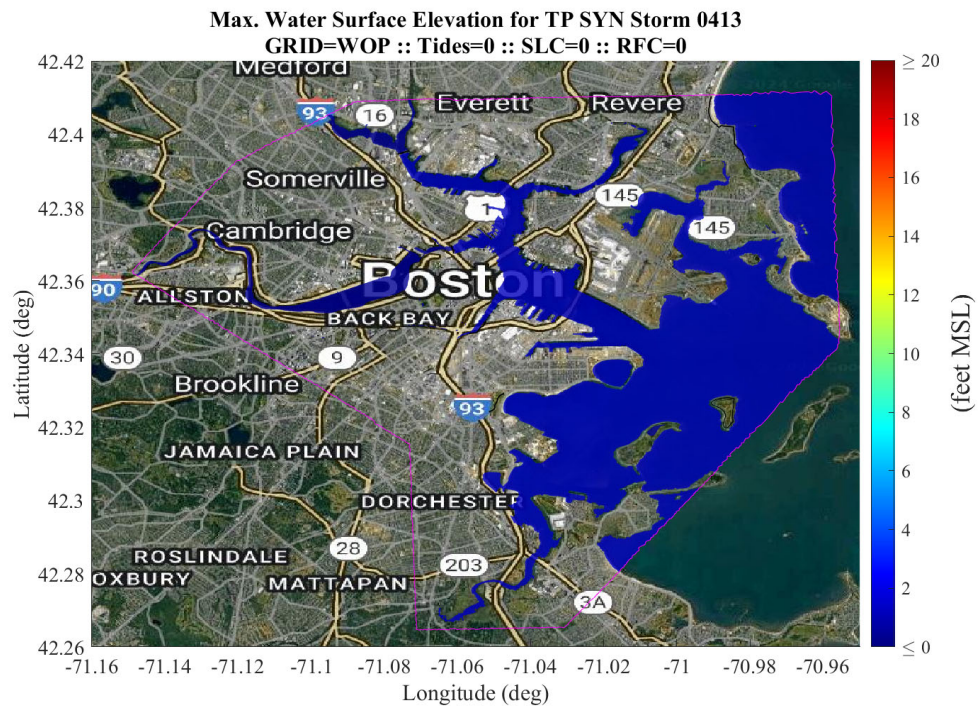


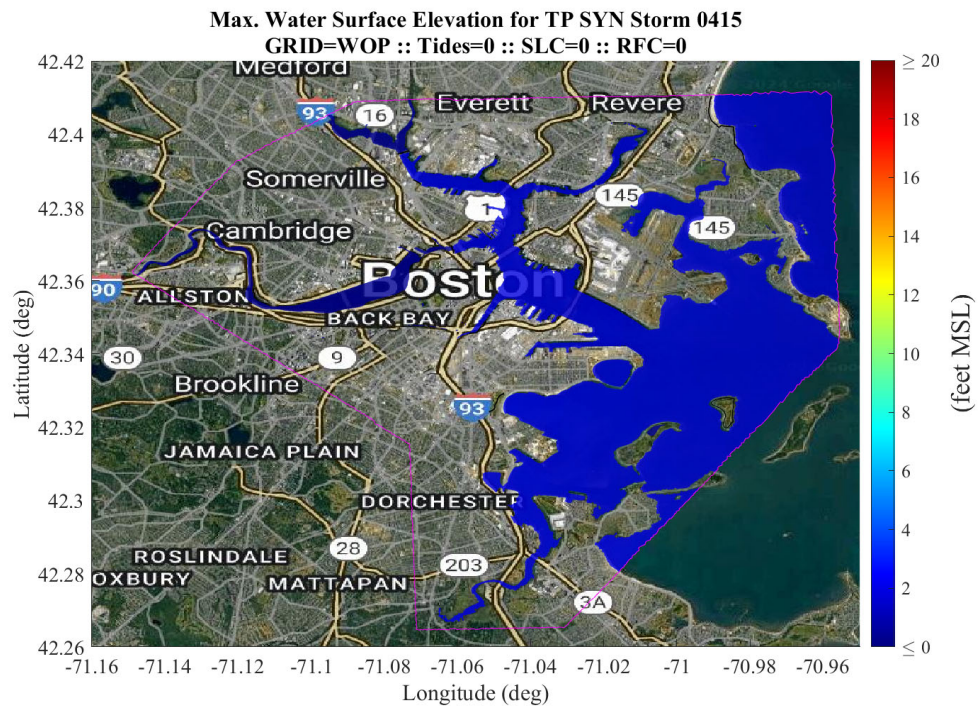


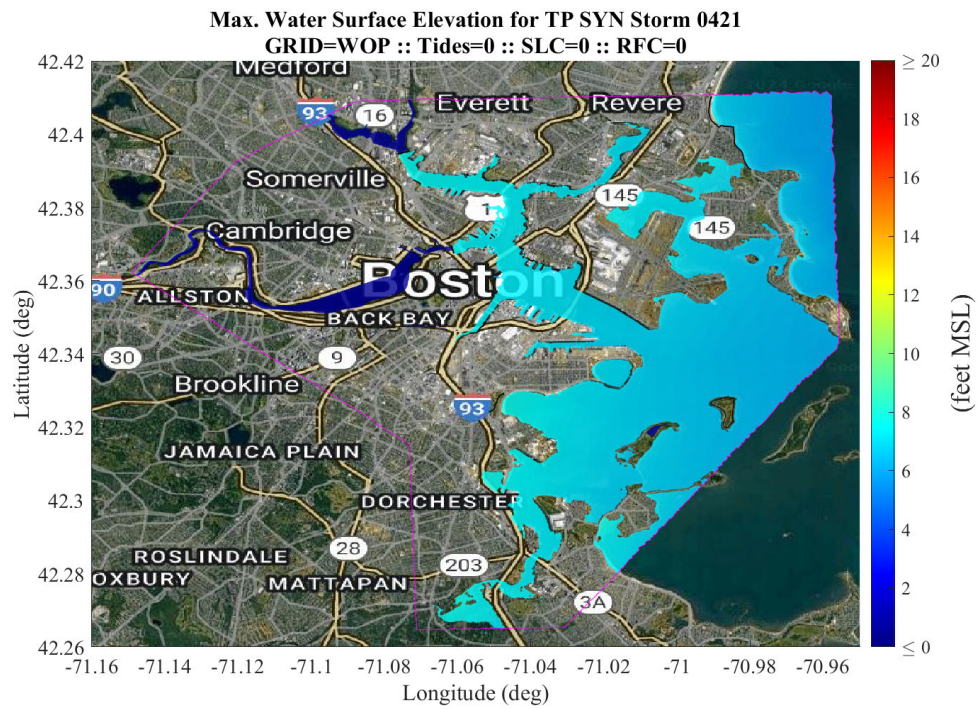


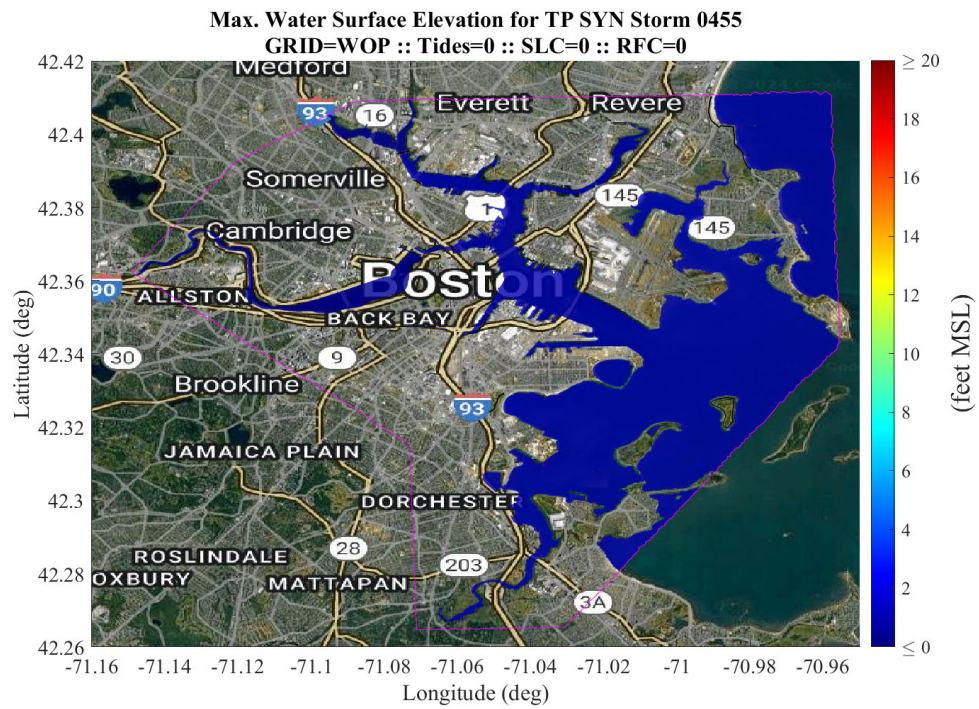


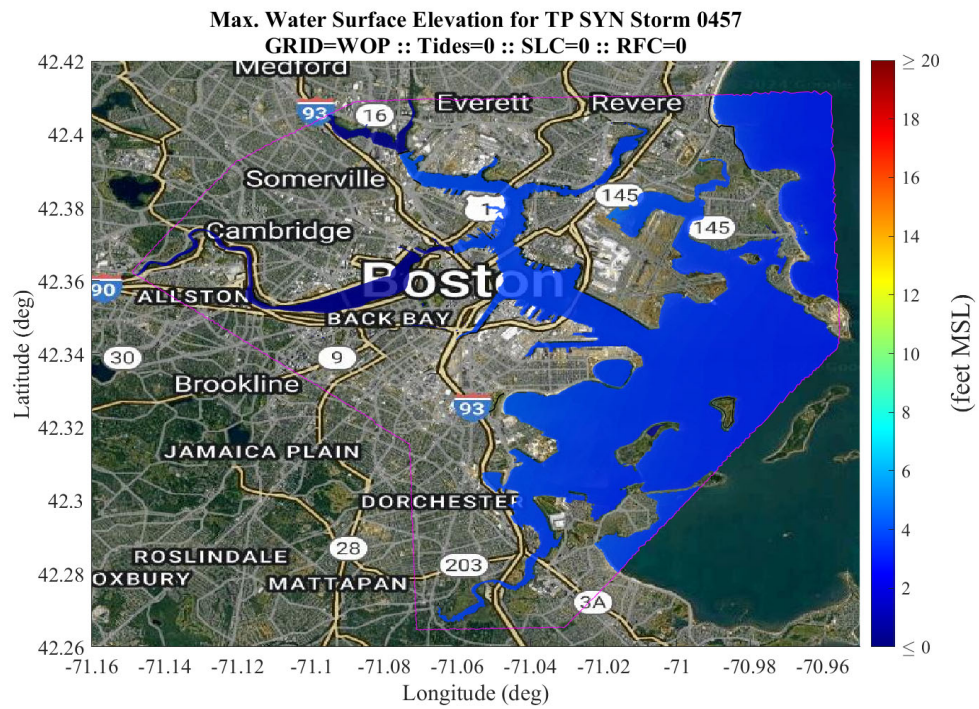


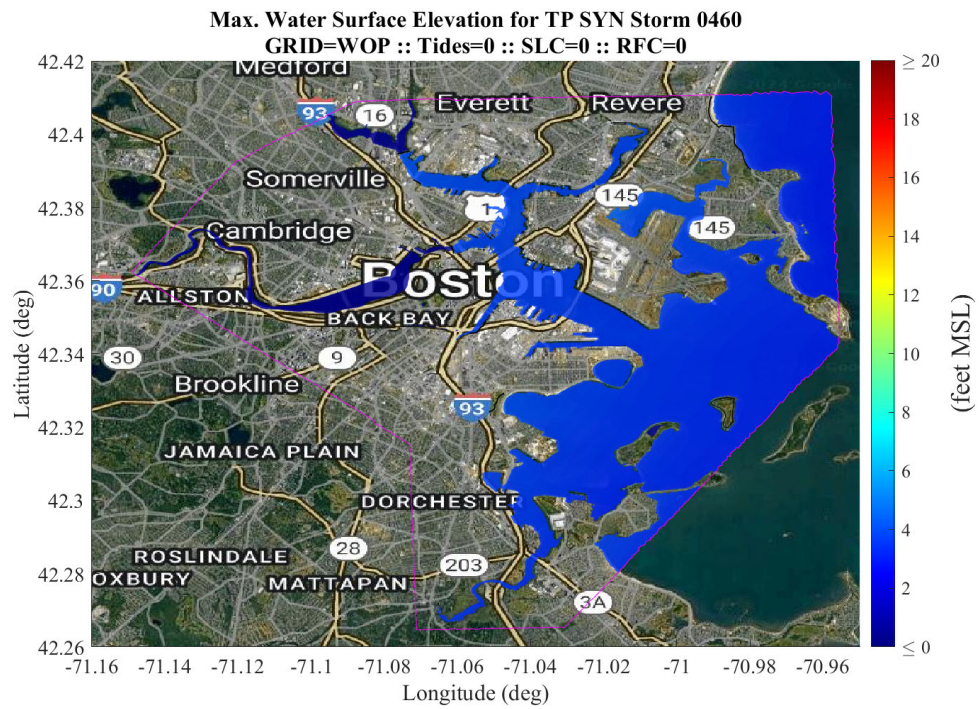


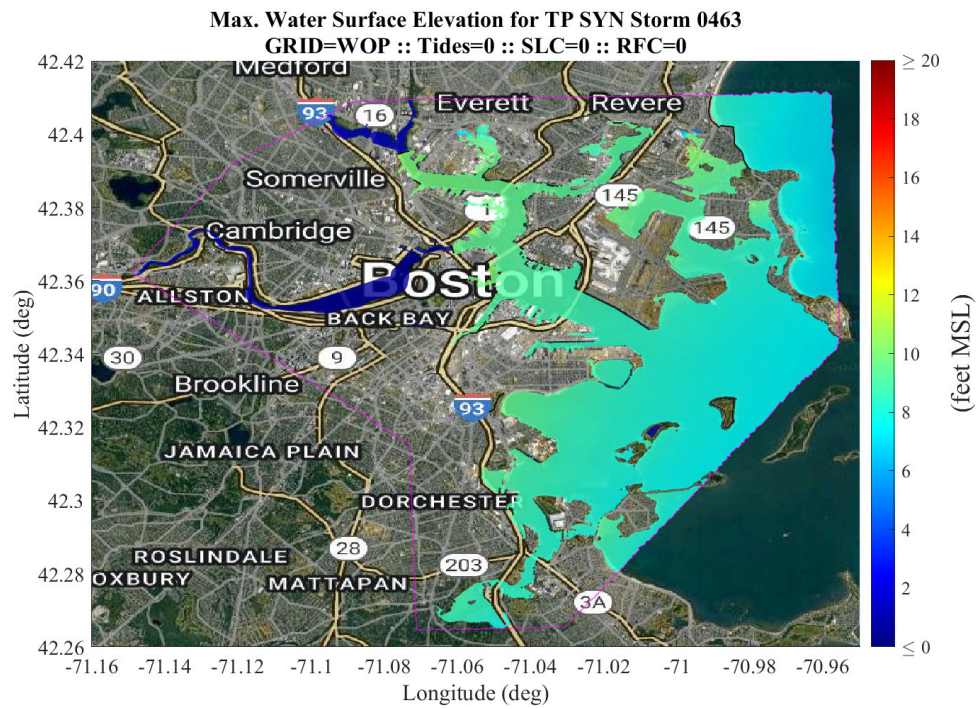


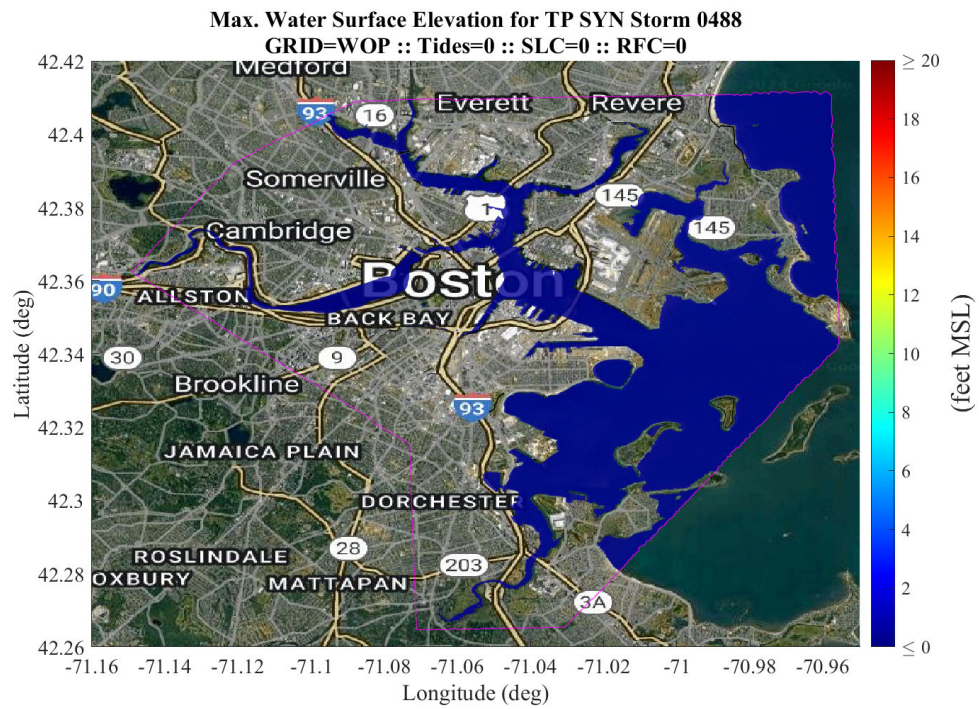


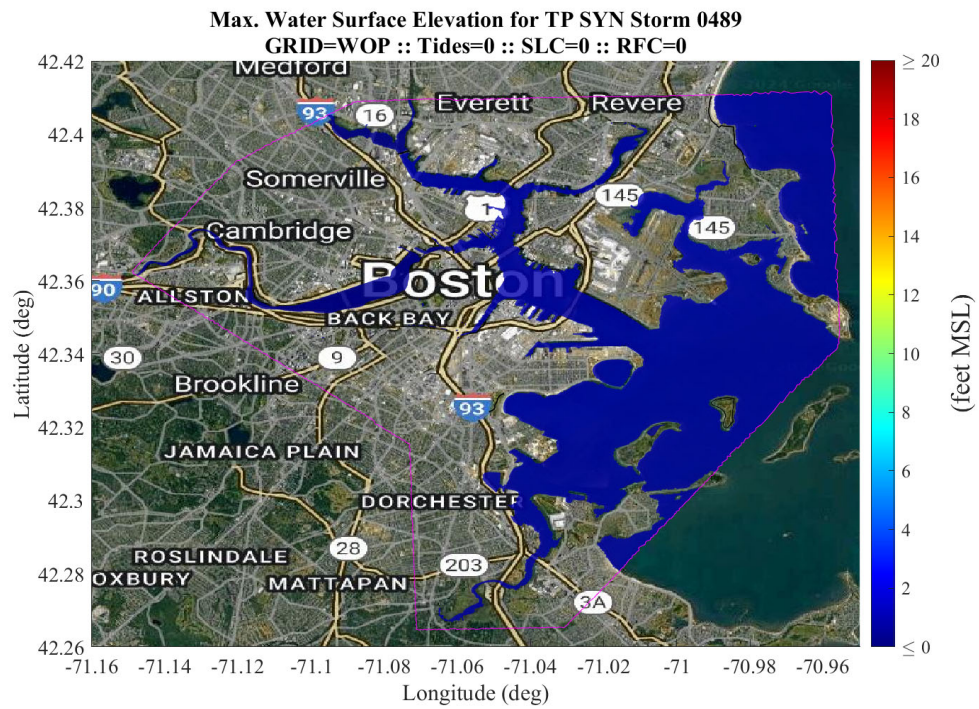


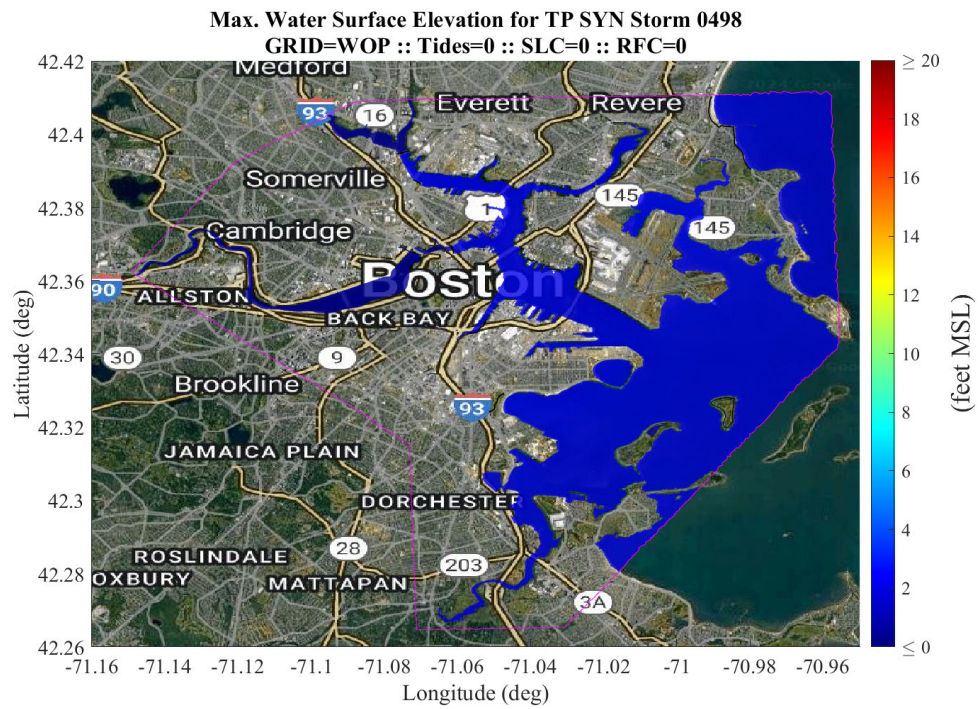


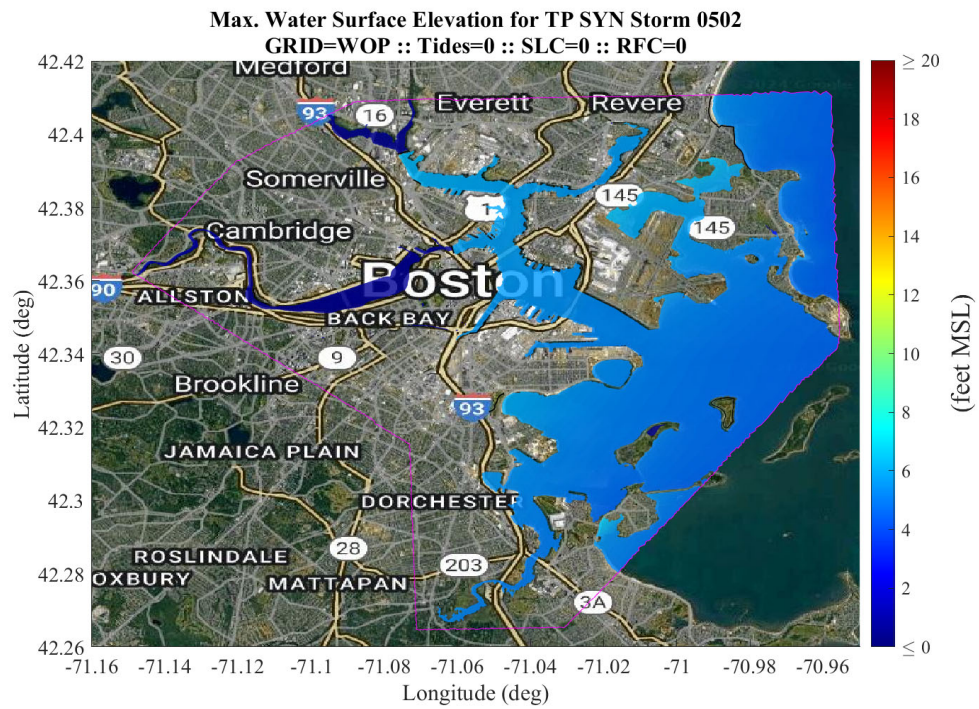


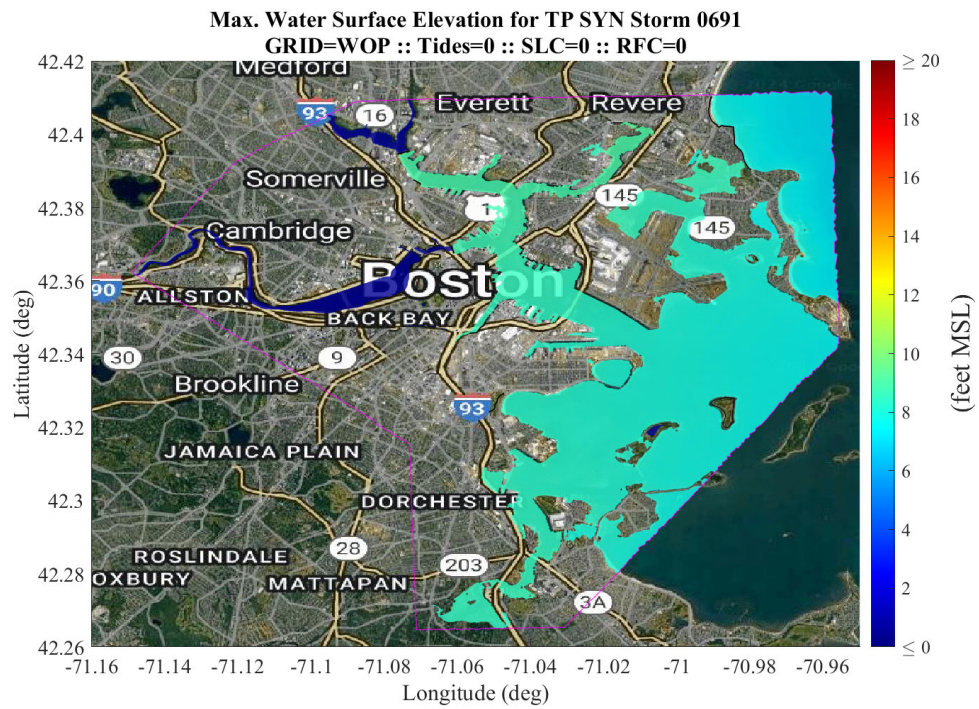


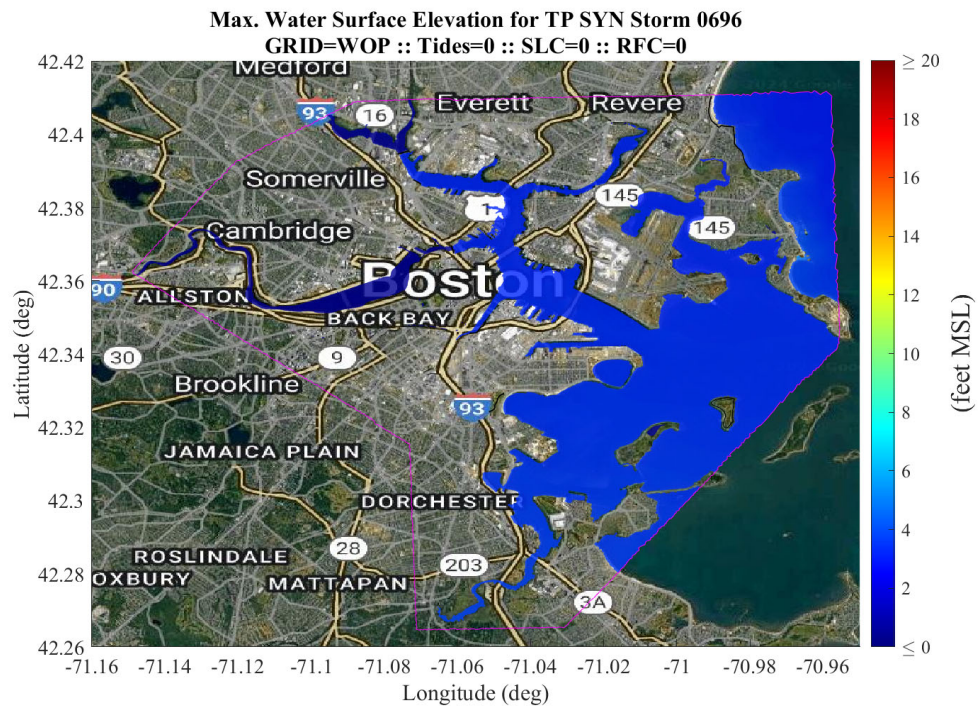


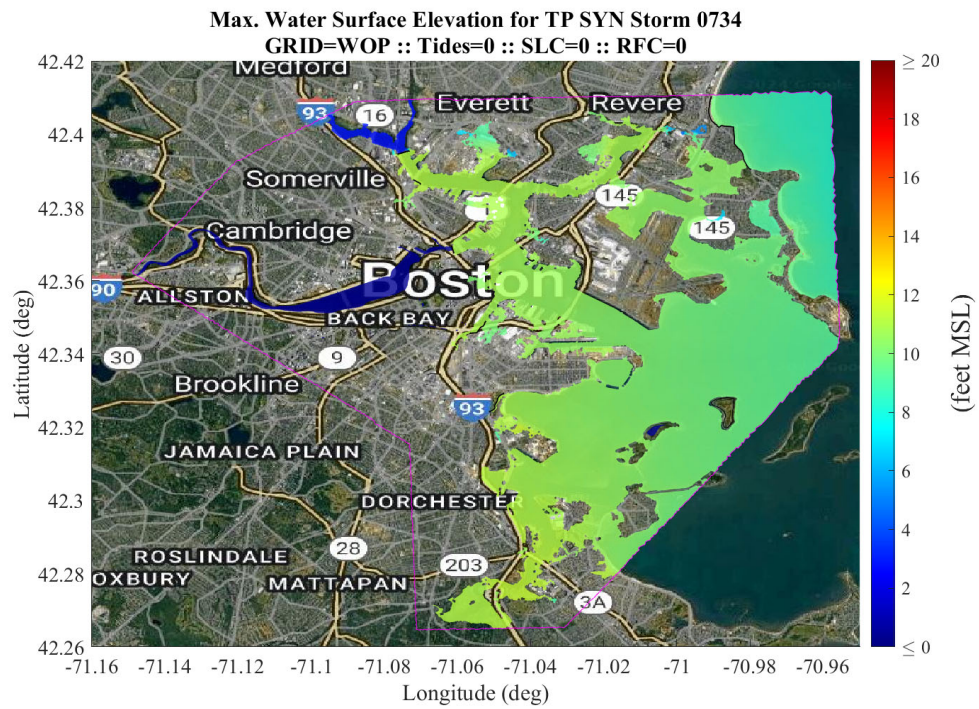


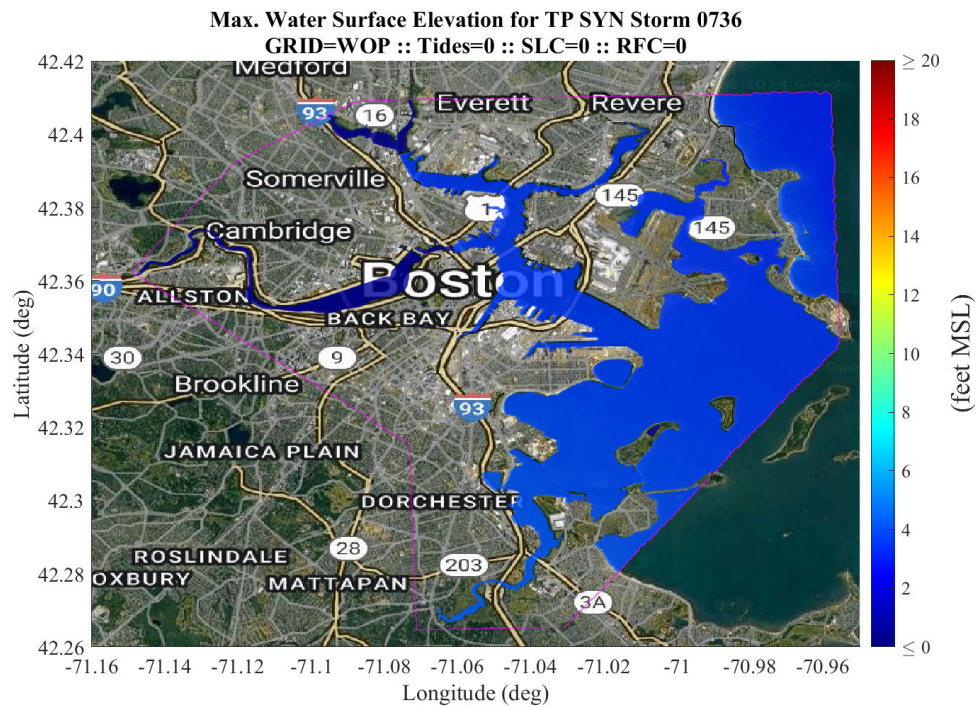


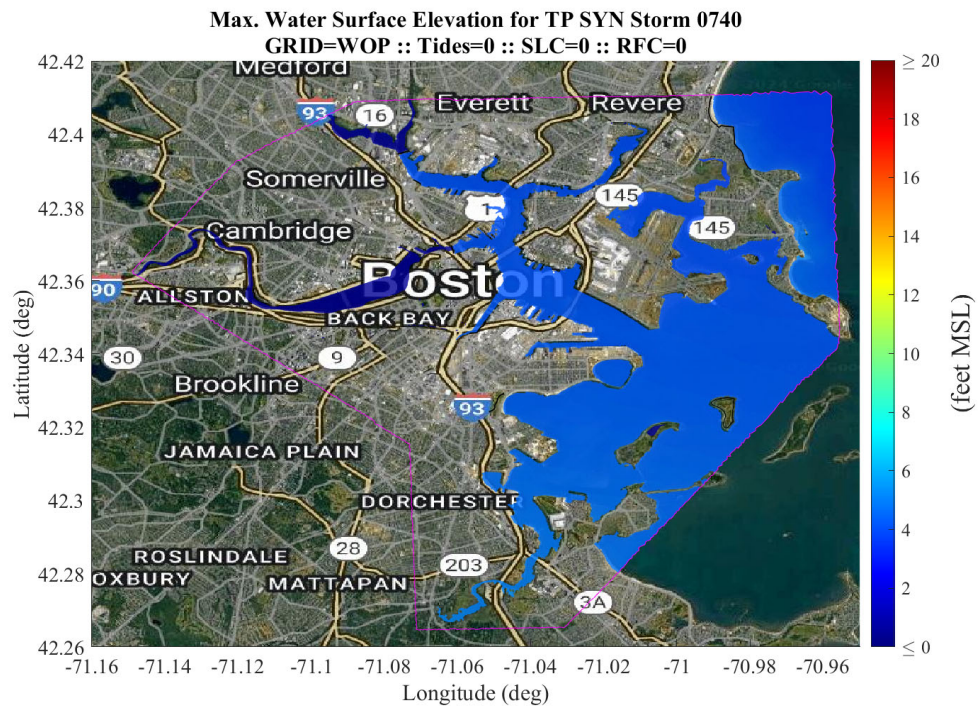


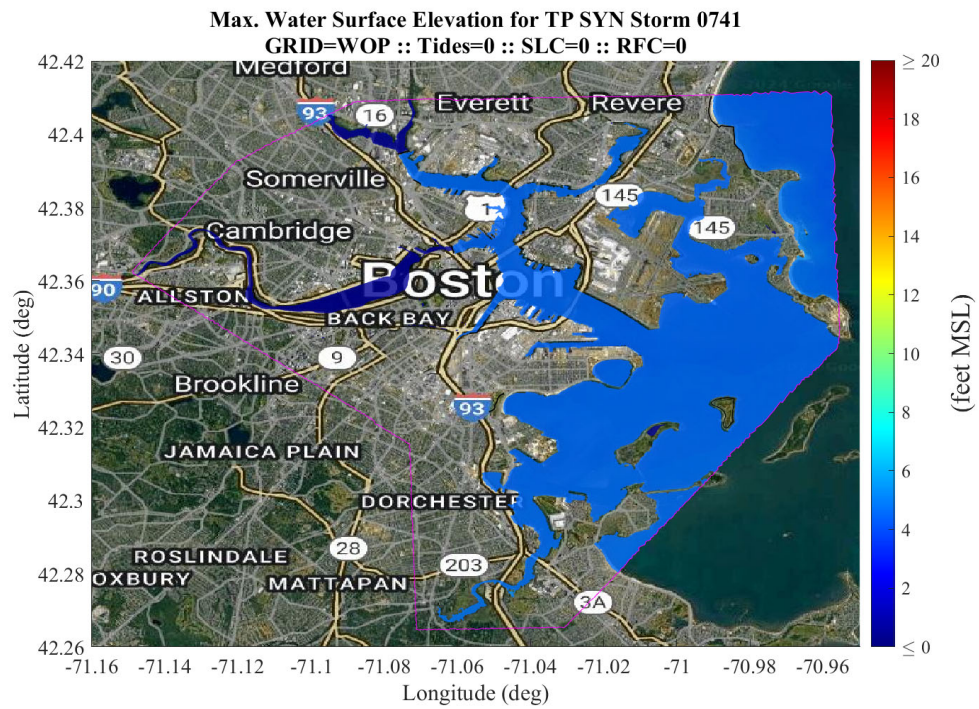


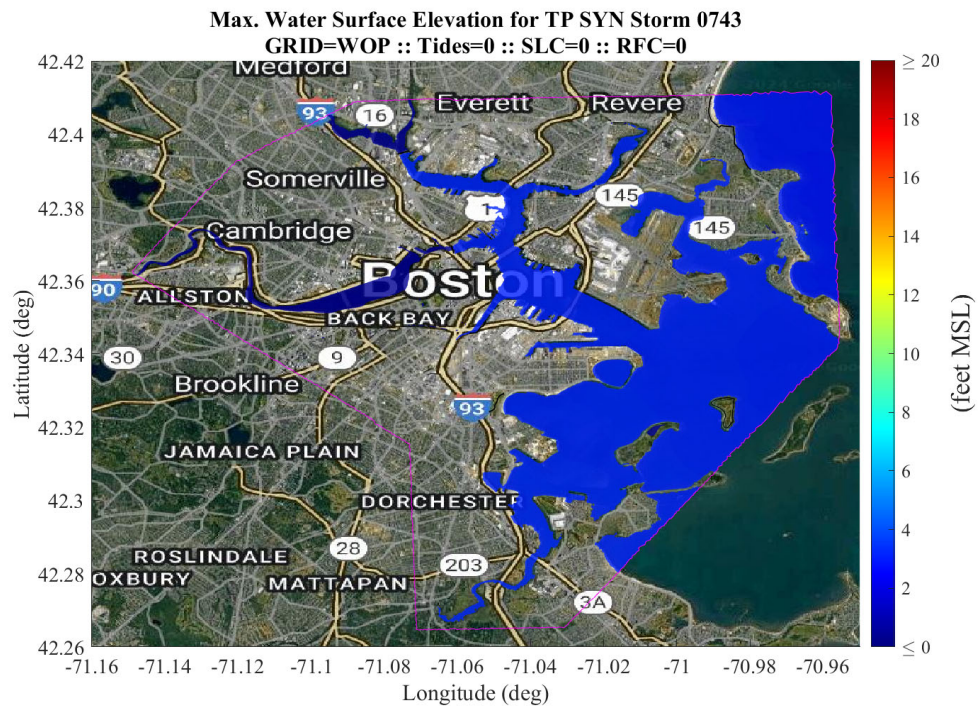


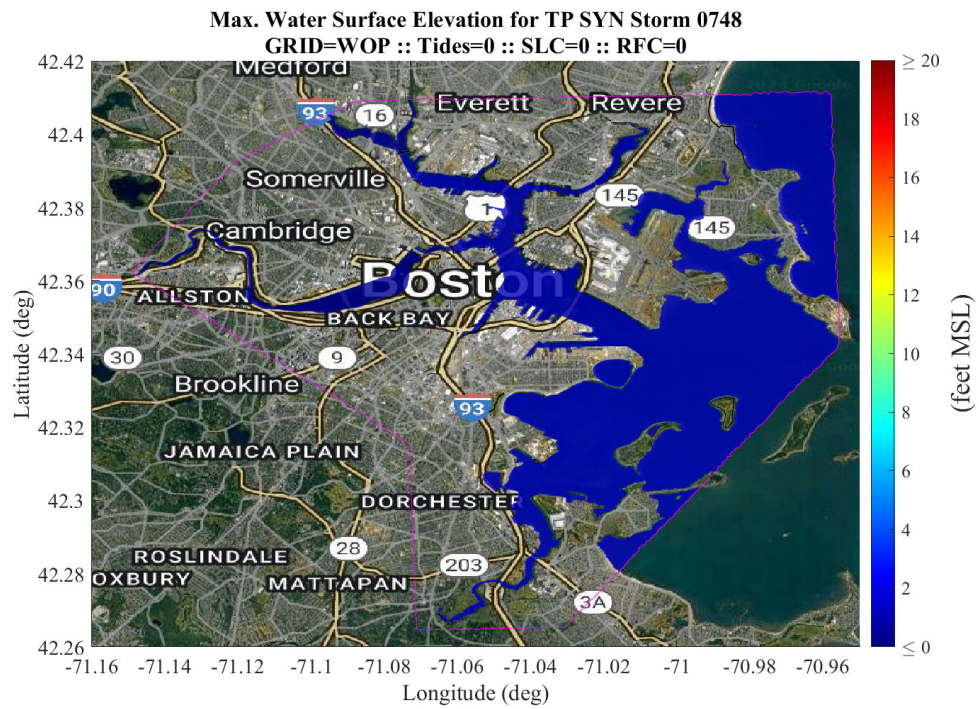


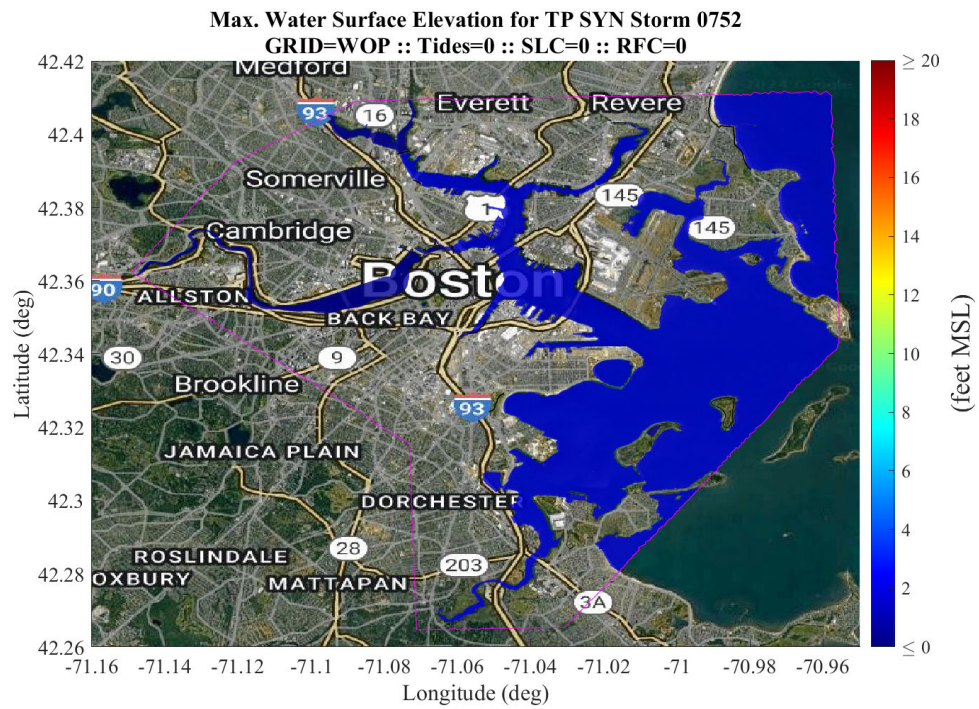


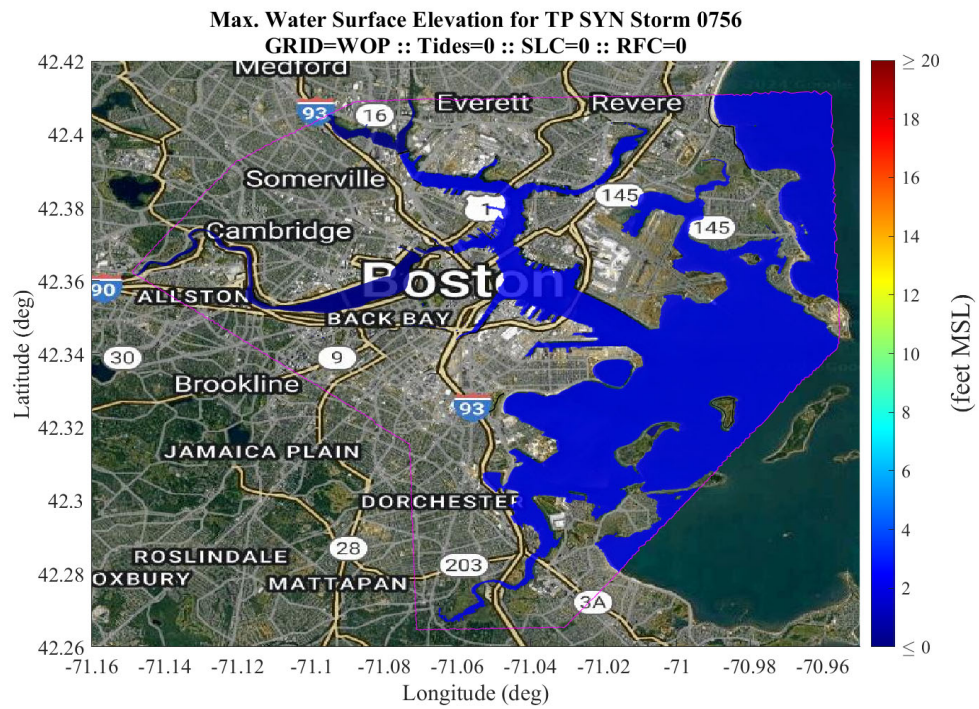


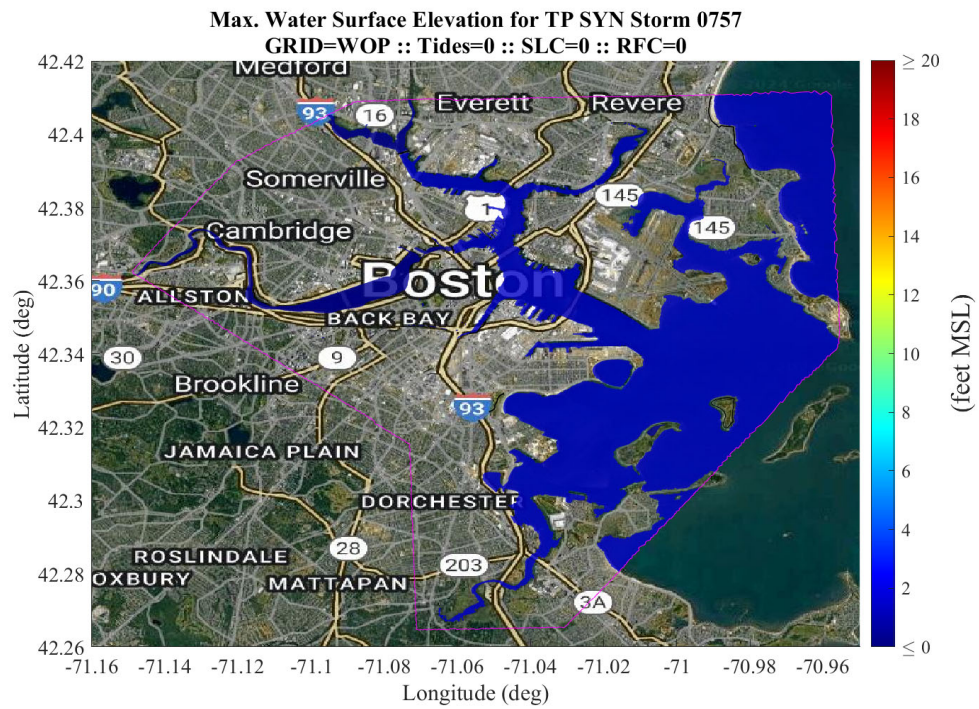


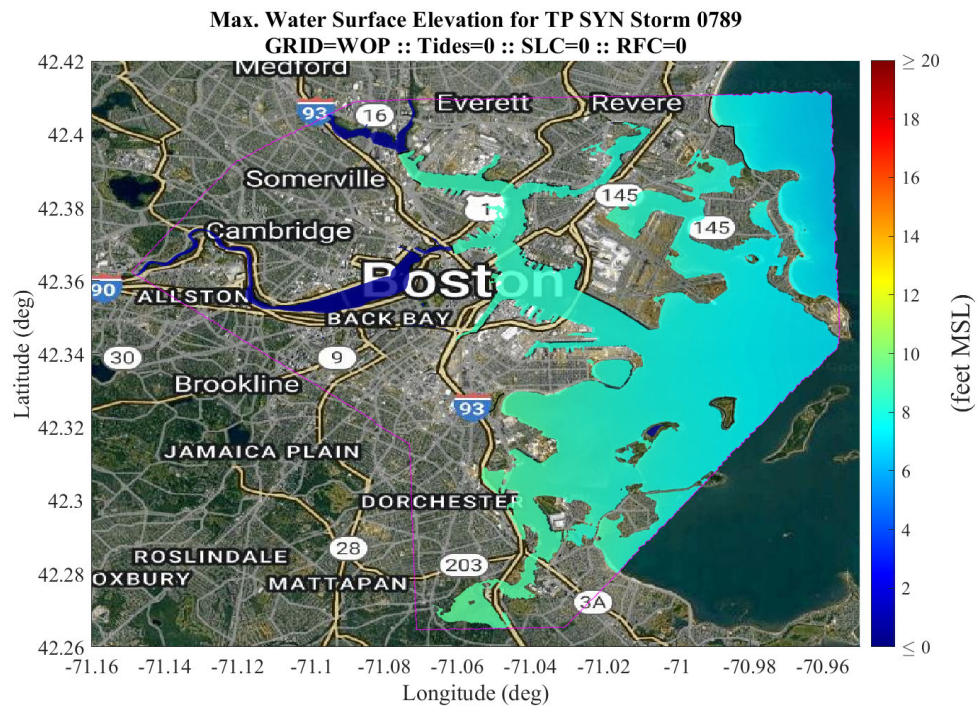


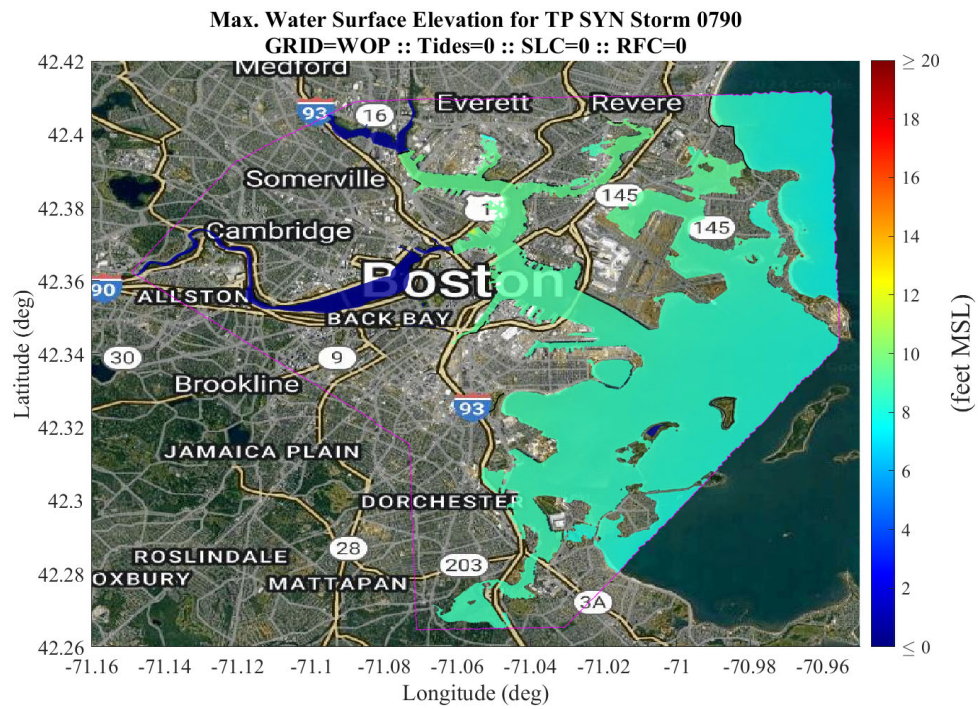


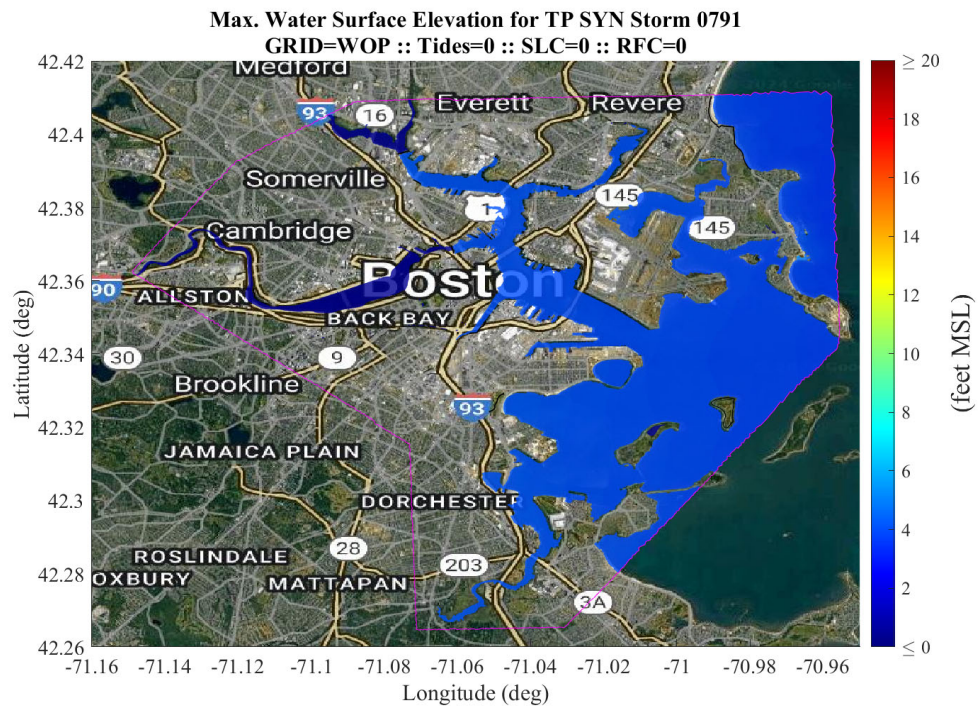


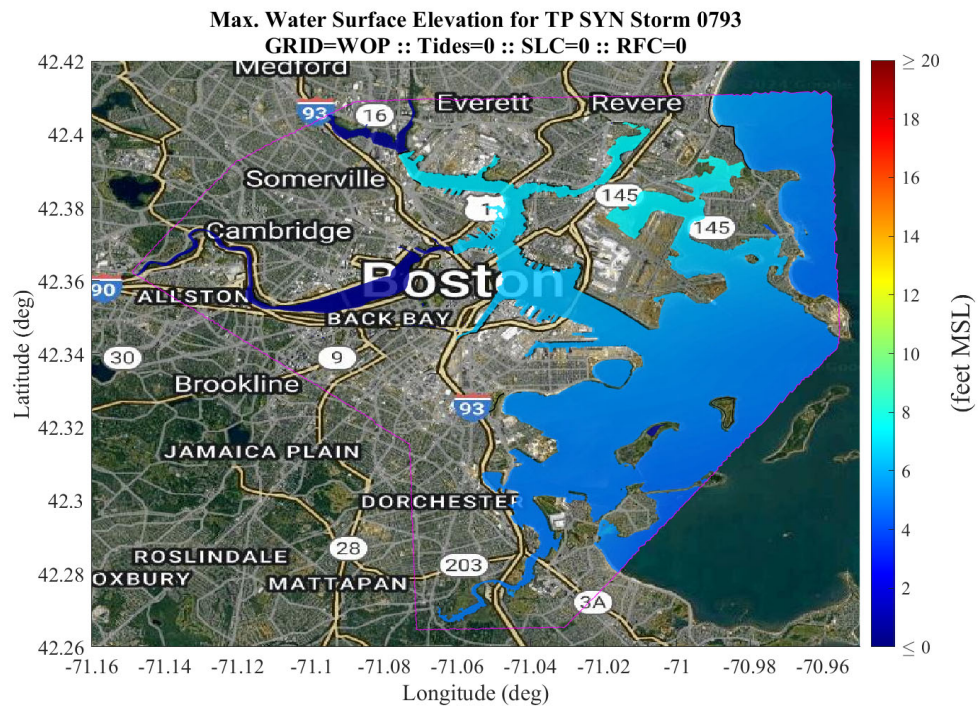


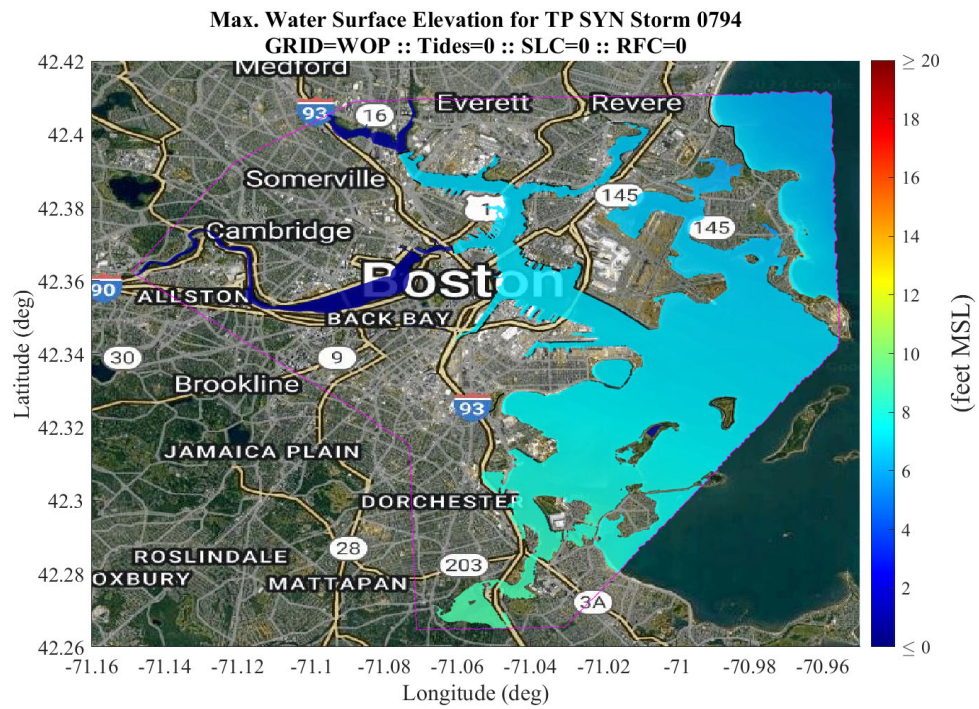


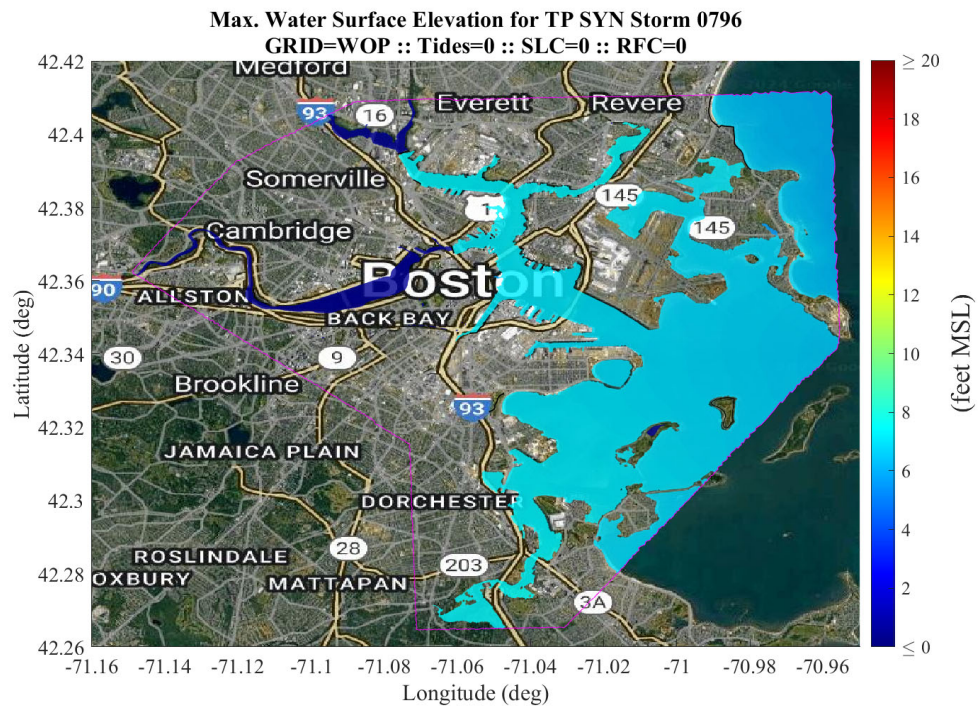


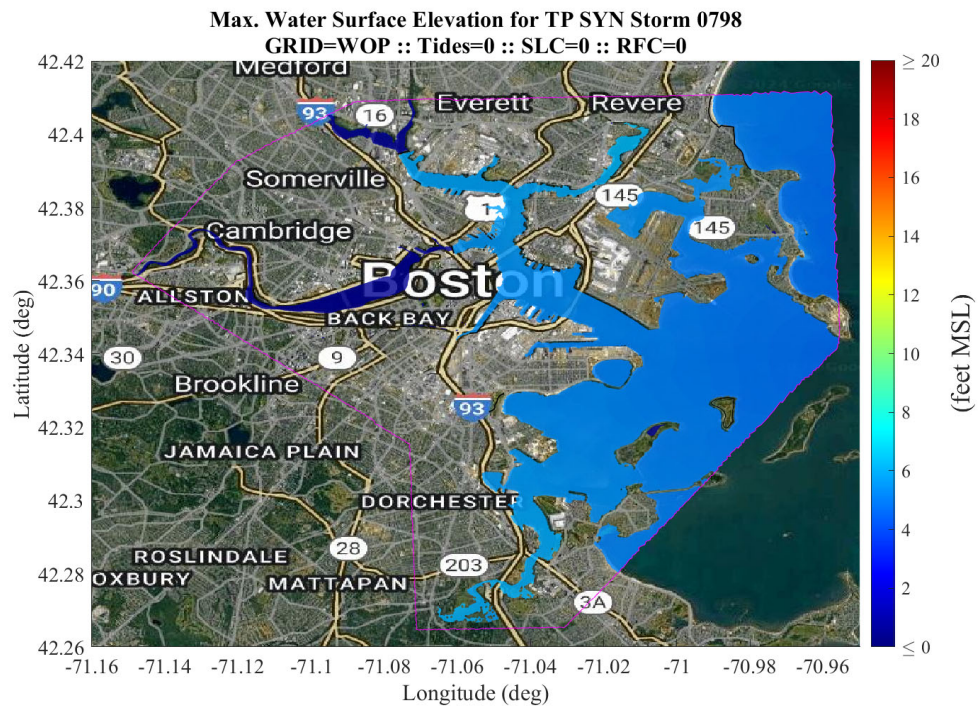


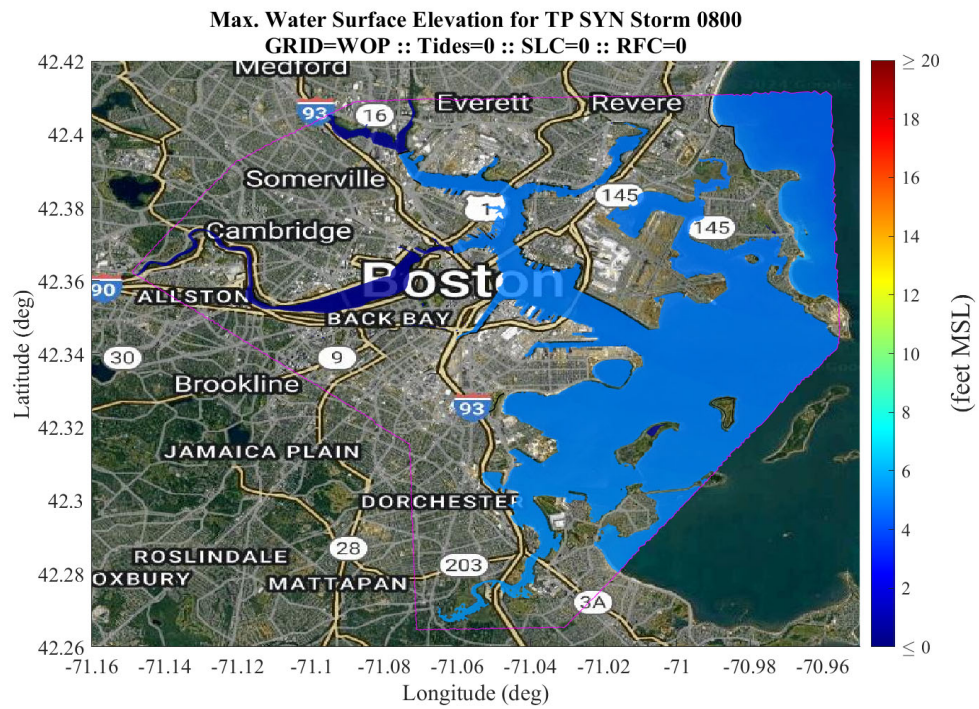


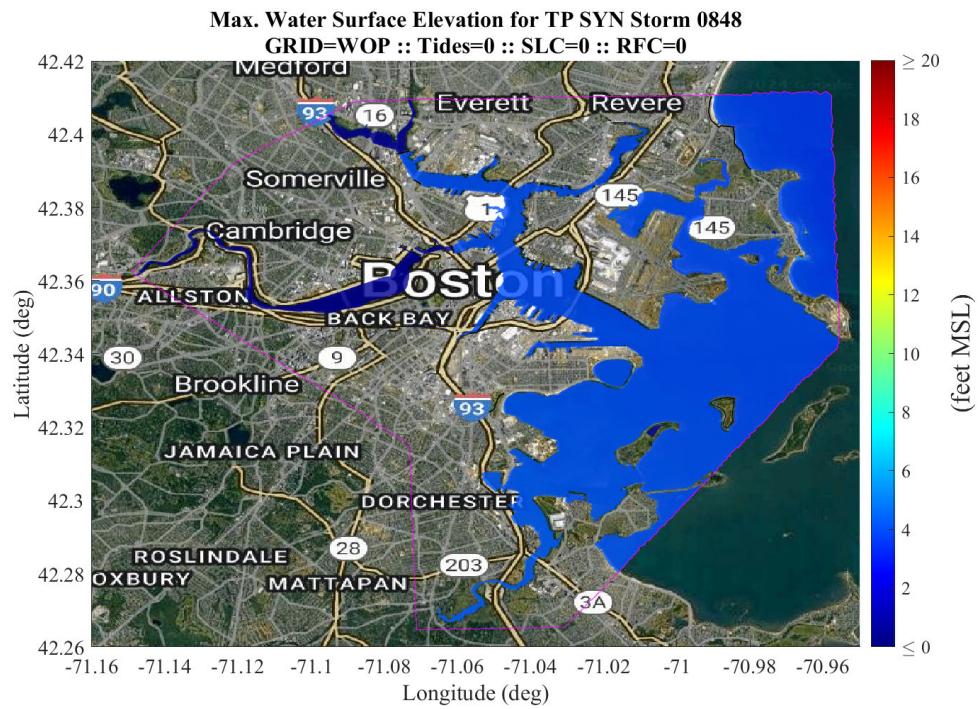


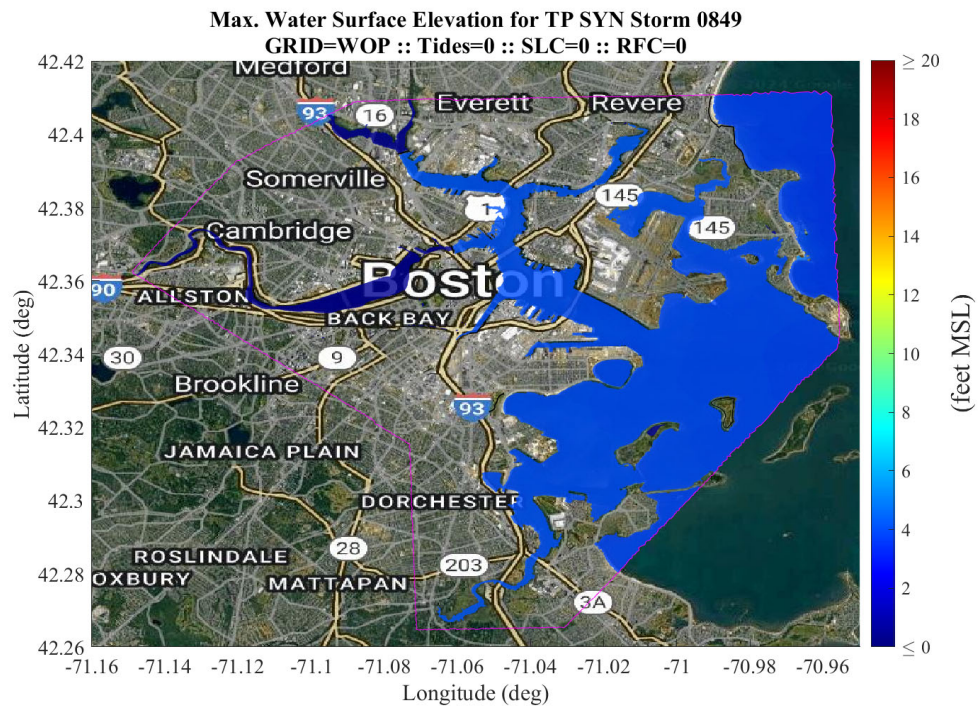


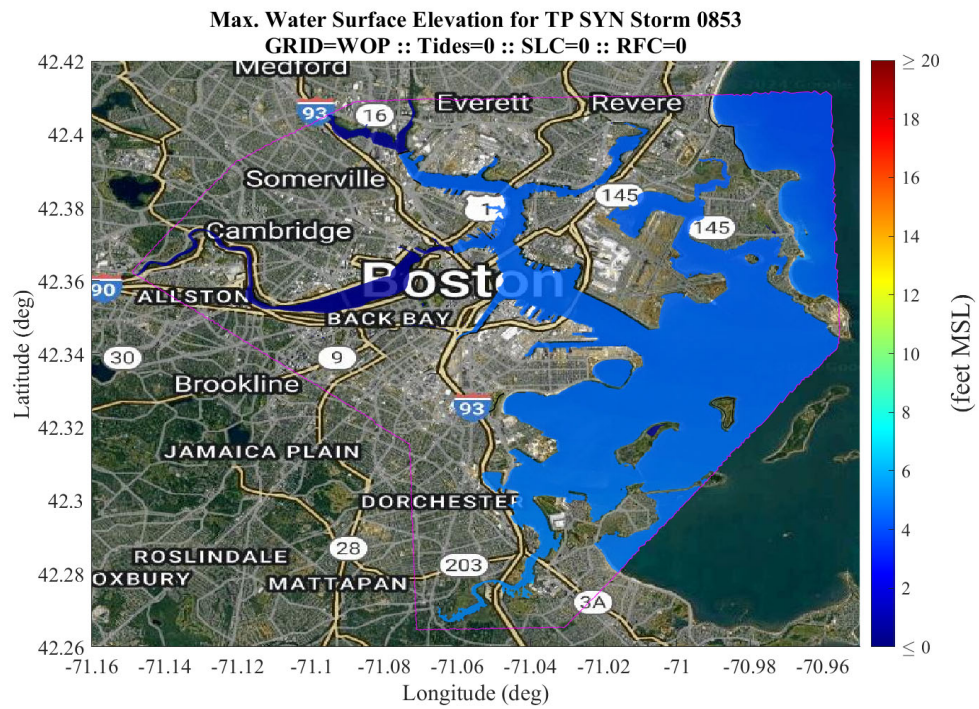


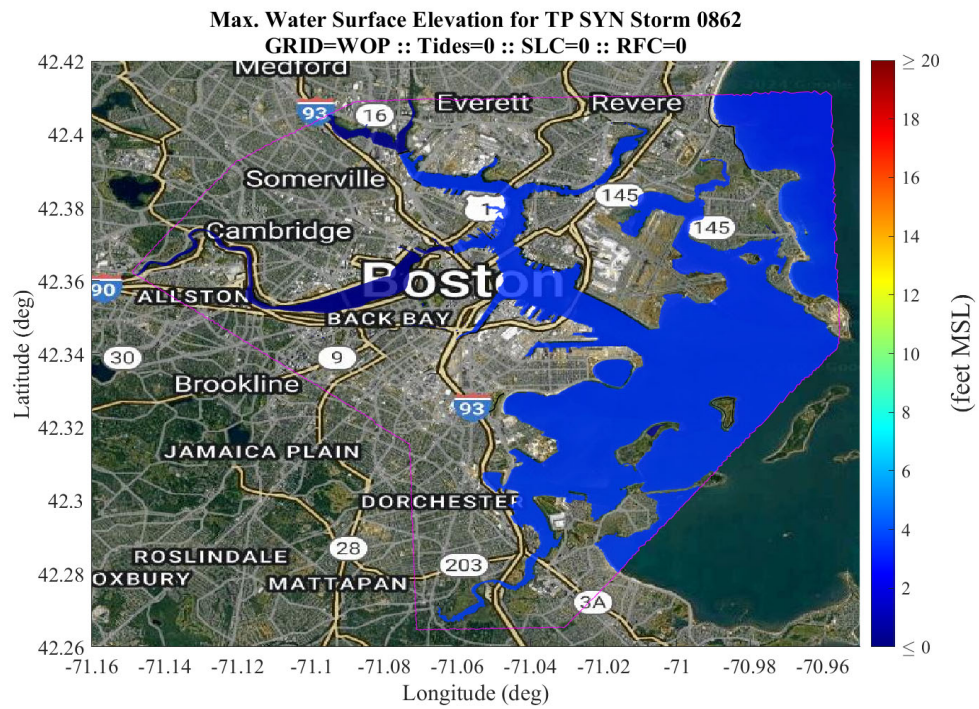


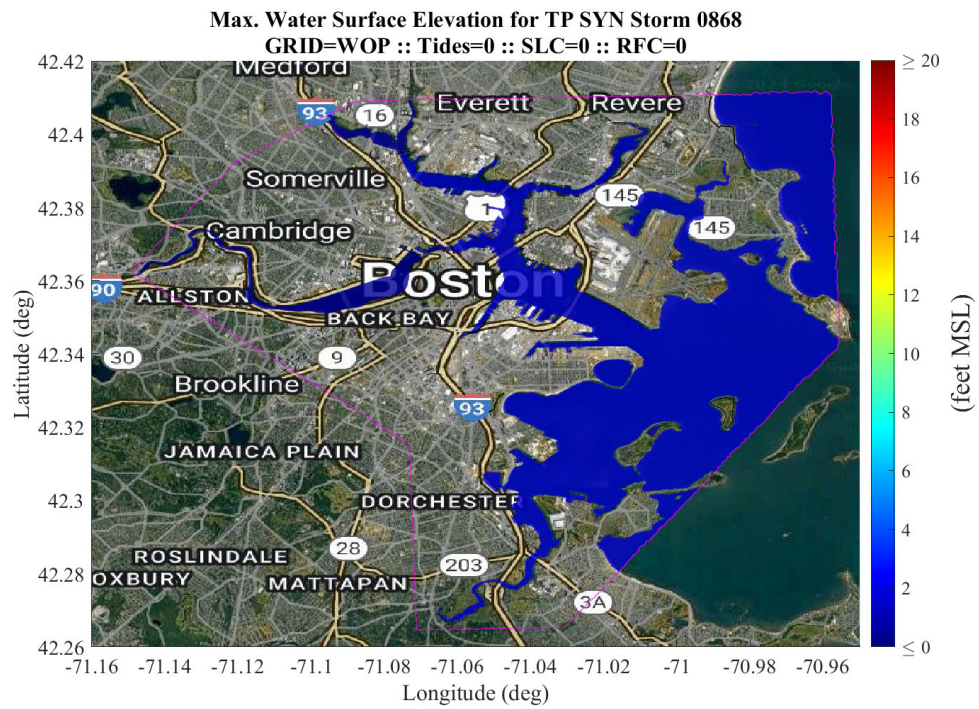


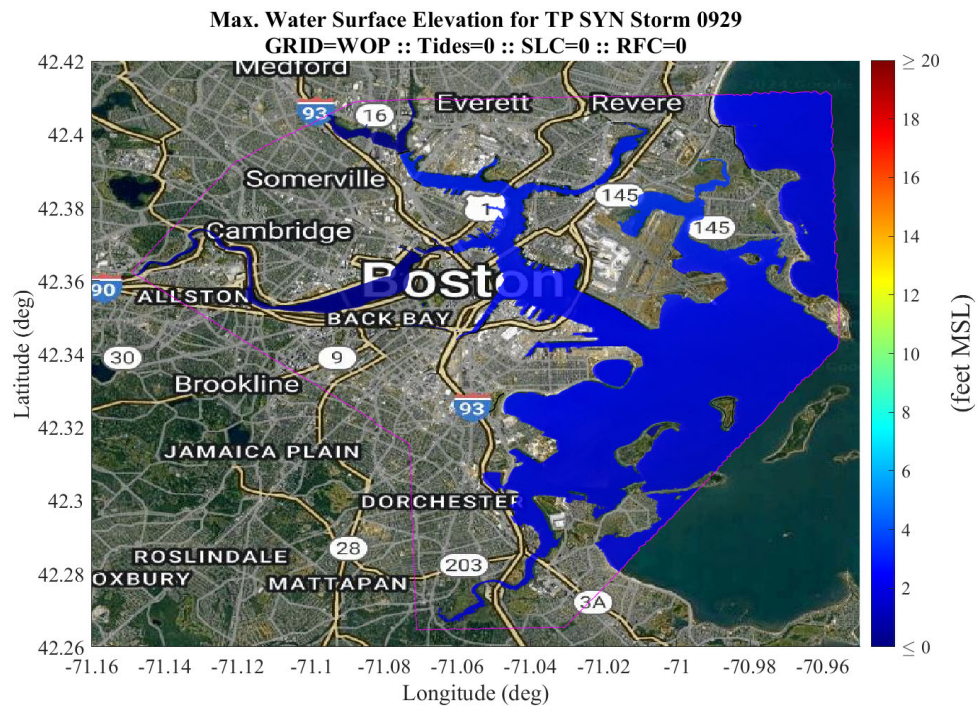


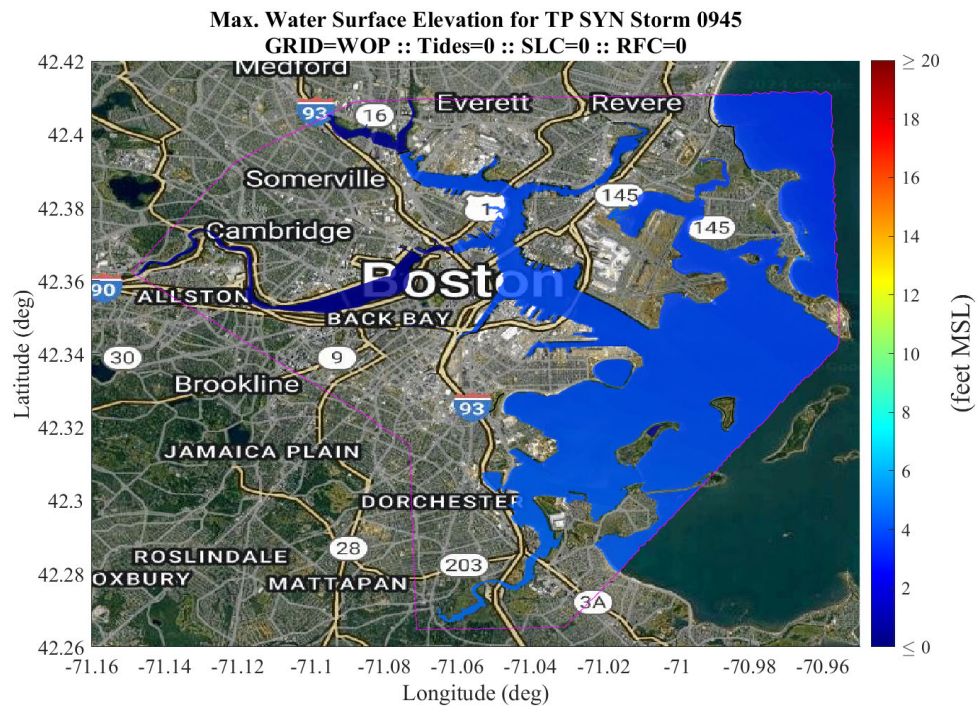


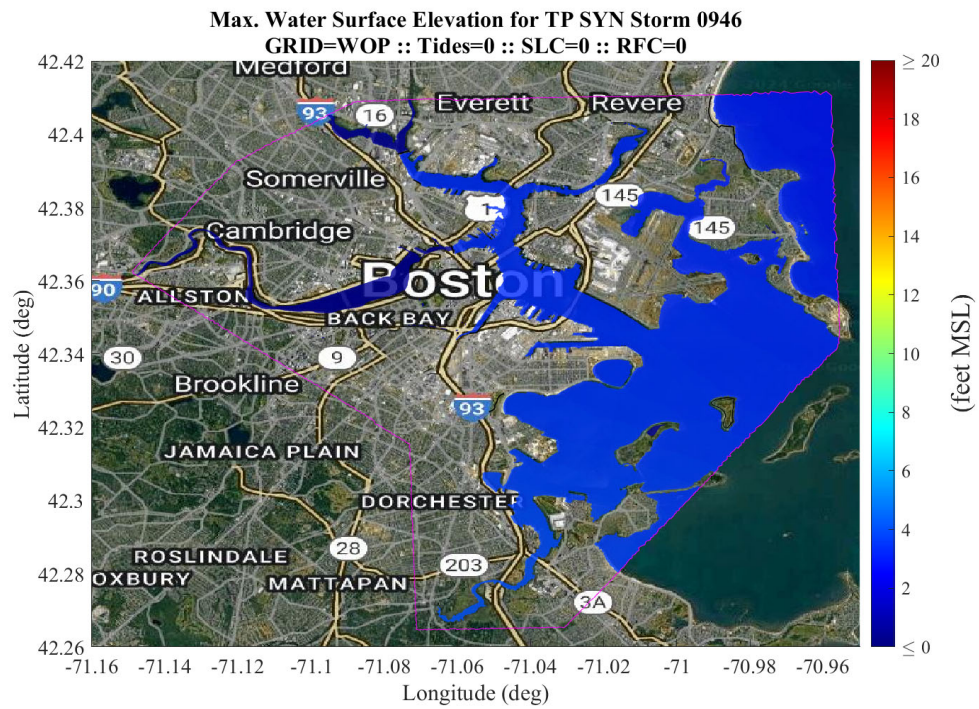


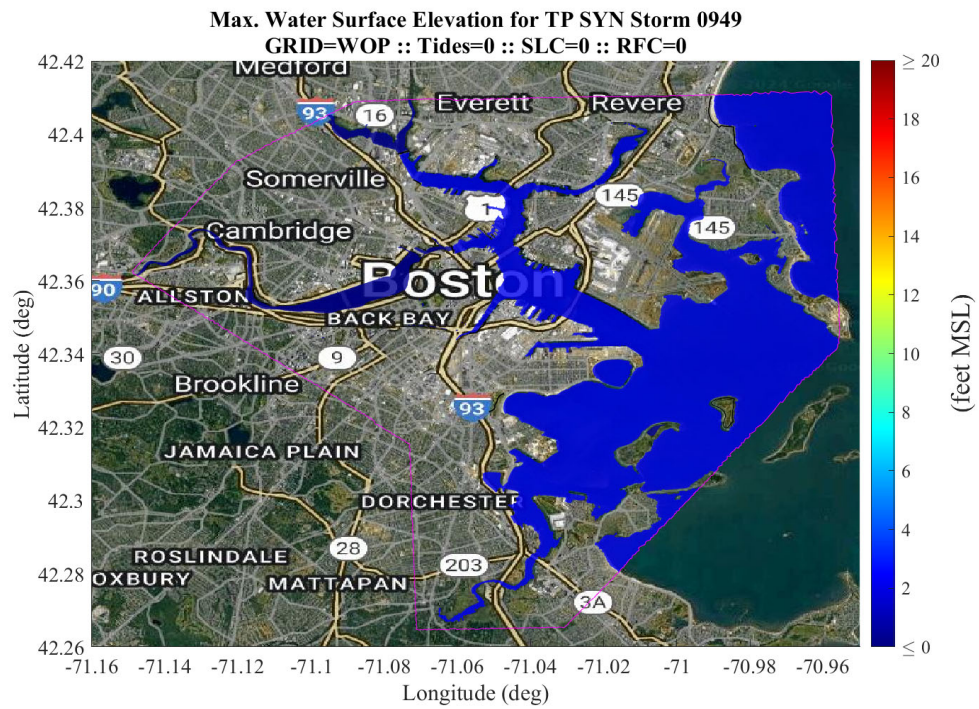


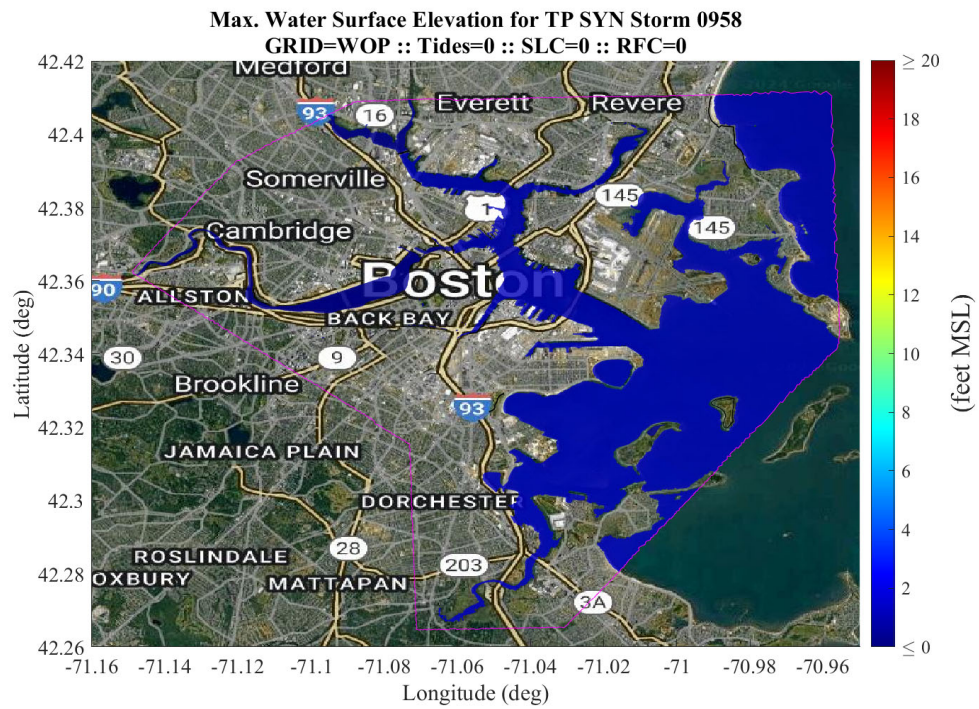


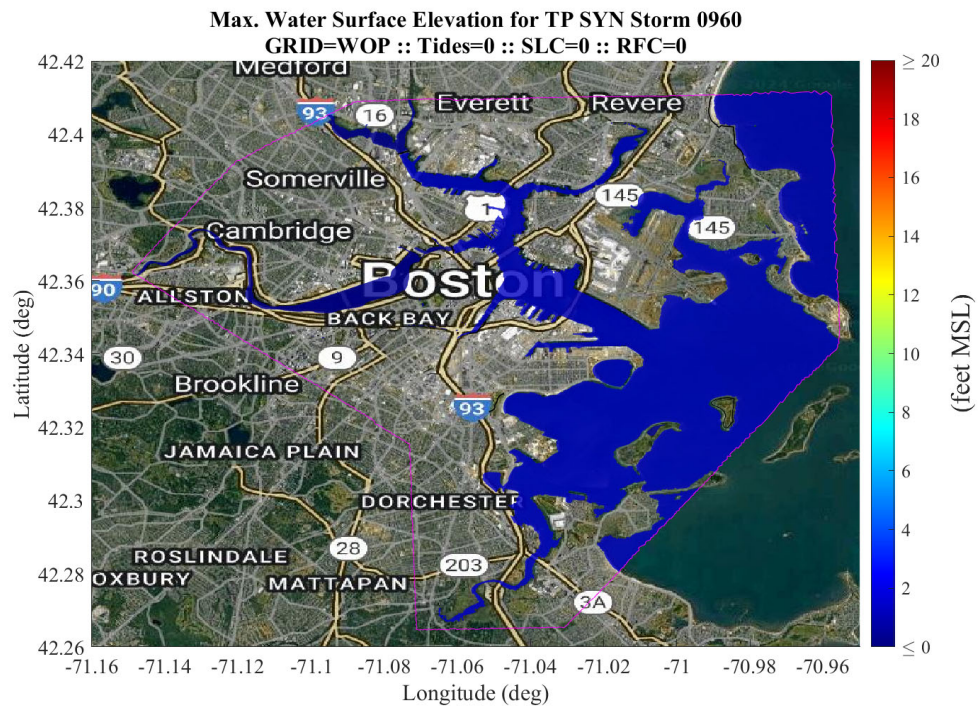


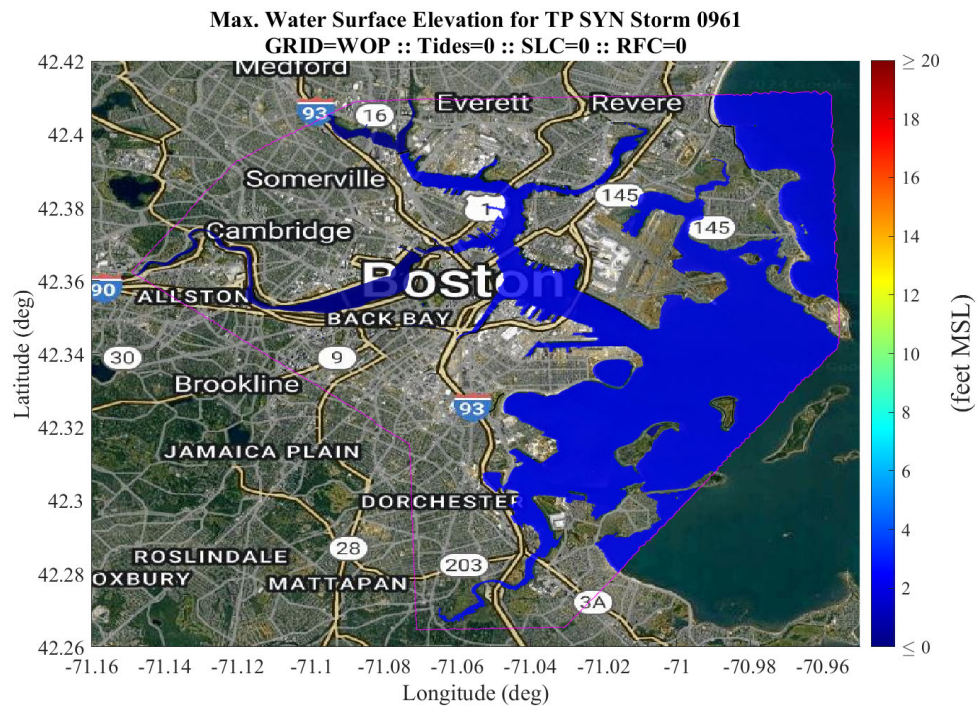


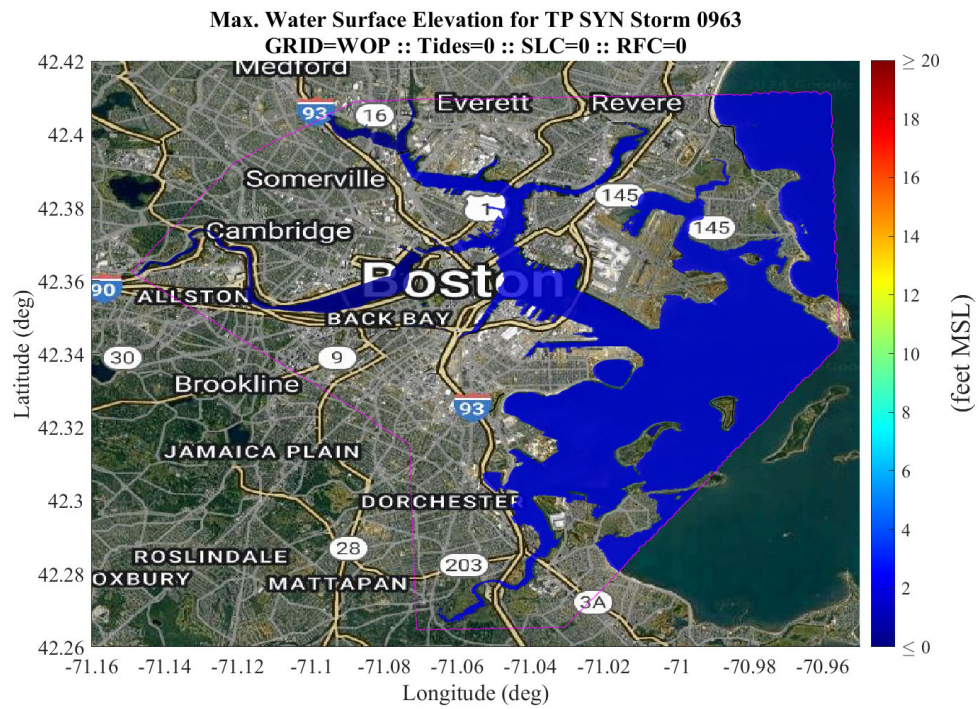


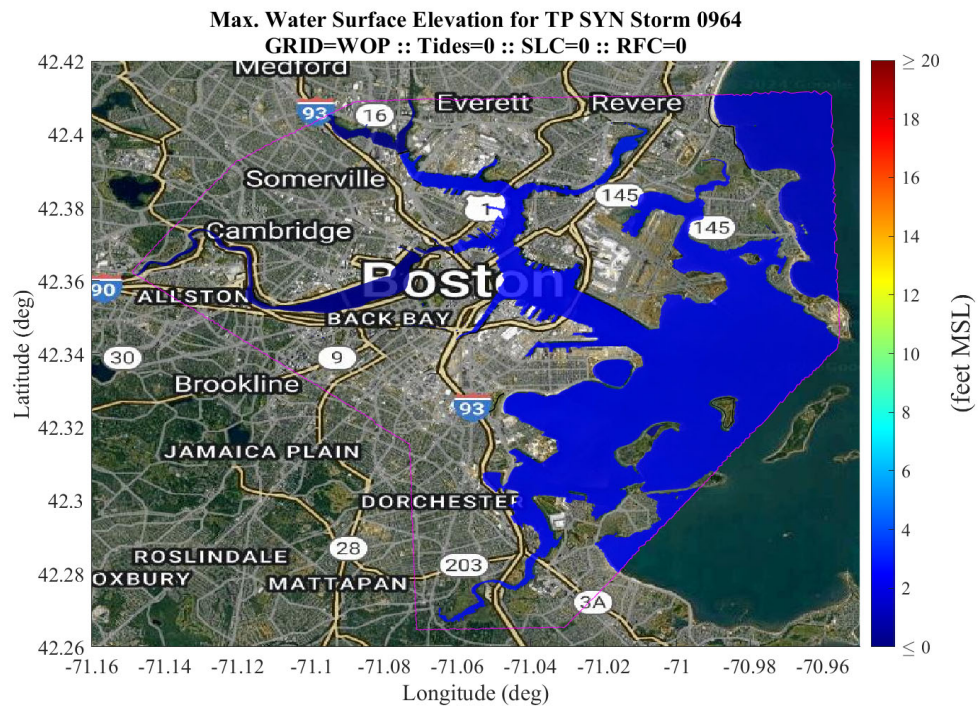


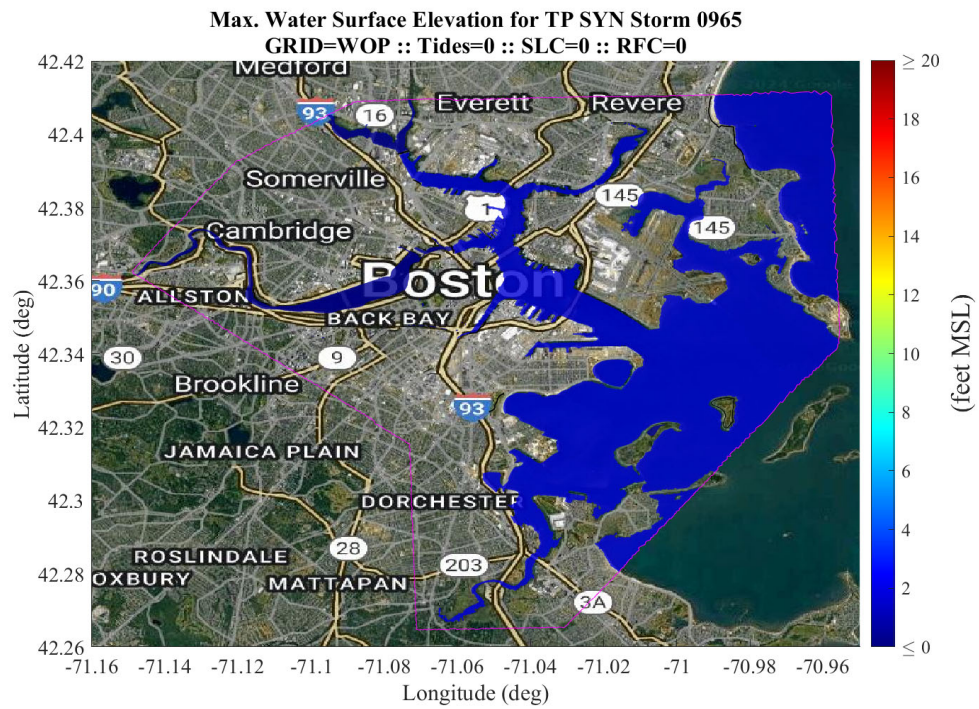


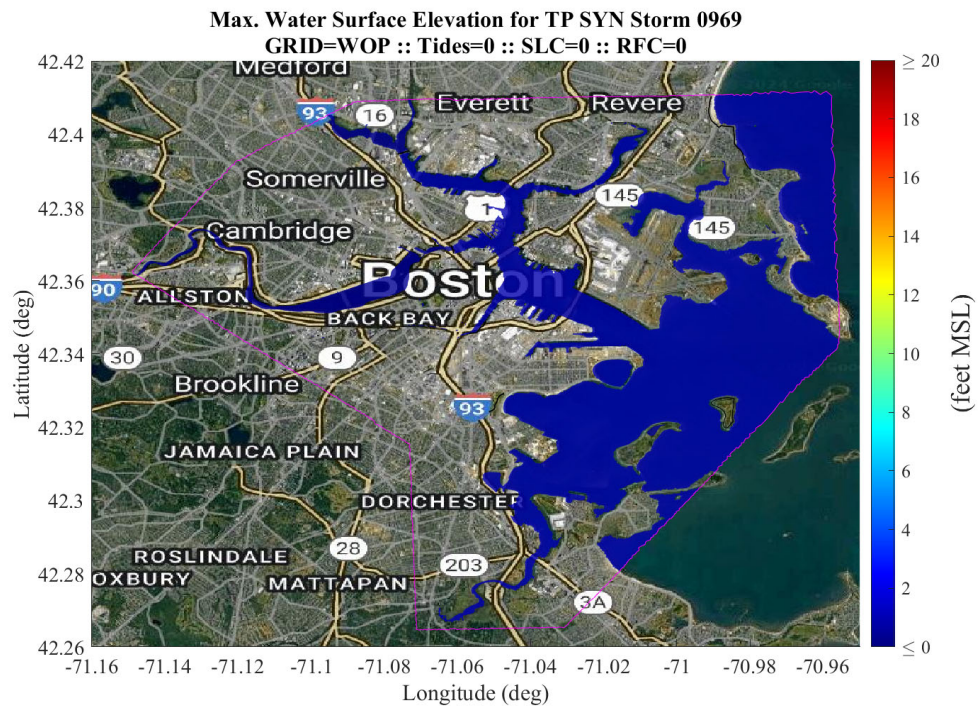


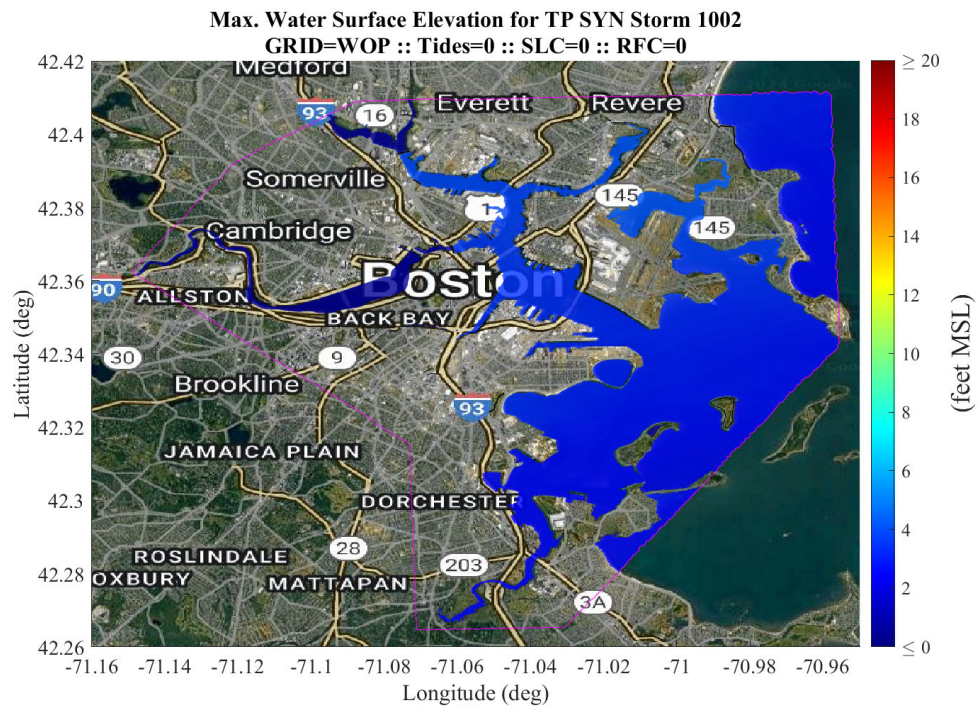


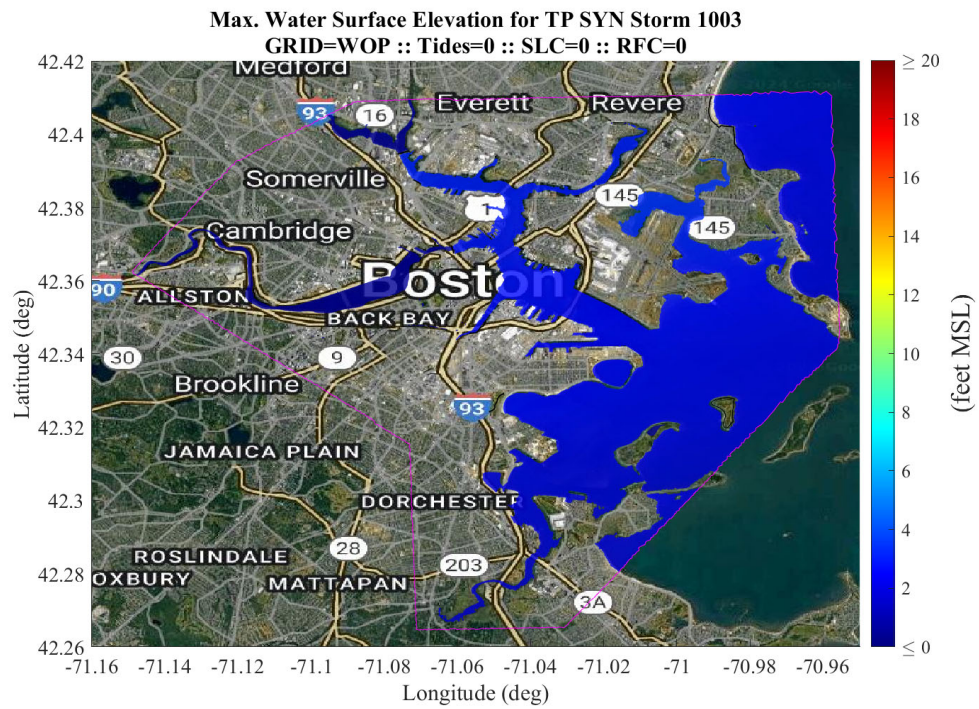


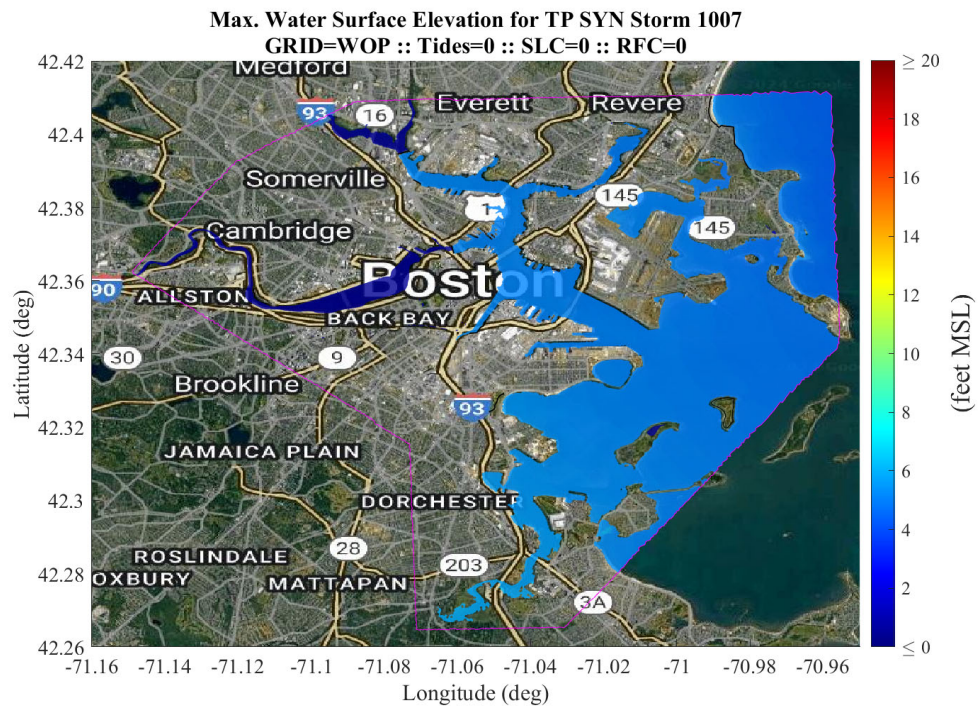


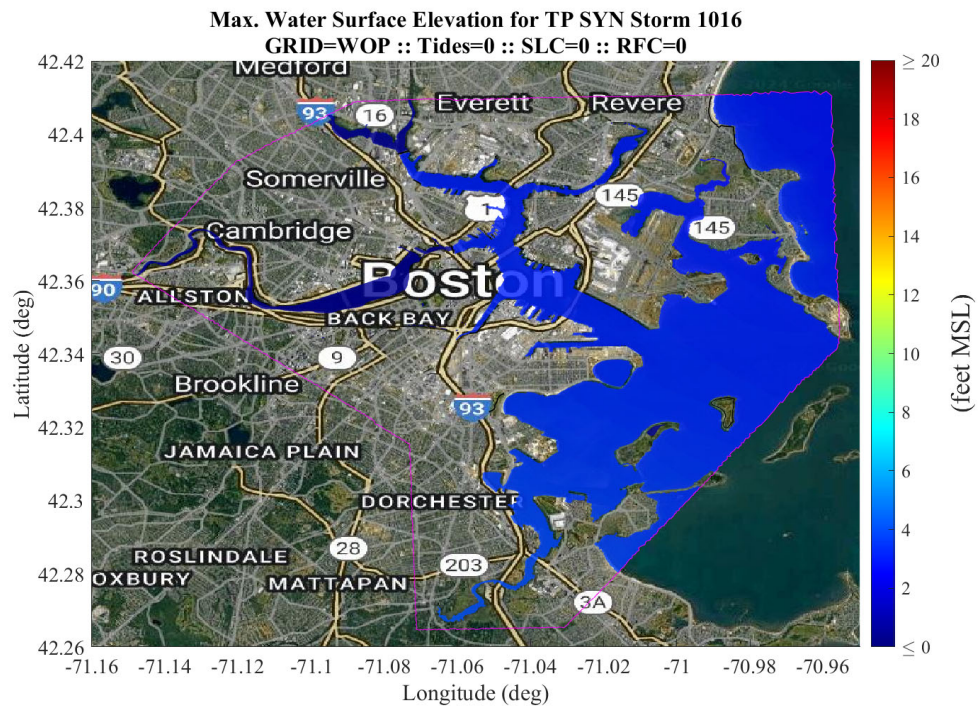


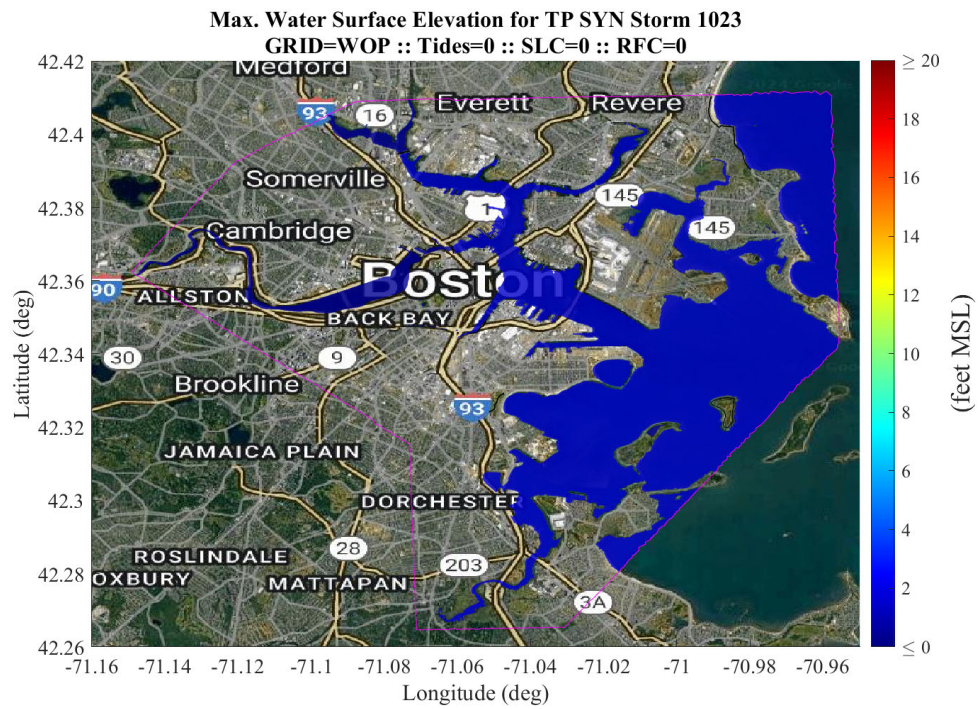


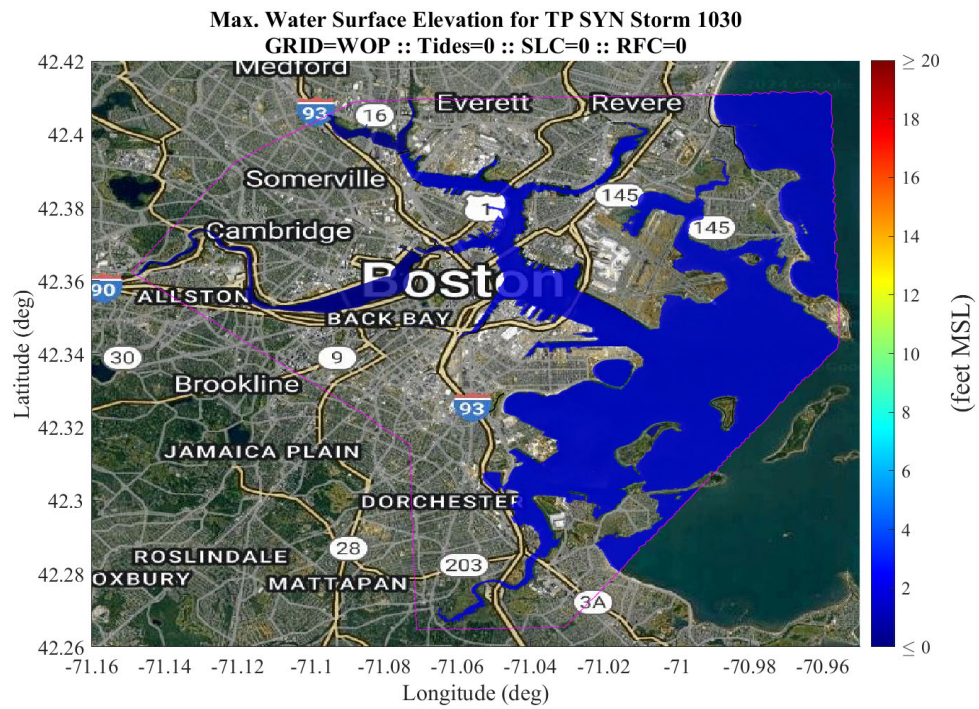


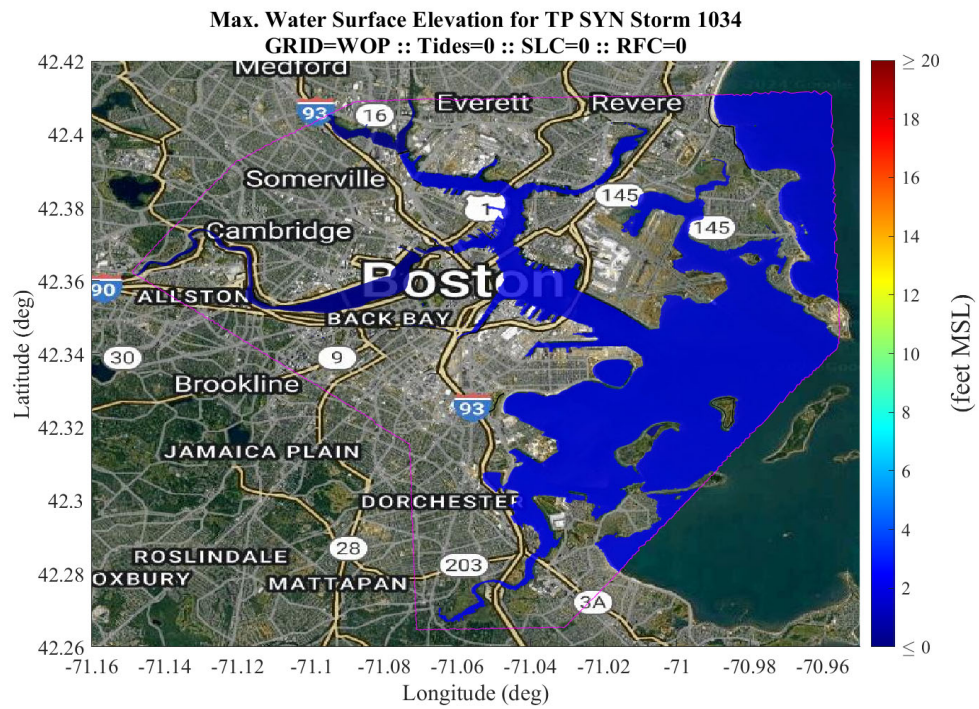


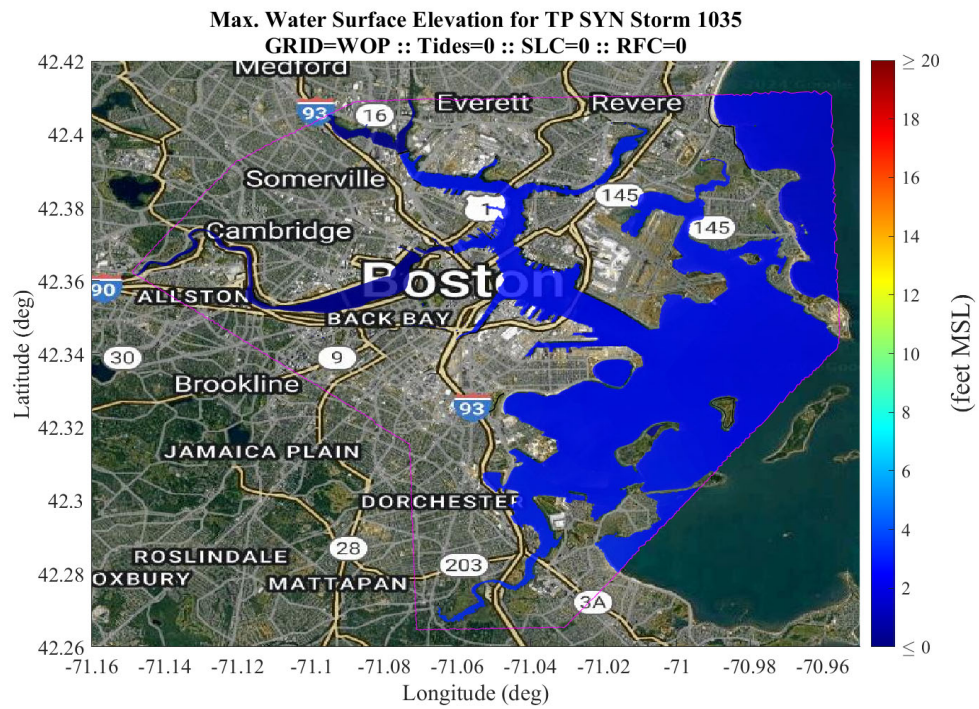






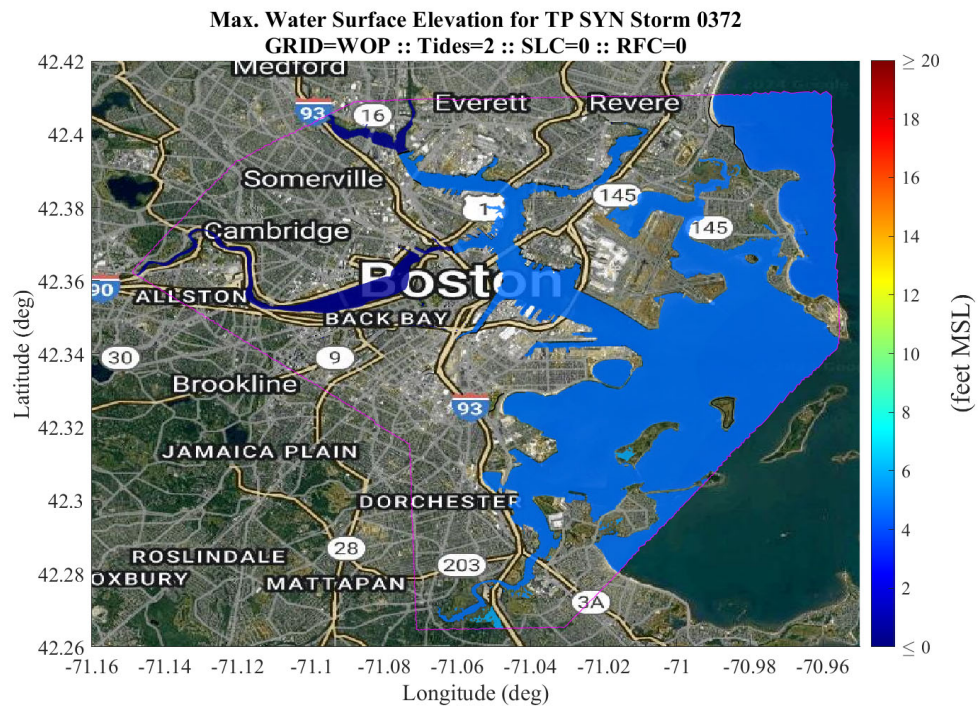


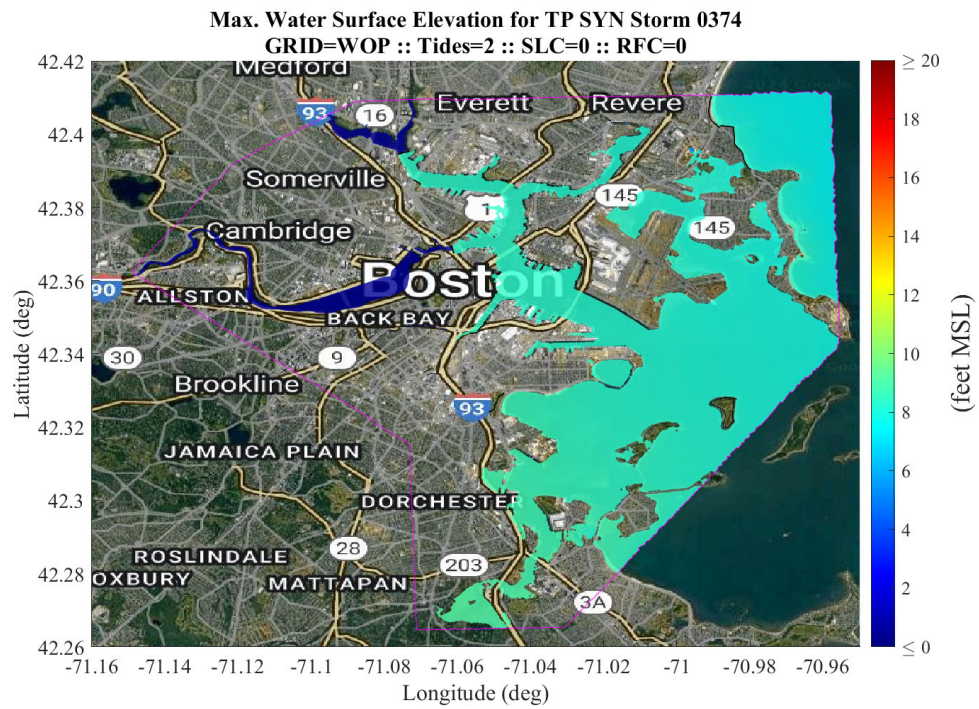


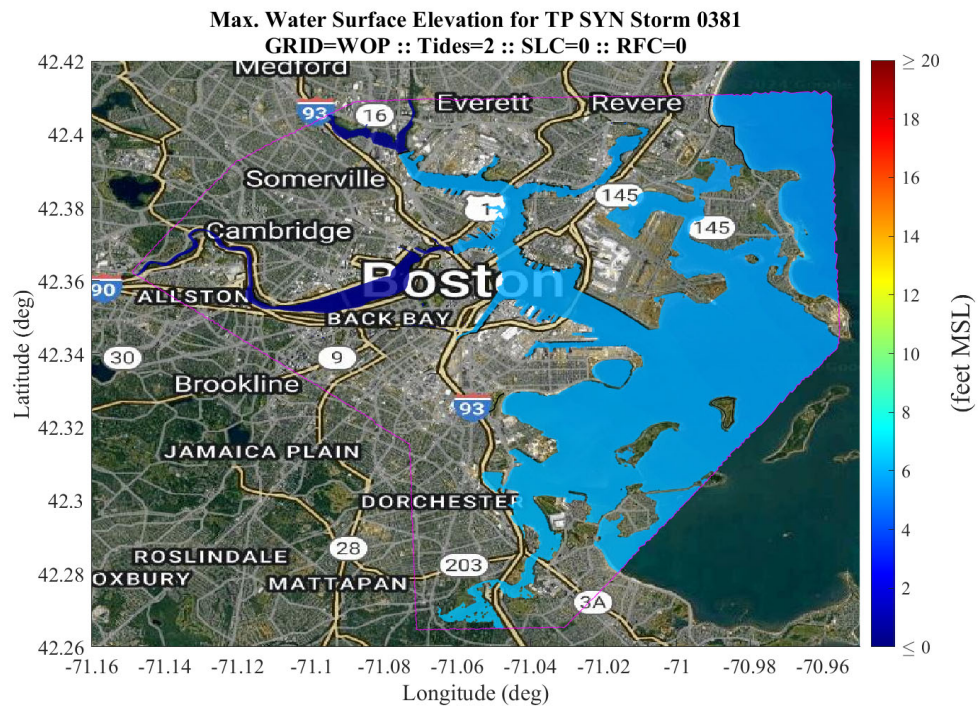


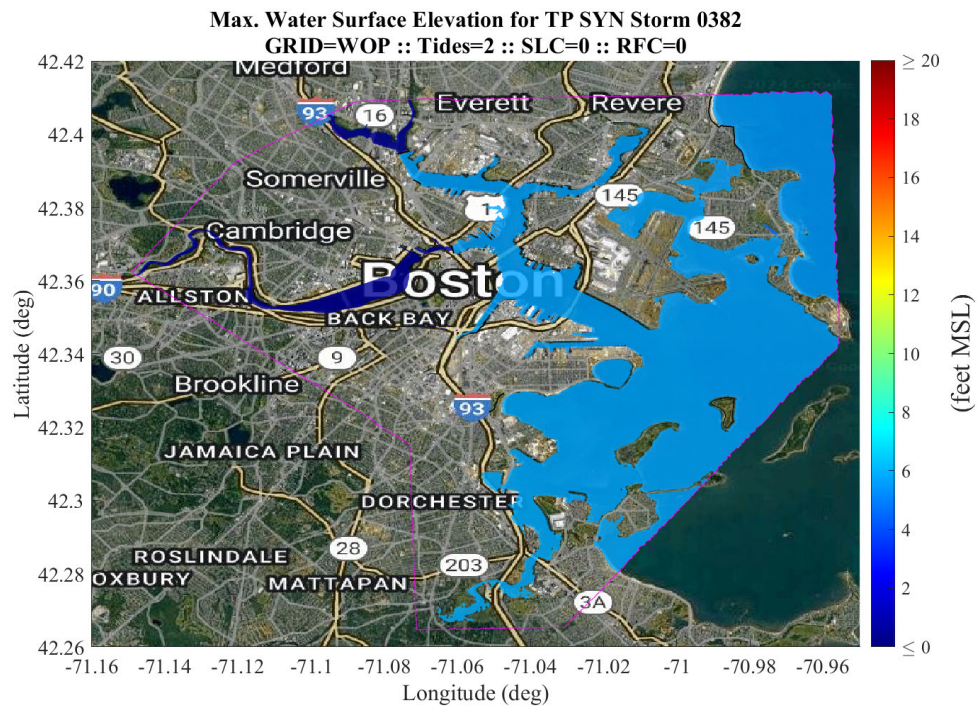
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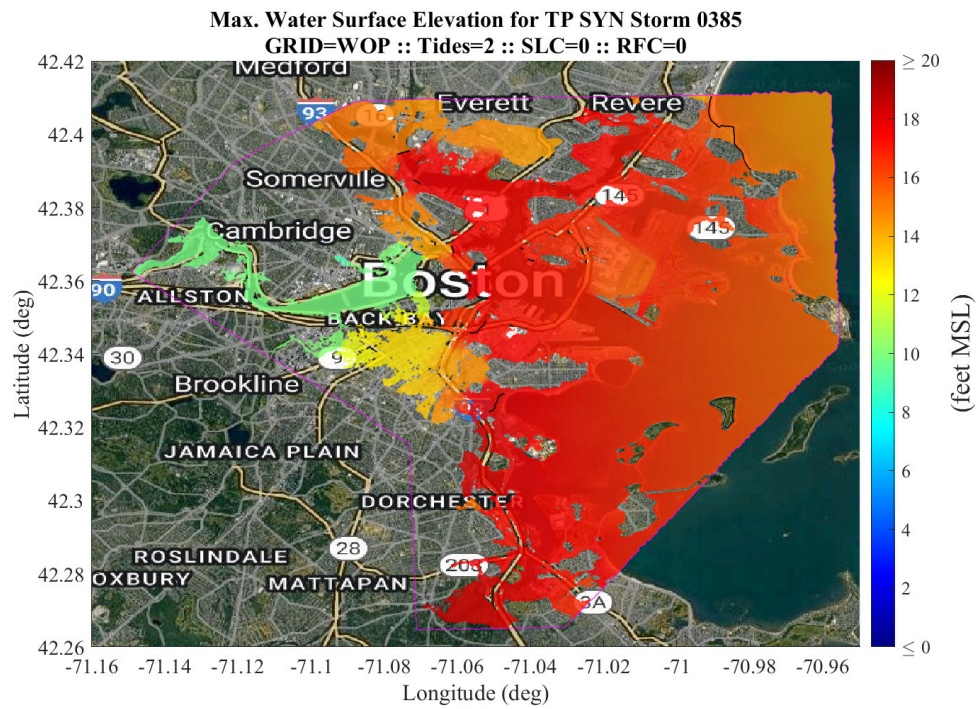
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 60 synthetic tropical cyclone TC events for SLC0 and random tides.

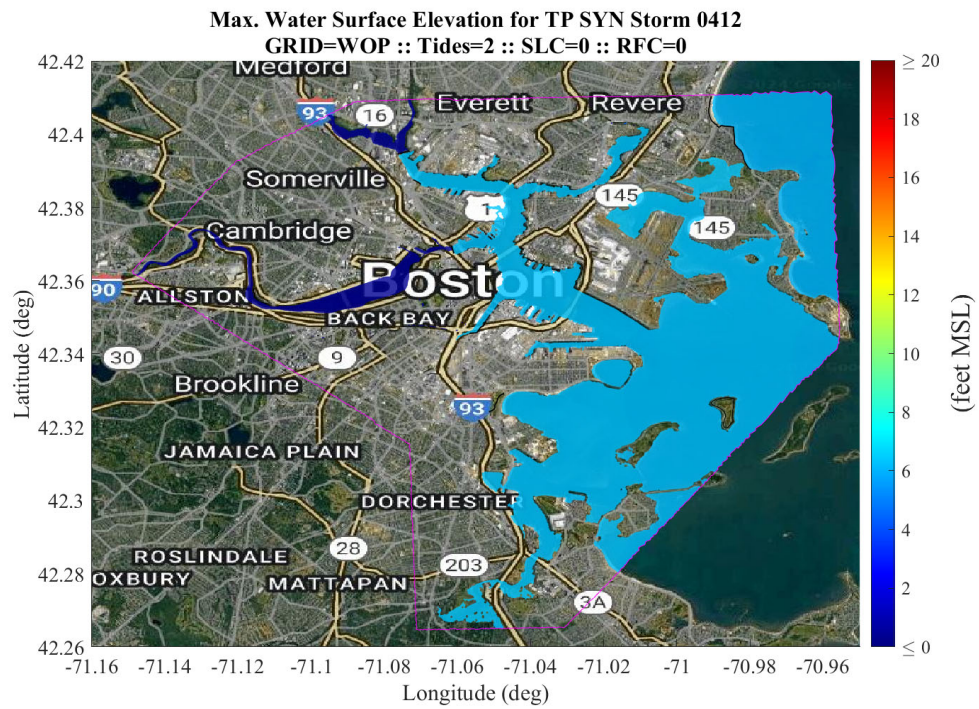


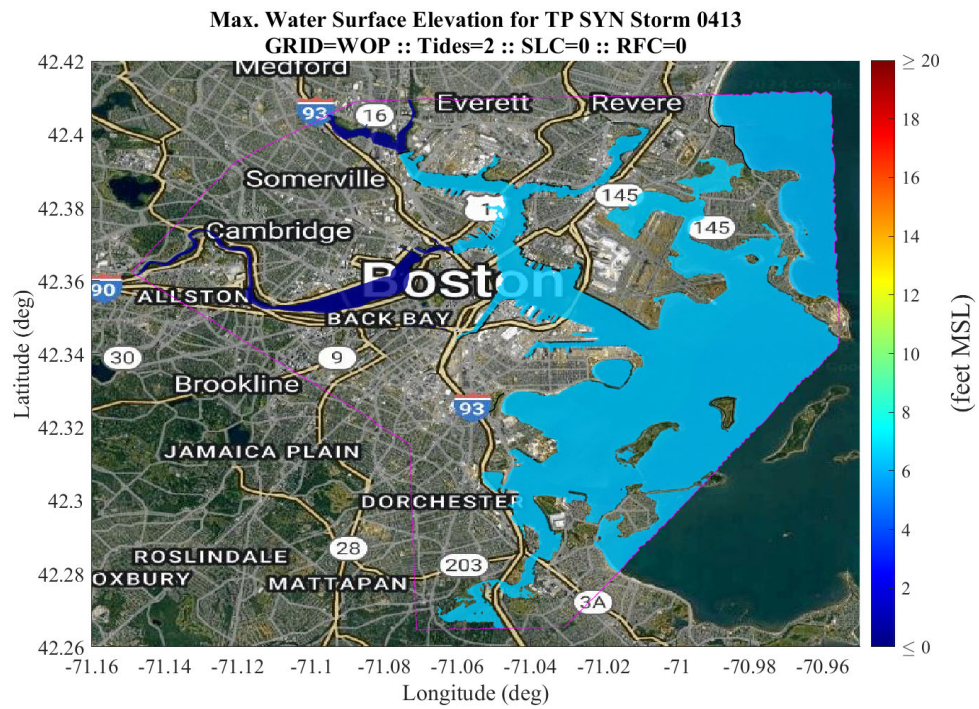


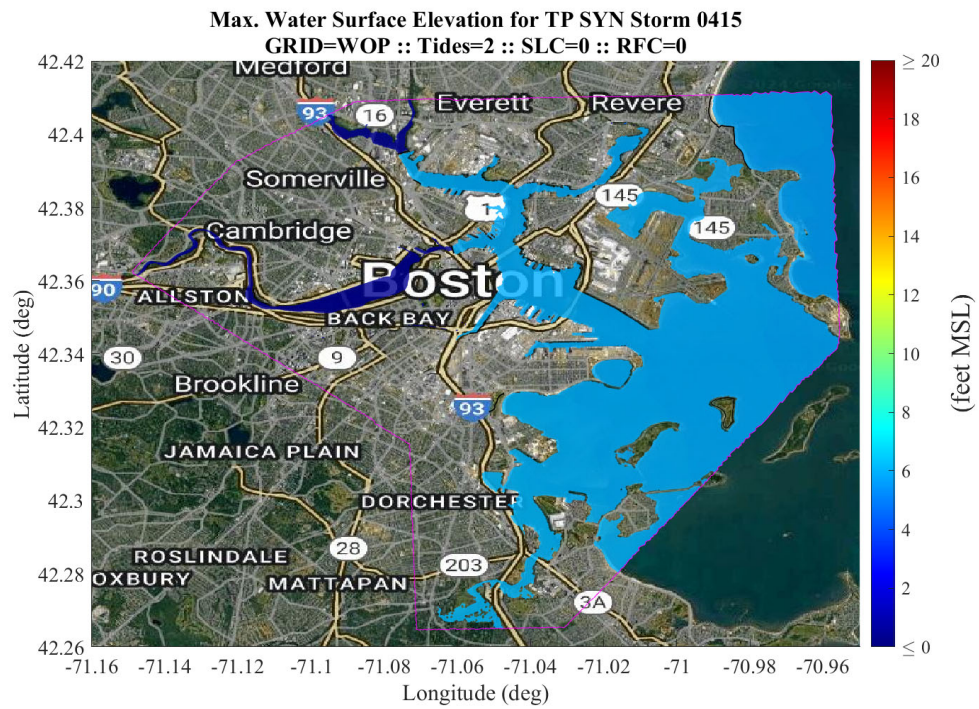


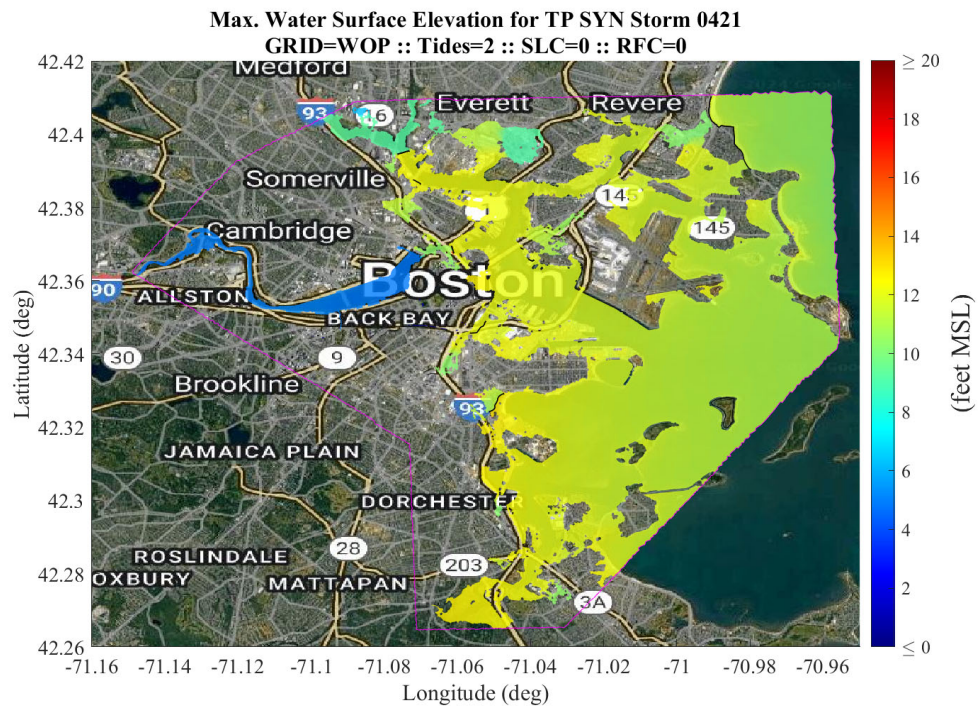


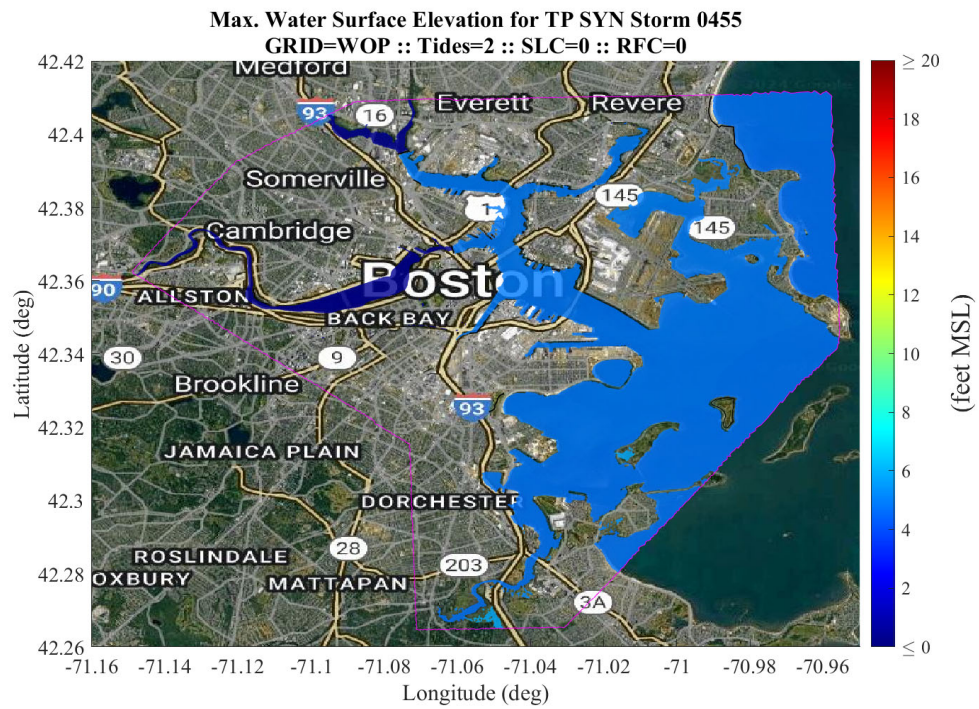


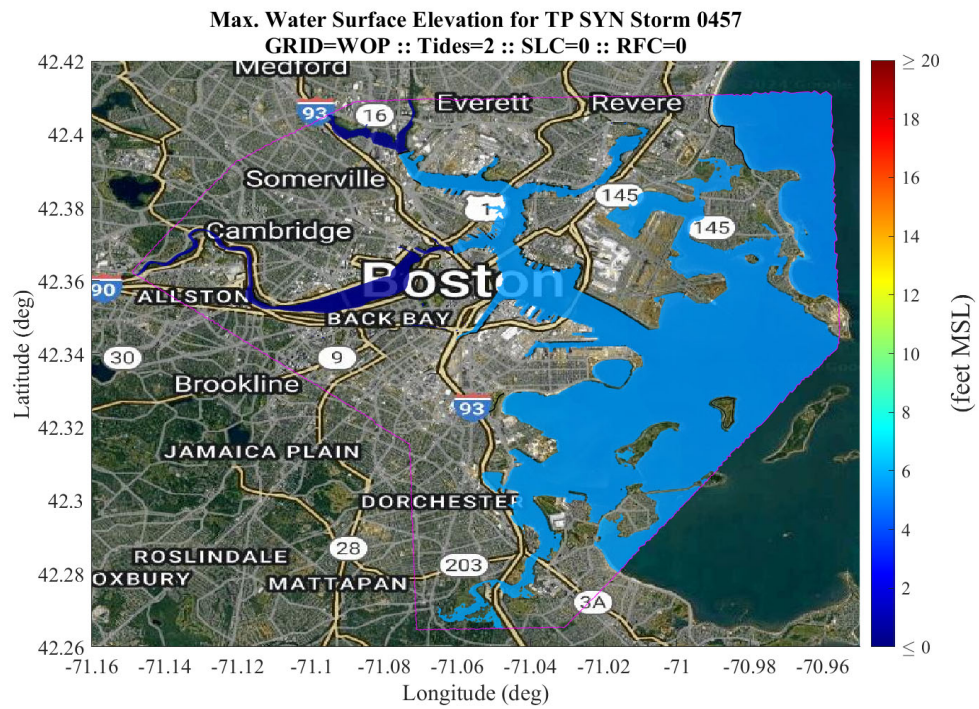


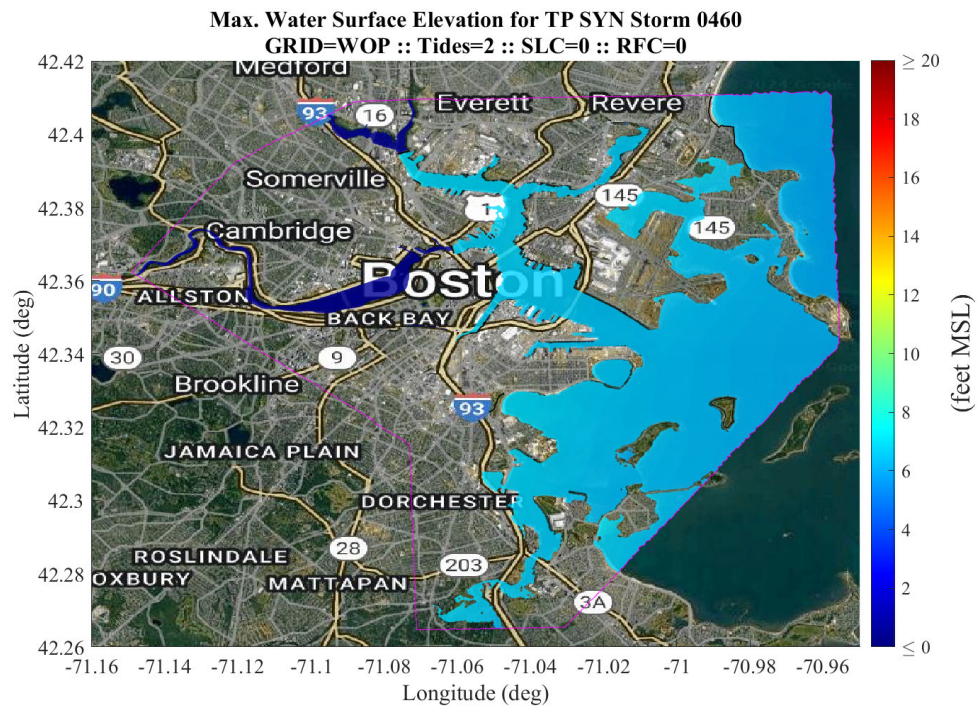


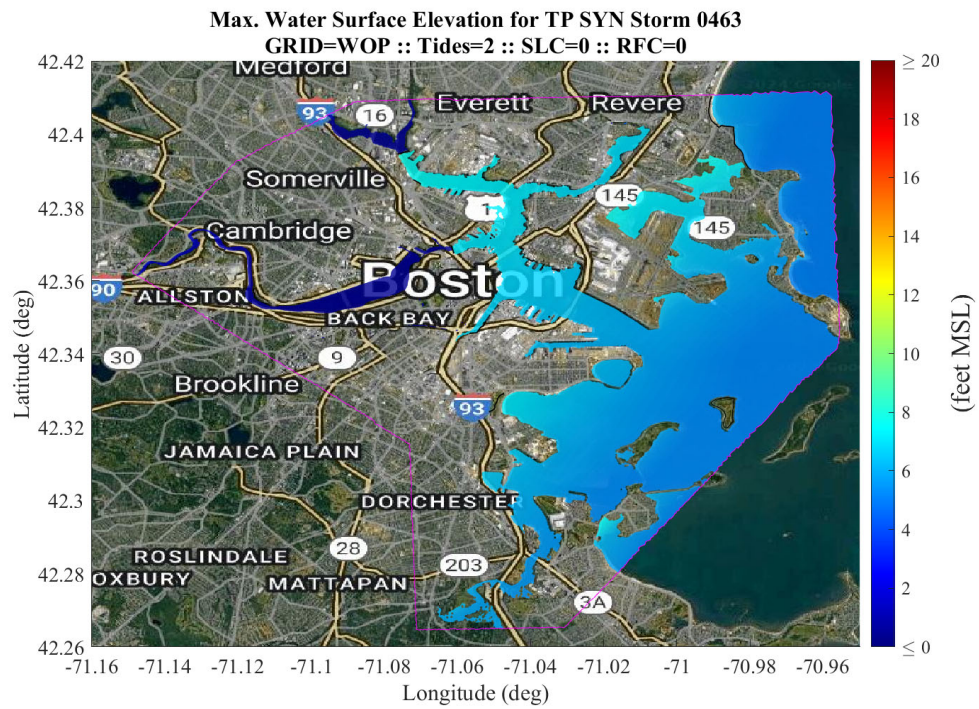


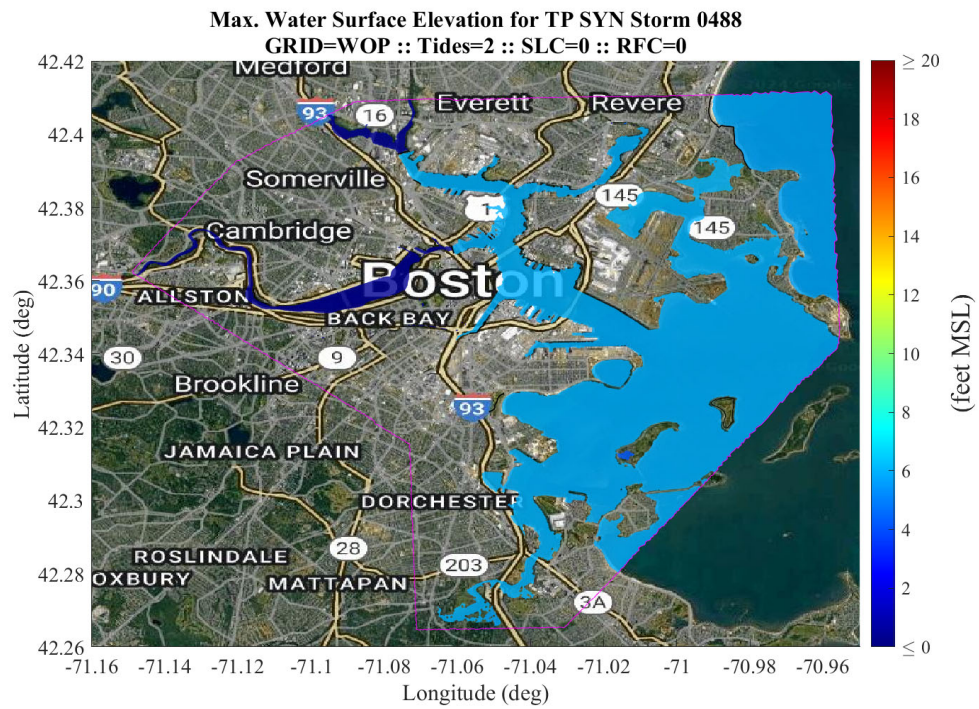


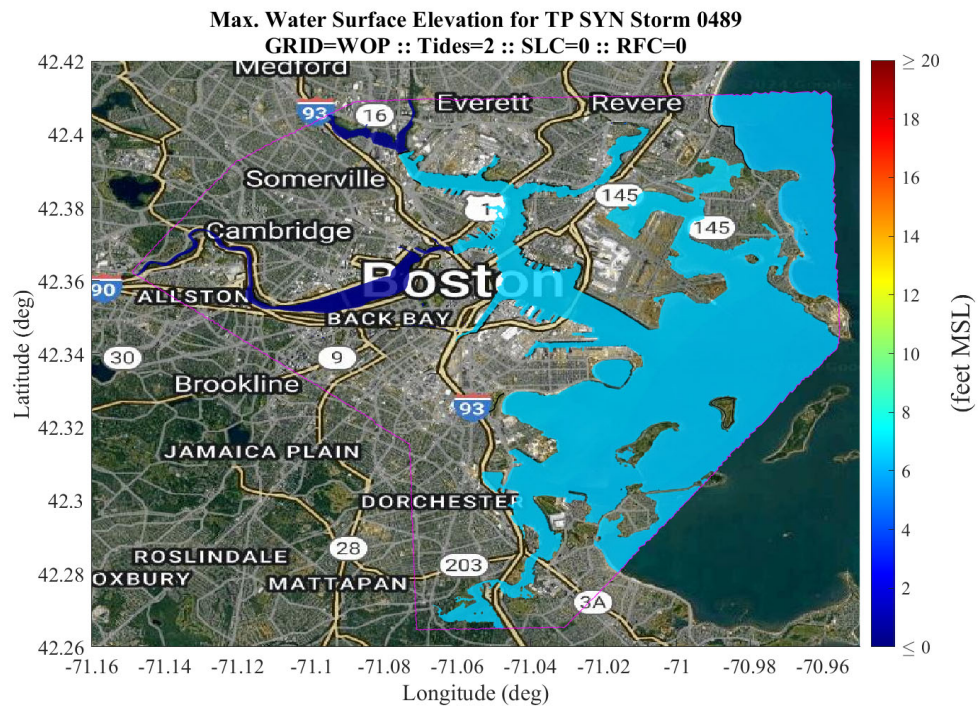


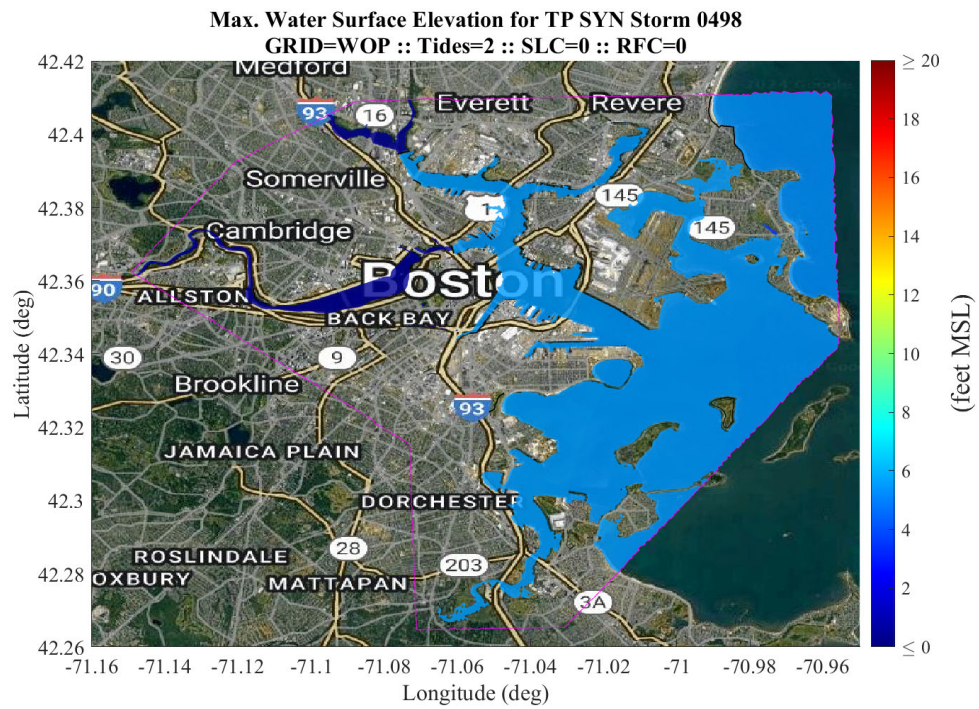


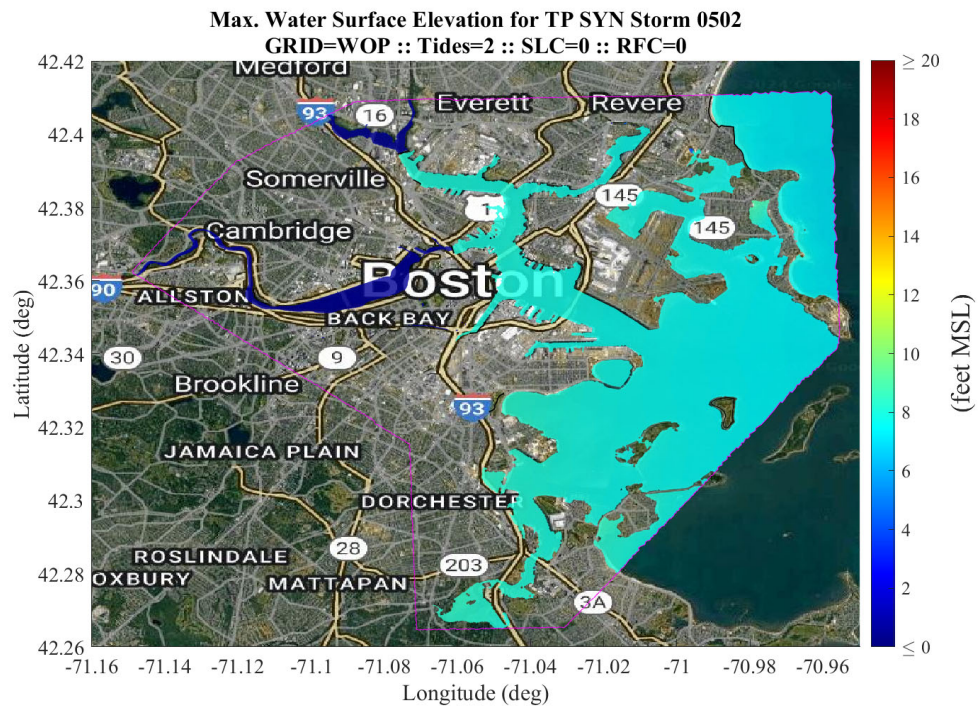


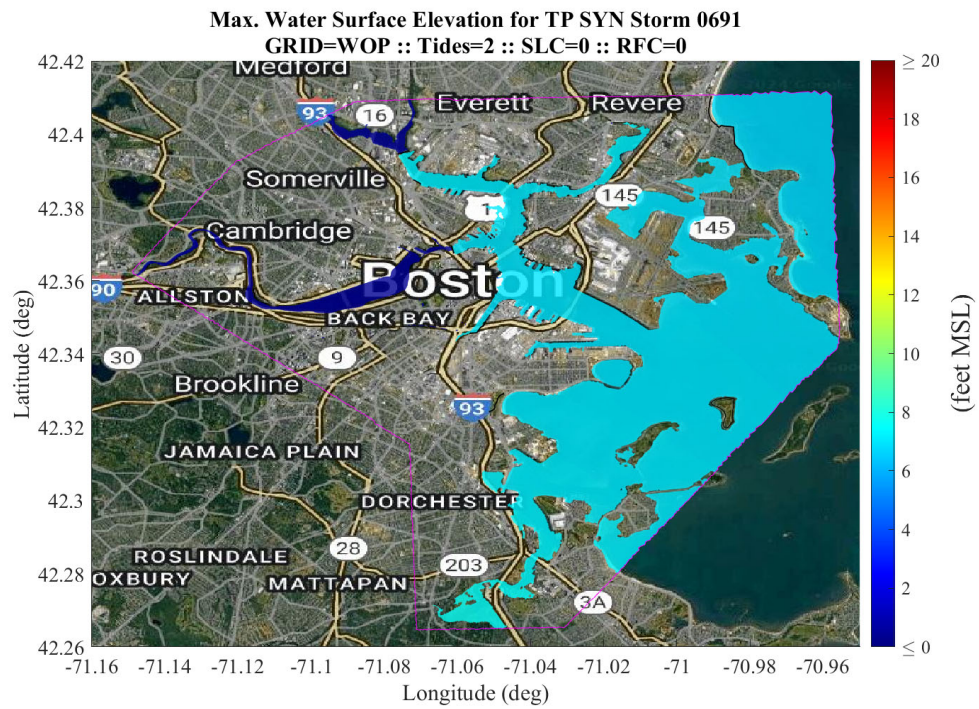


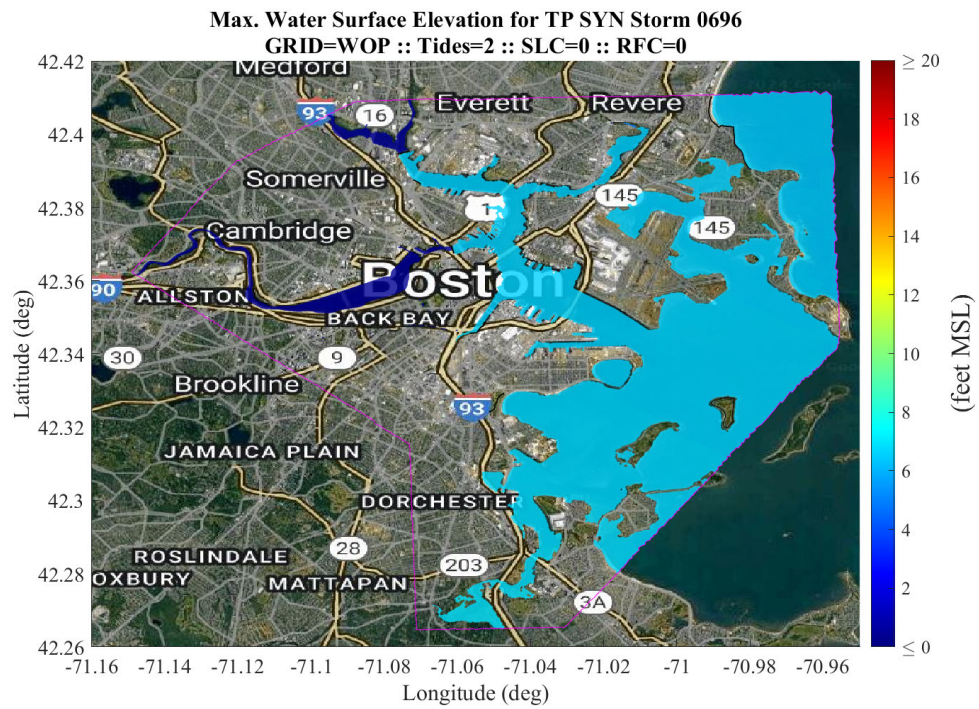


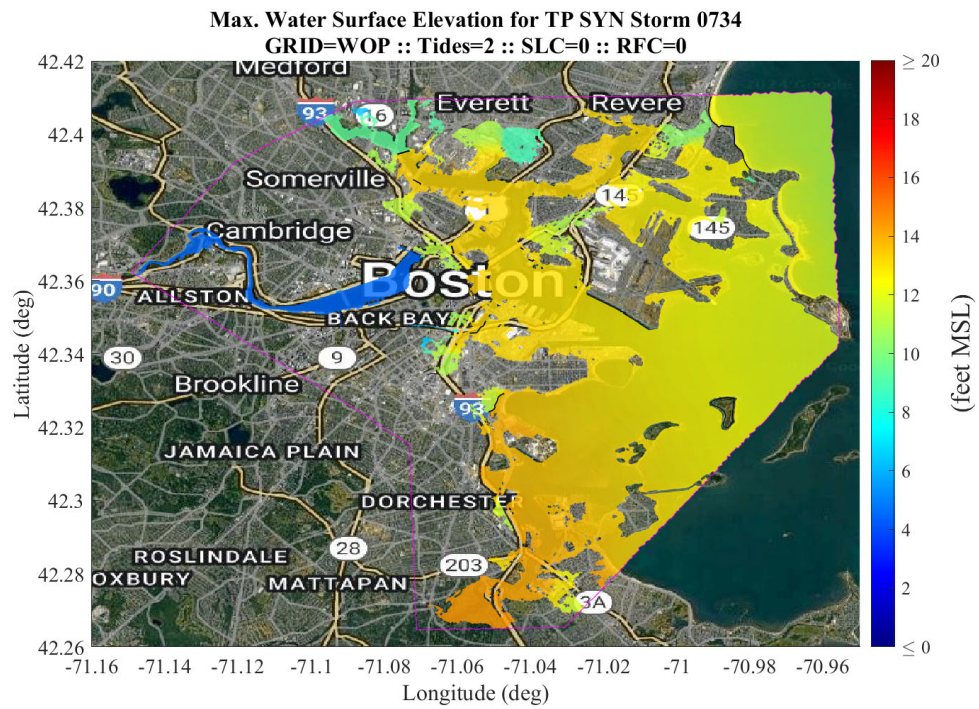


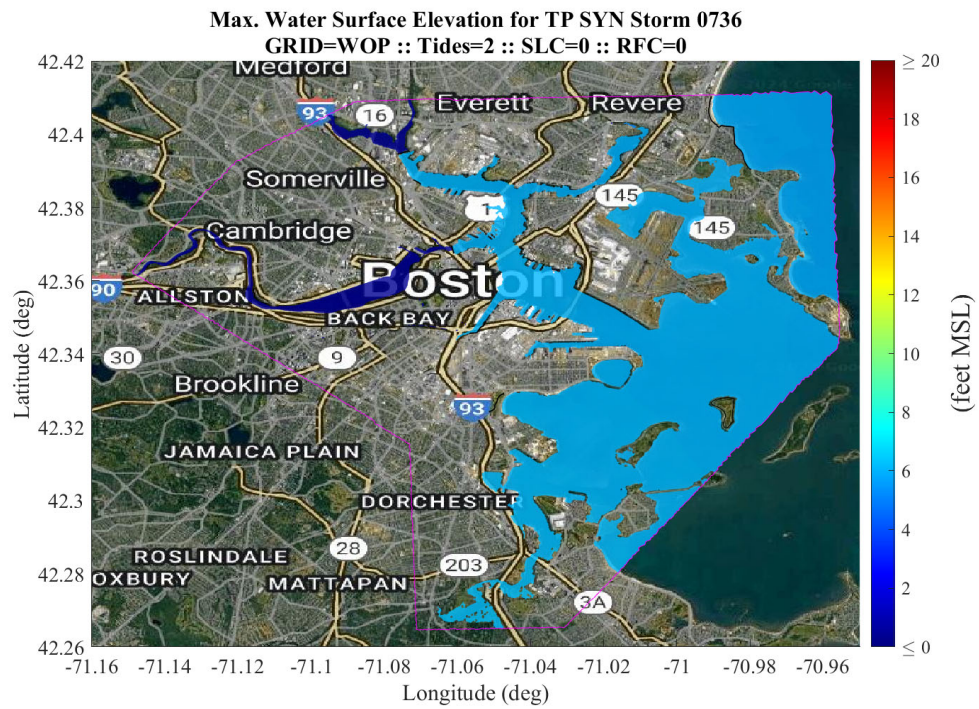


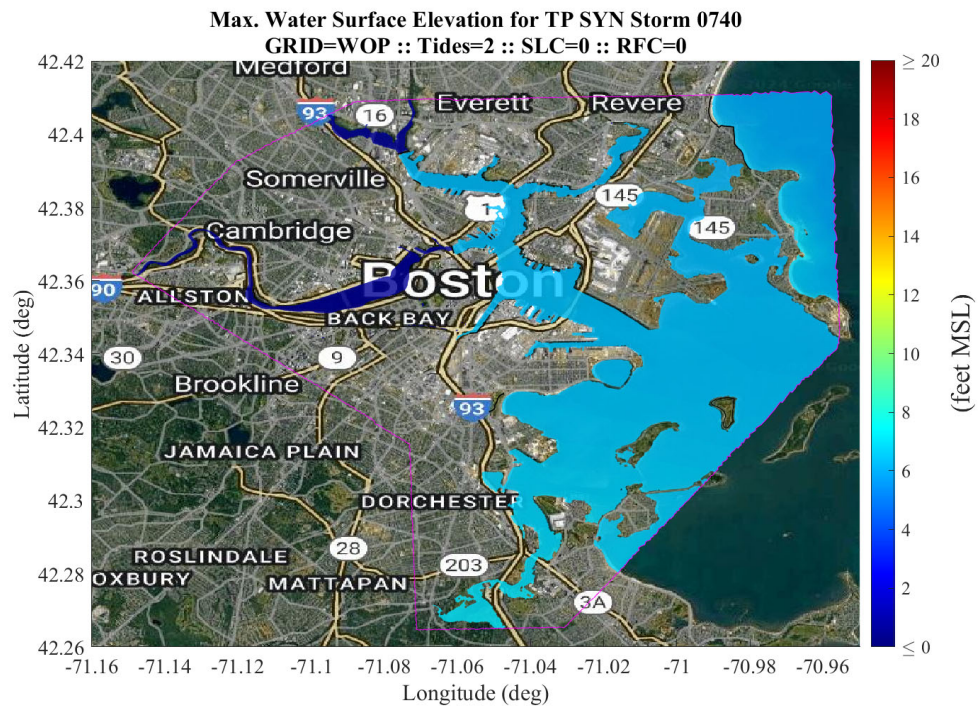


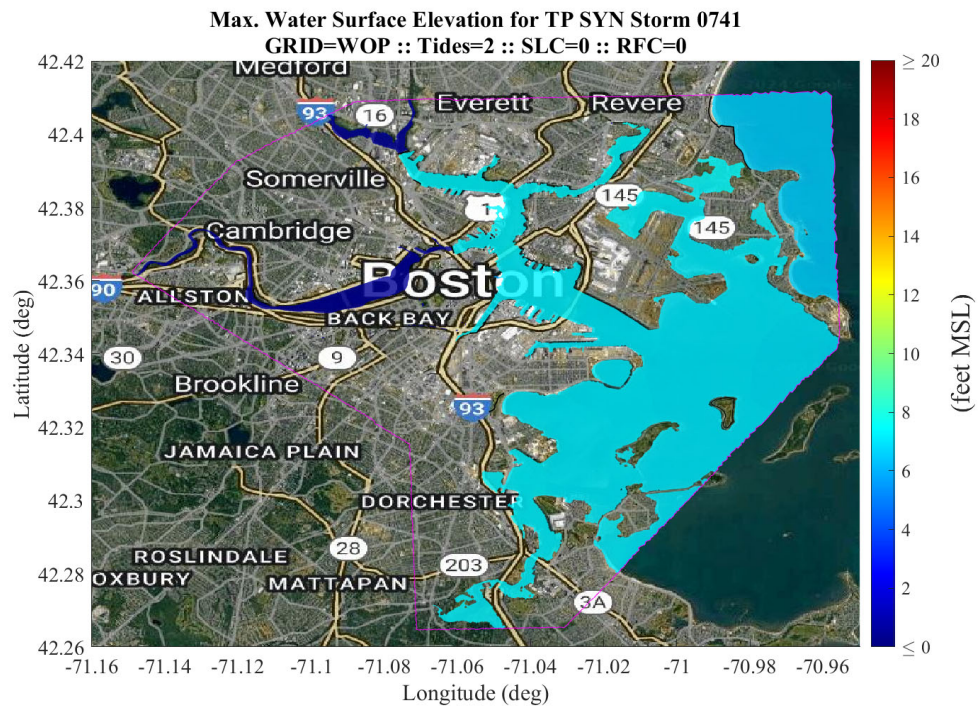


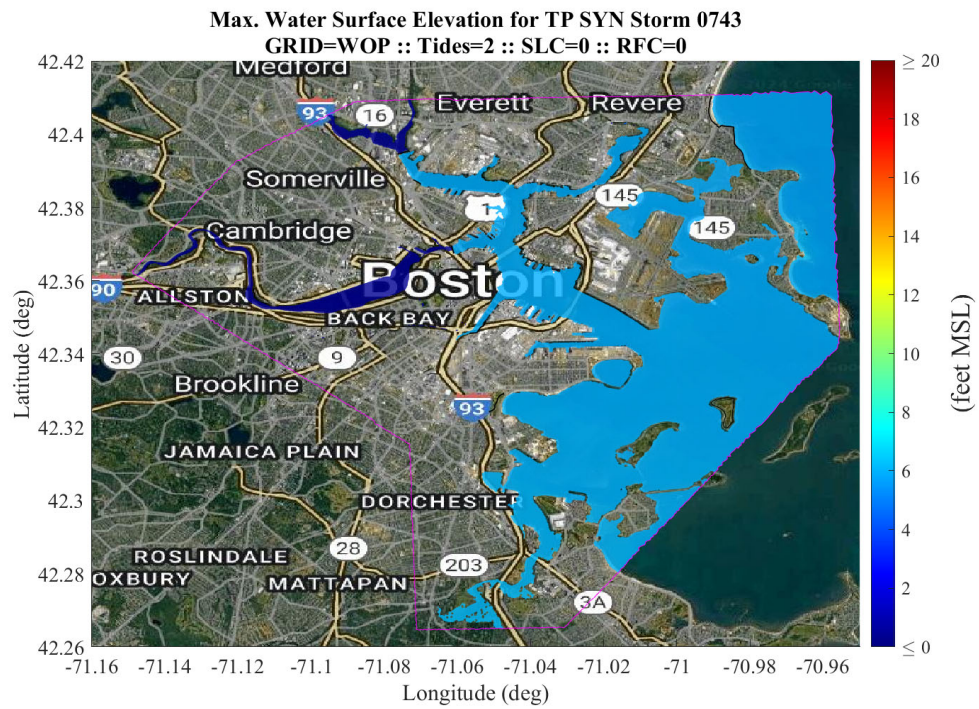


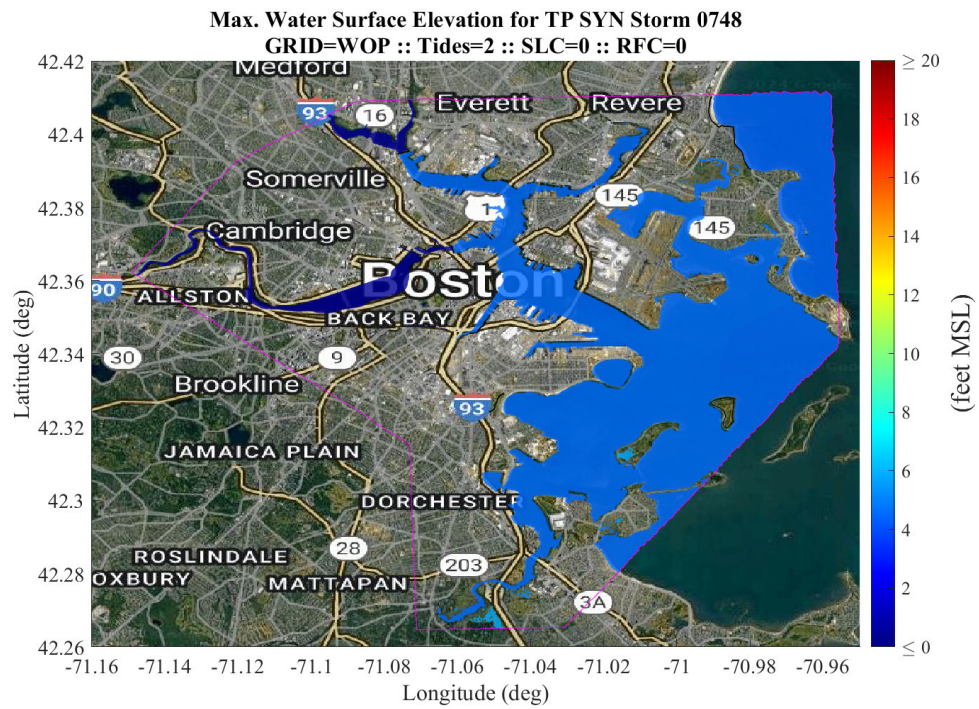


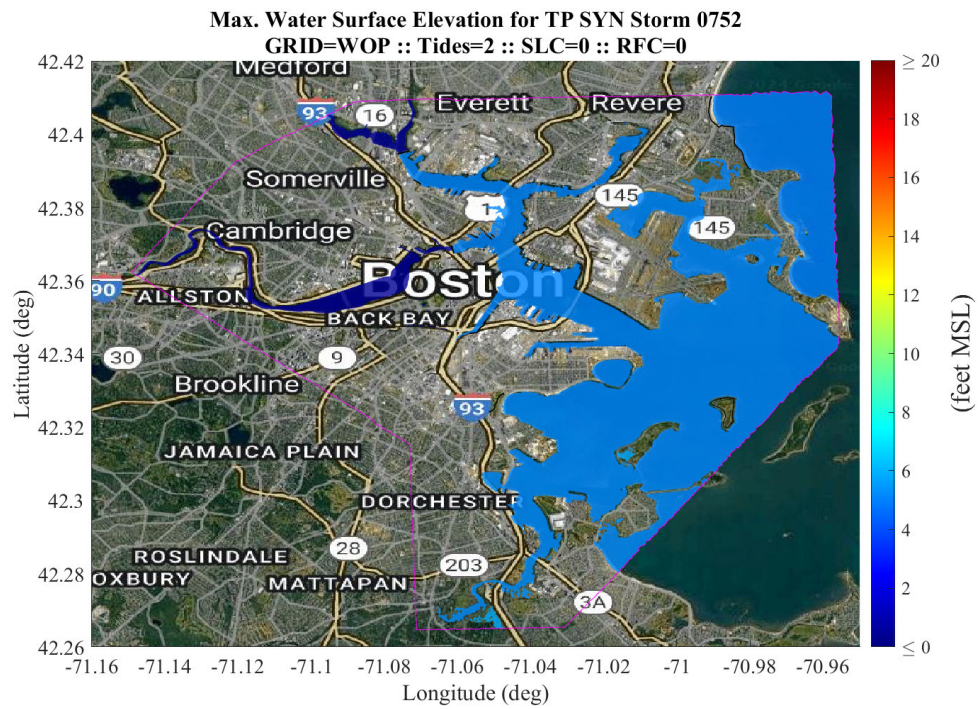


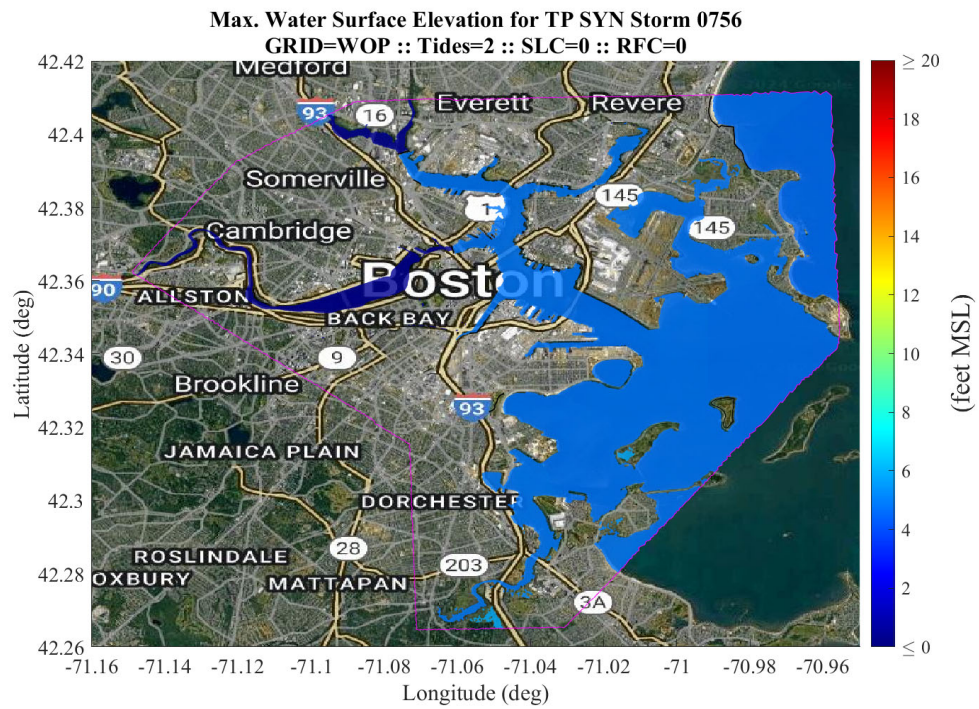


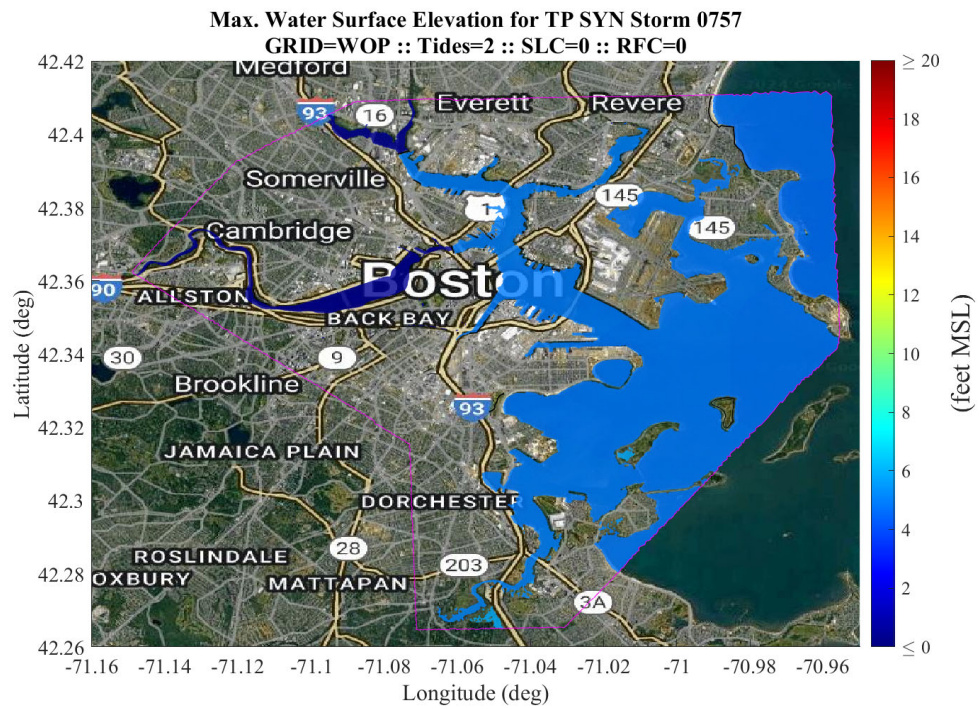


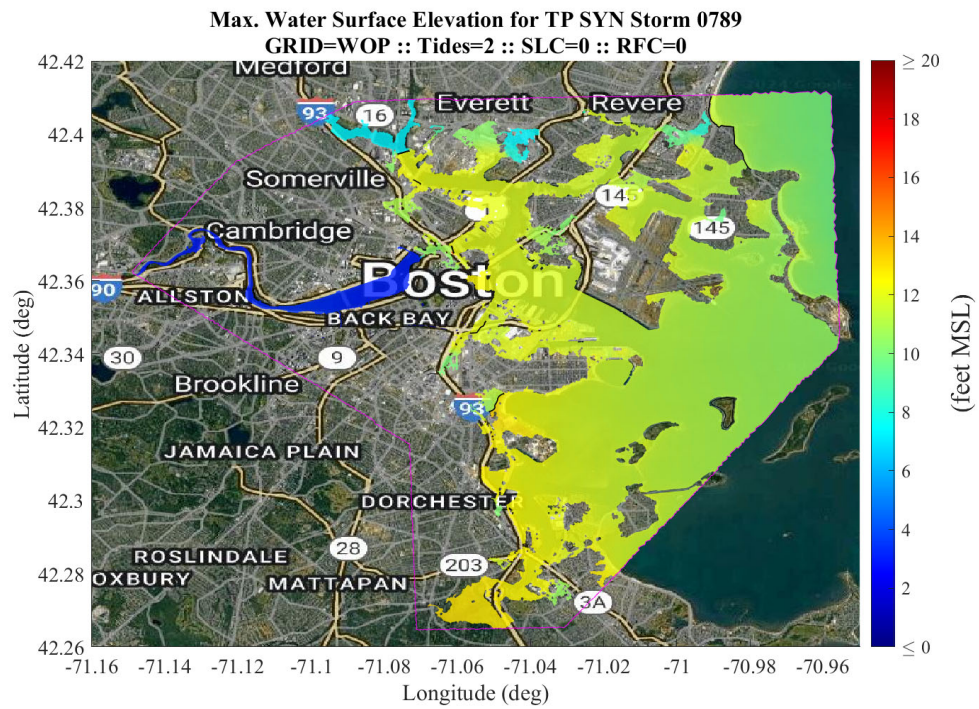


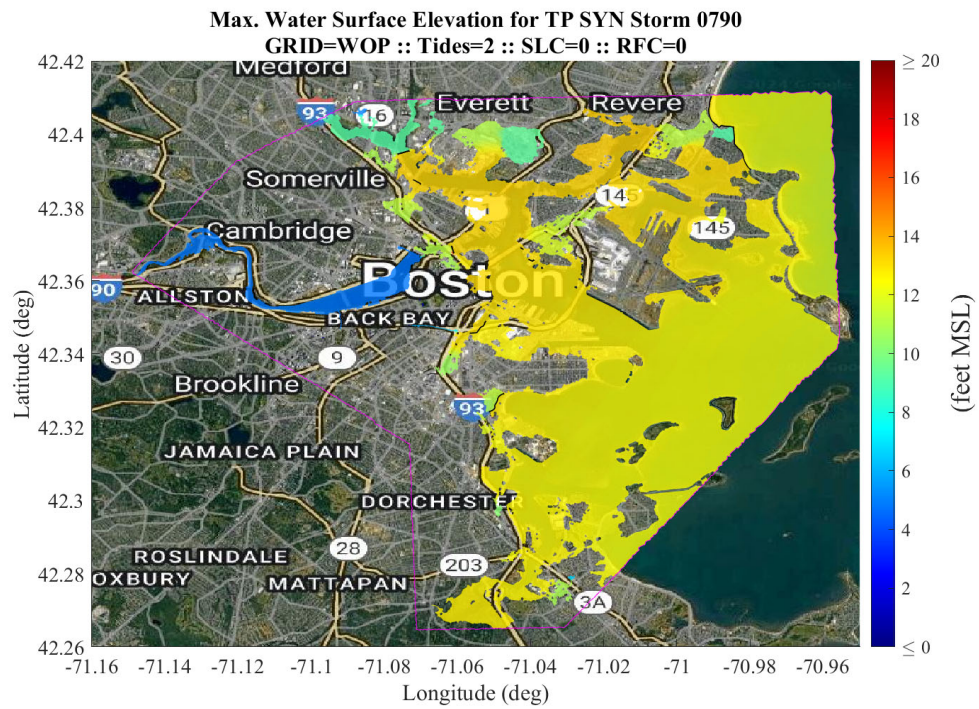


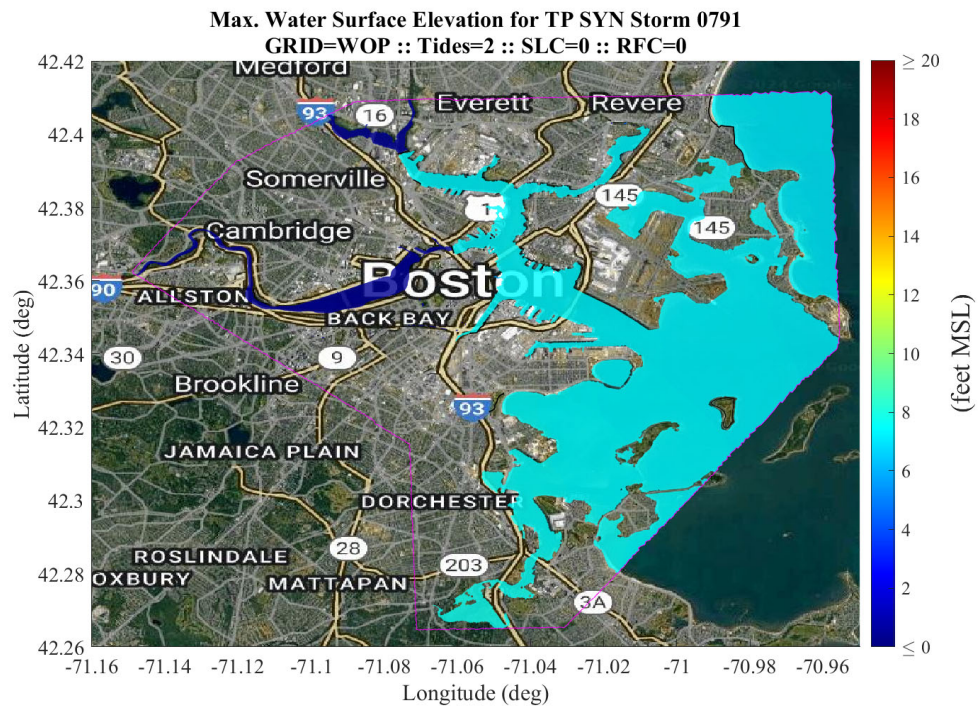


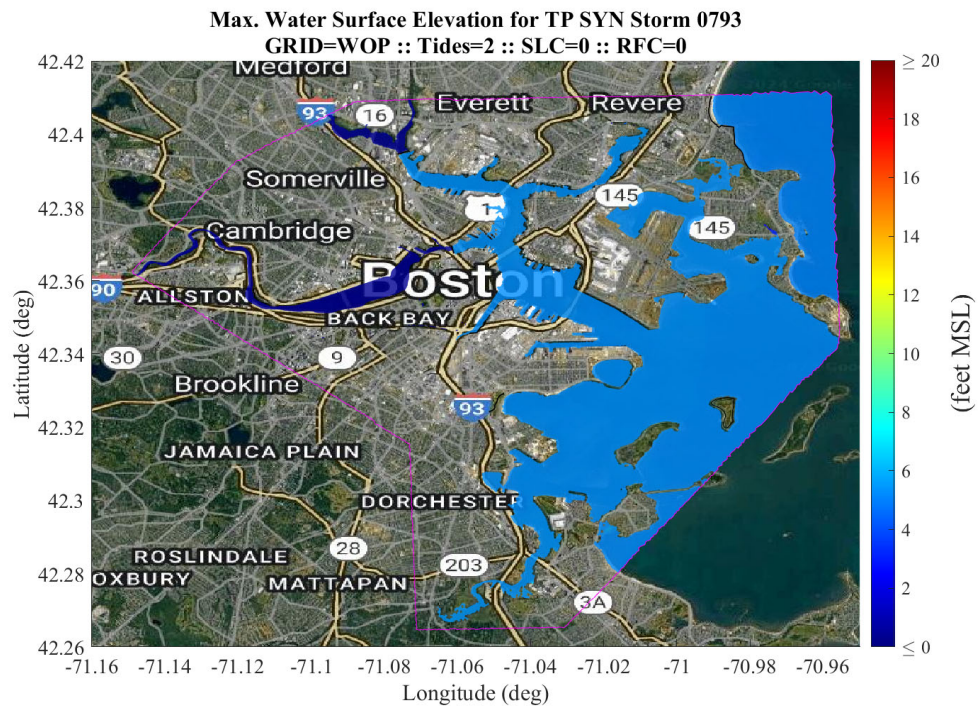


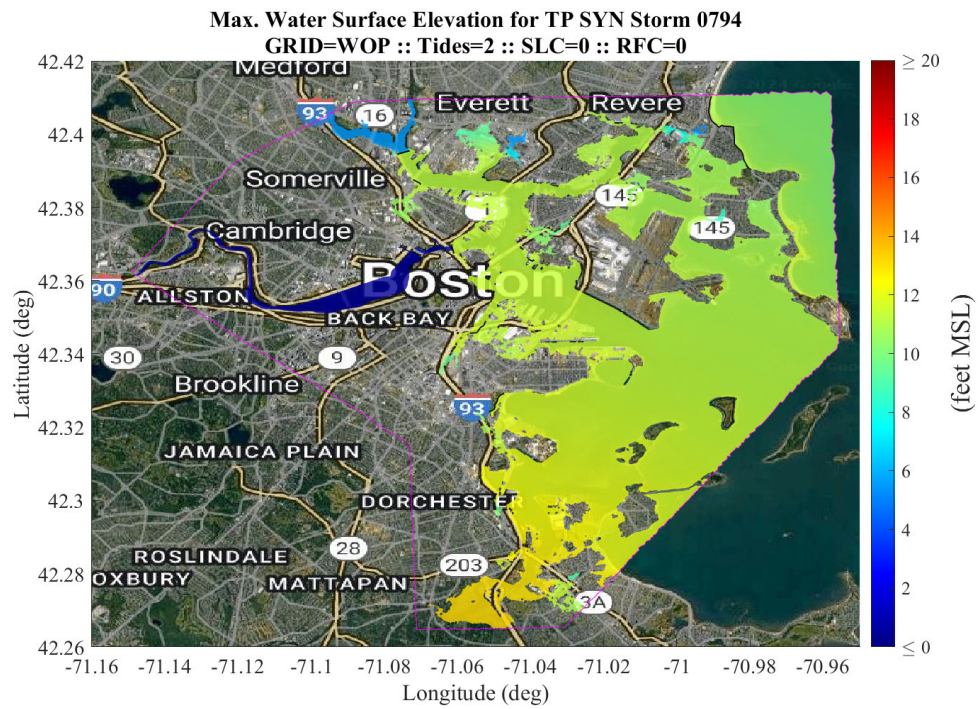


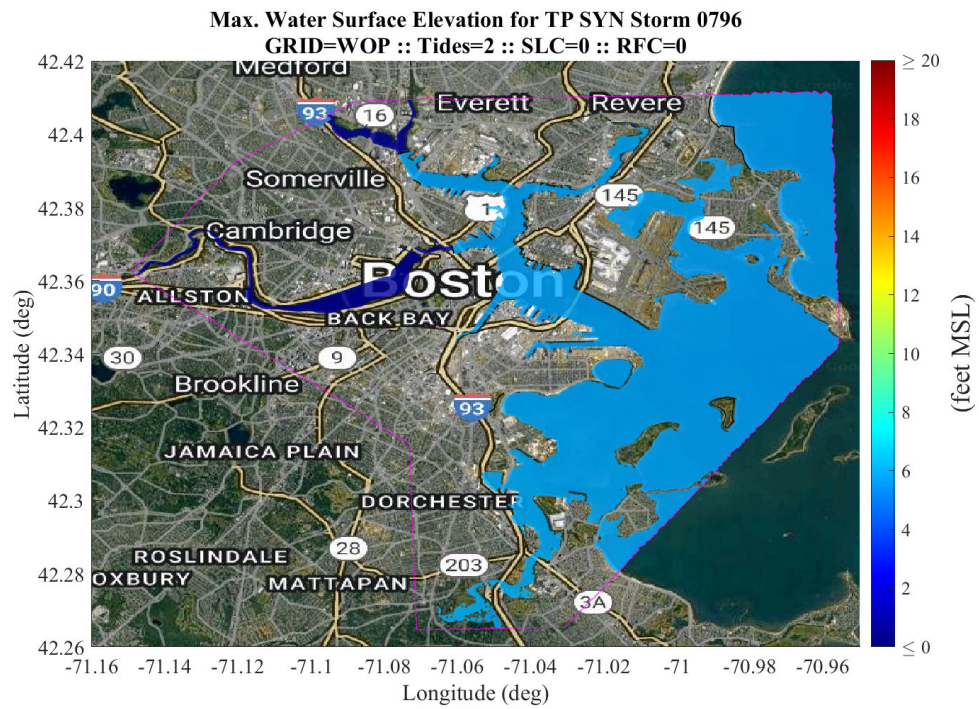


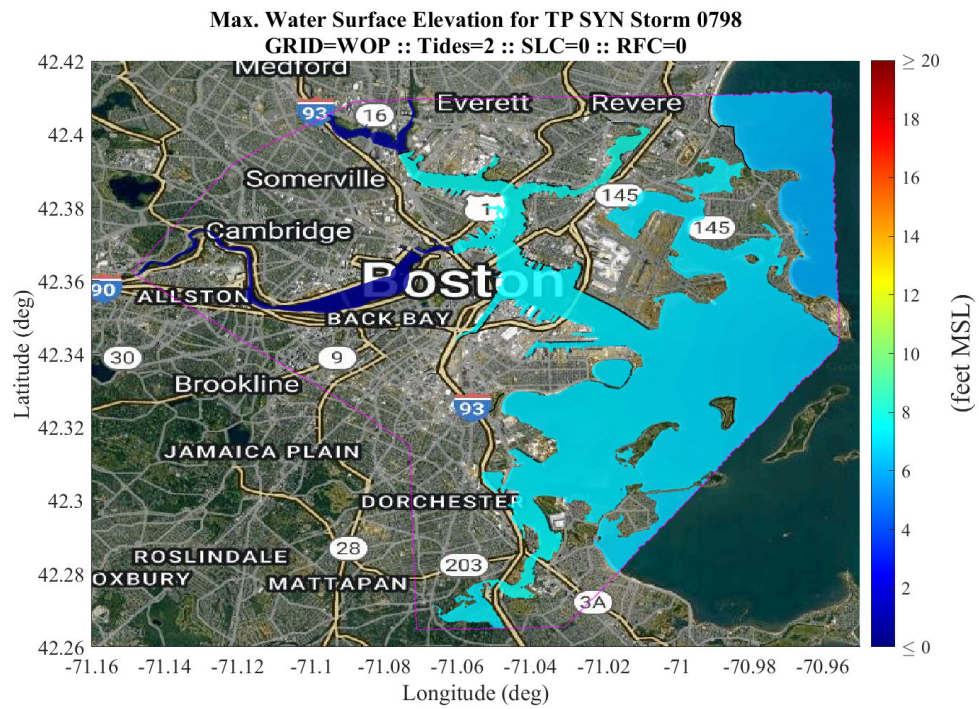


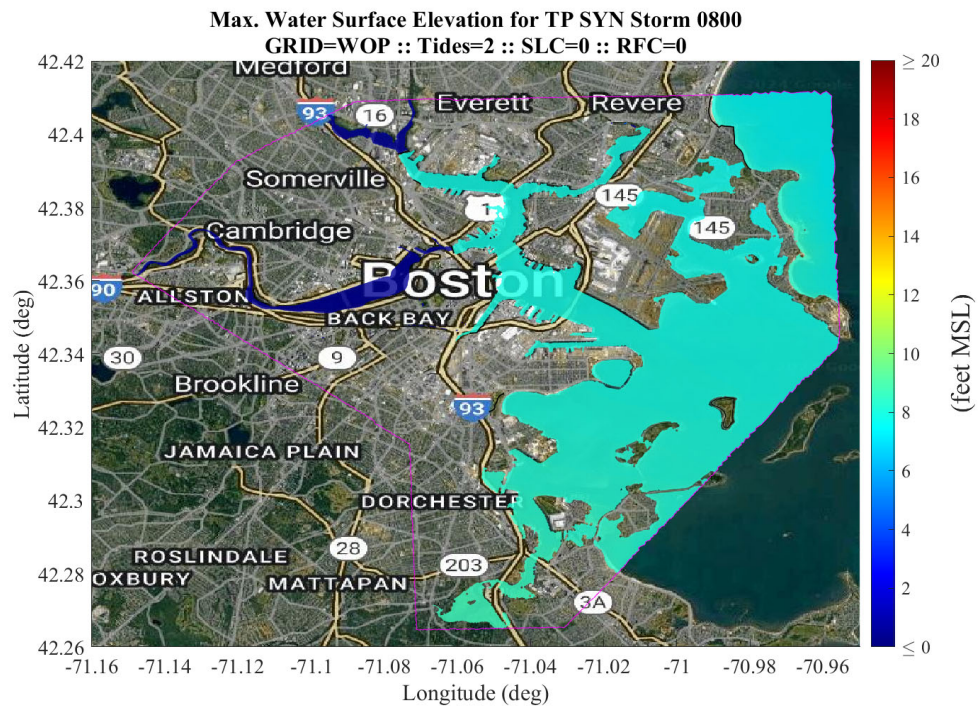


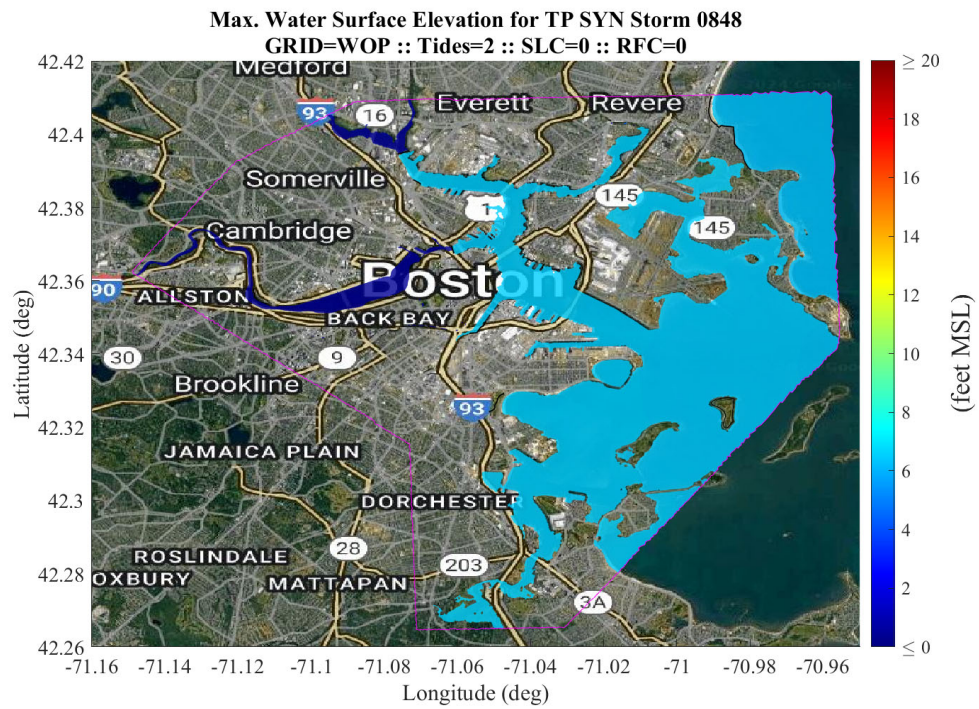


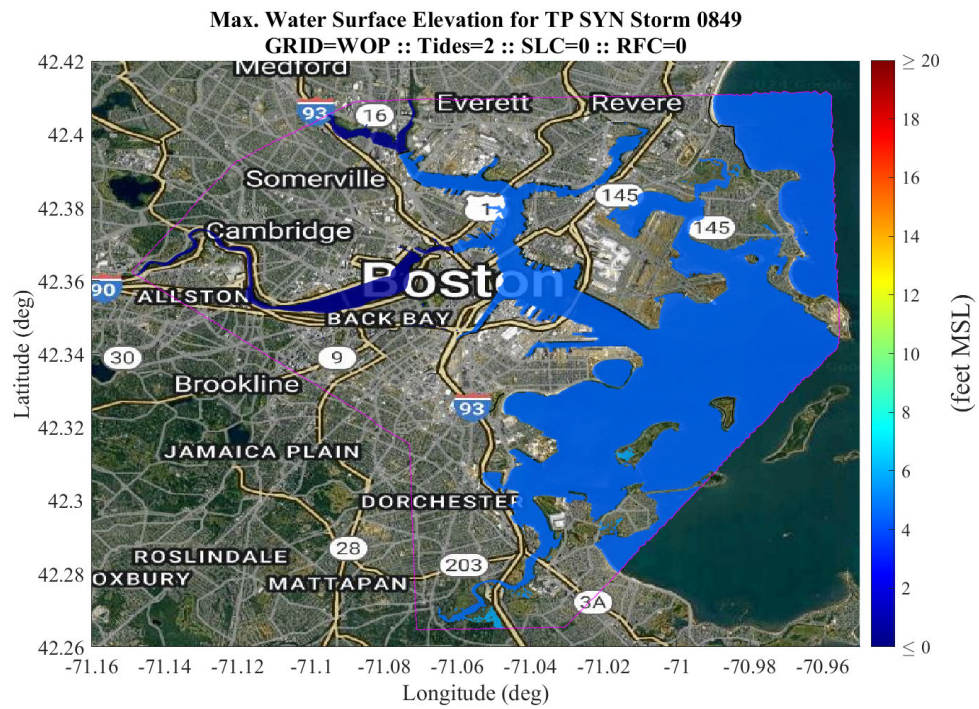


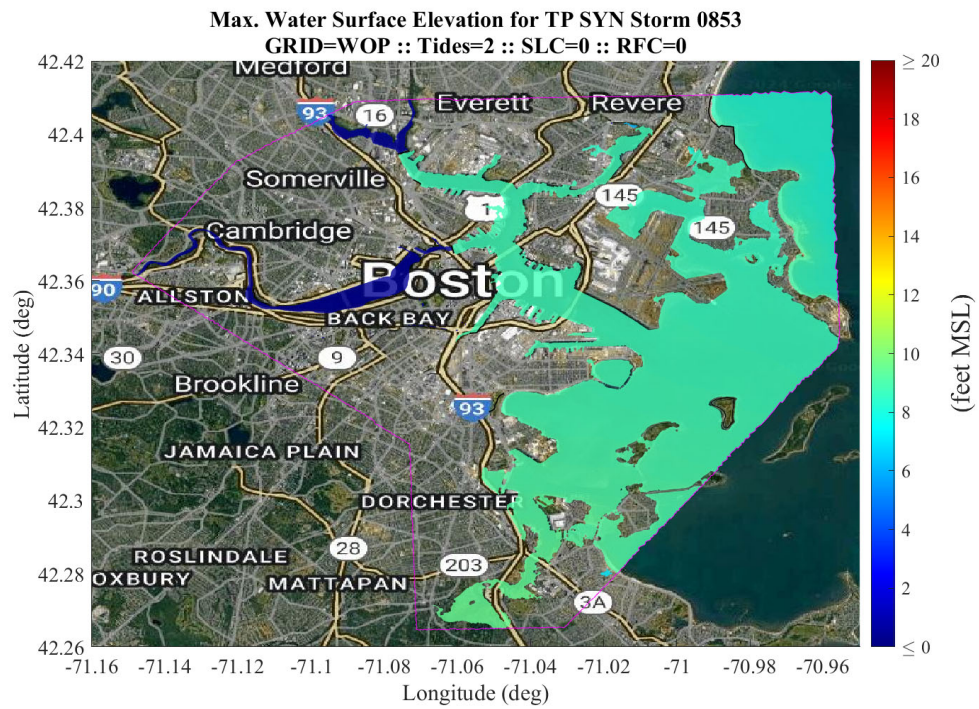


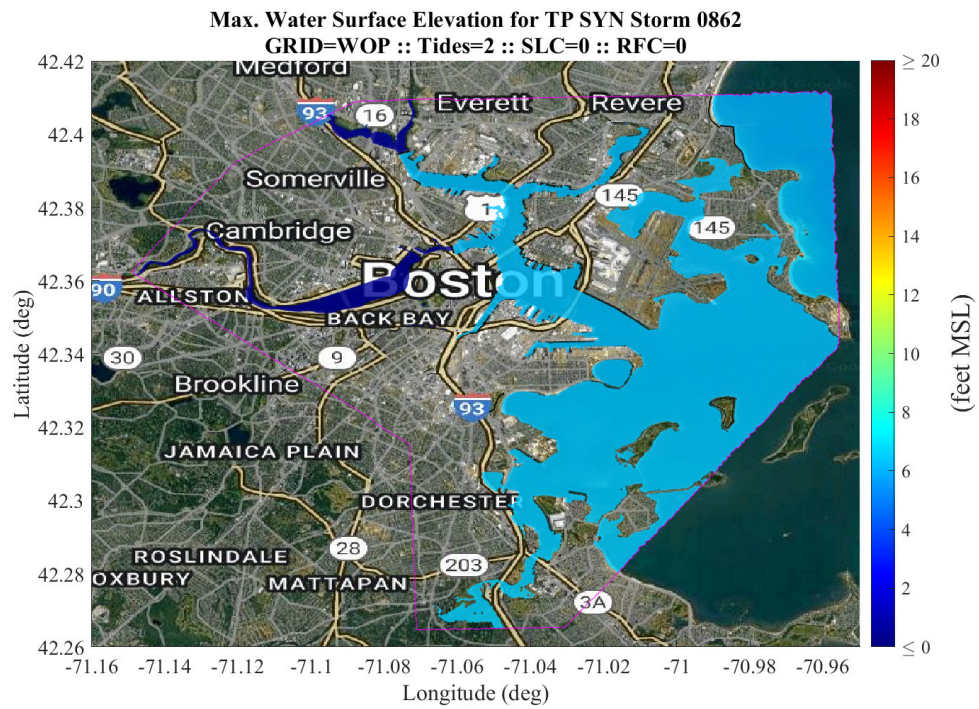


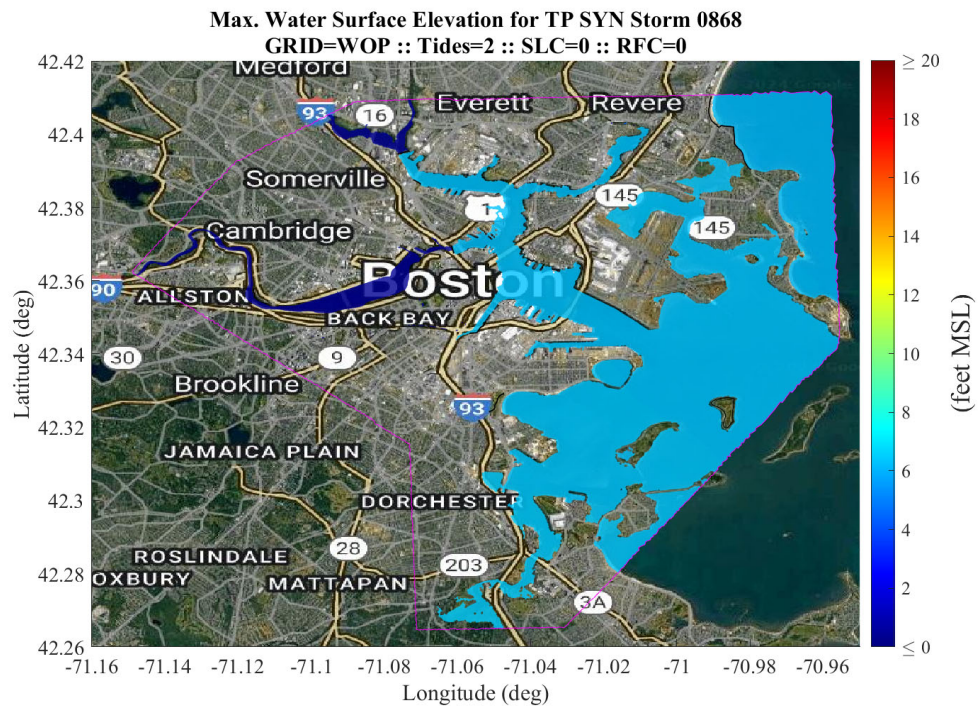


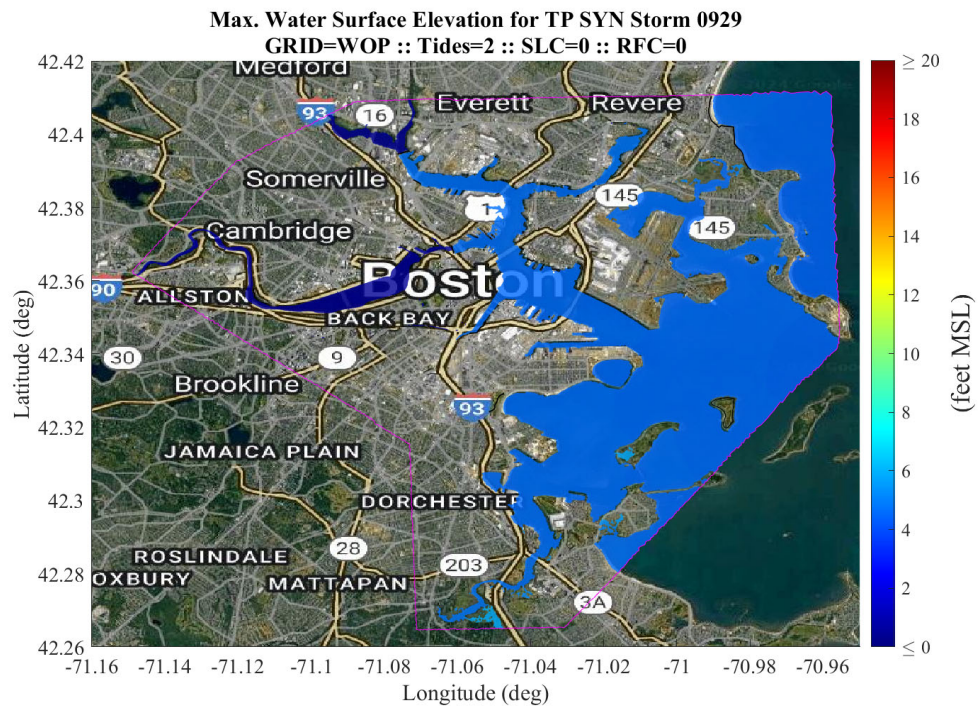


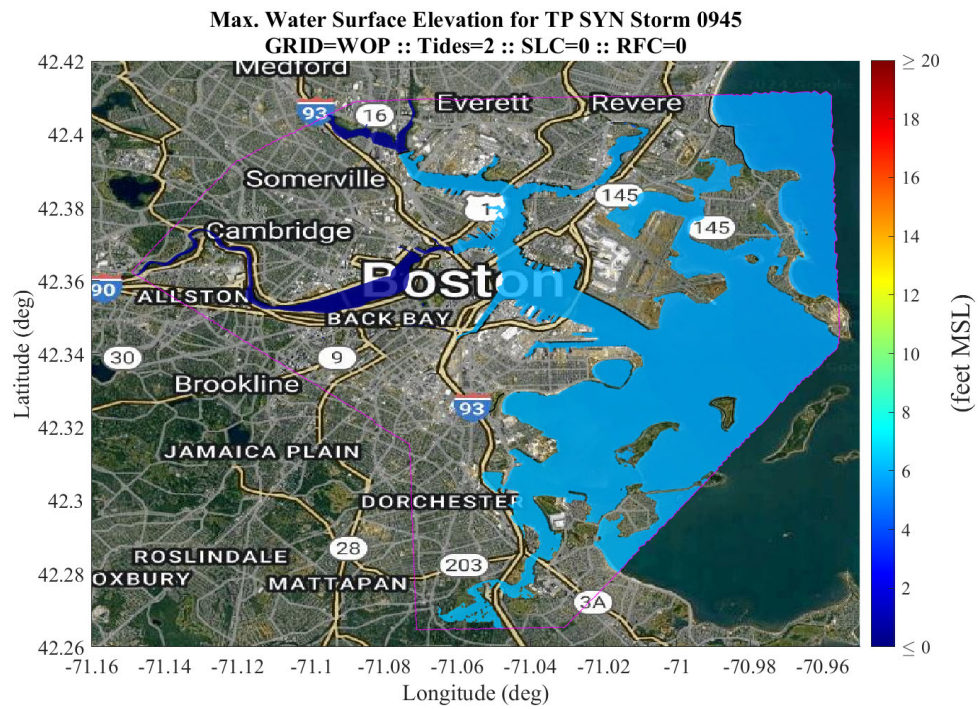


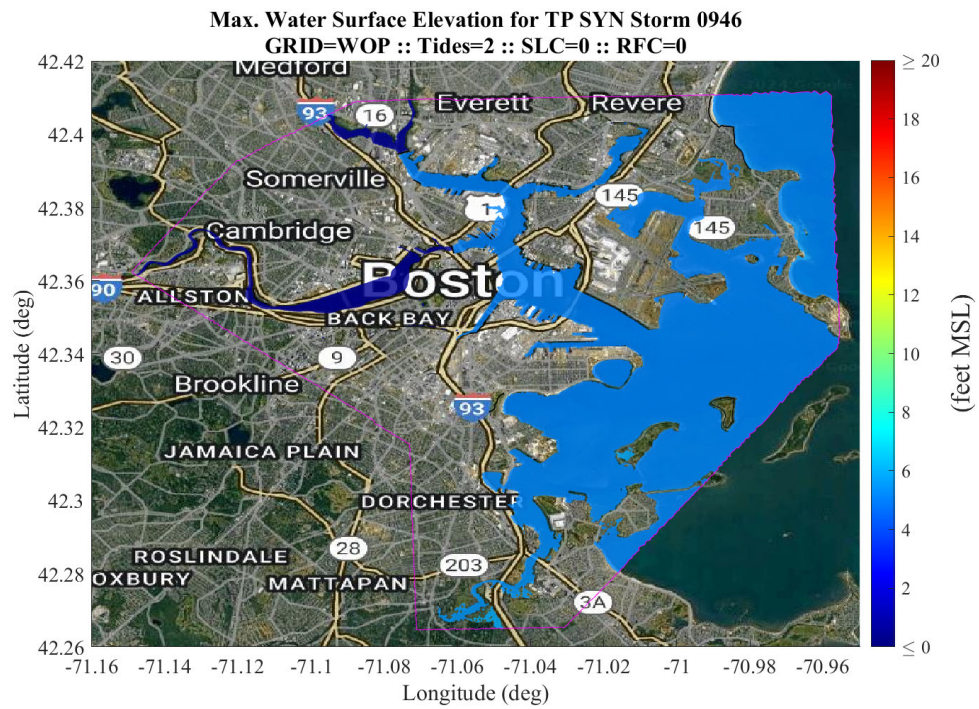


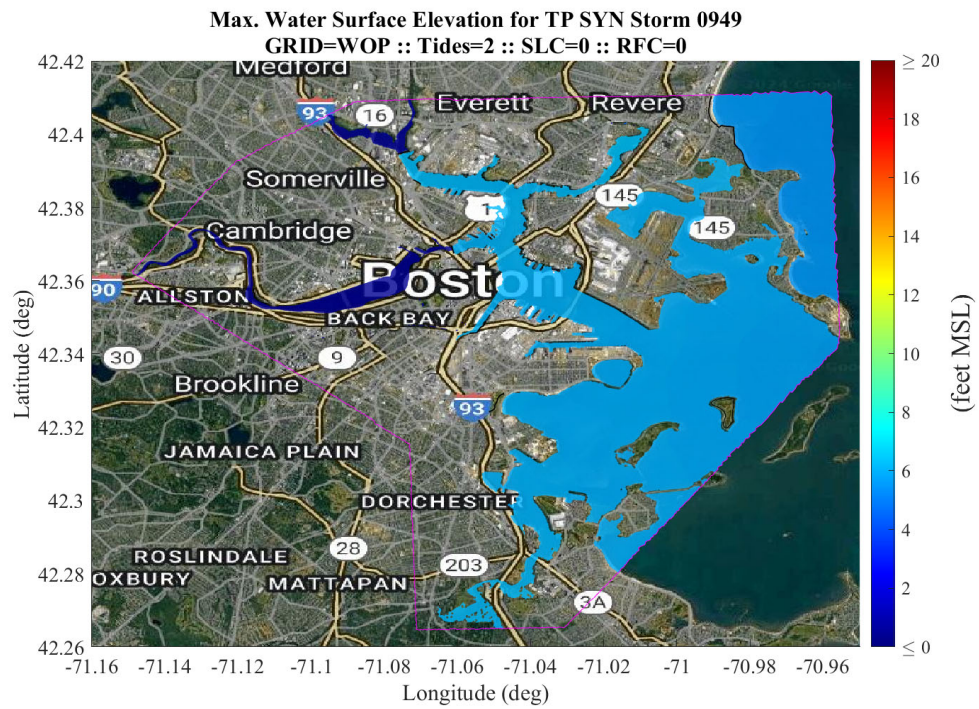


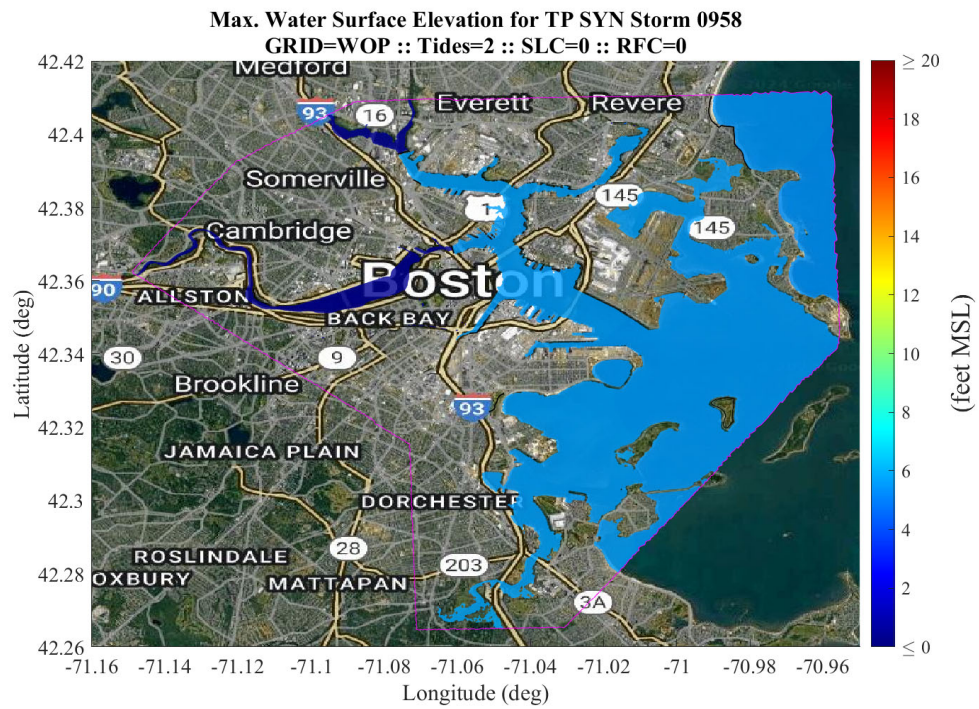


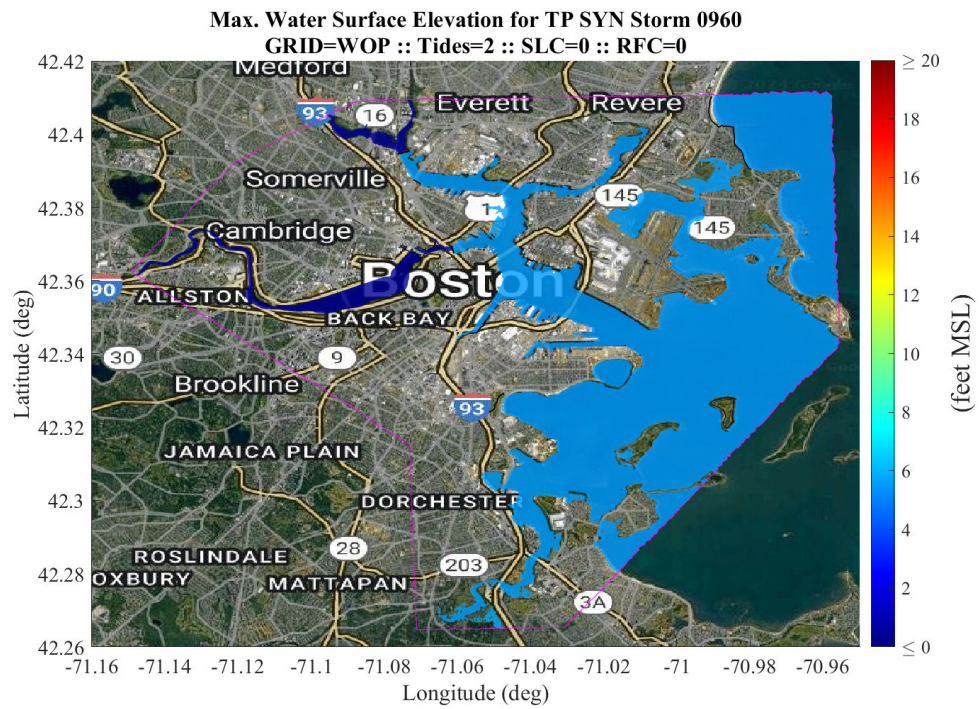


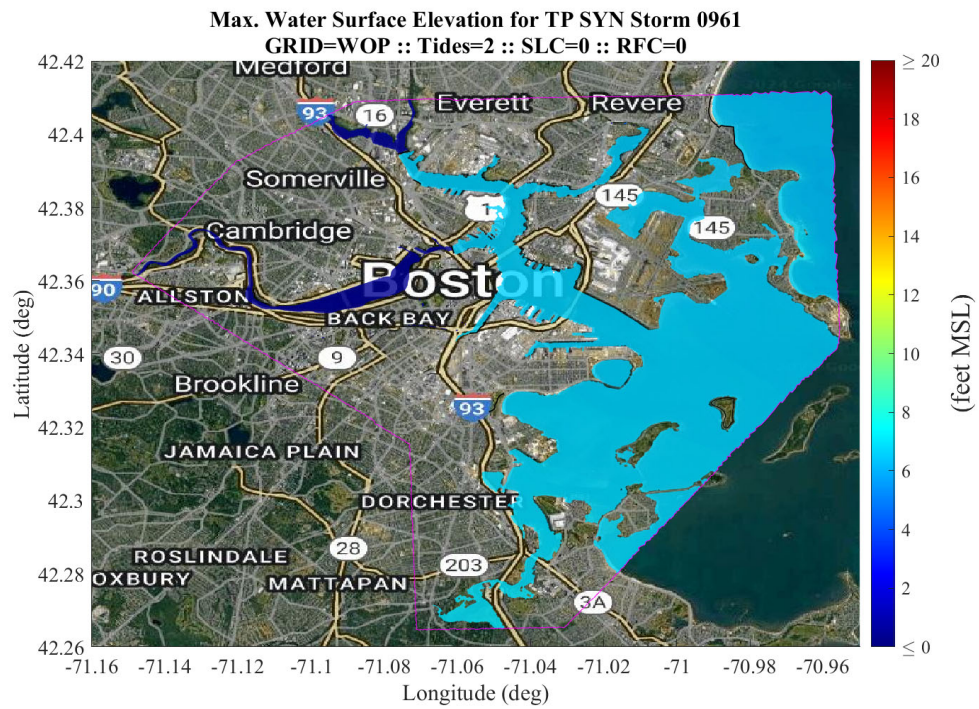


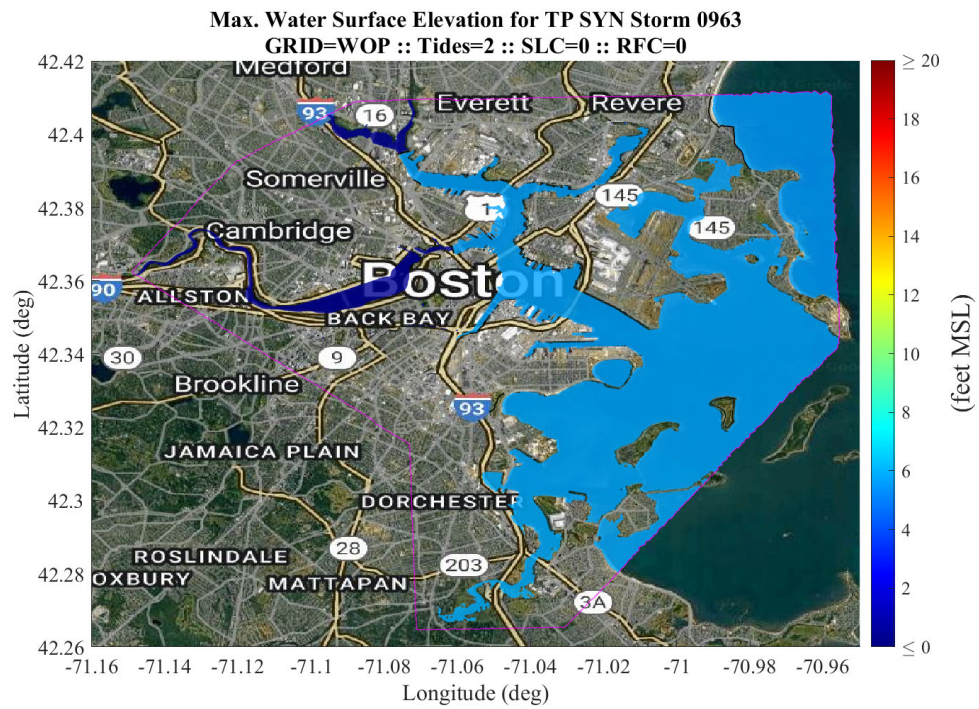


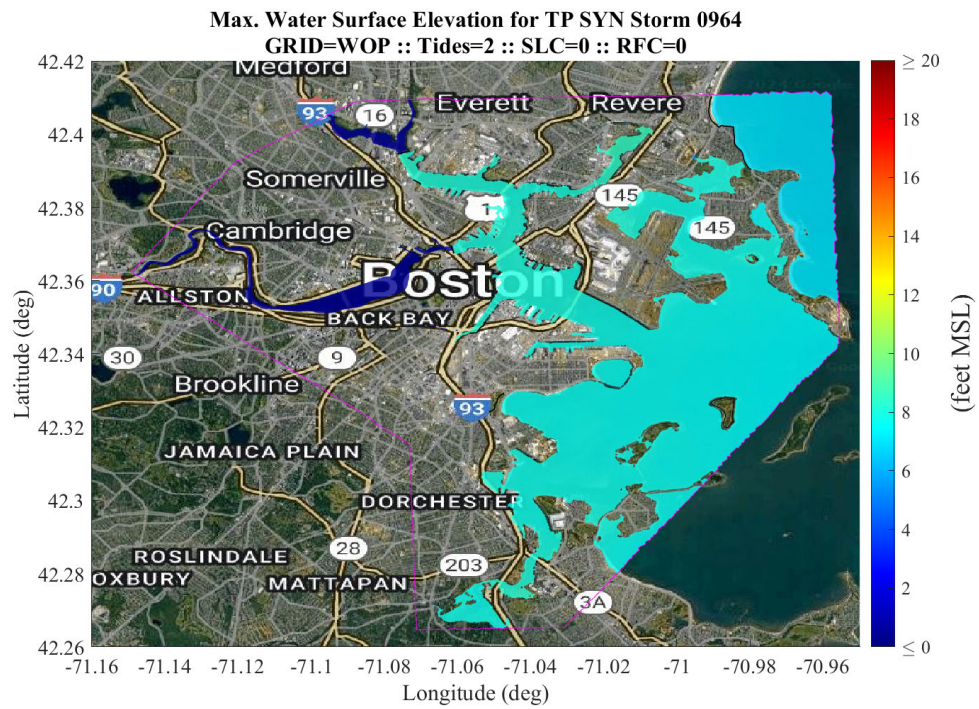


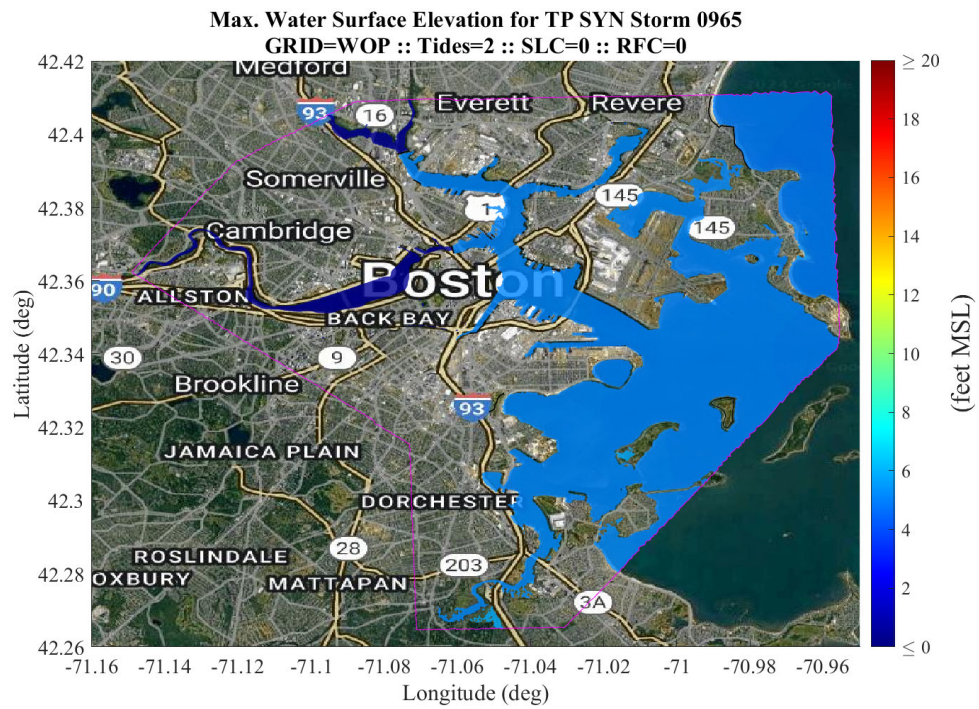


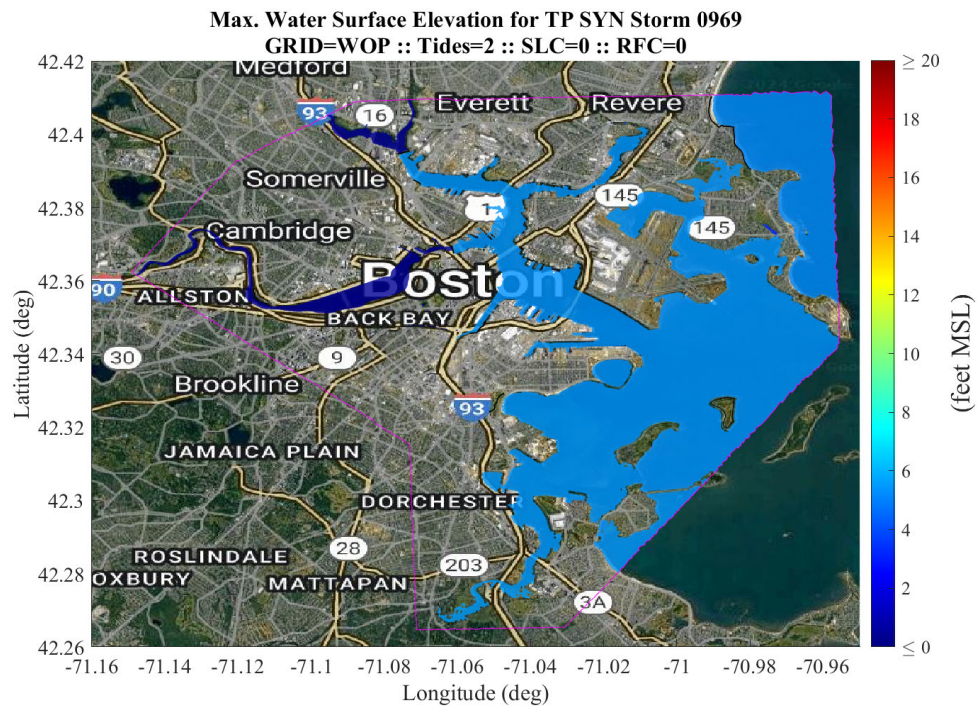


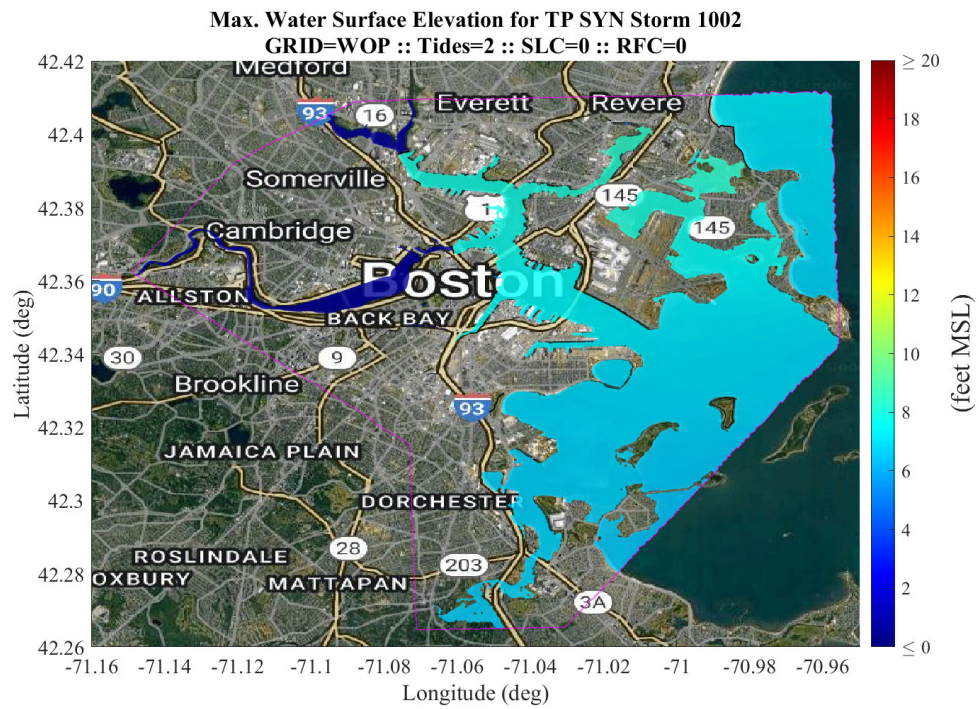


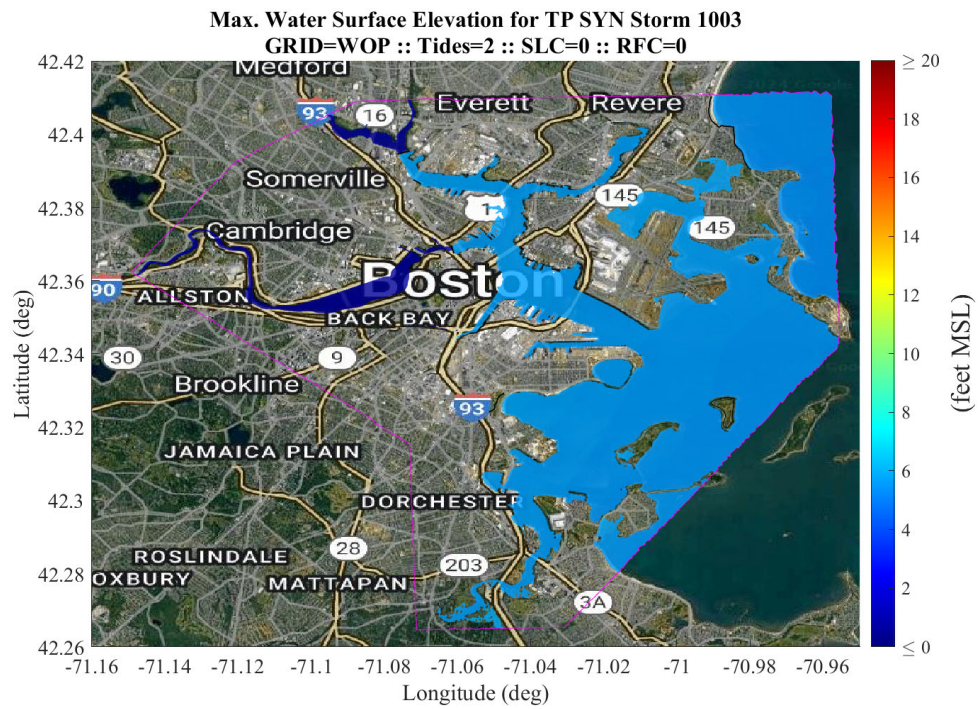


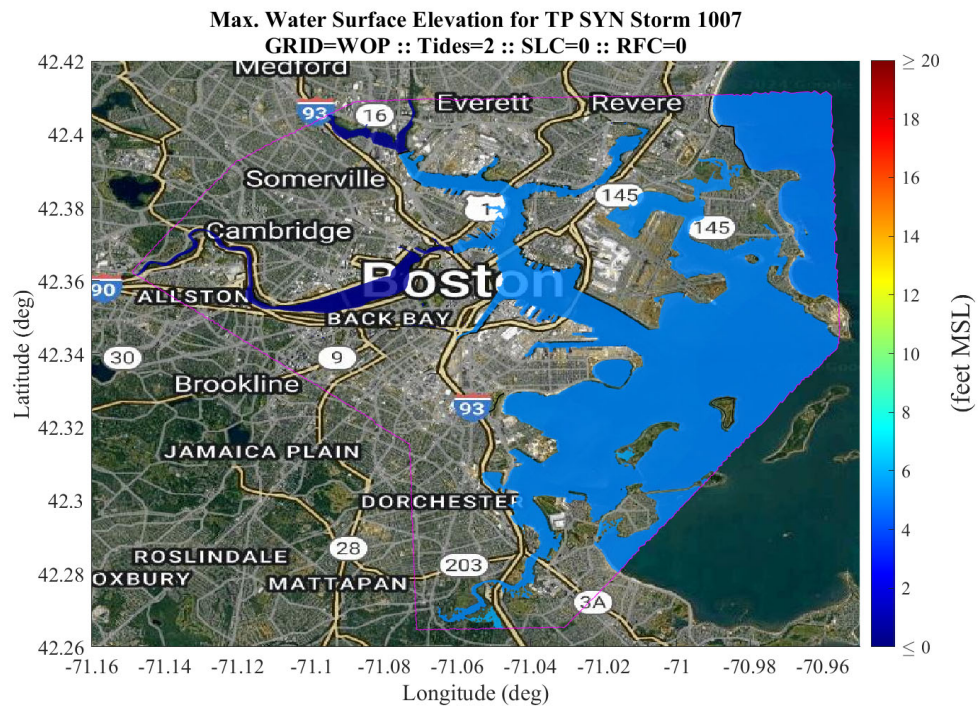


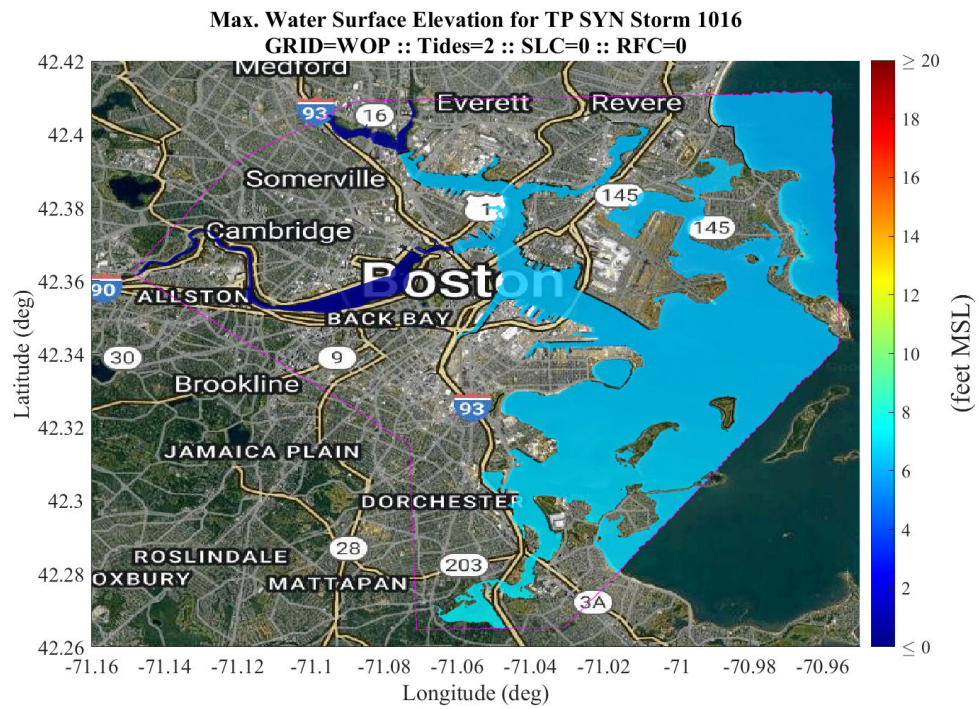


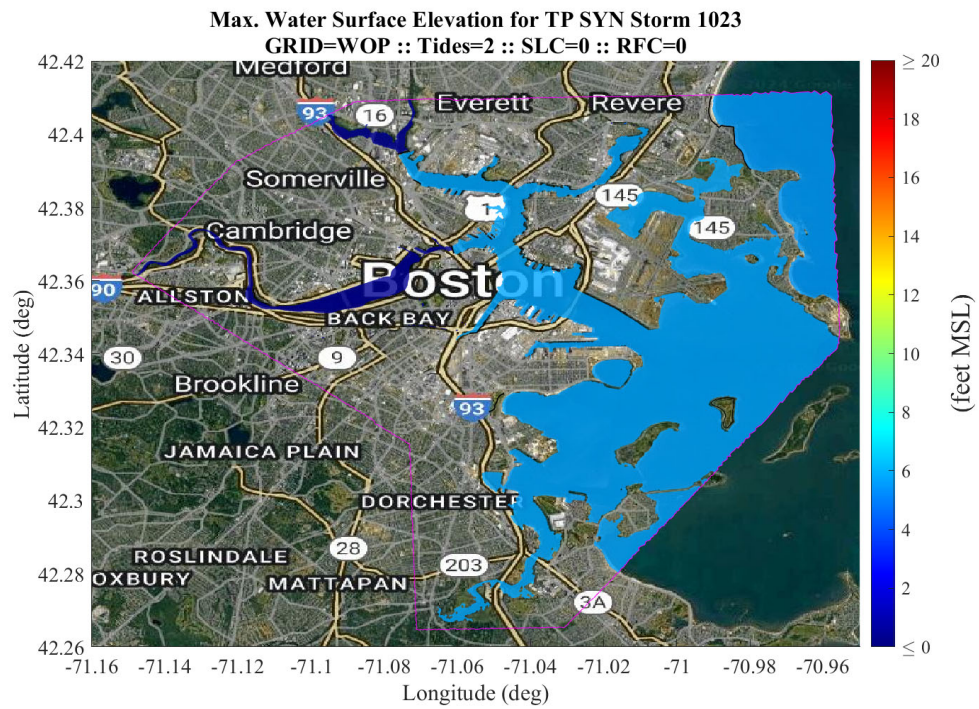


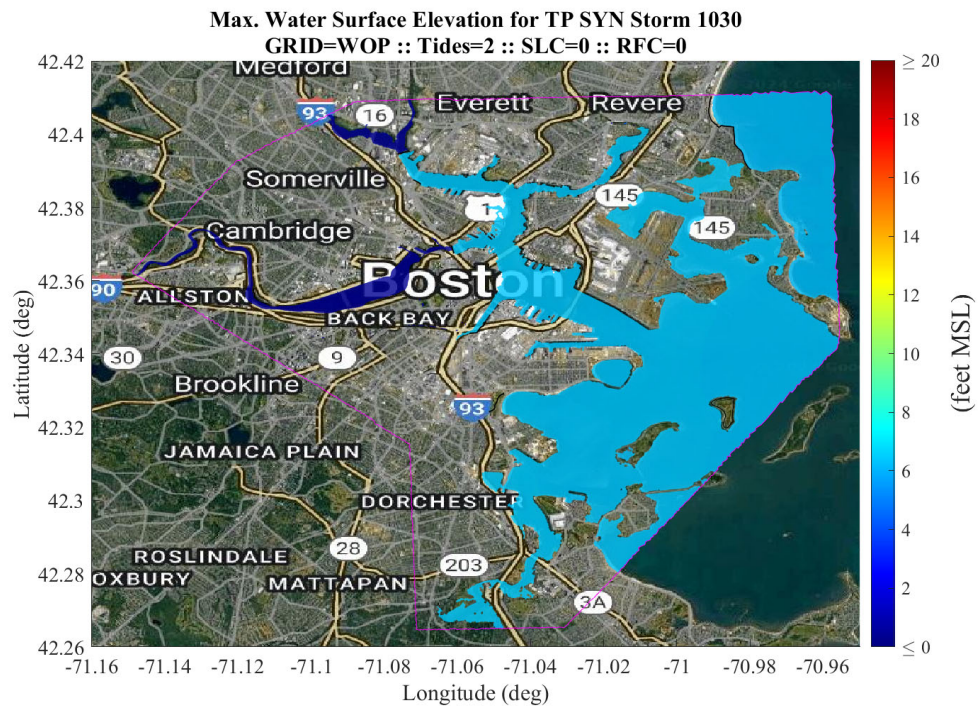


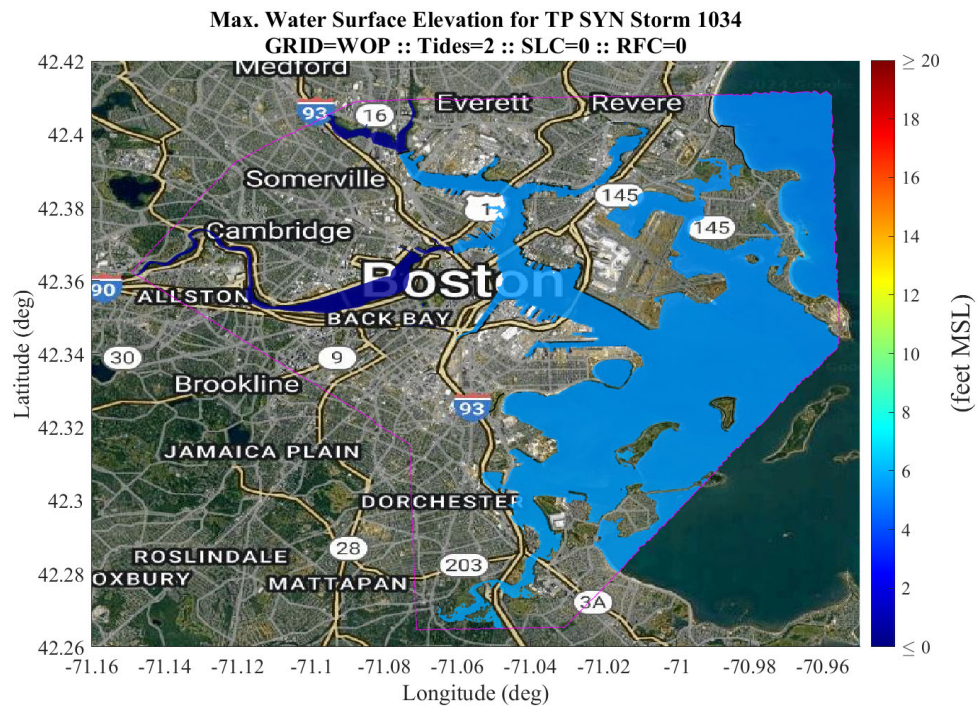


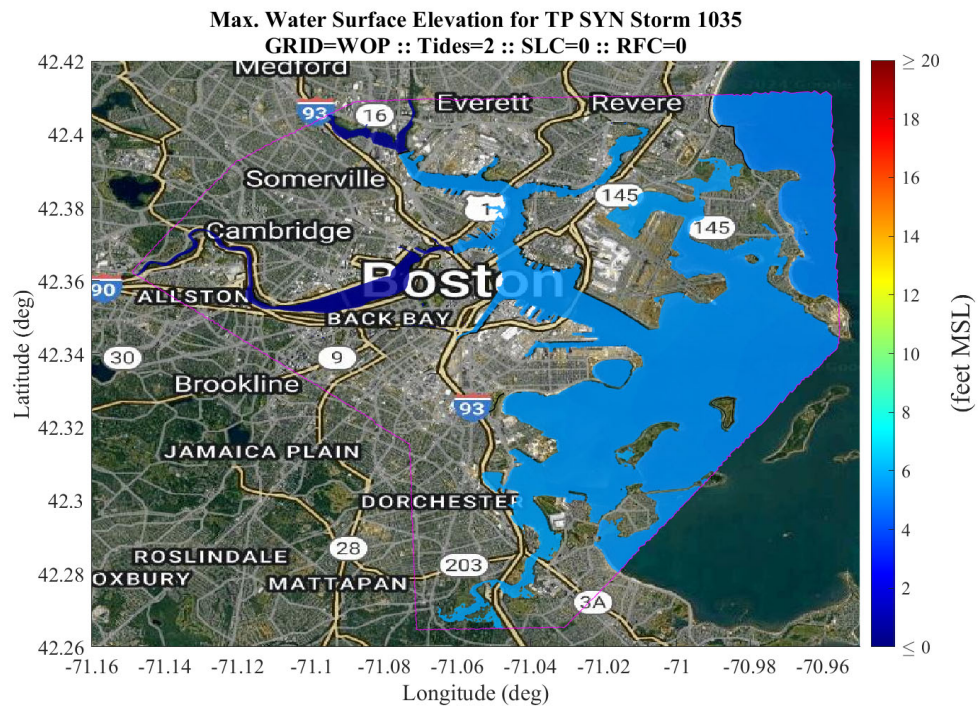






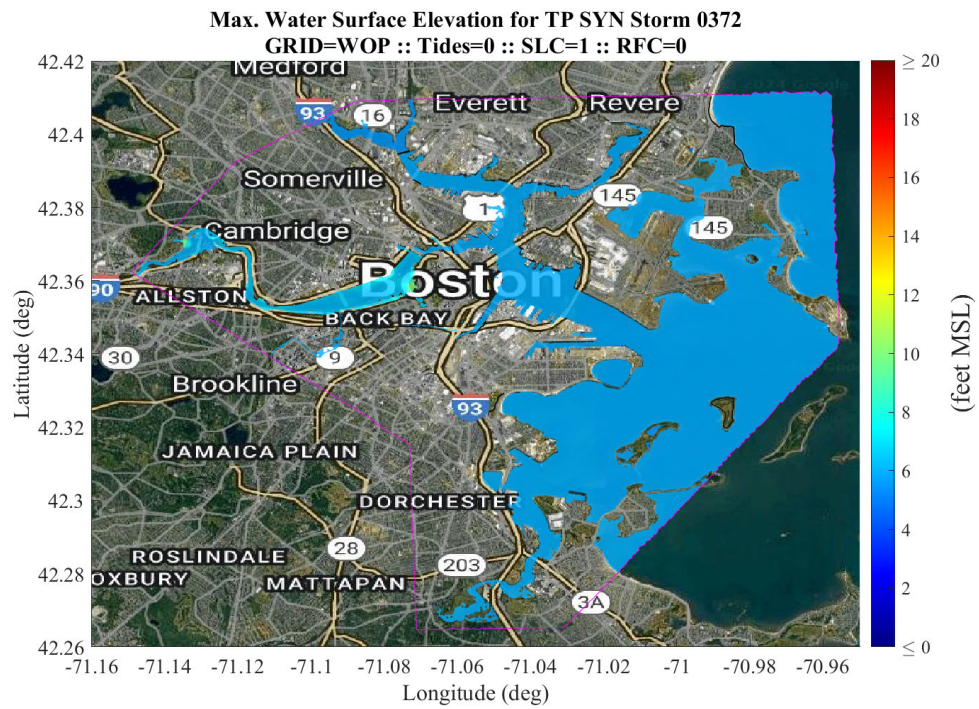


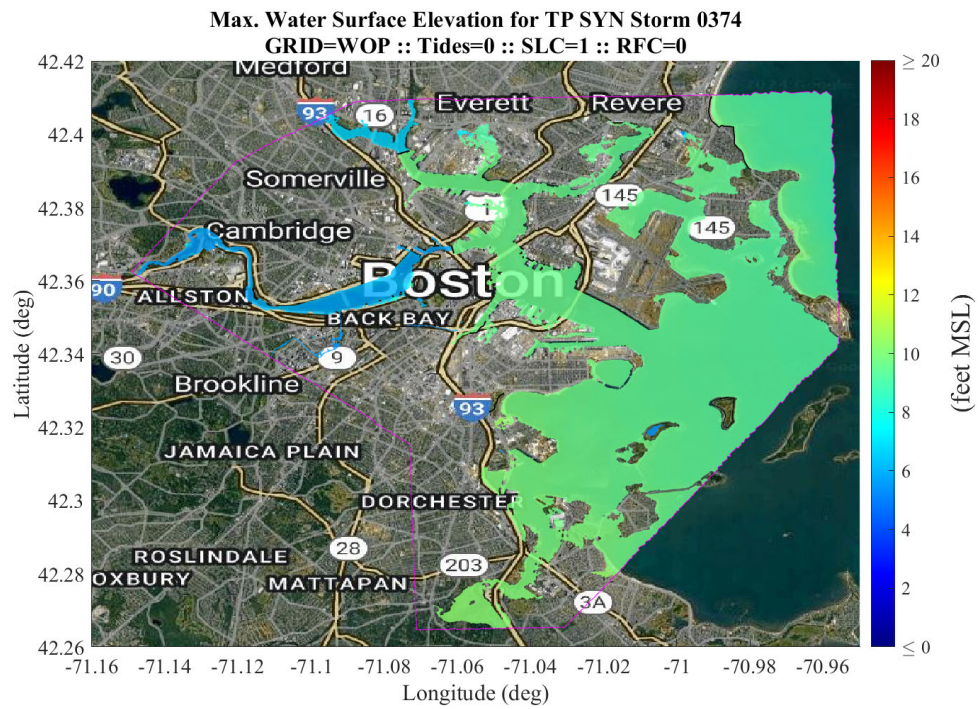


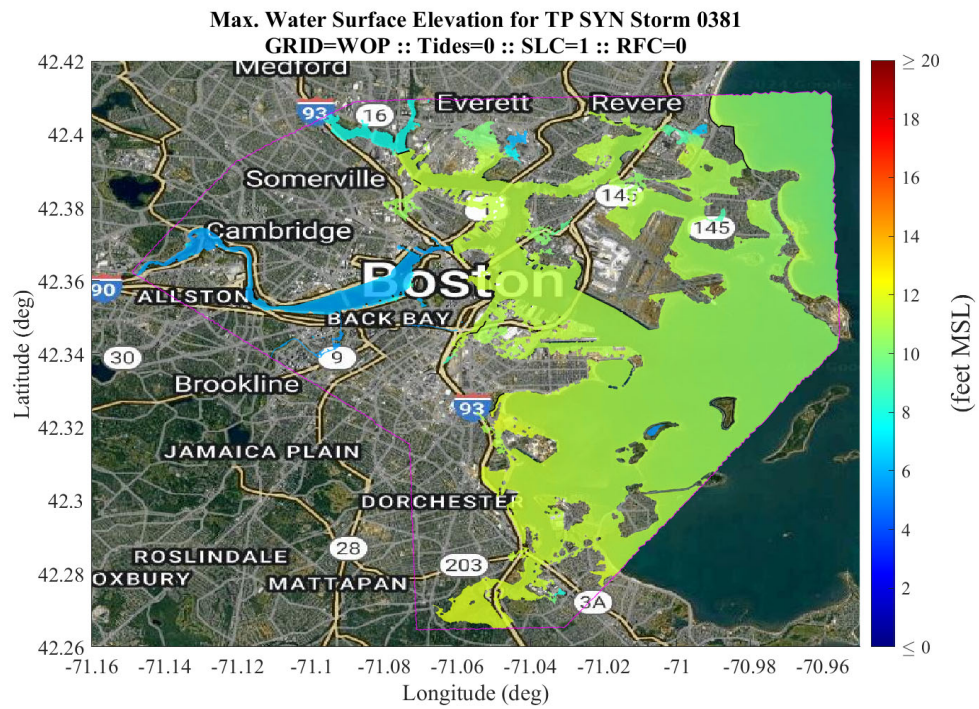


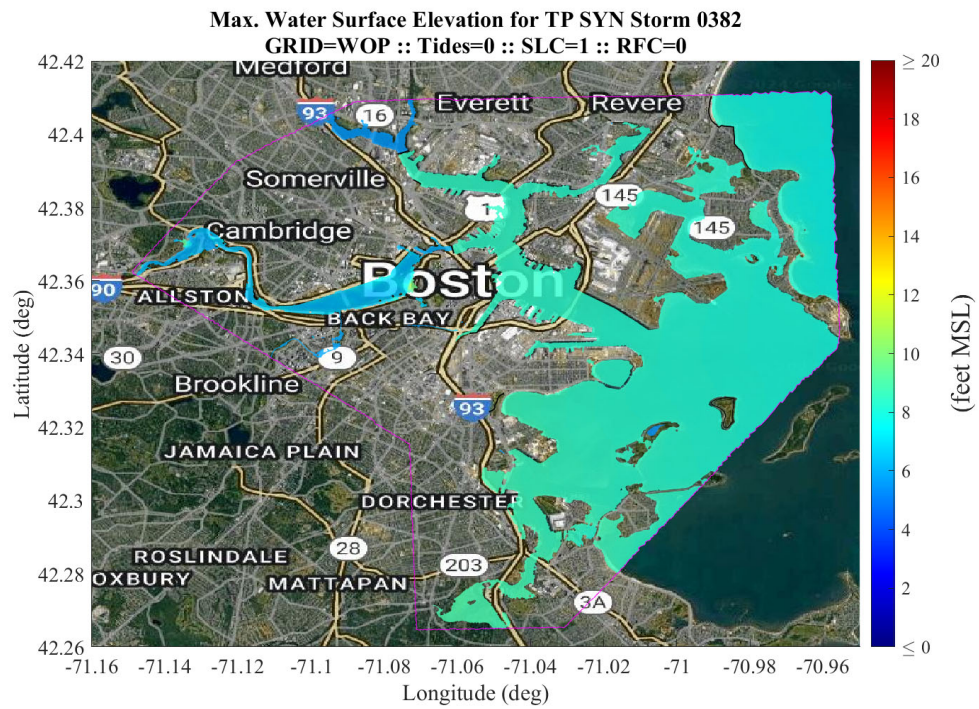
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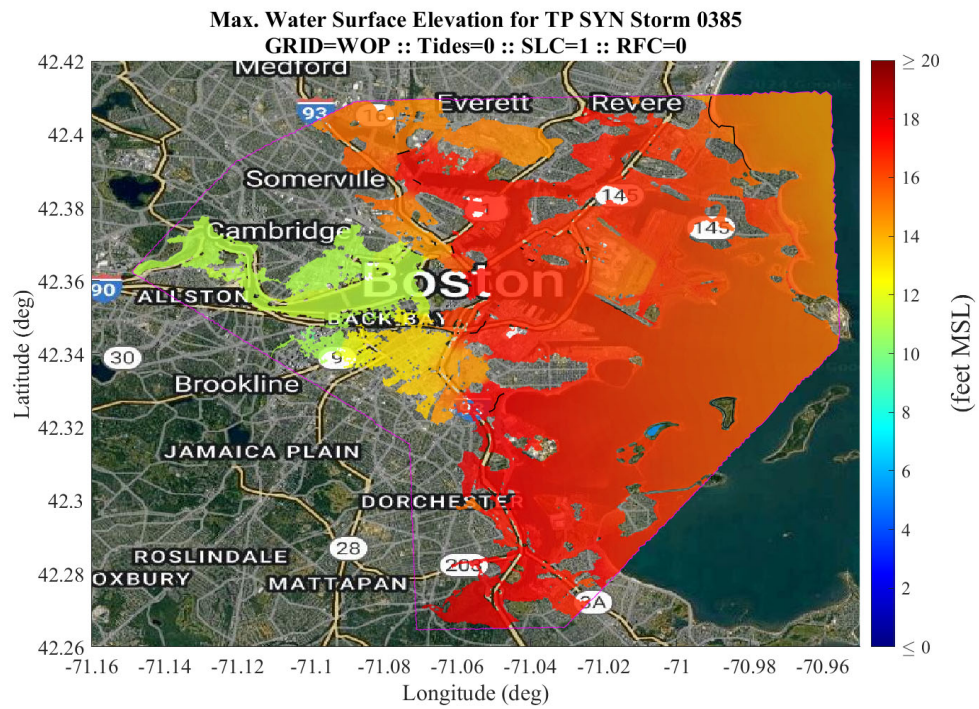
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 60 synthetic tropical cyclone TC events for SLC1 and no tides.

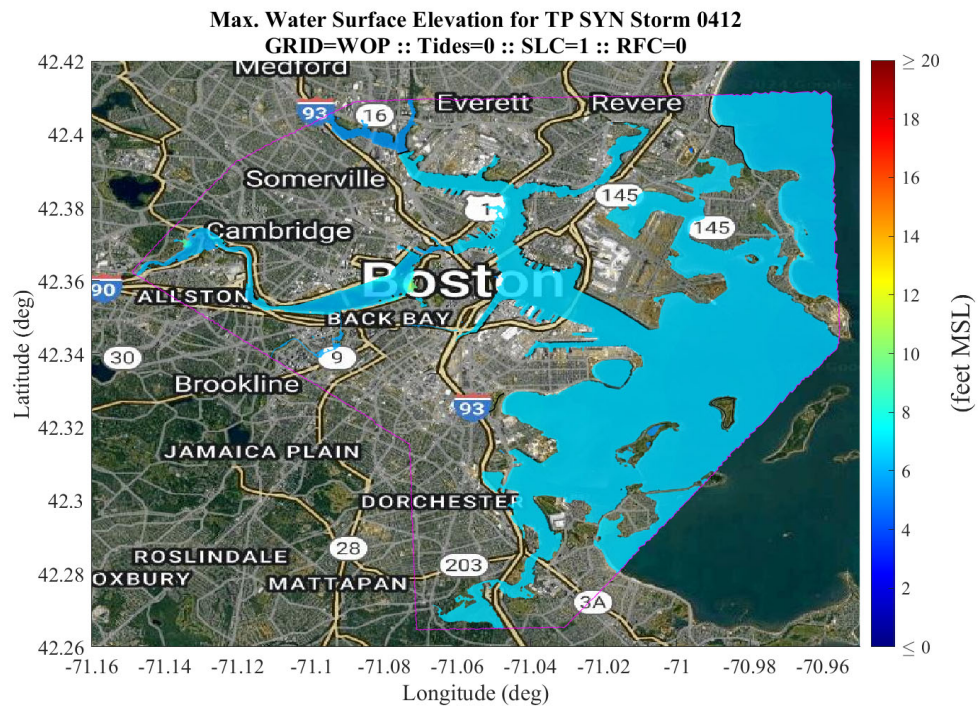


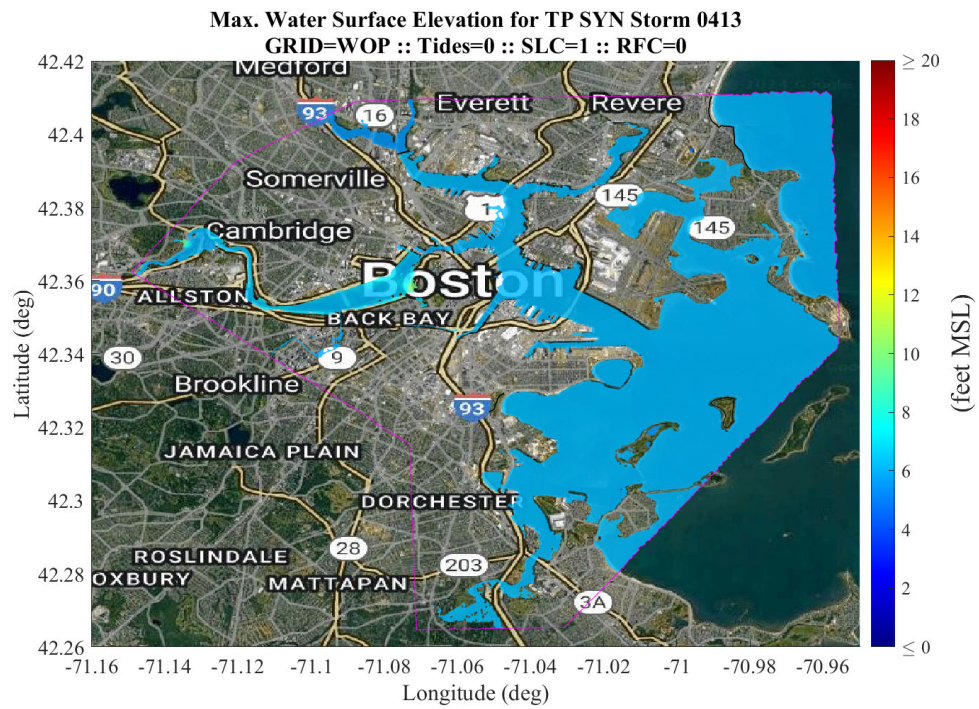


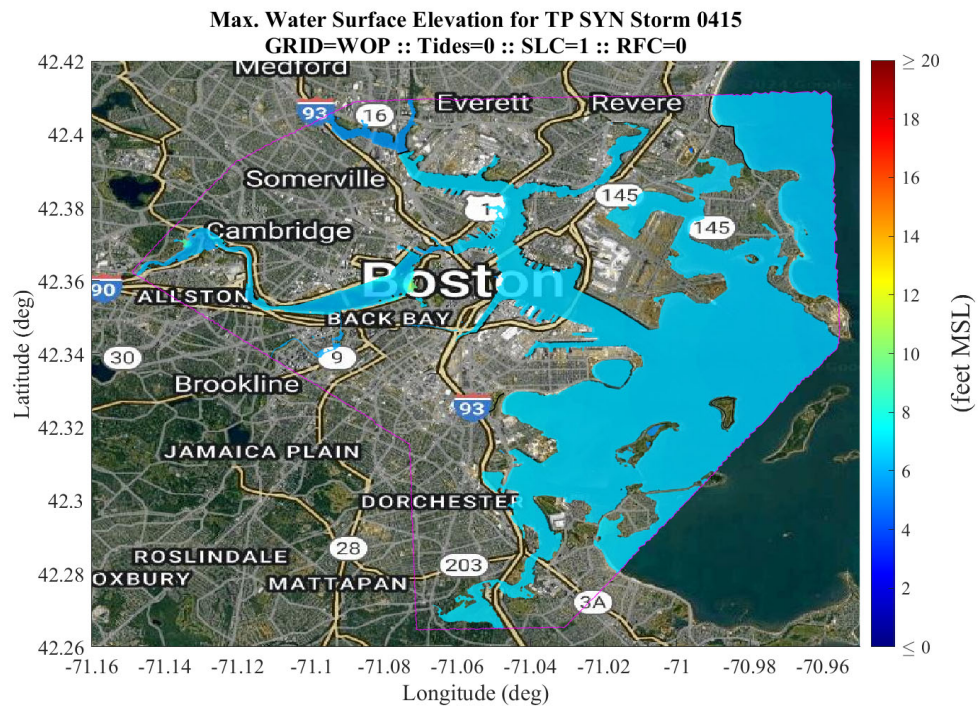


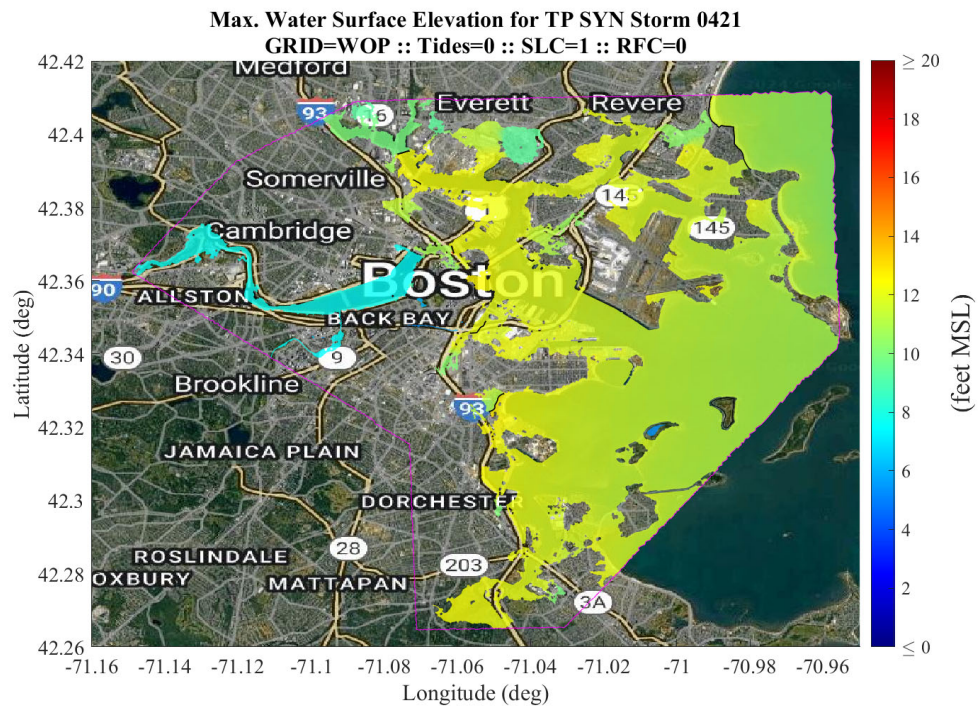


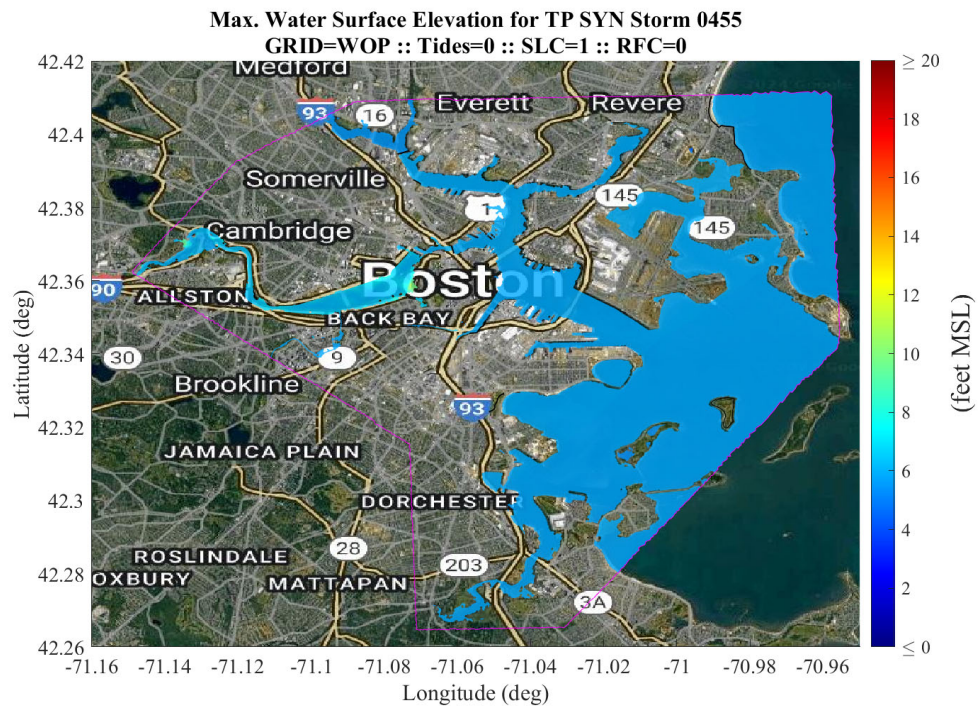


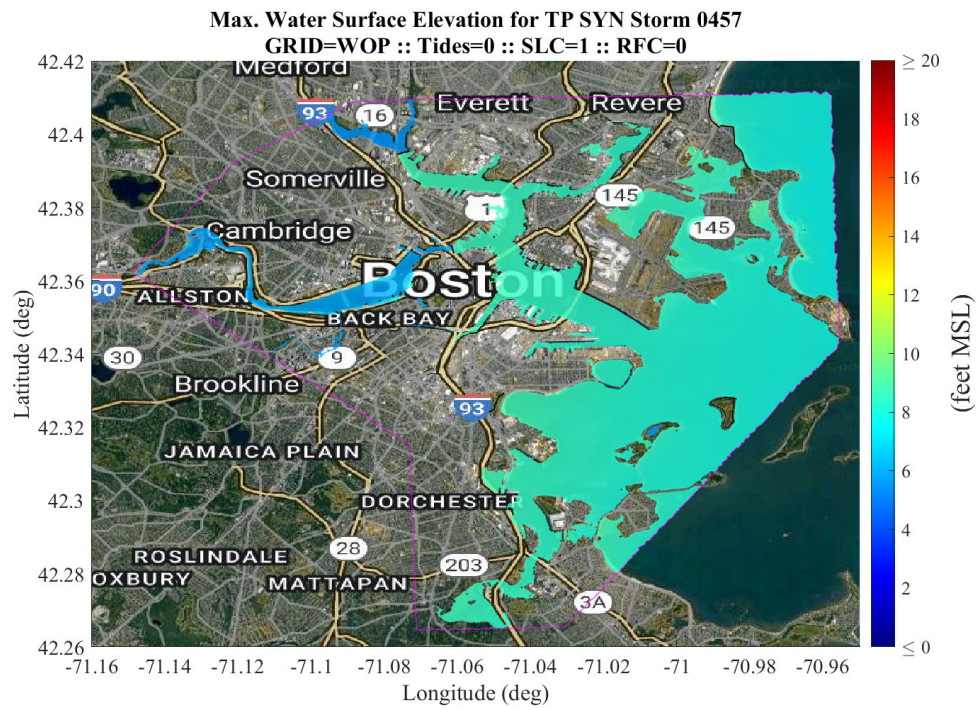


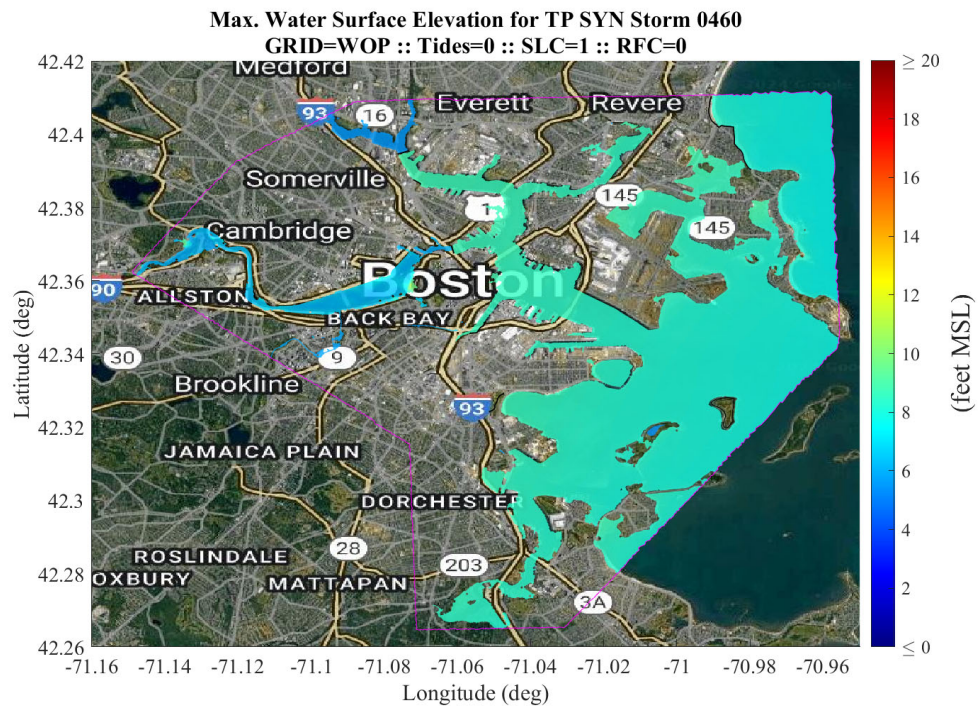


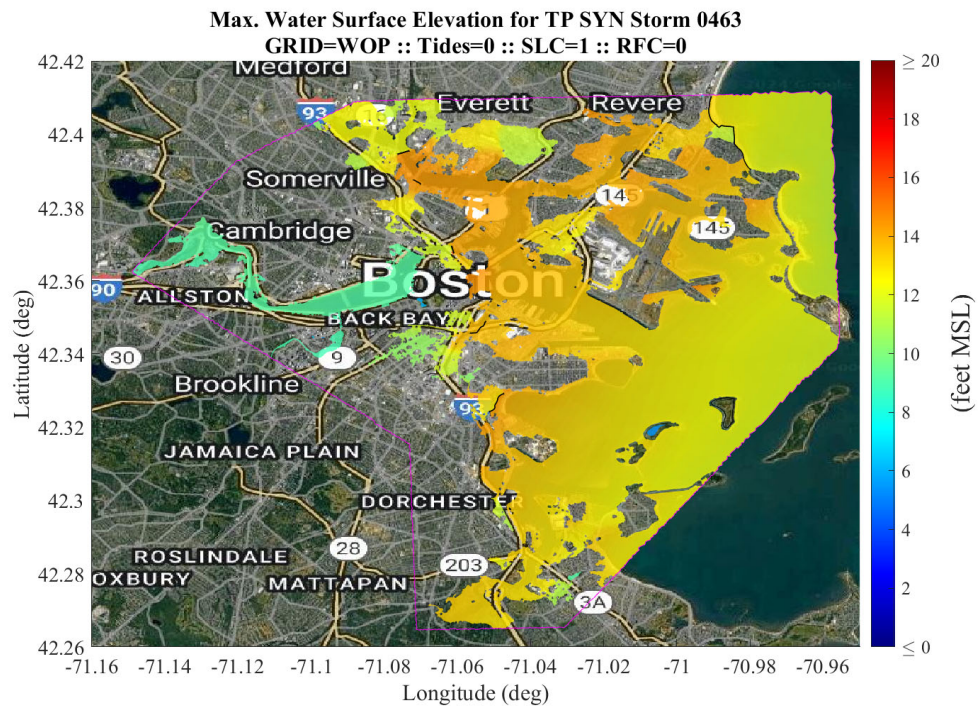


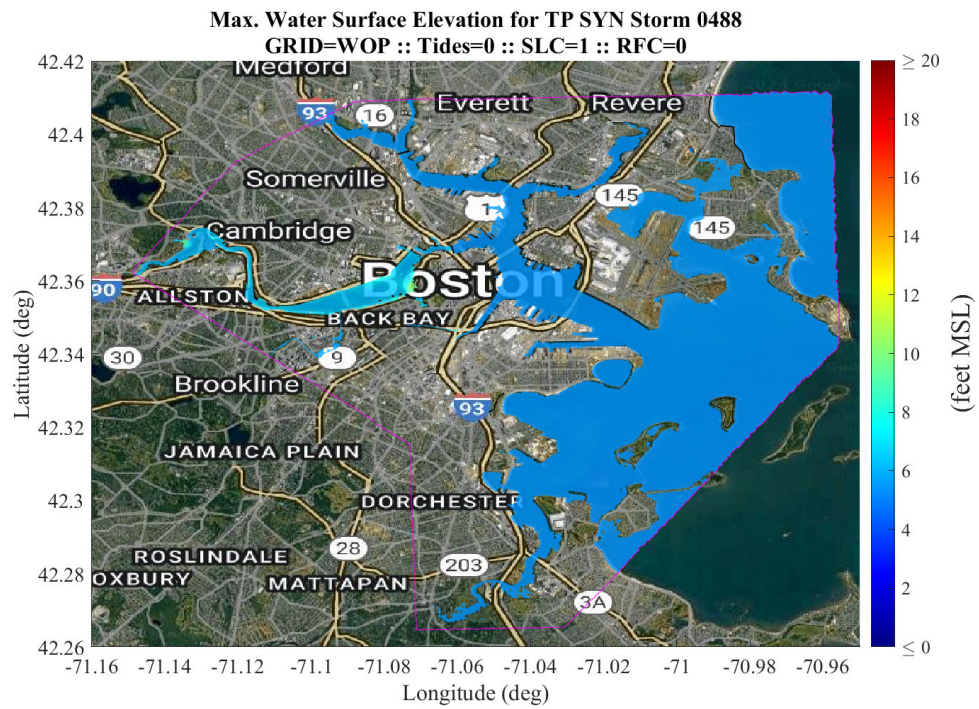


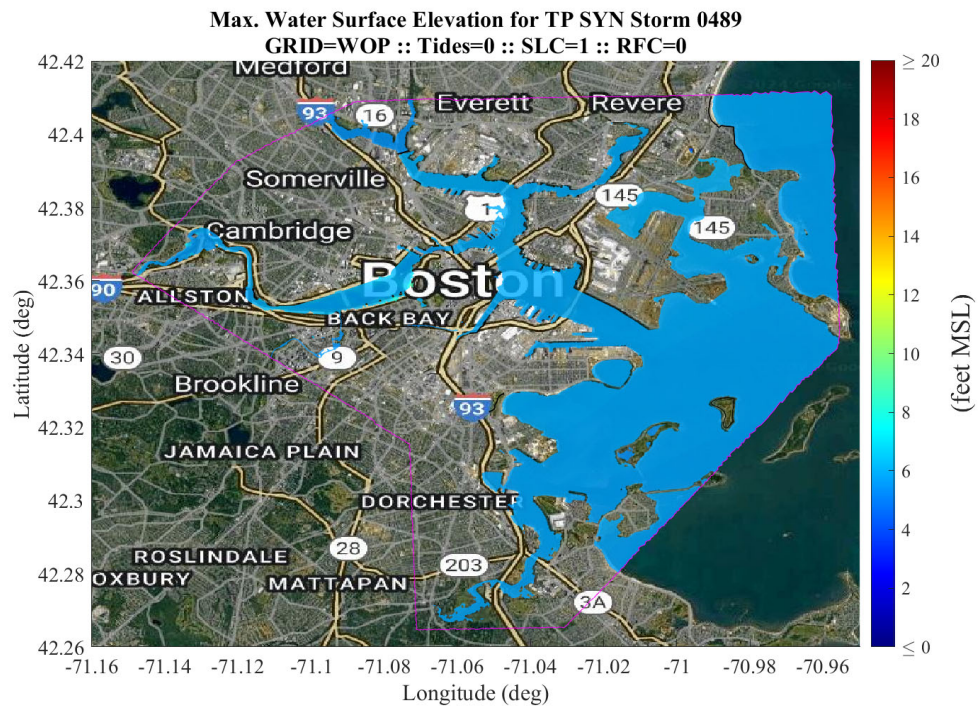


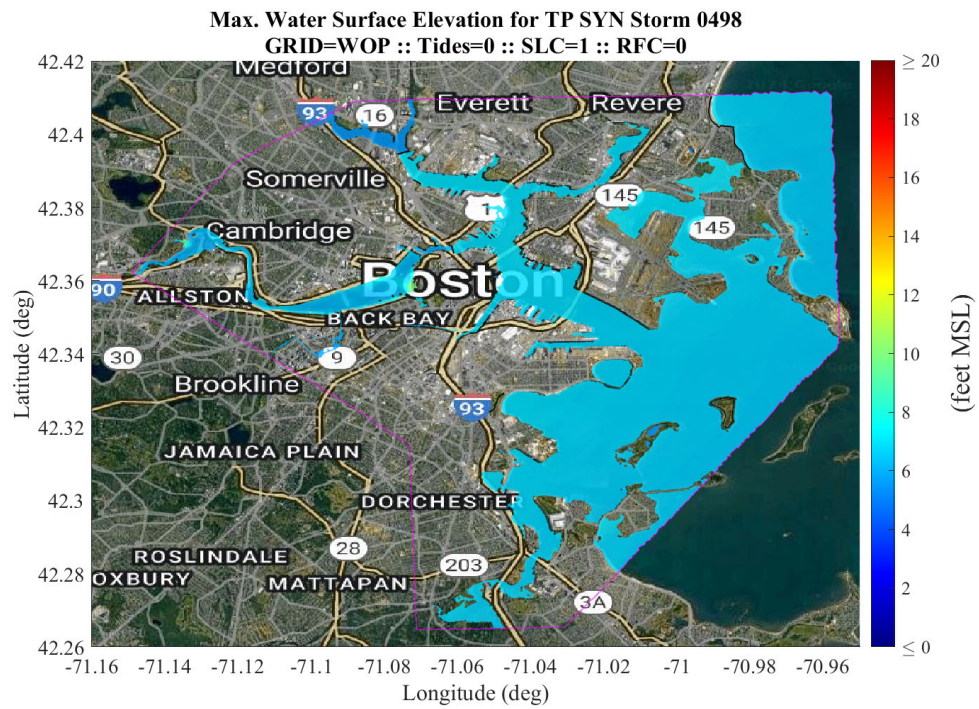


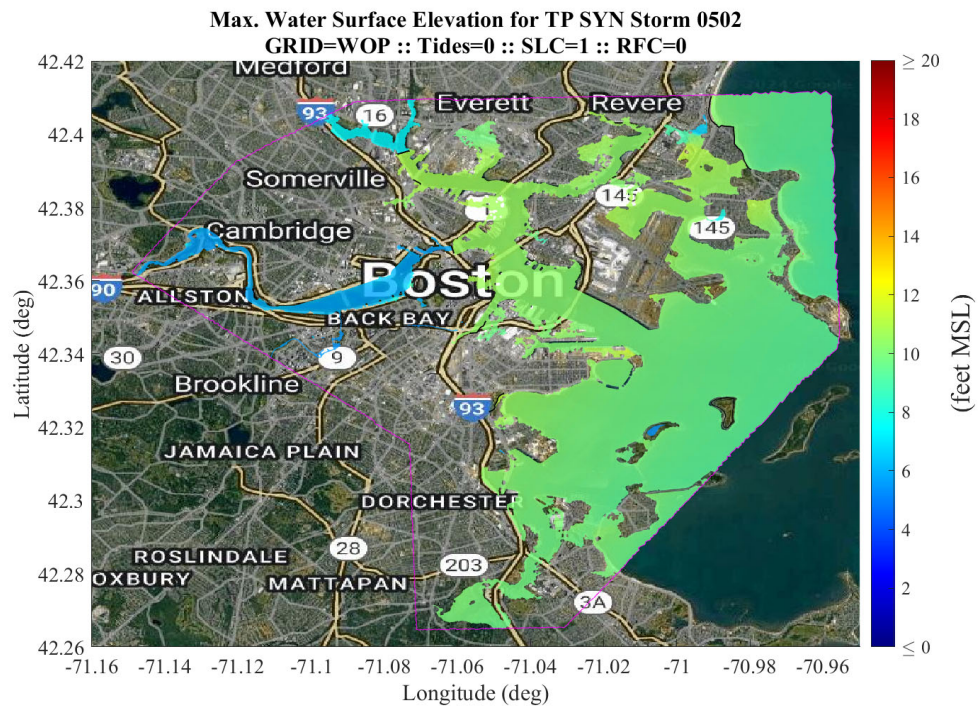


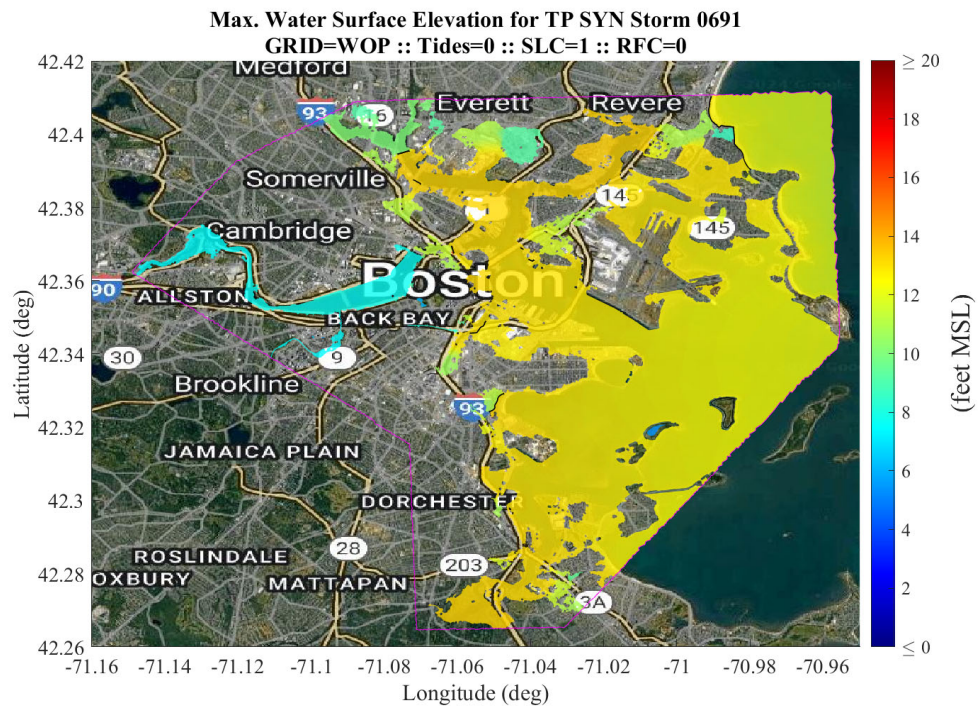


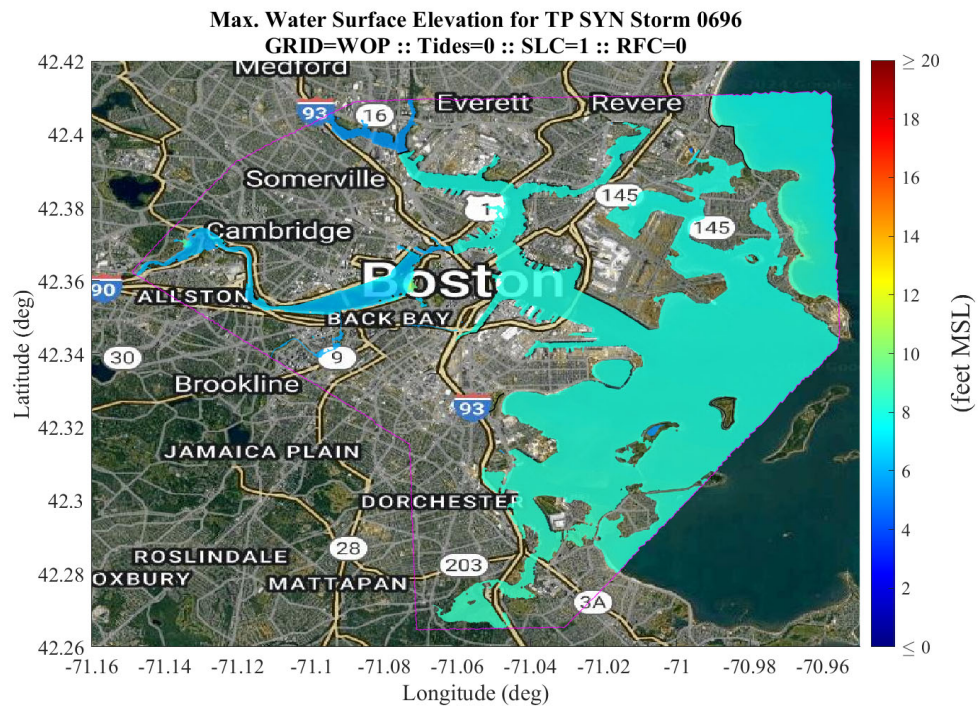


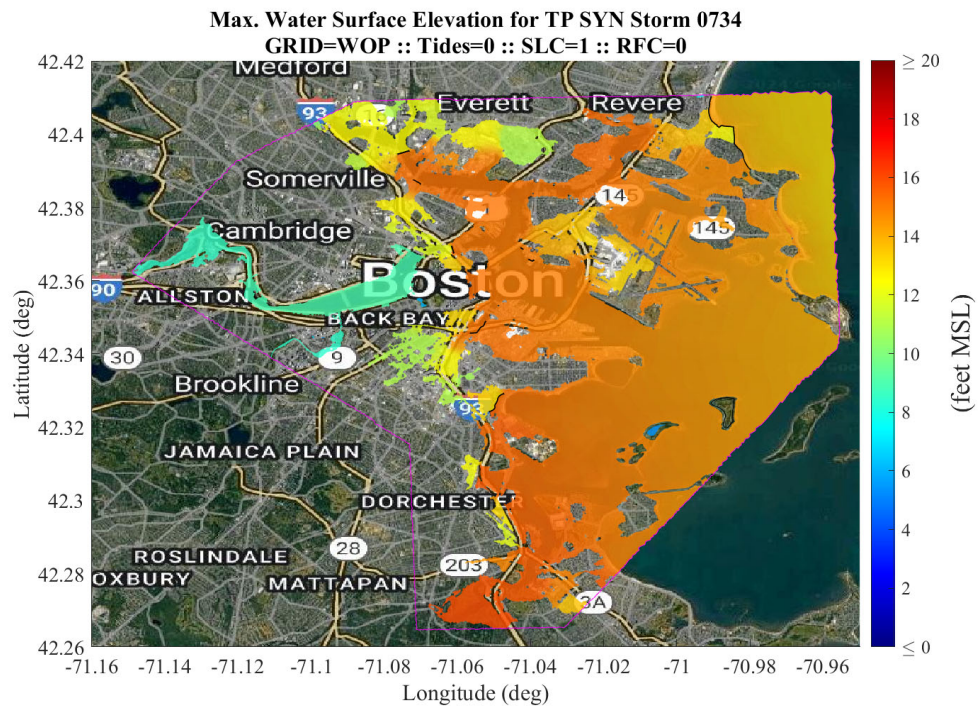


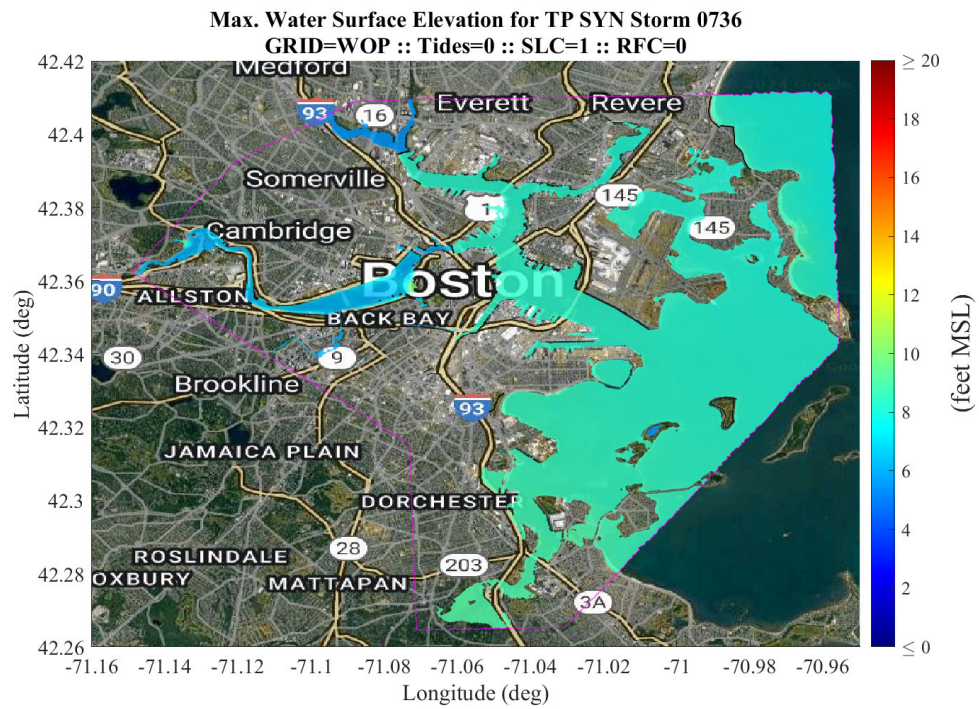


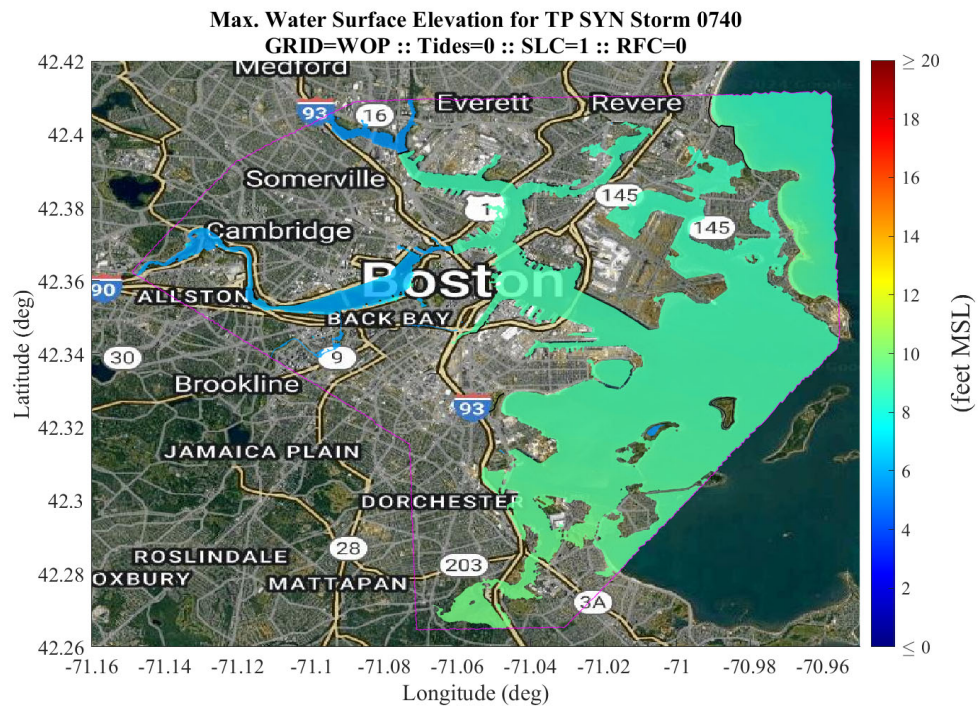


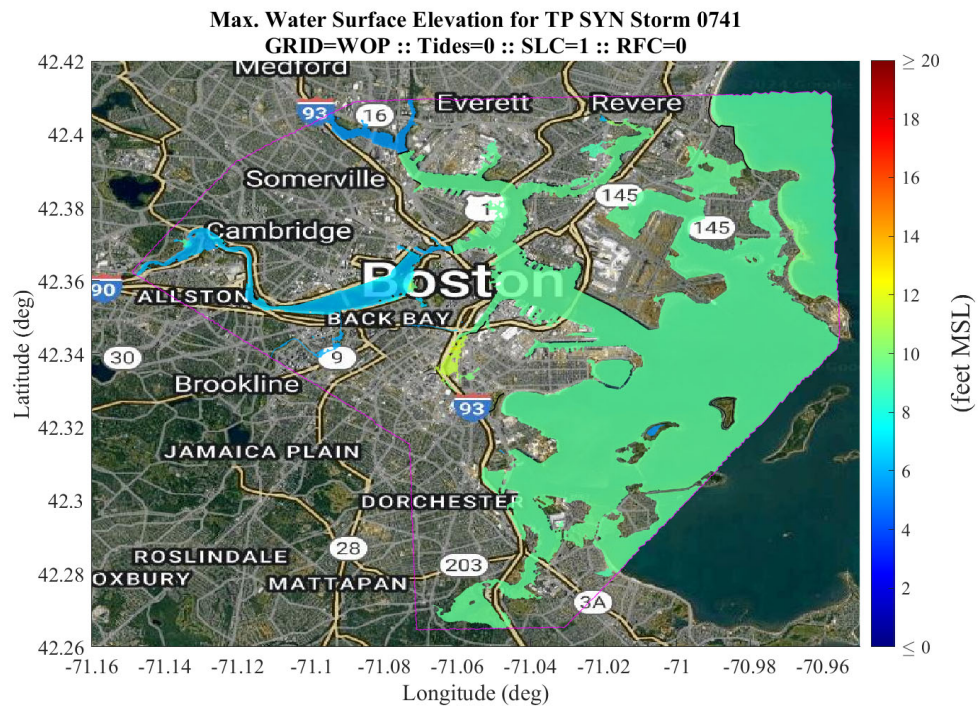


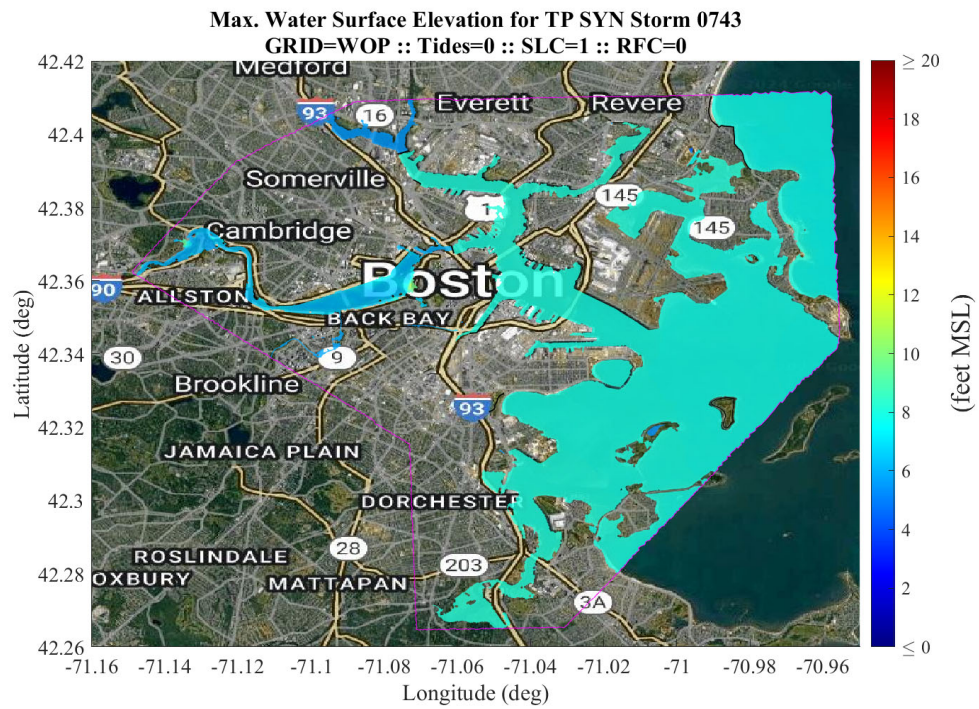


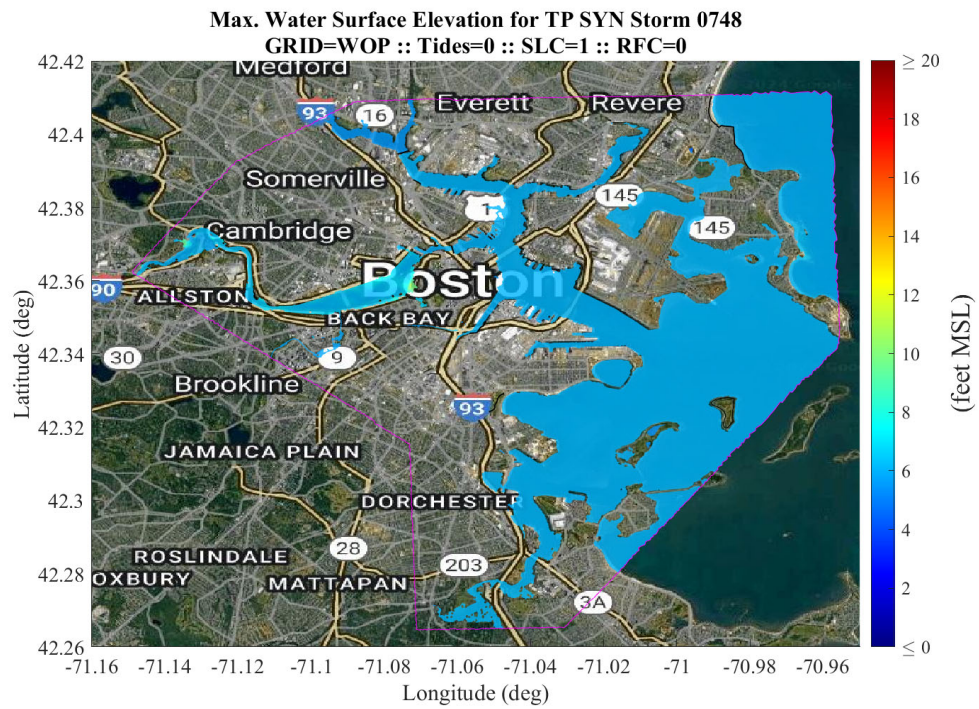


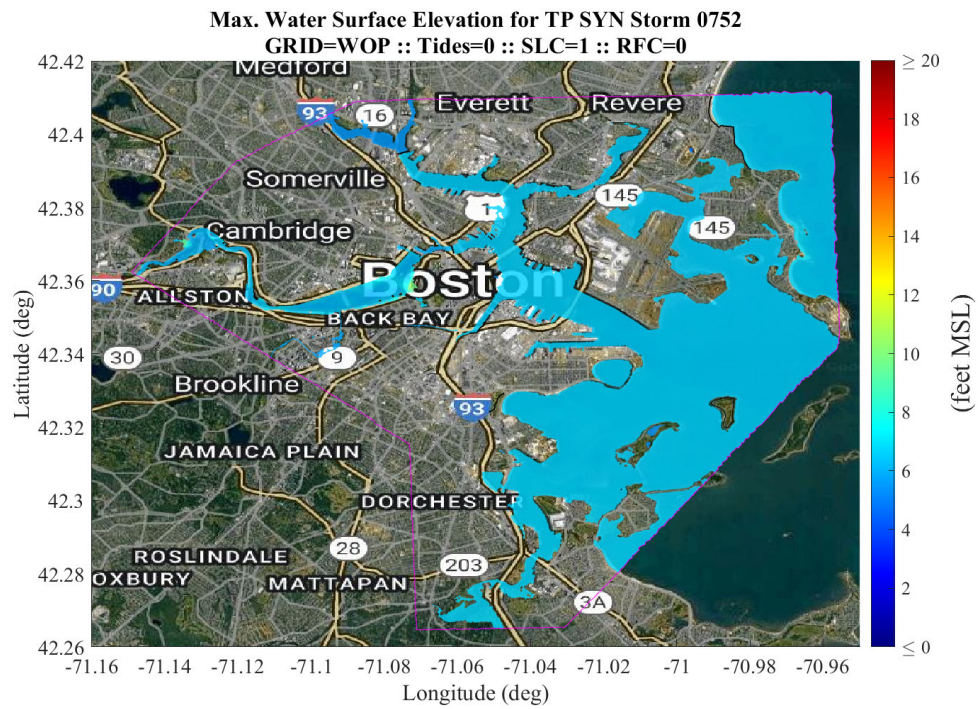


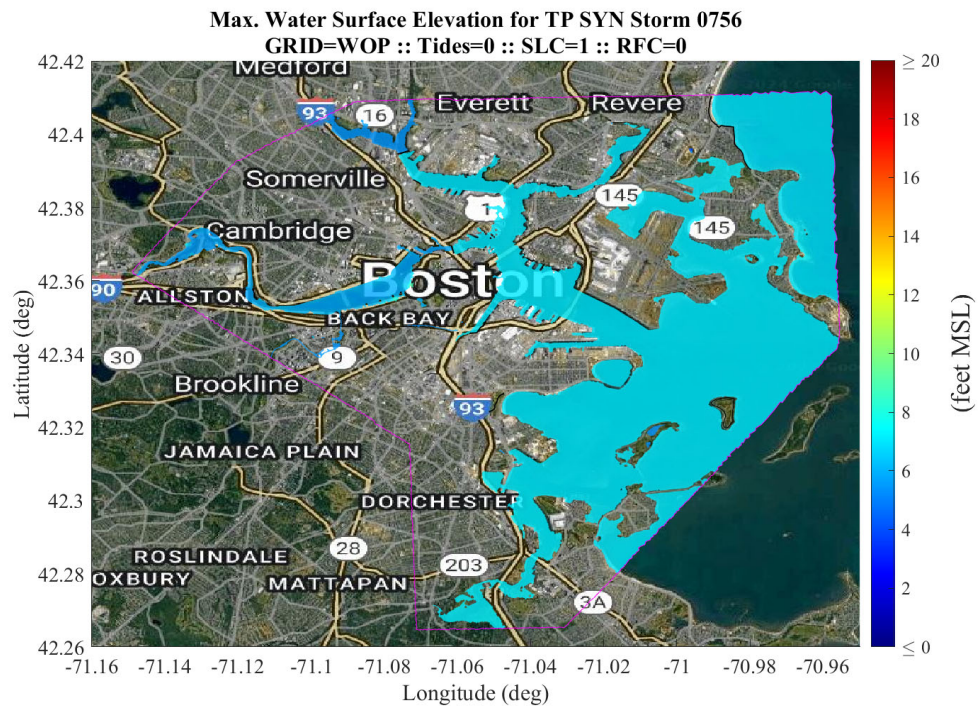


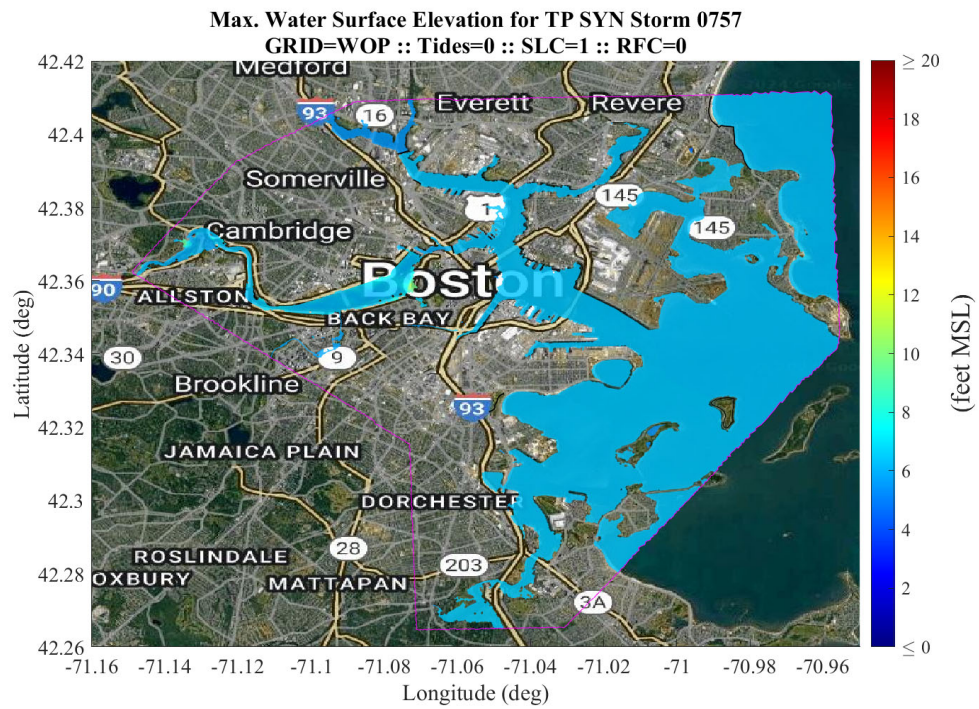


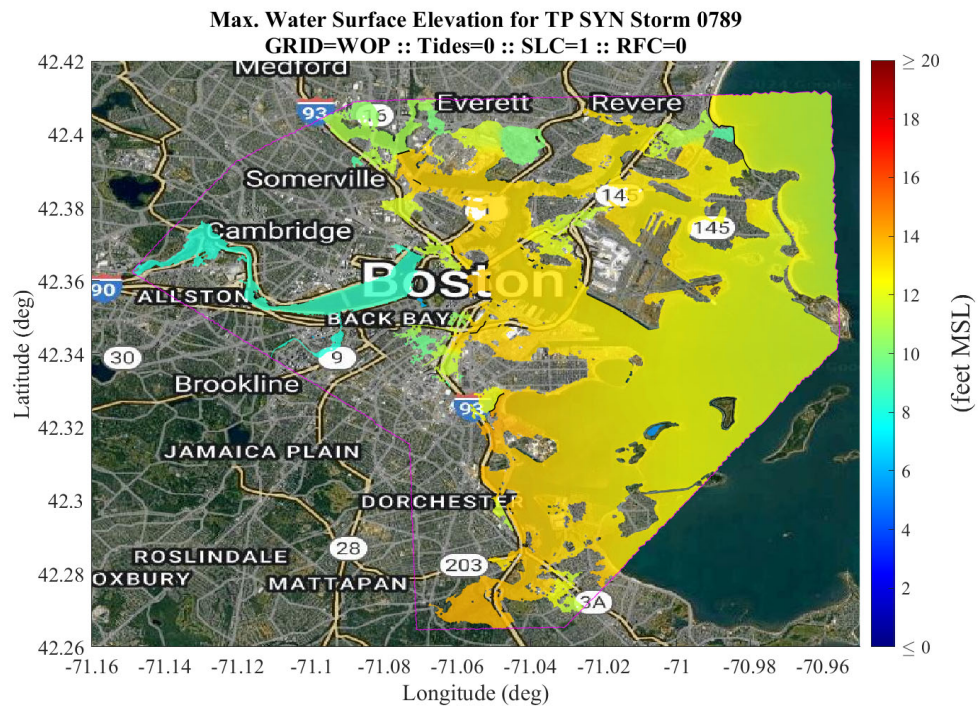


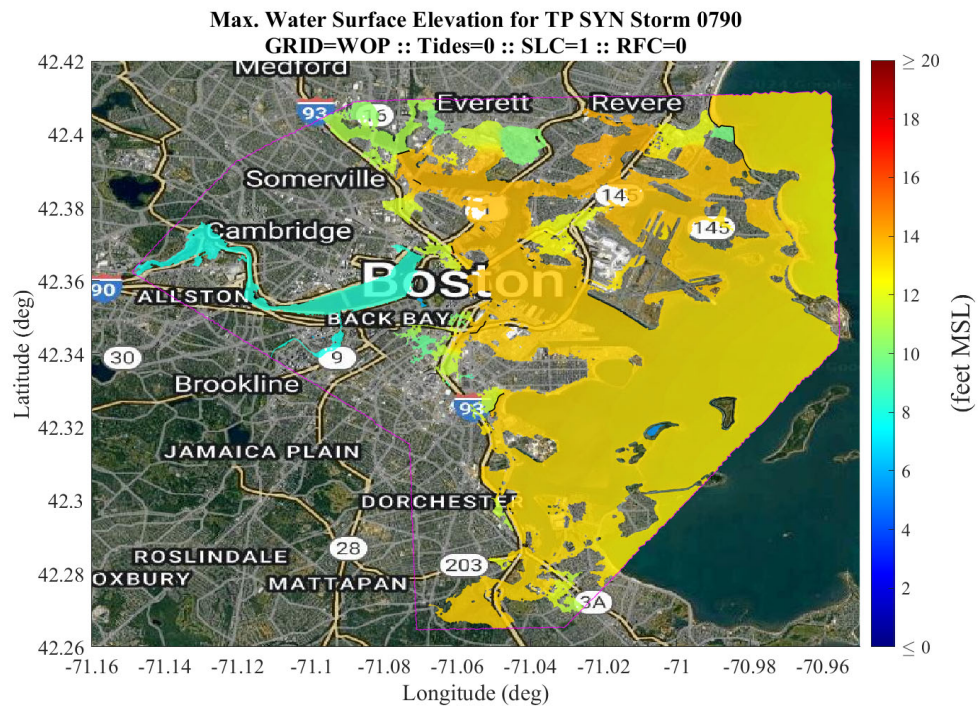


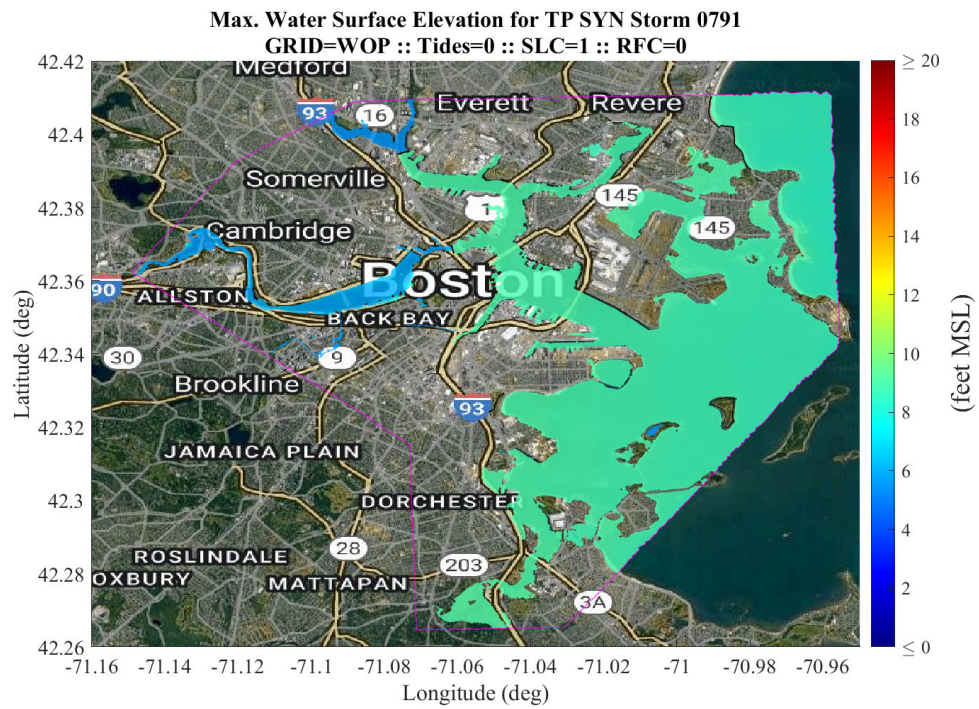


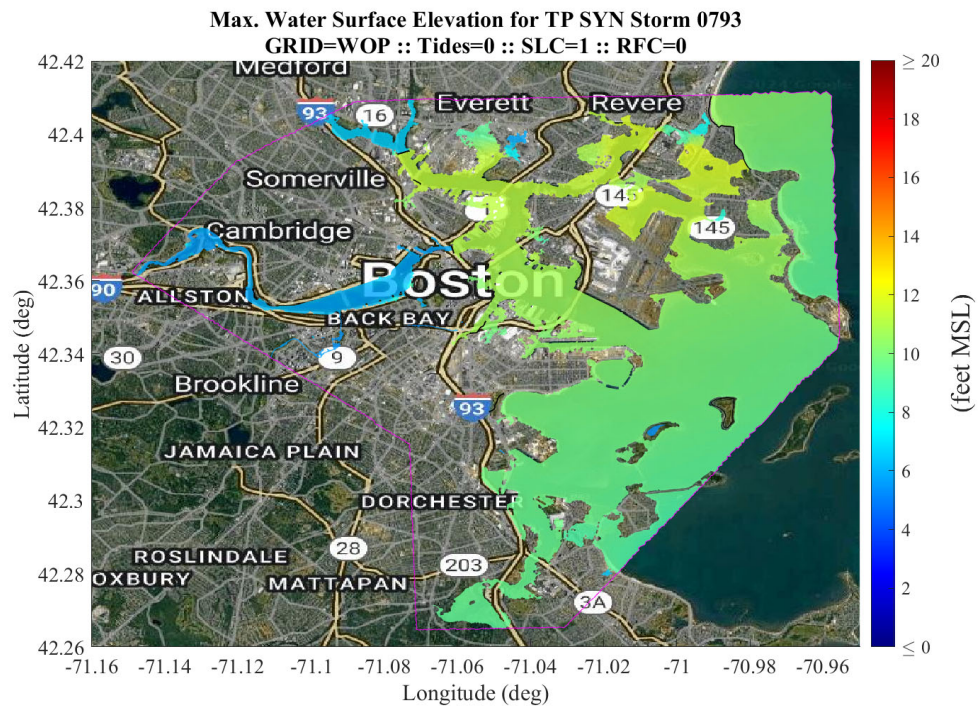


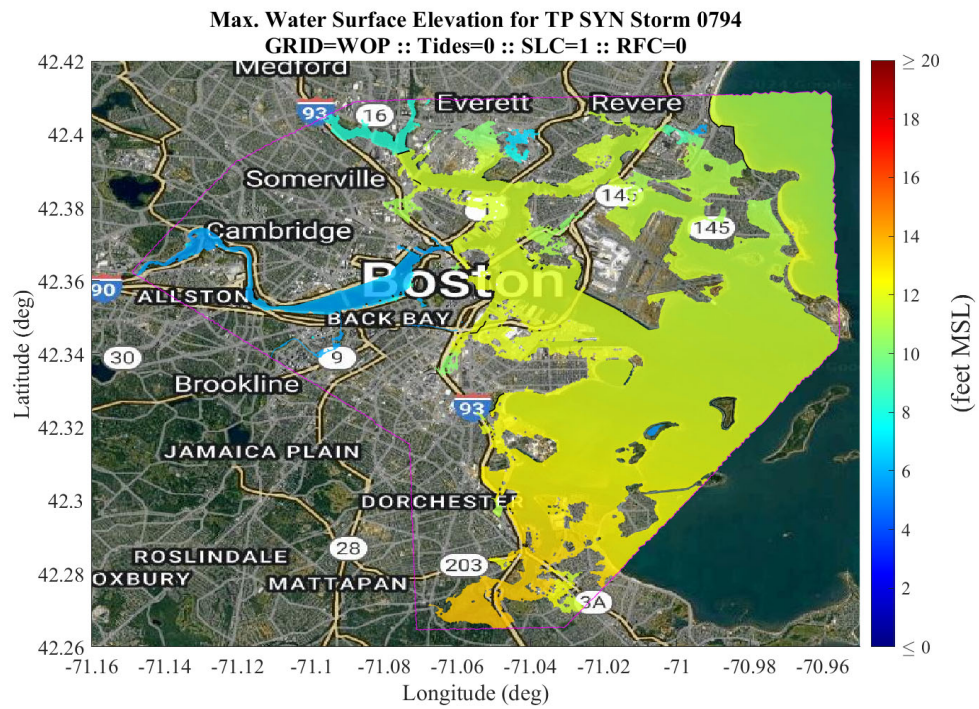


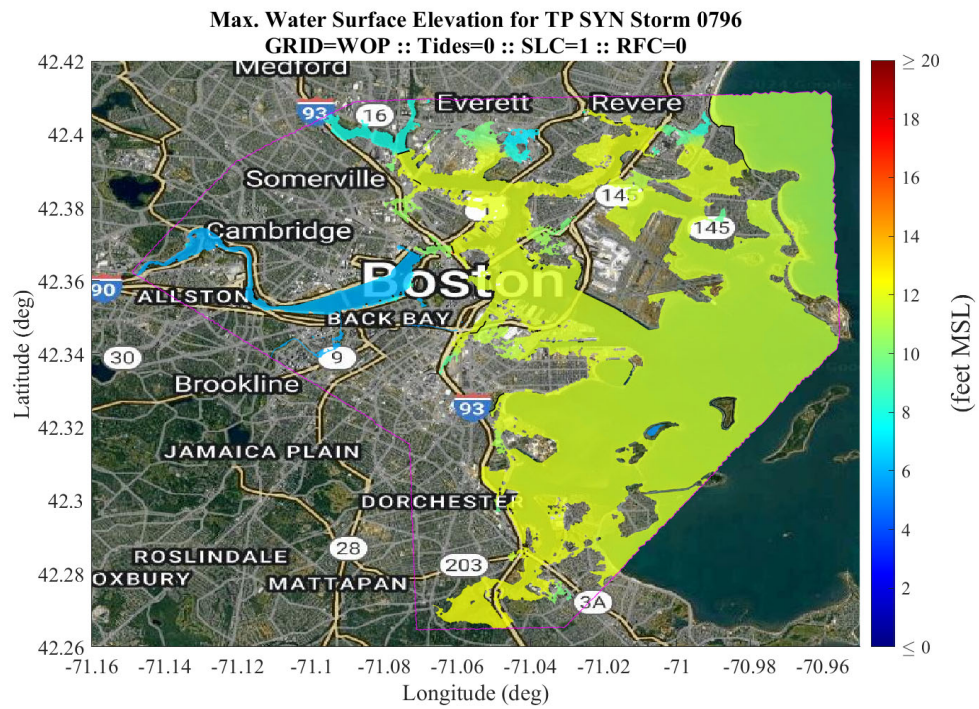


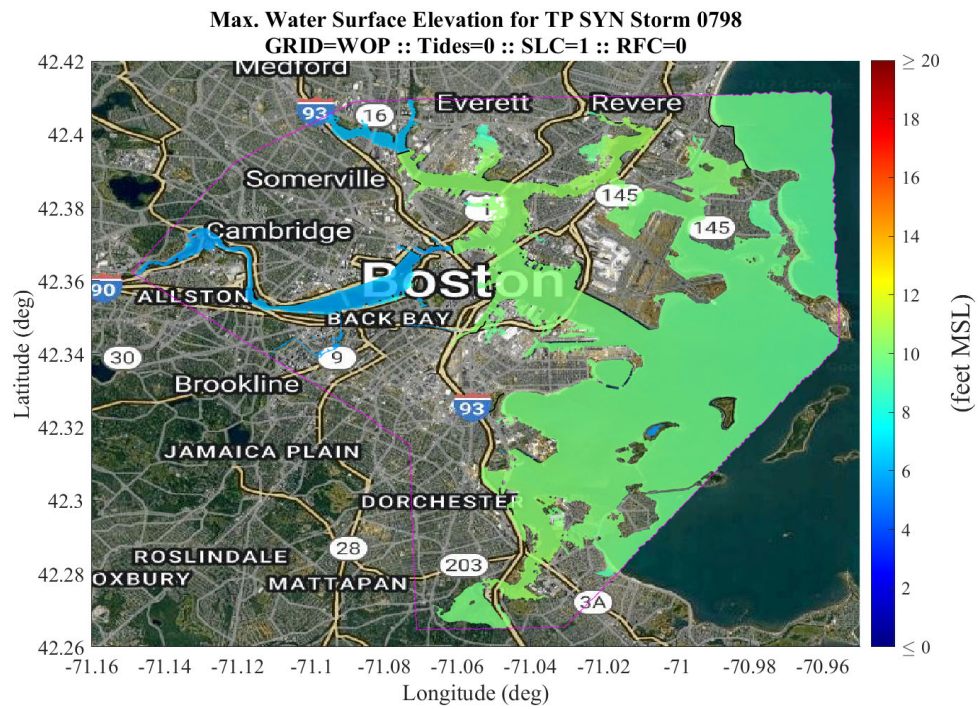


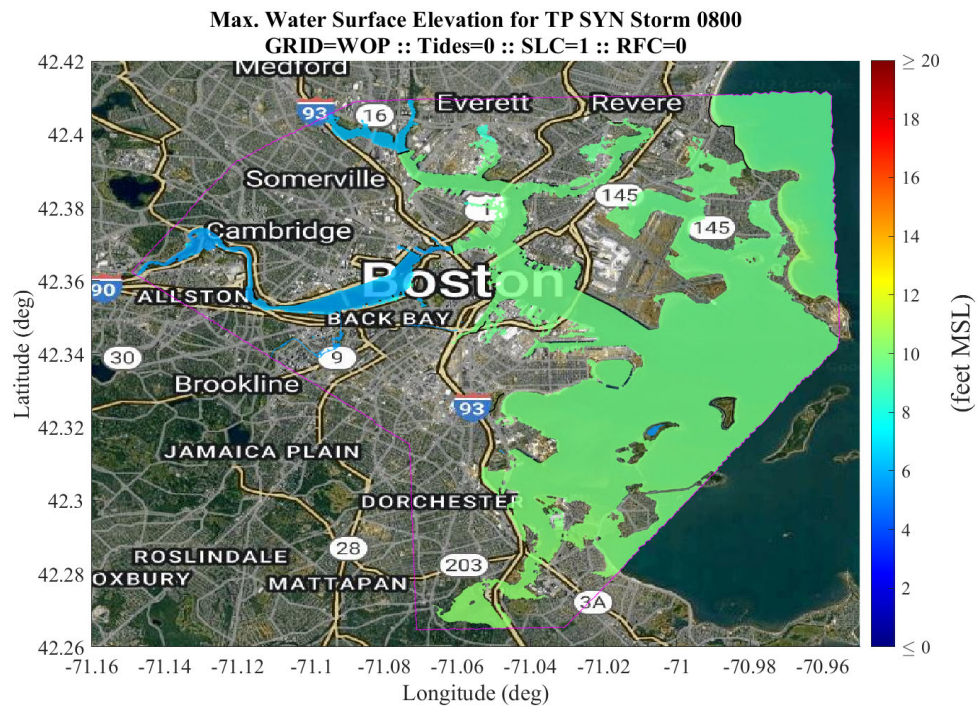


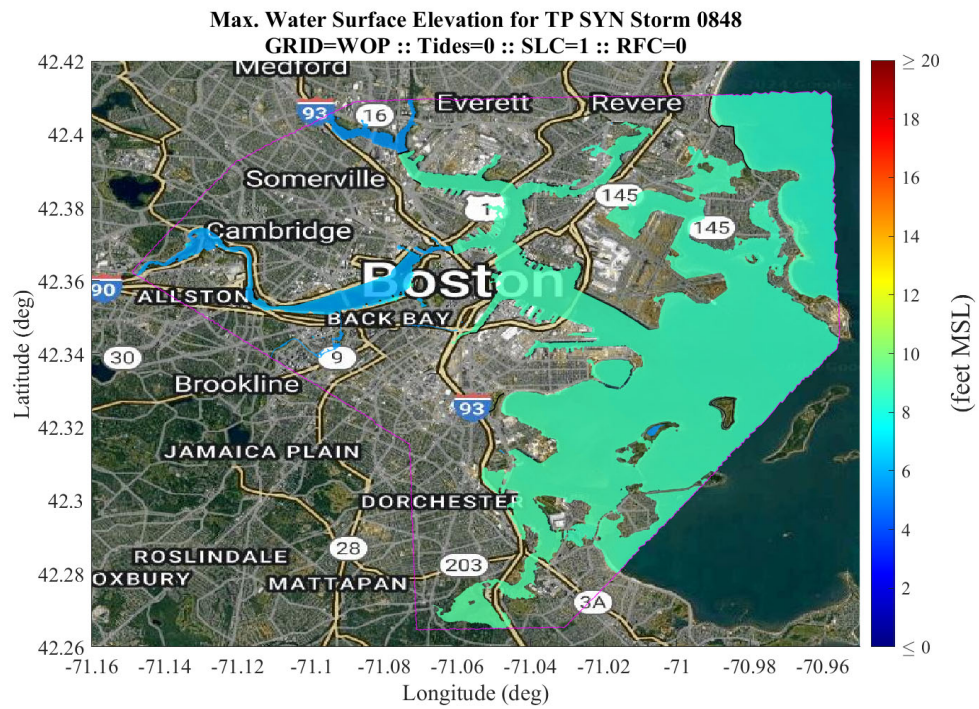


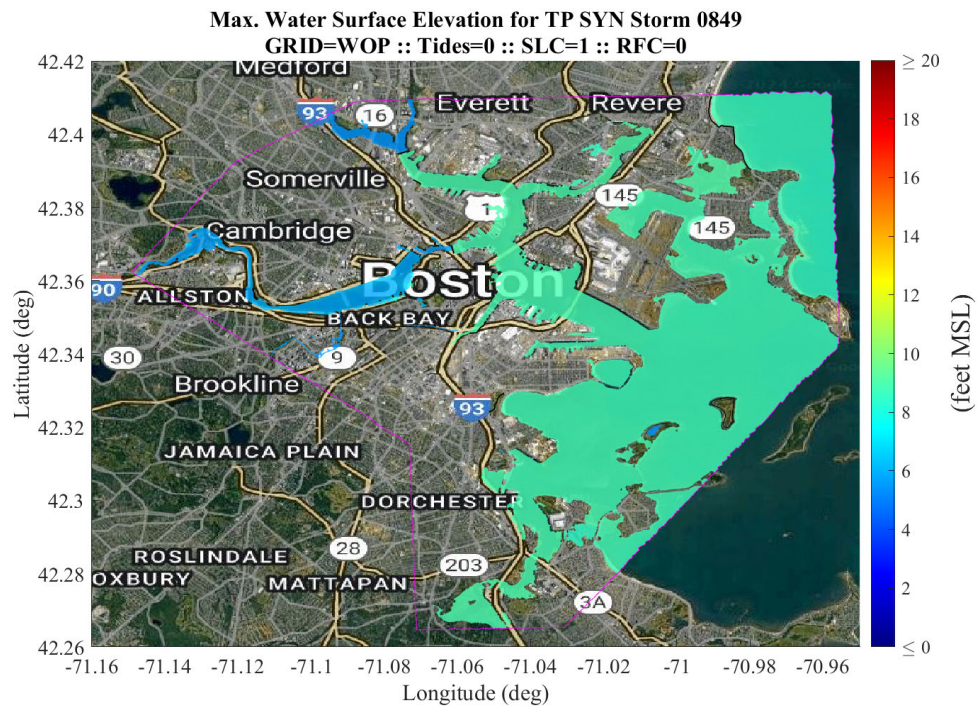


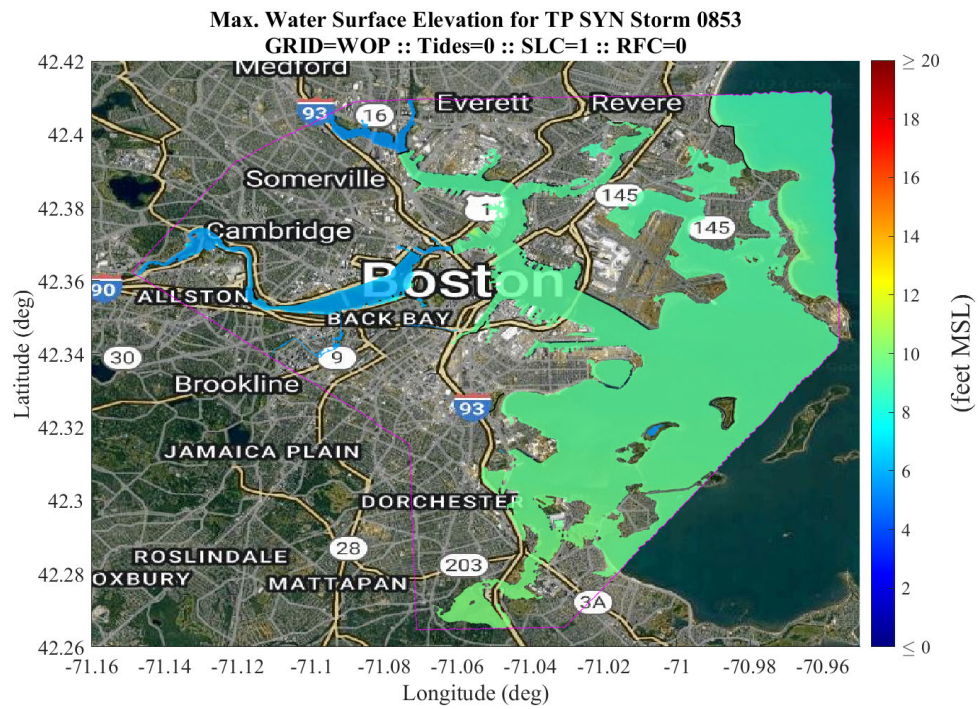


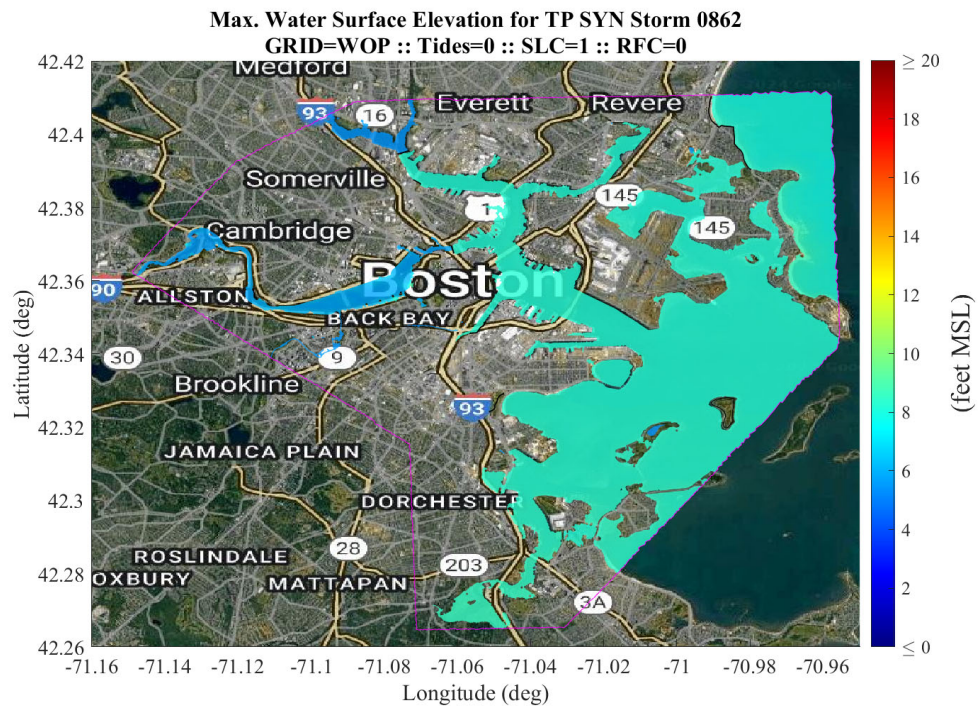


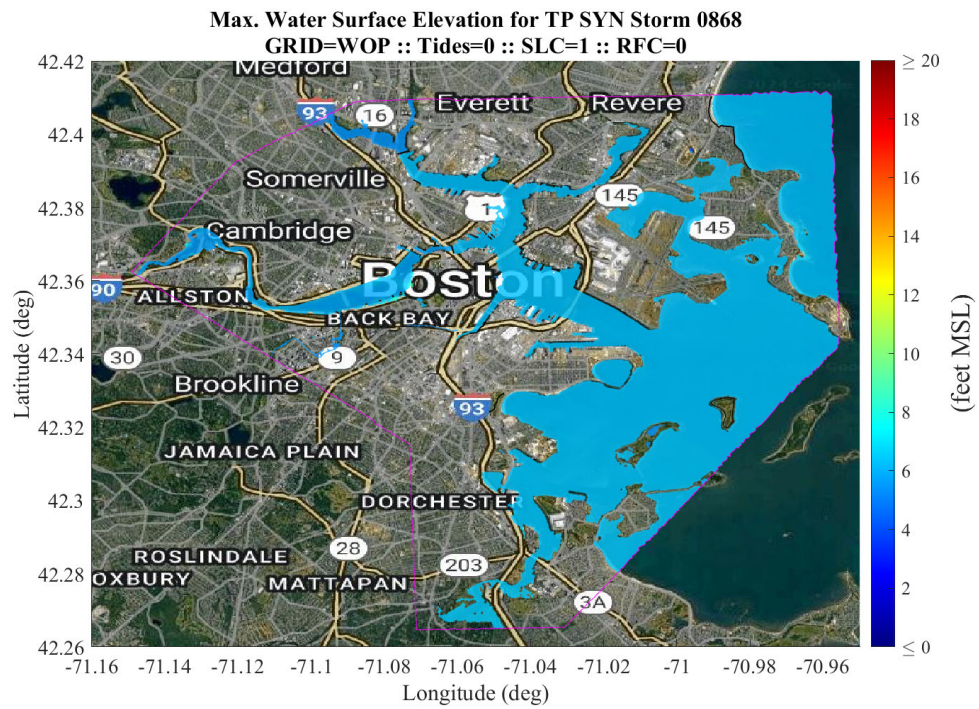


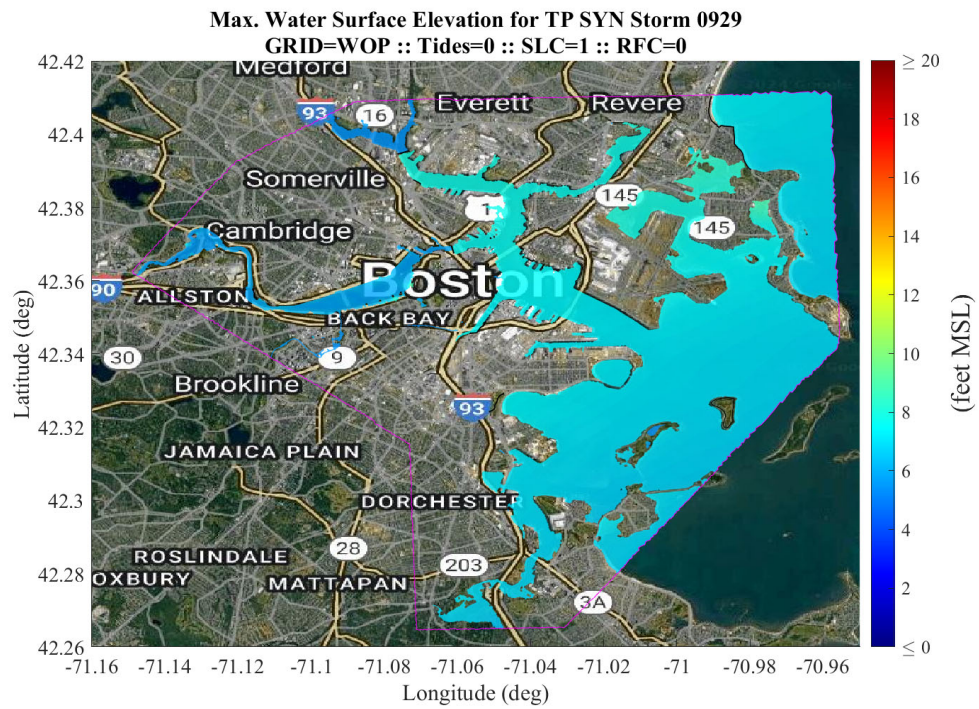


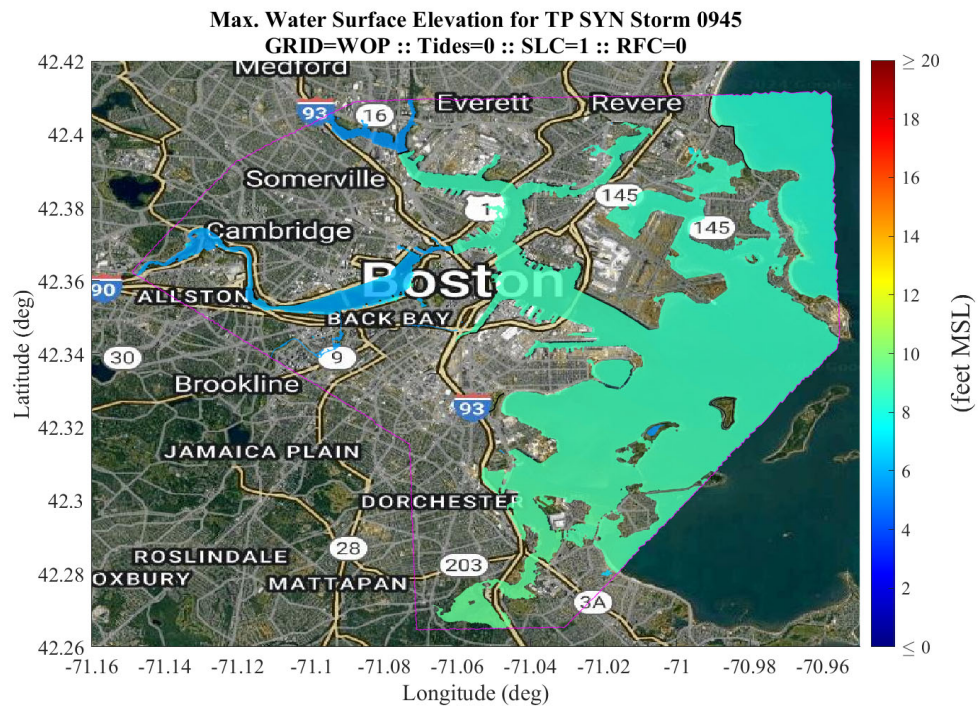


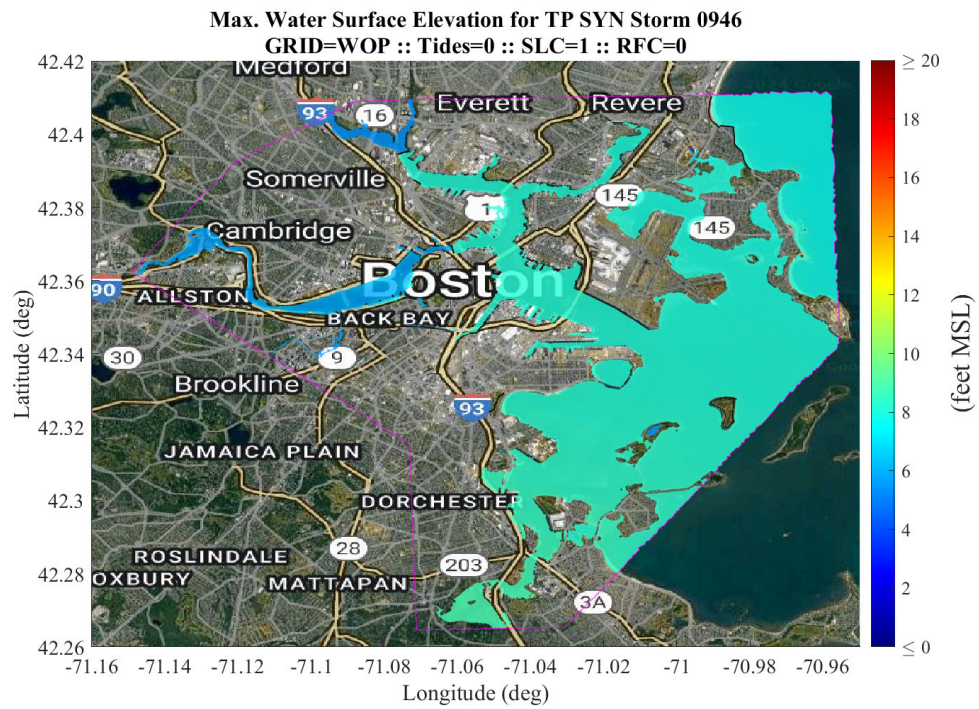


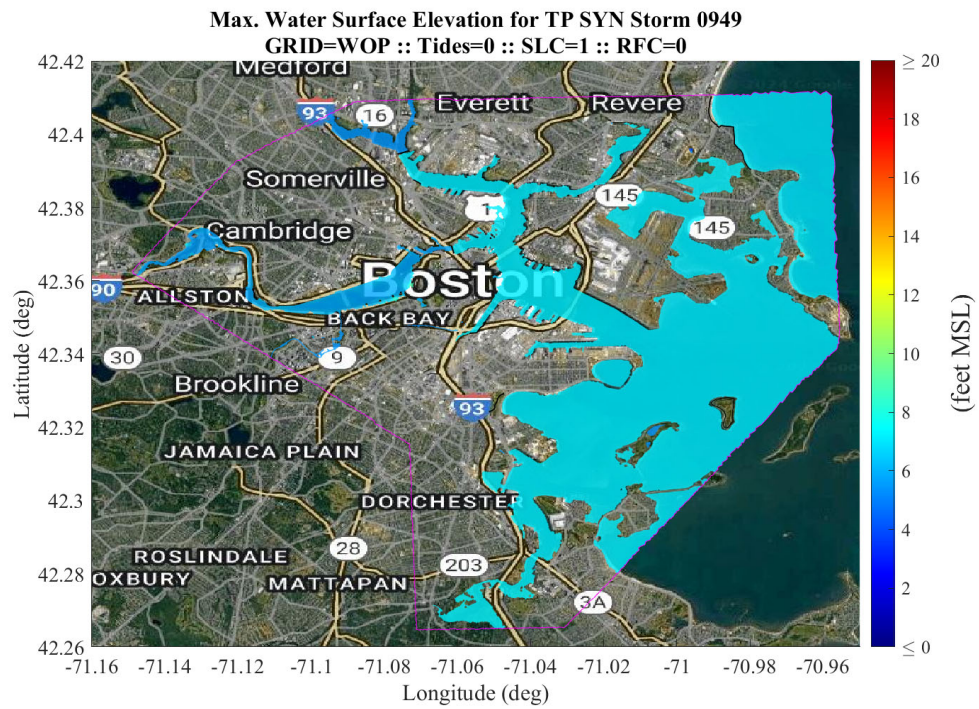


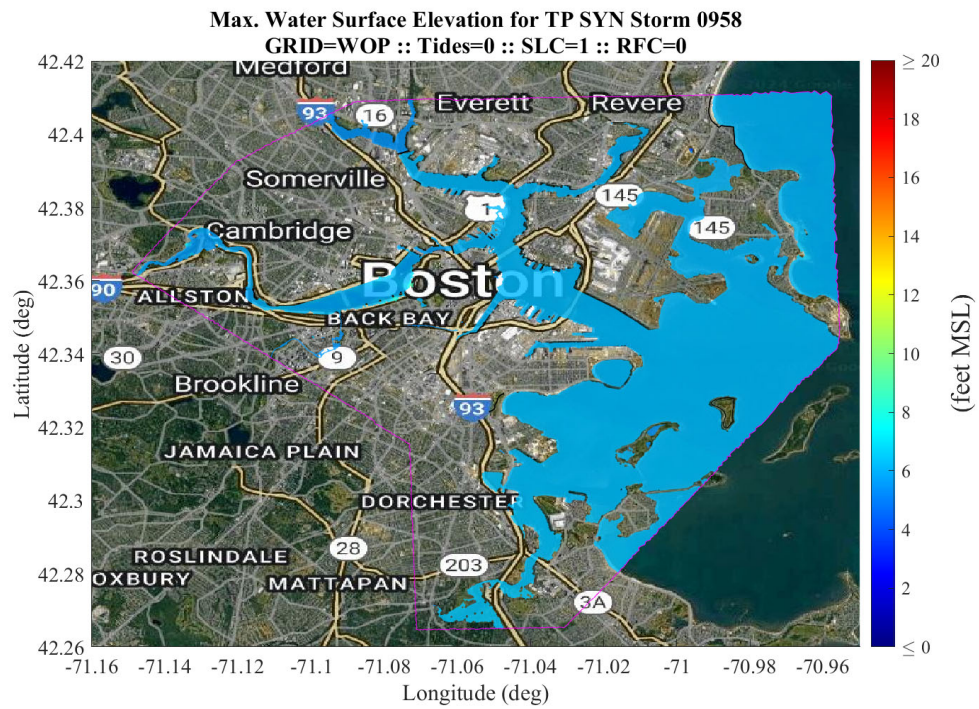


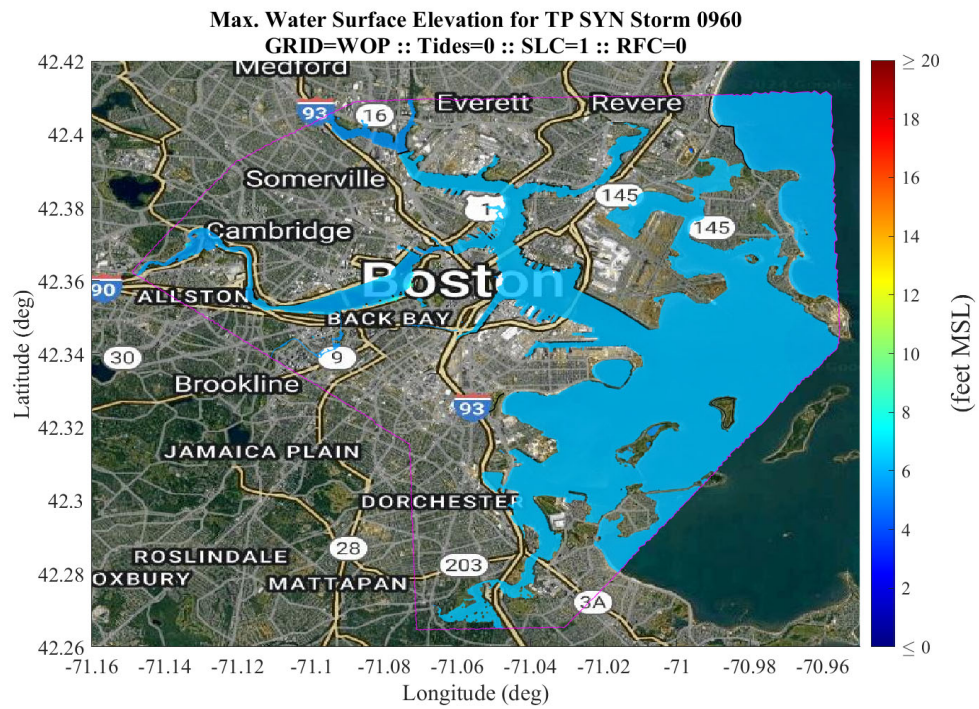


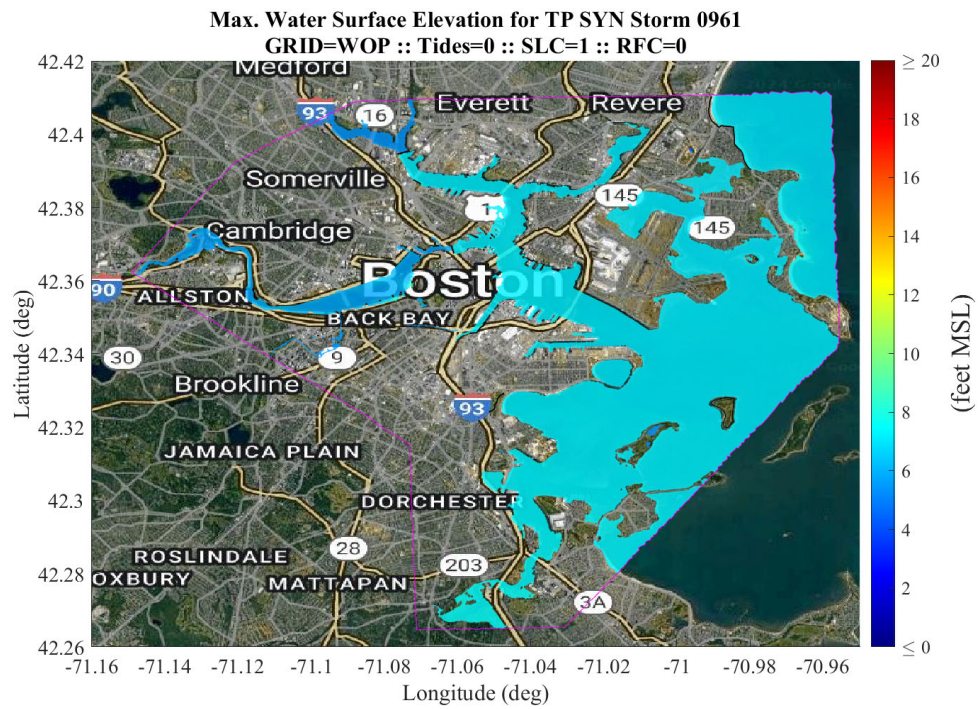


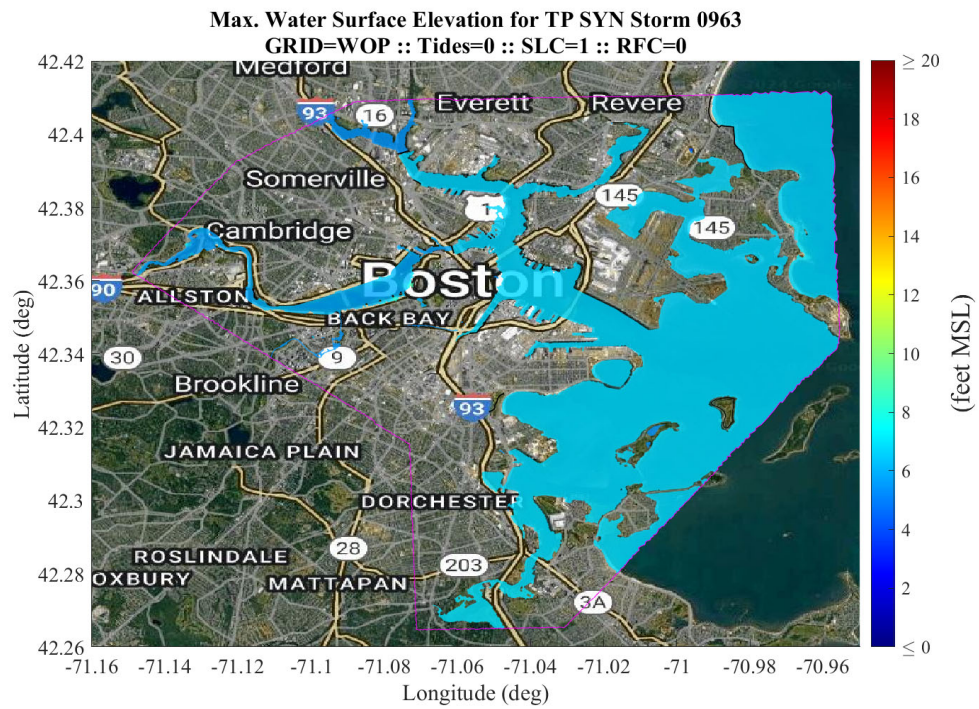


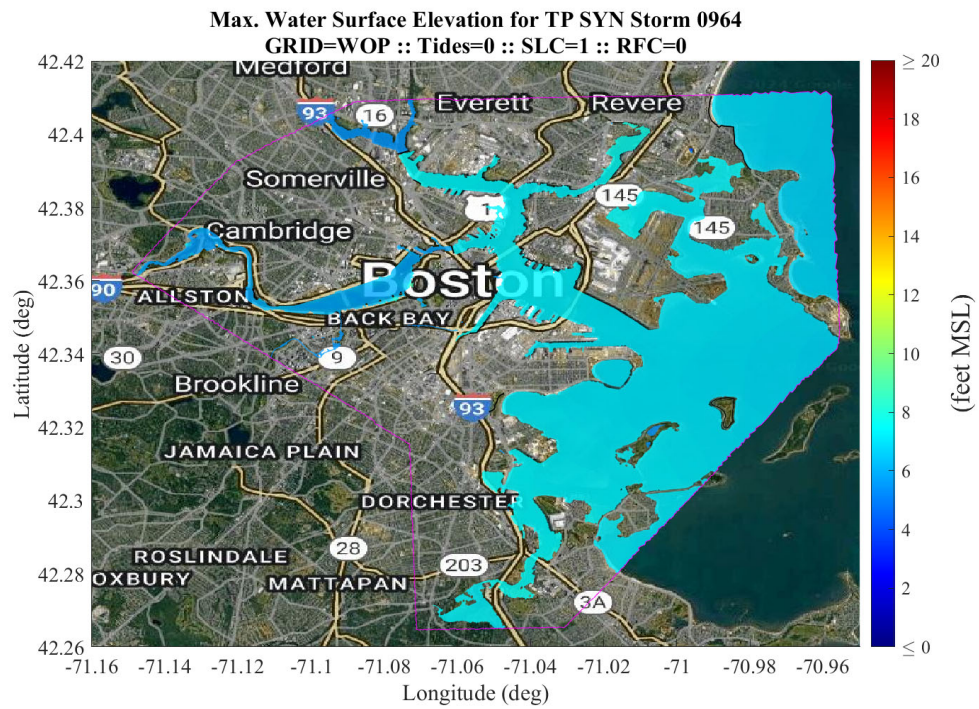


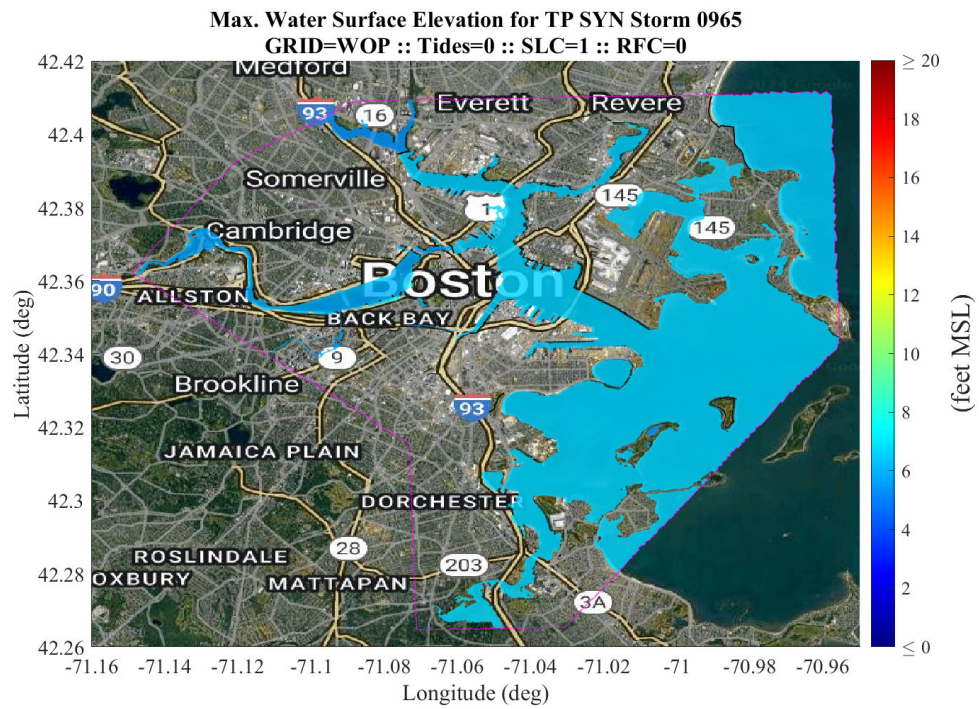


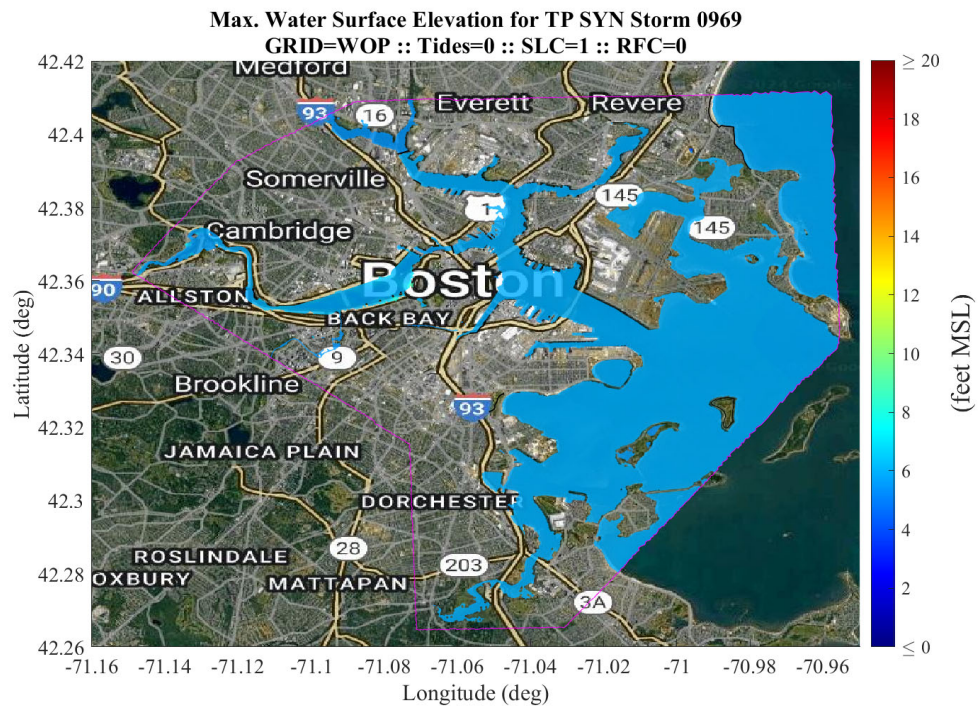


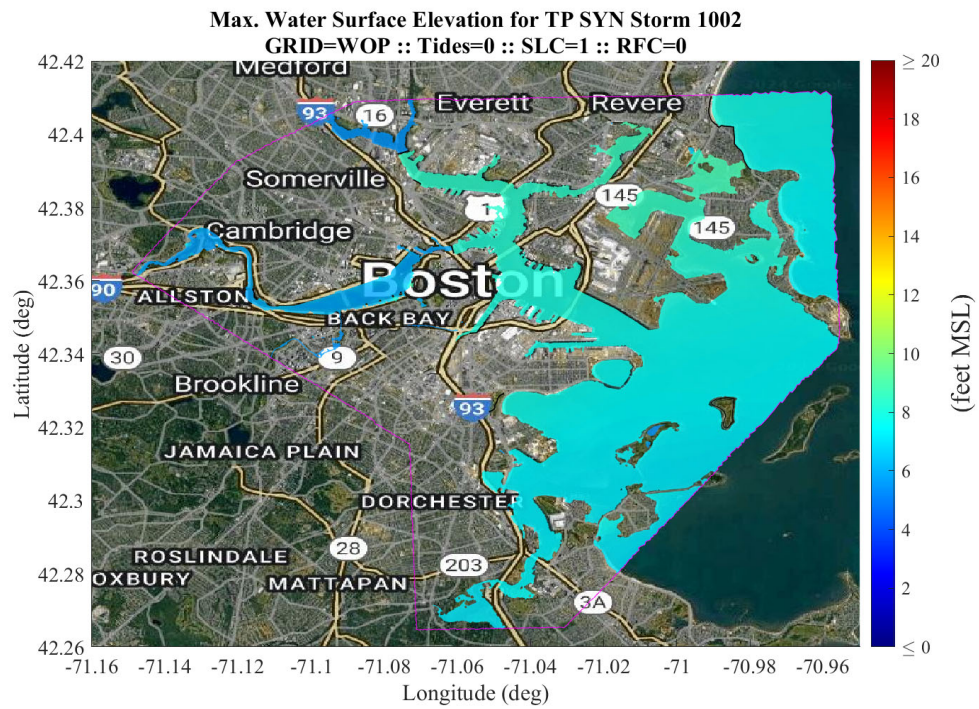


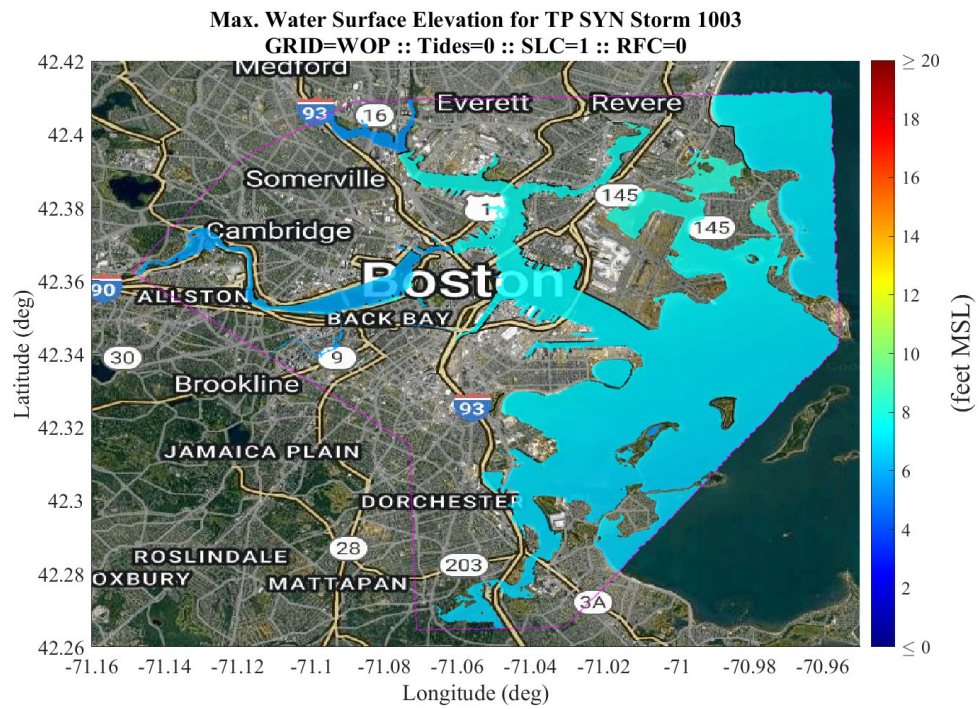


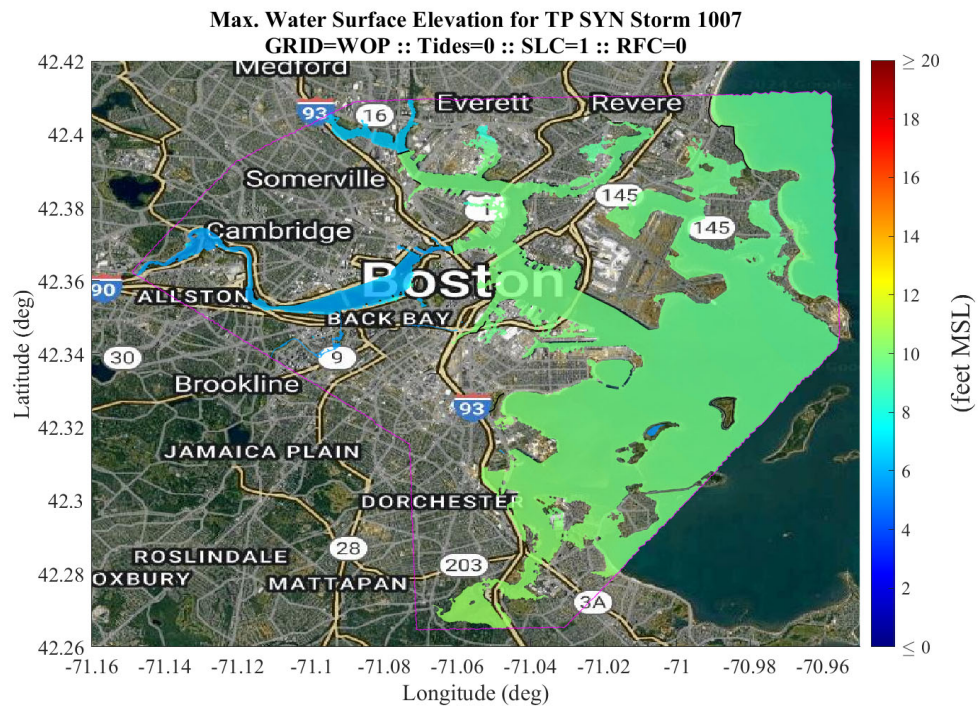


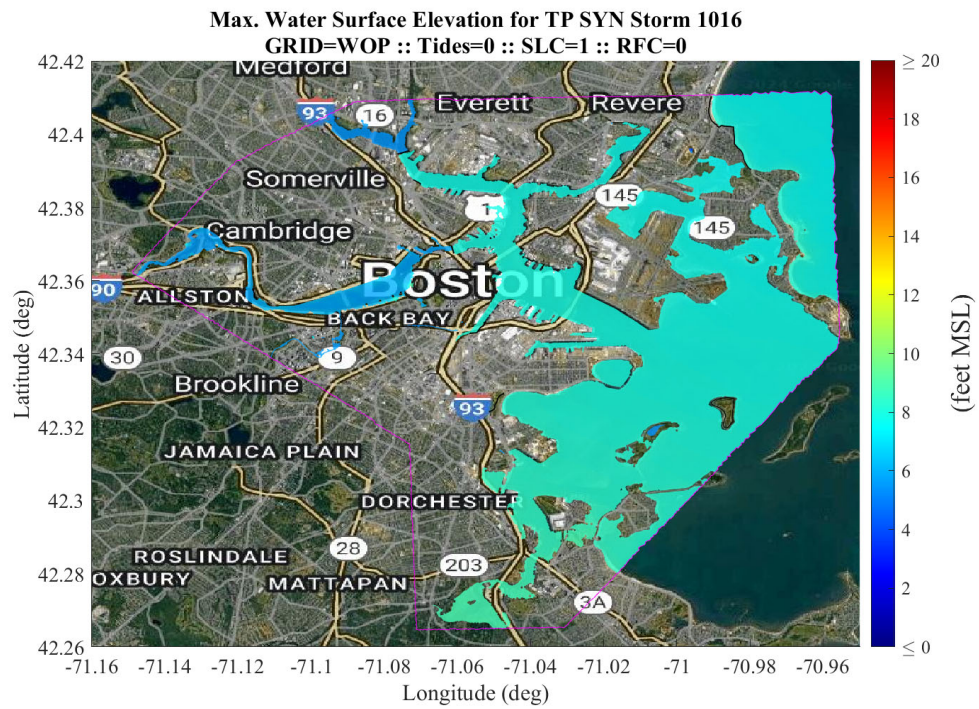


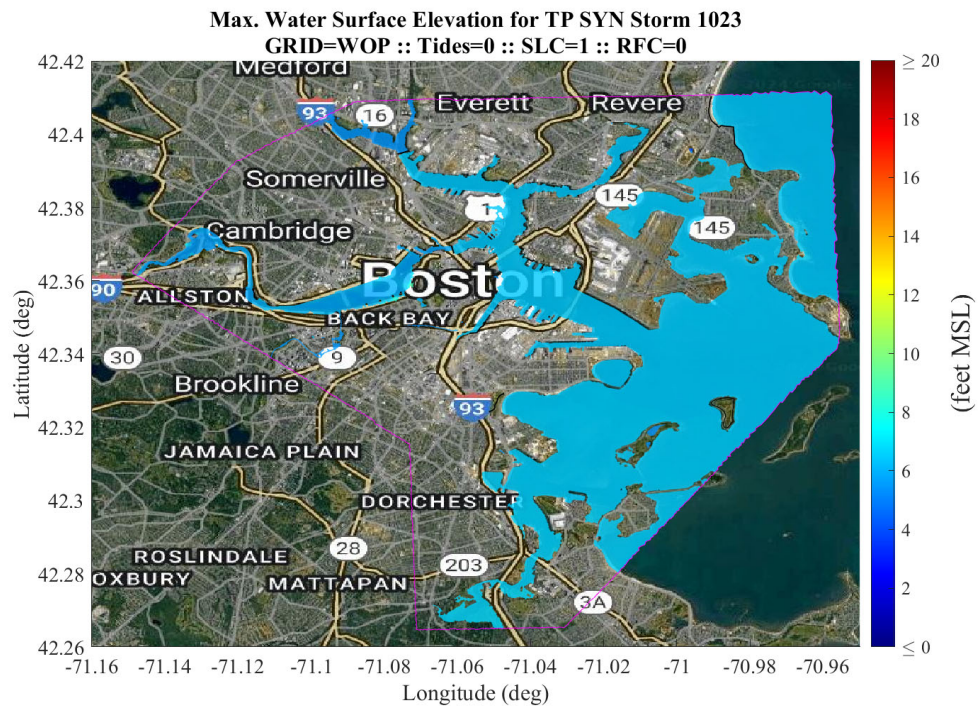


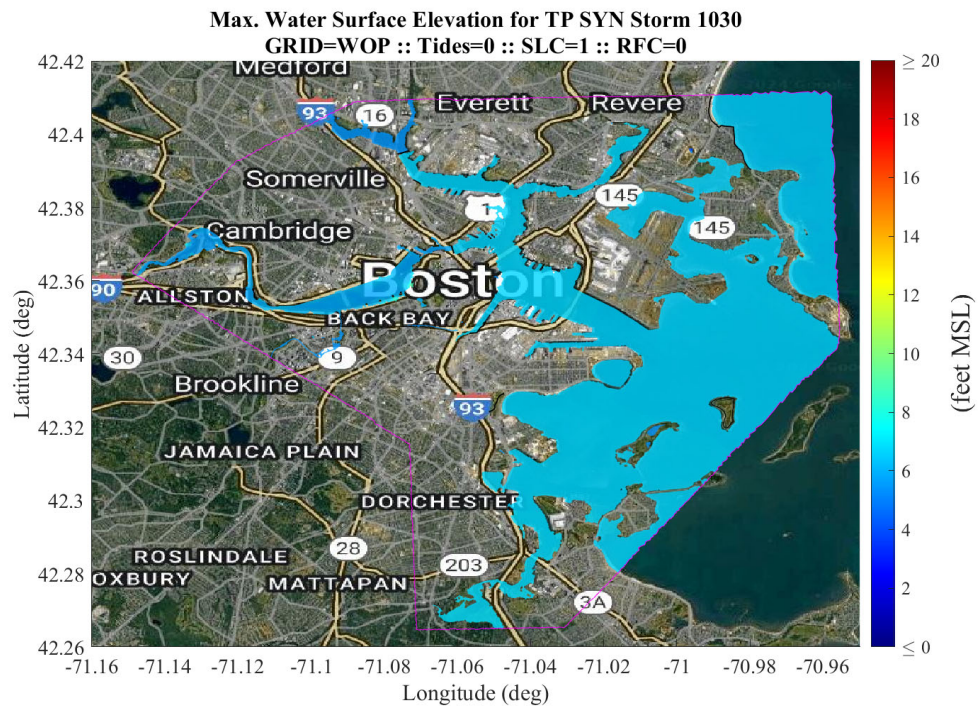


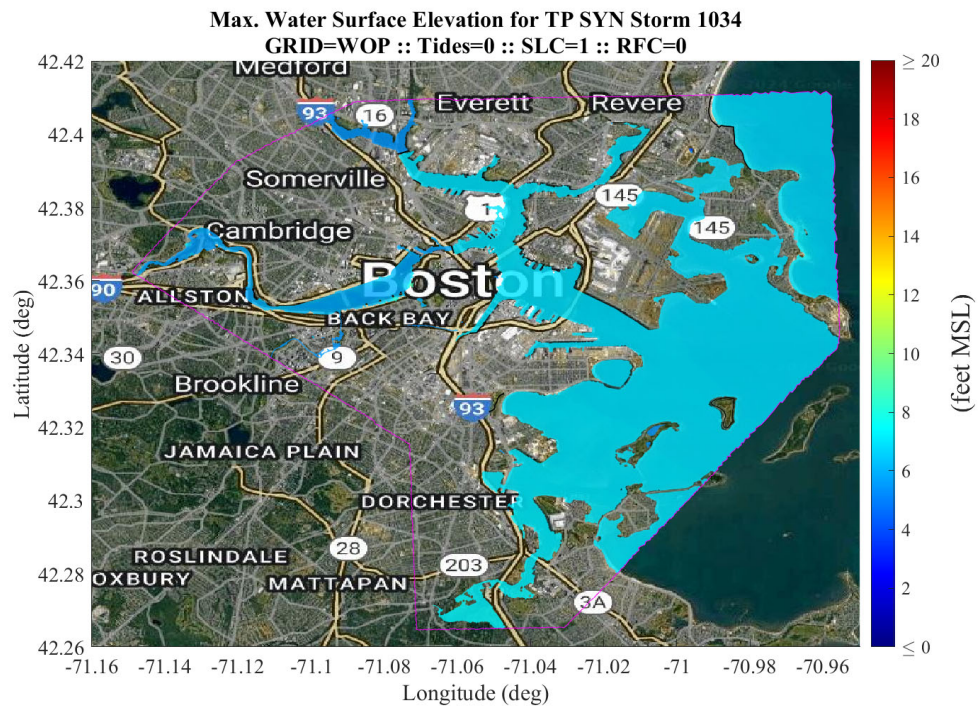


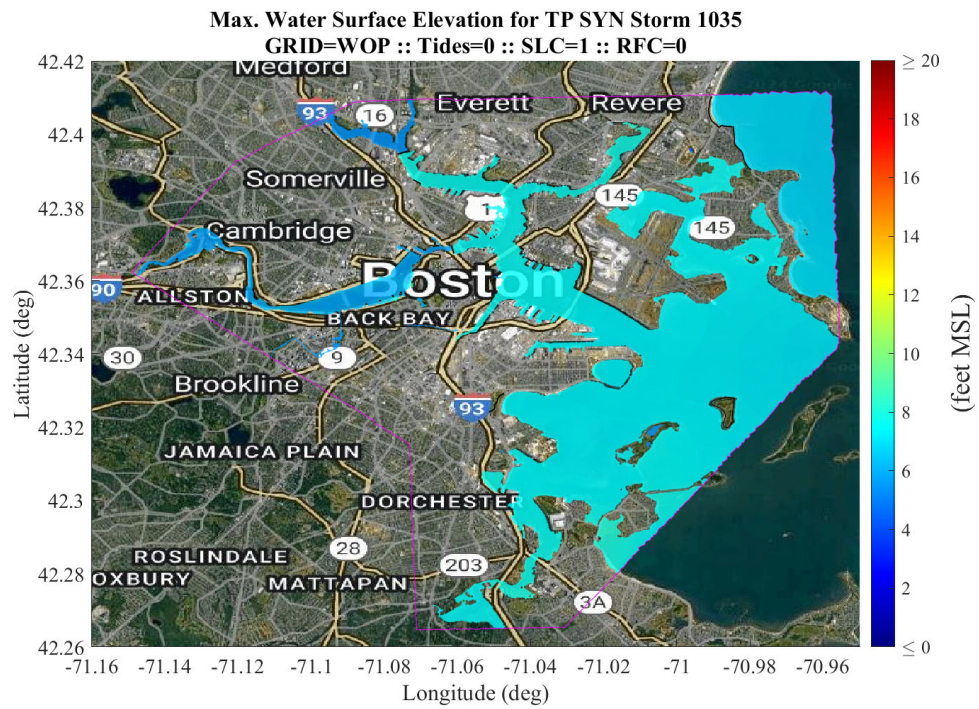






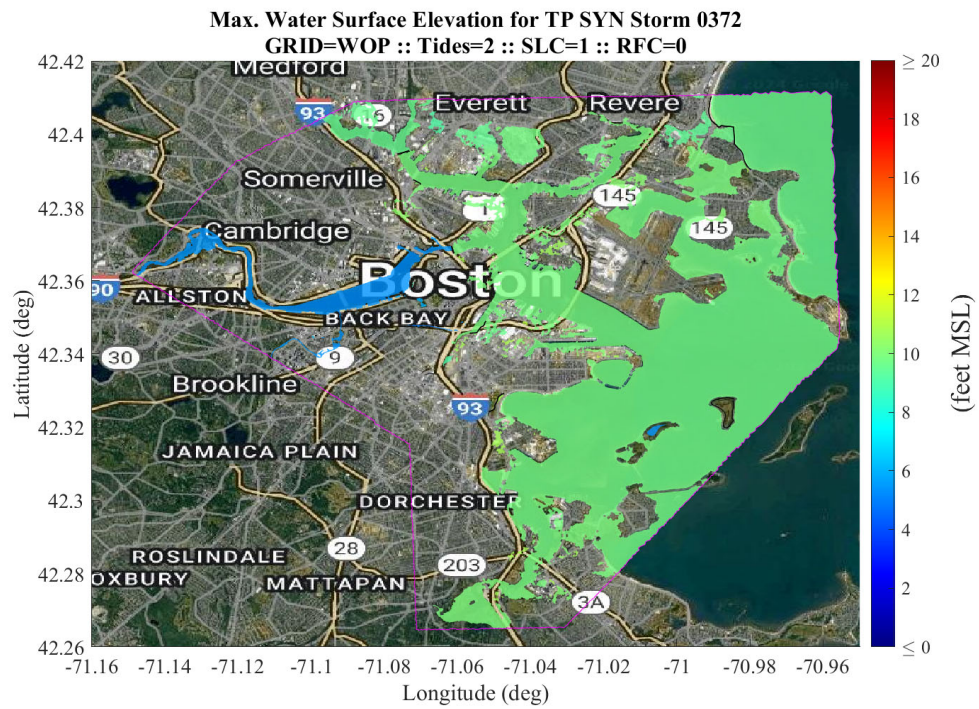


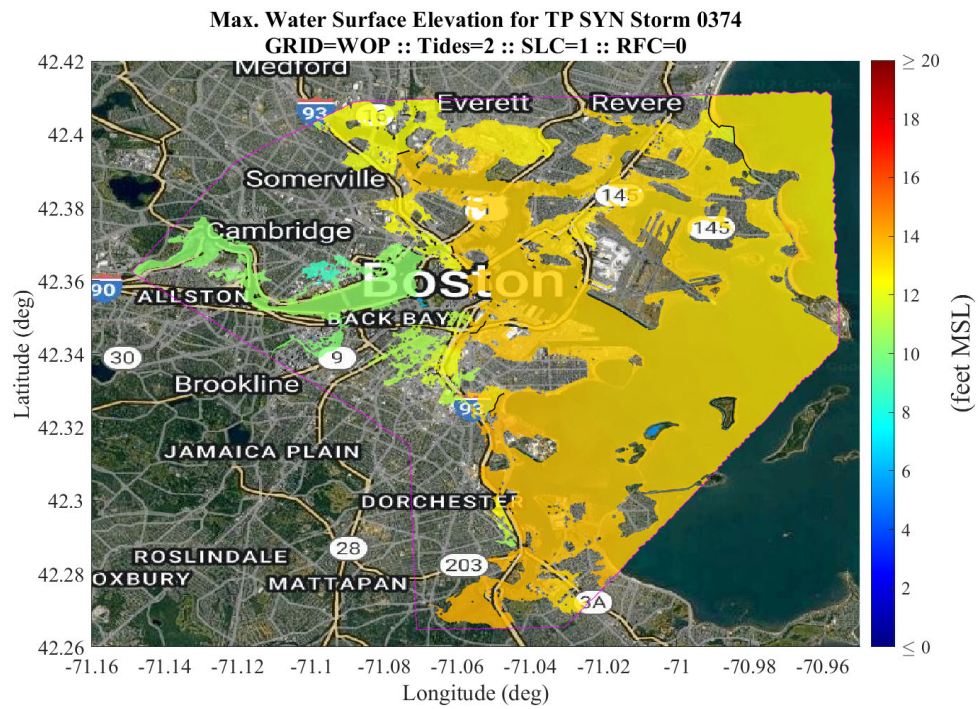


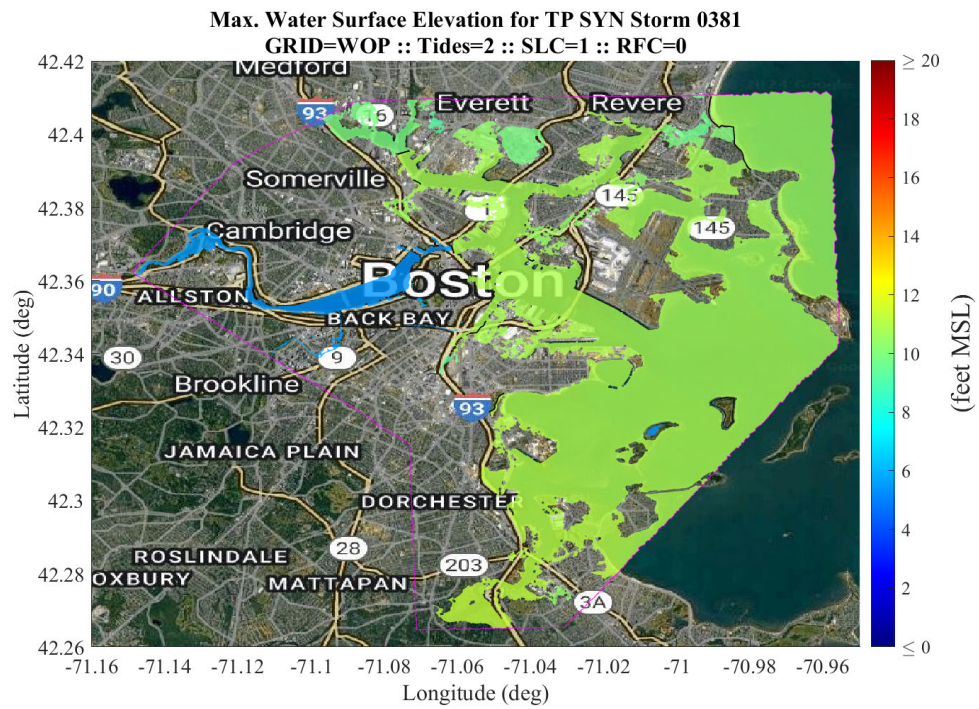


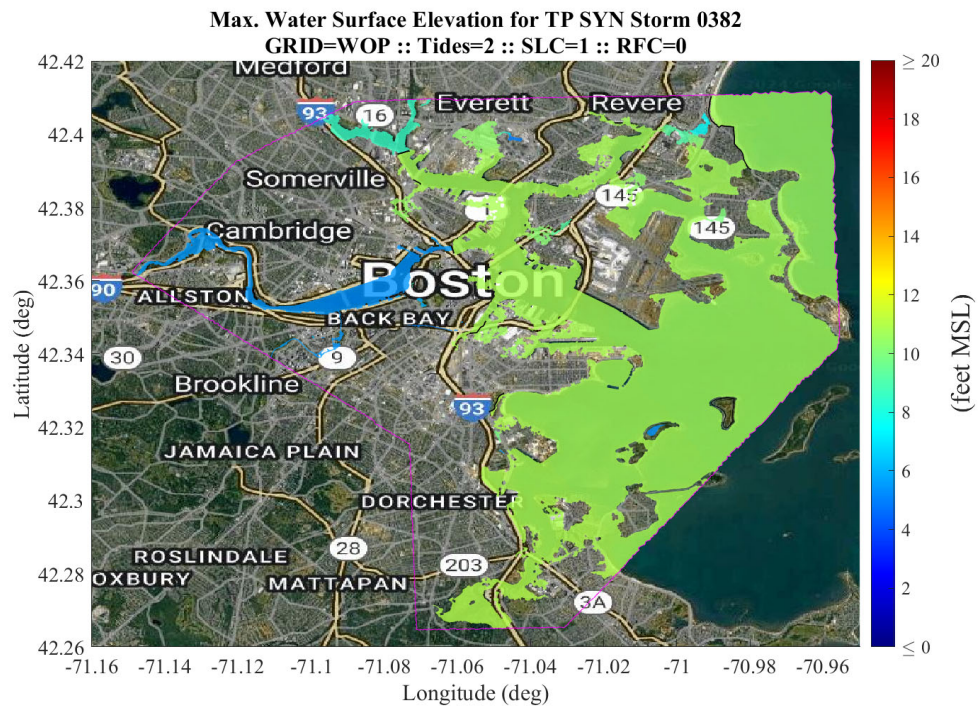
18 Appendix 9

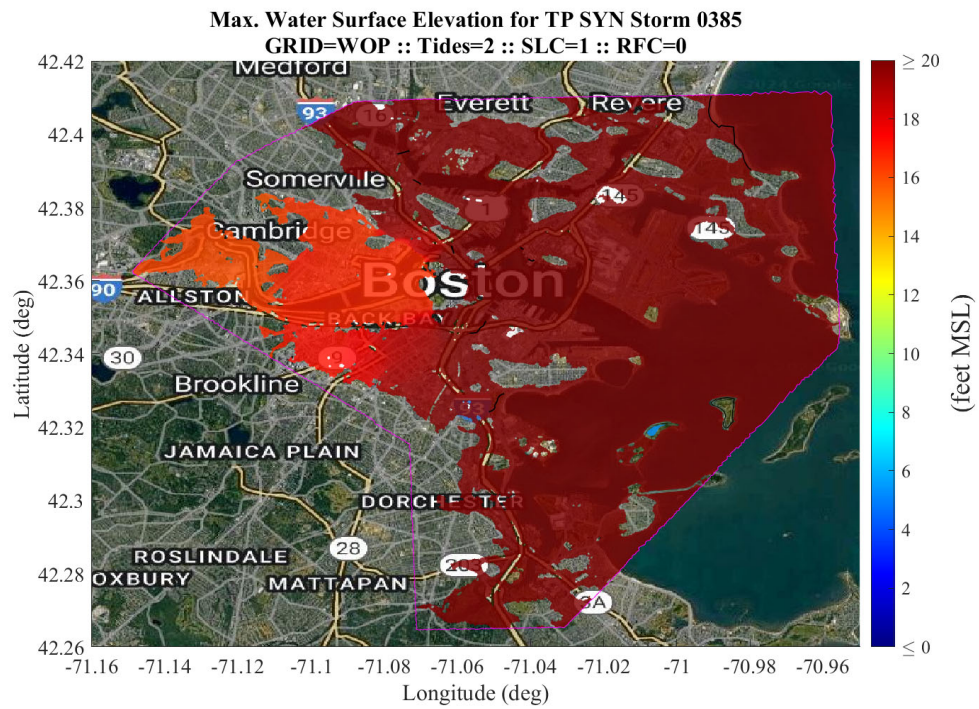
This appendix contains two-dimensional color contour plots of maximum water surface elevation for the CSTORM coupled ADCIRC+STWAVE model results for 60 synthetic tropical cyclone TC events for SLC1 and random tides.

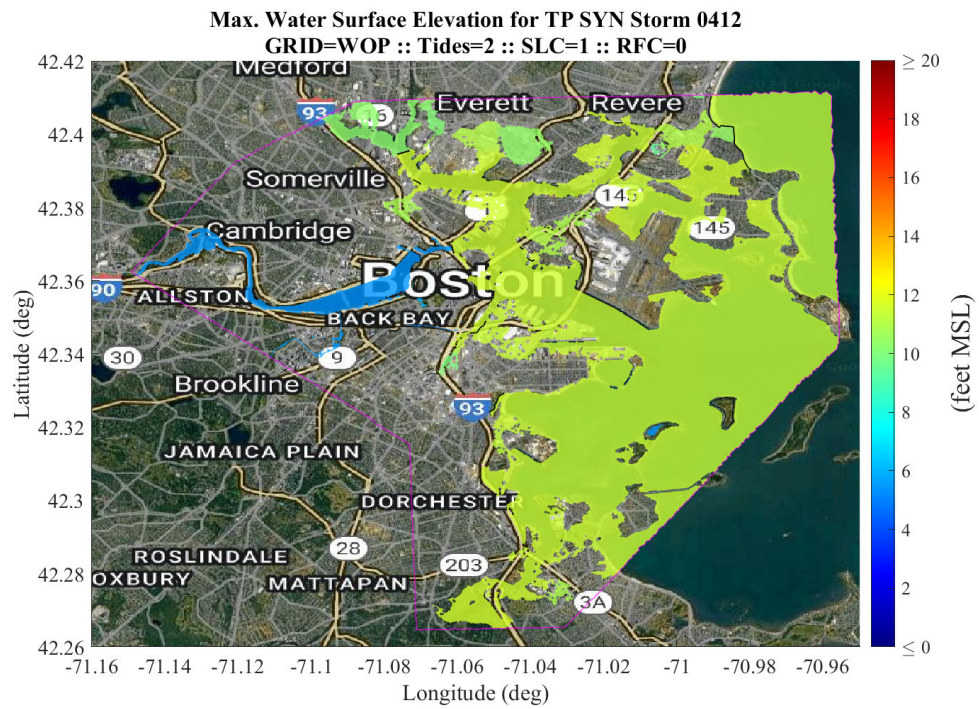


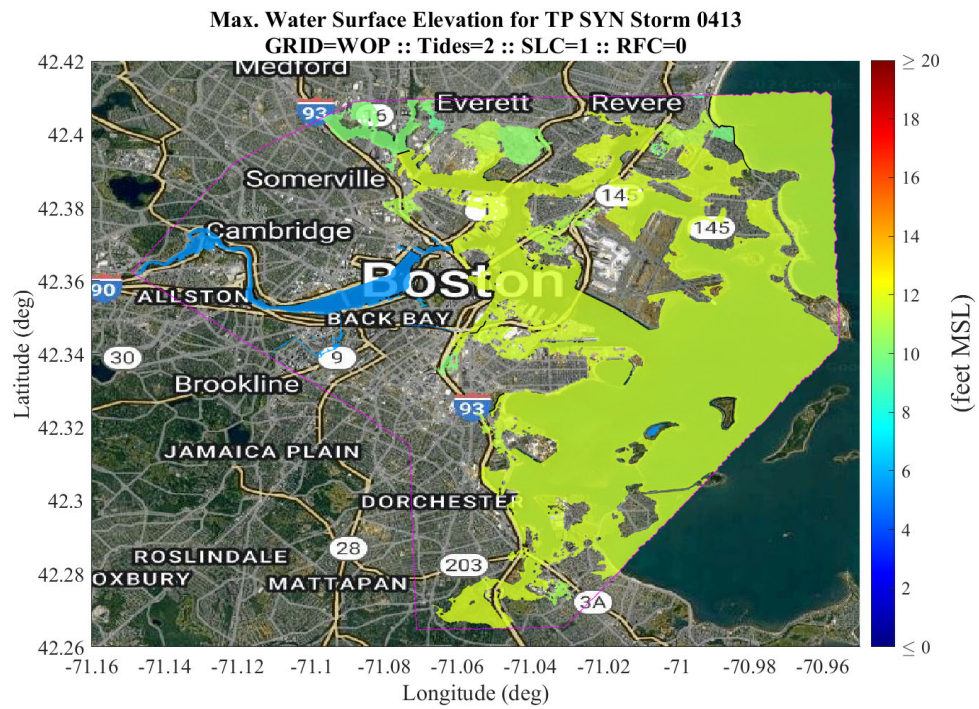


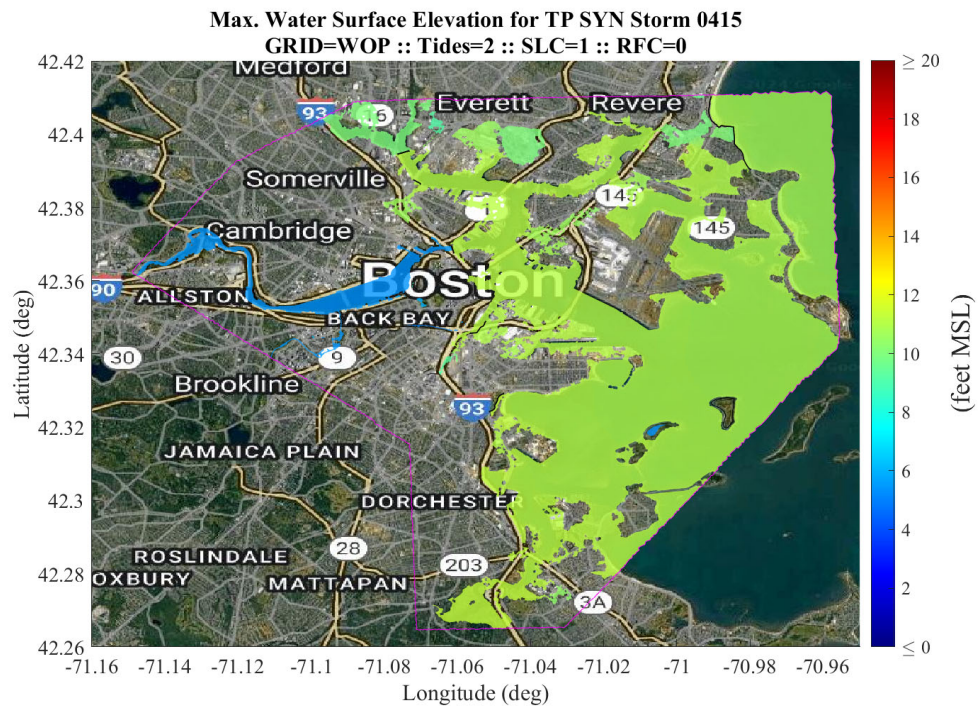


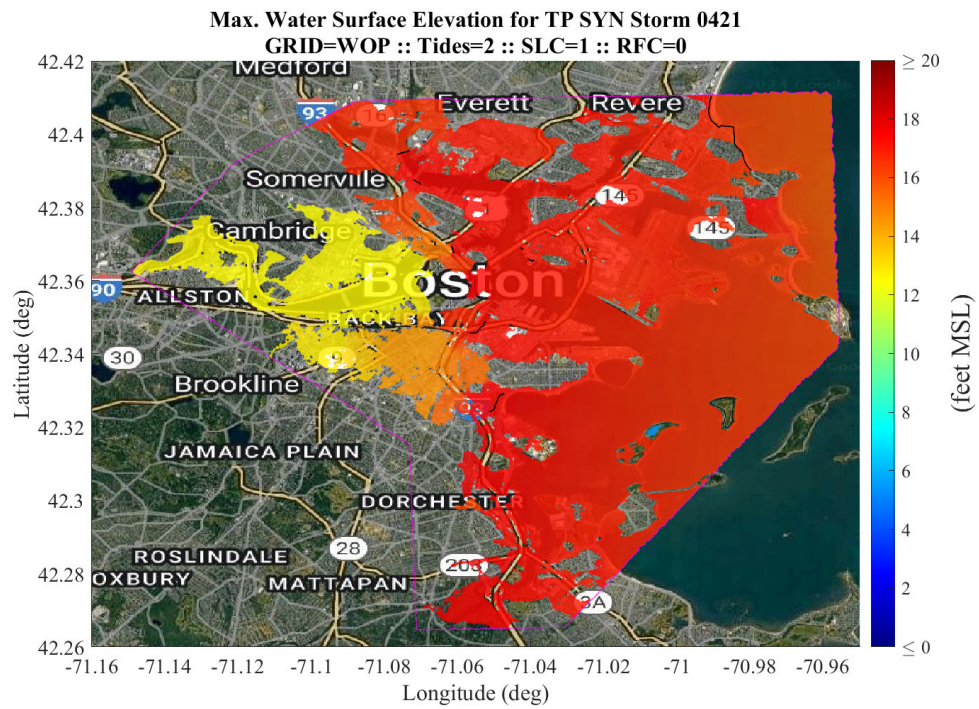


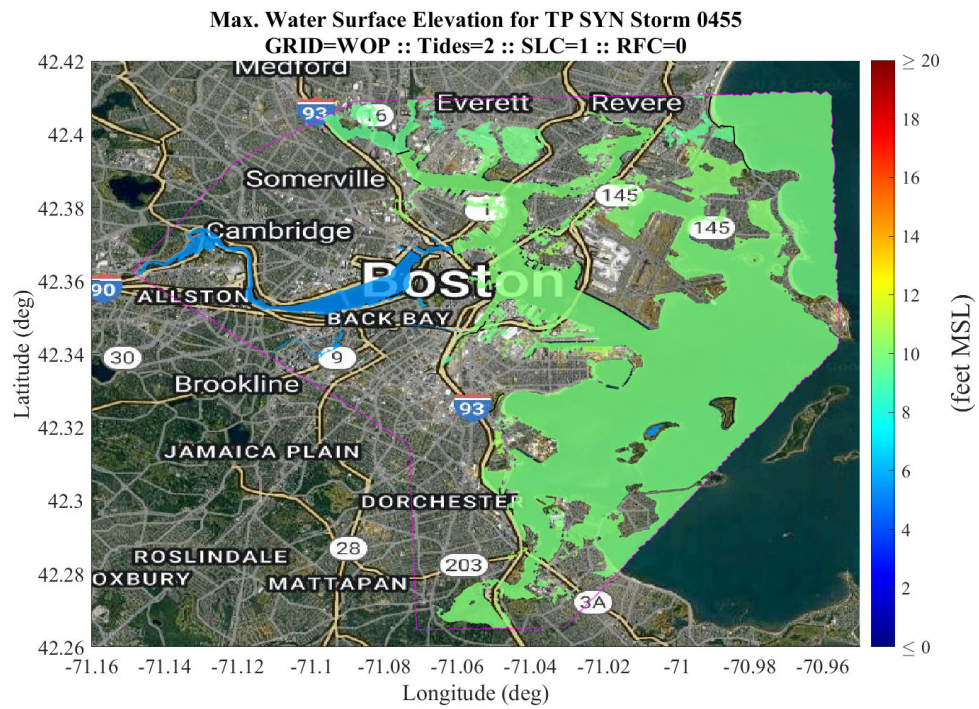


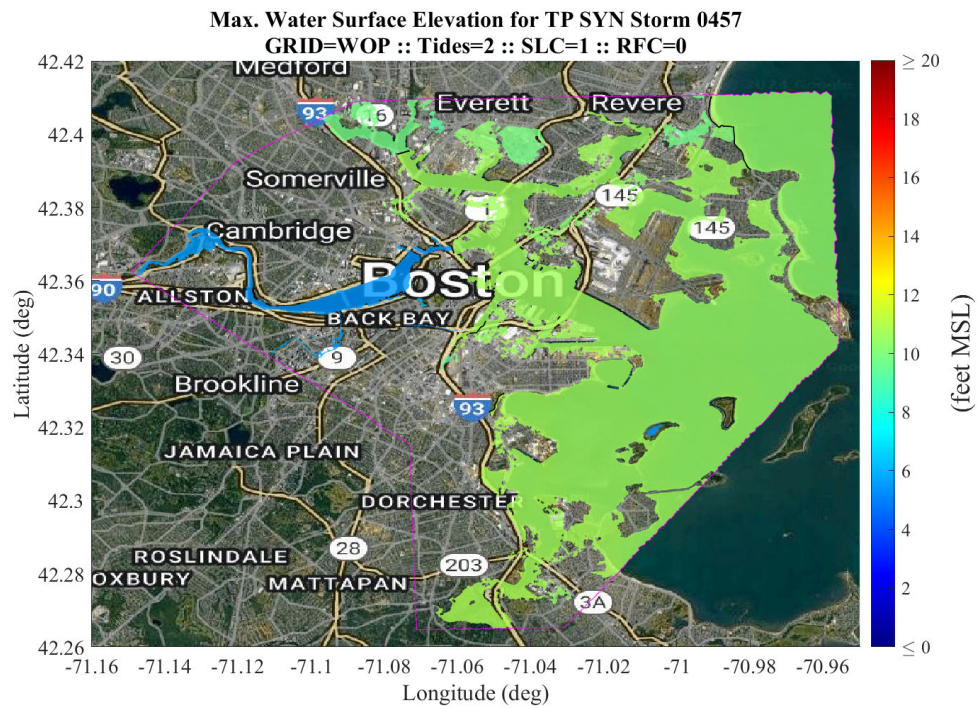


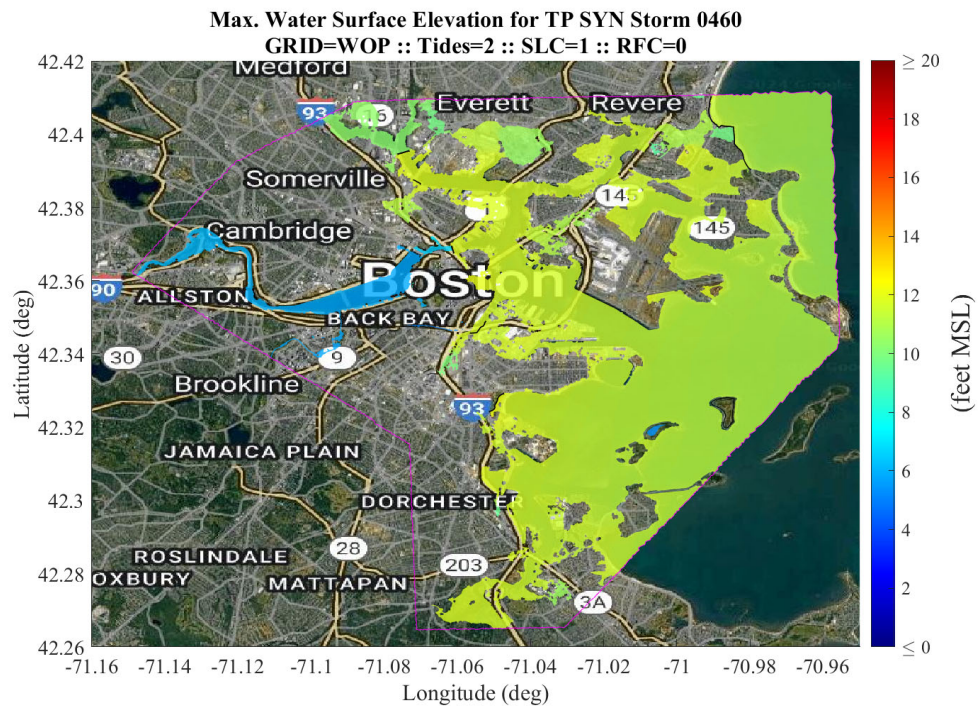


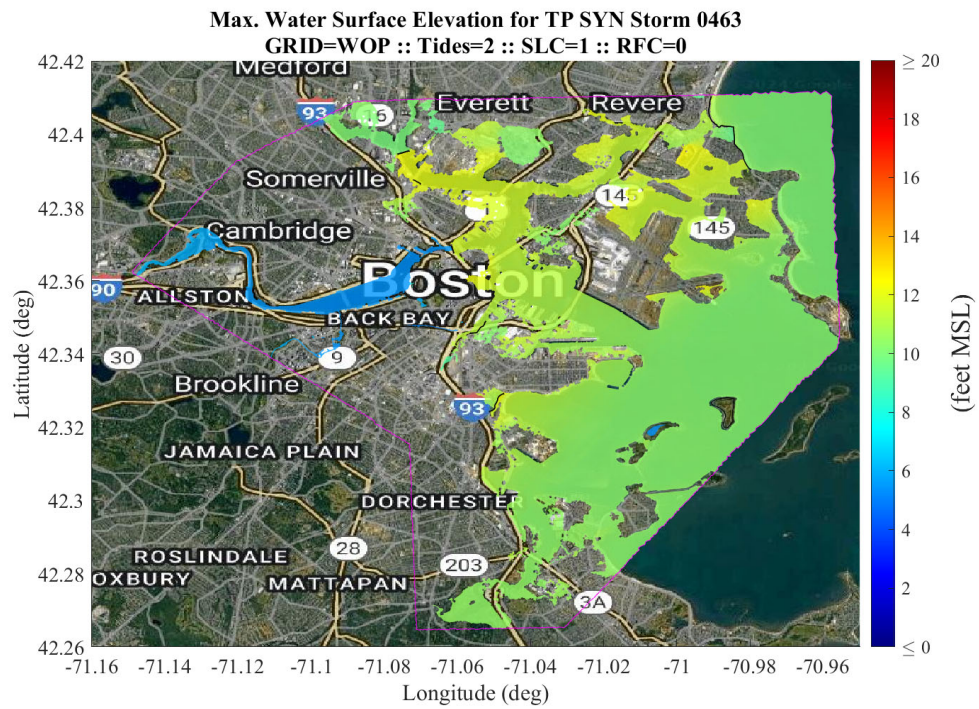


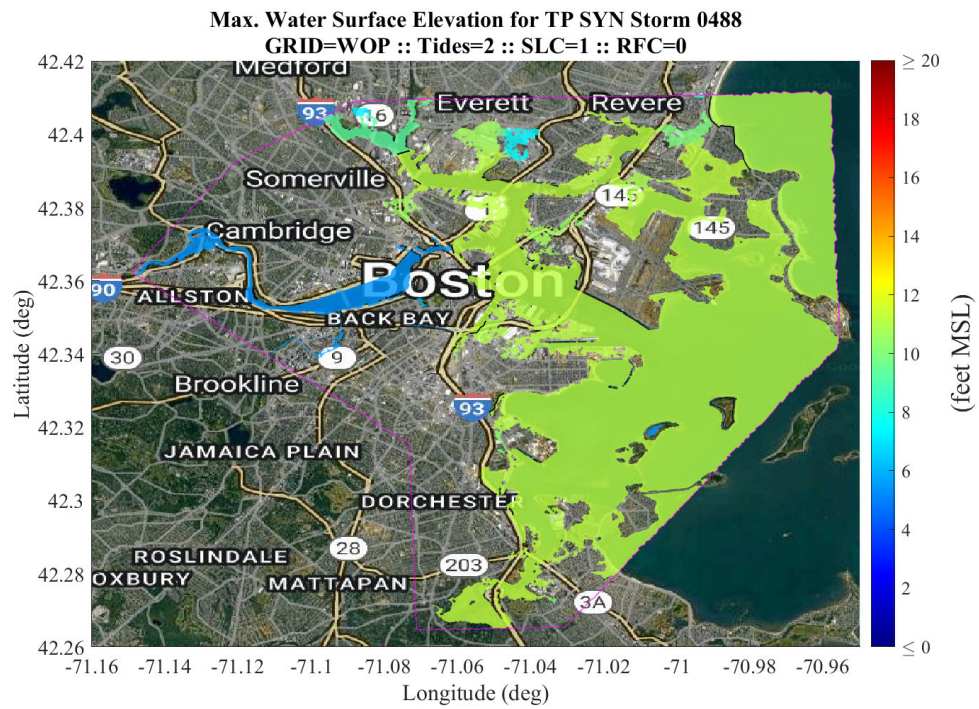


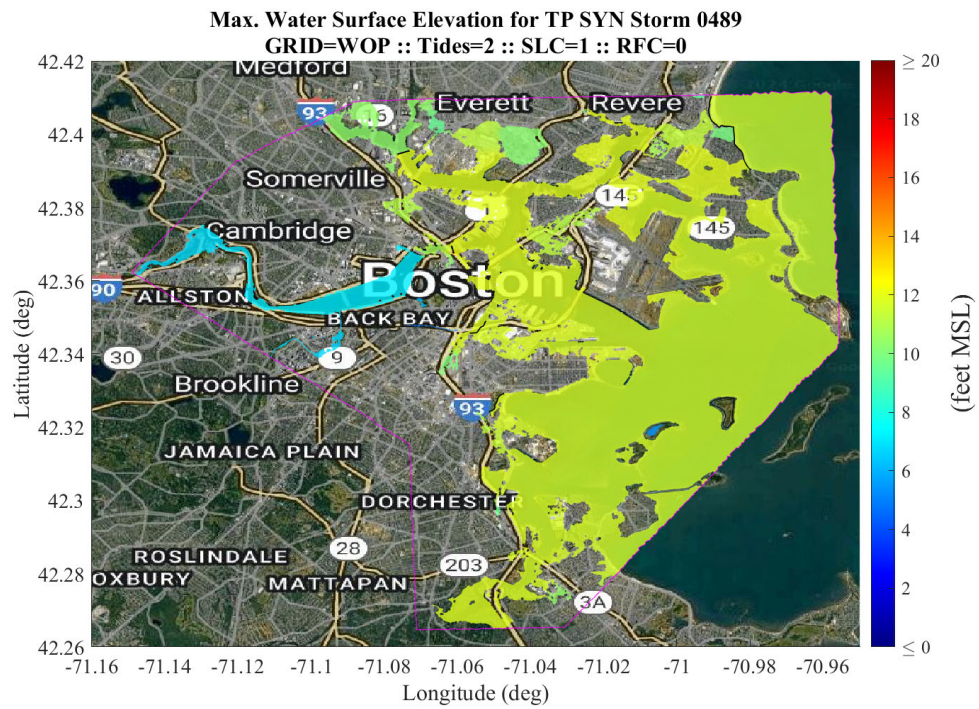


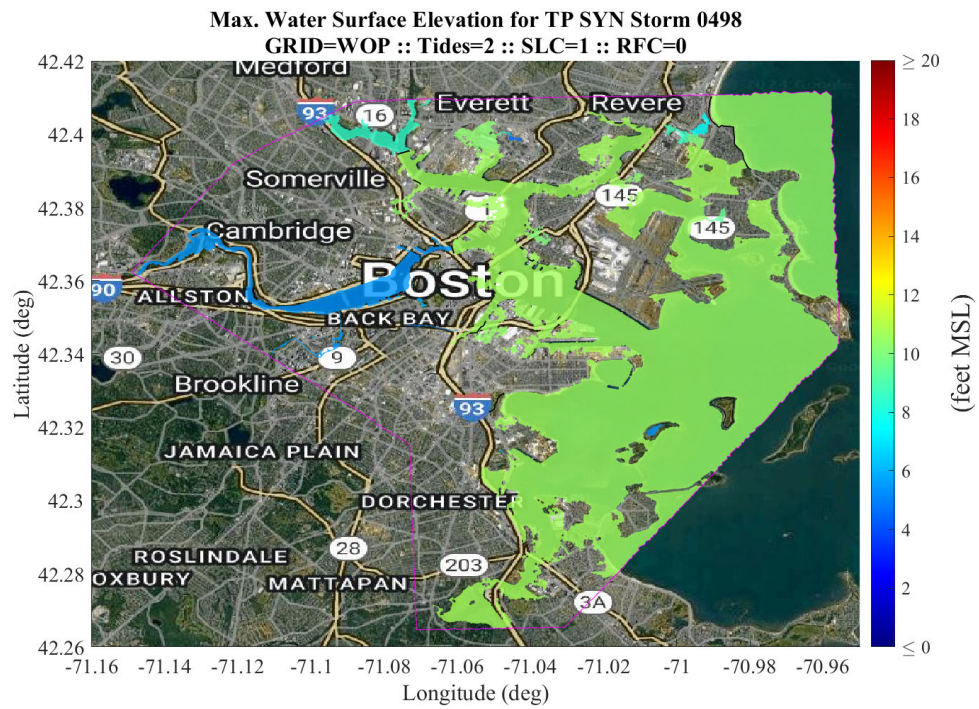


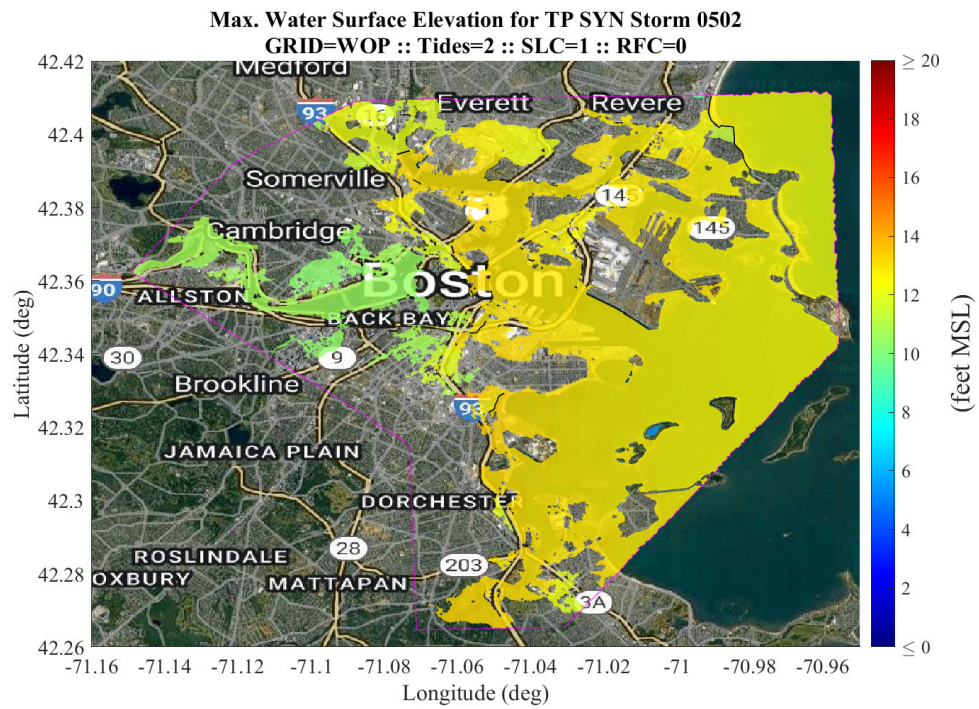


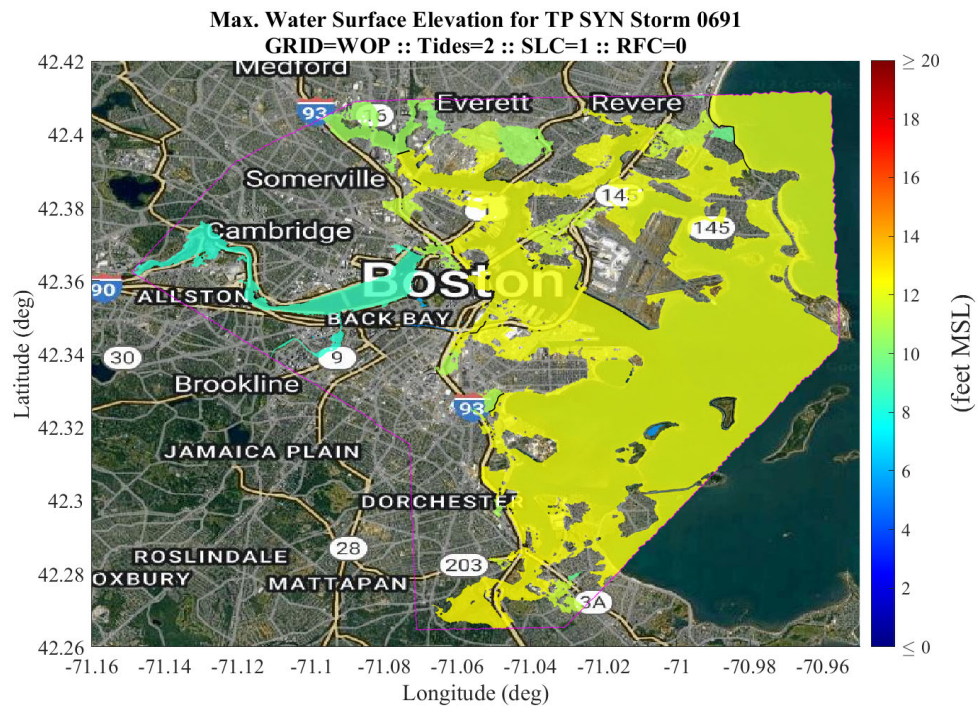


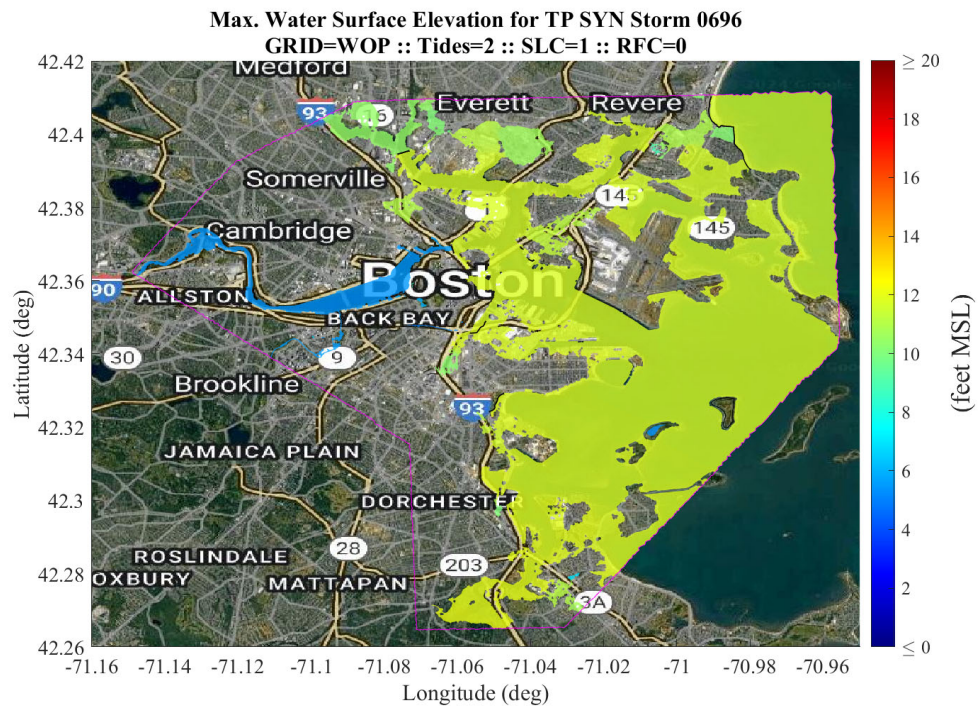


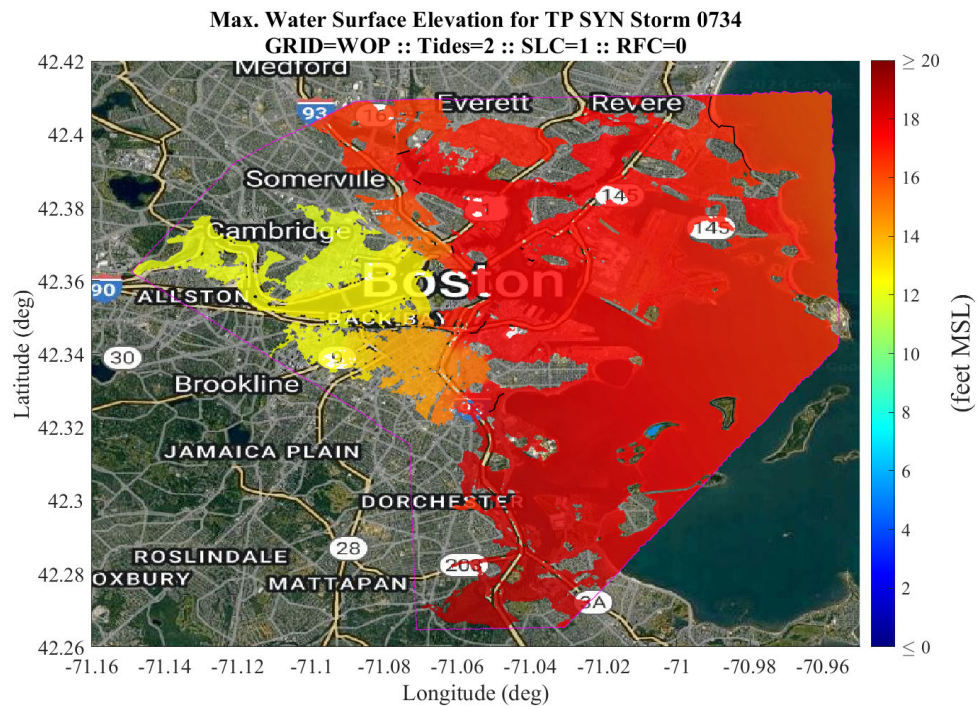


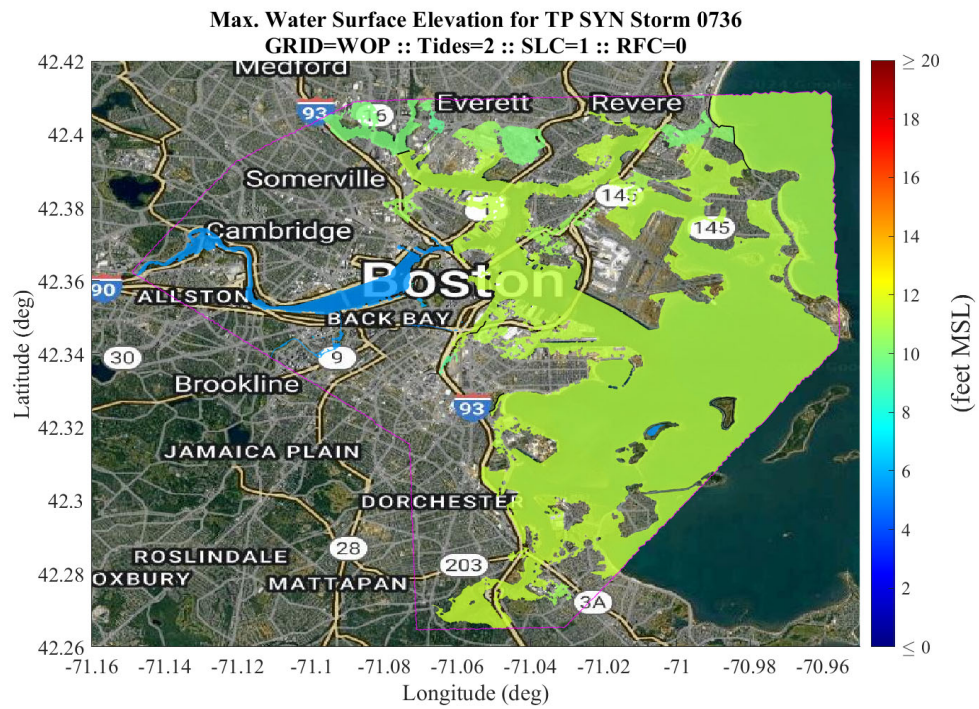


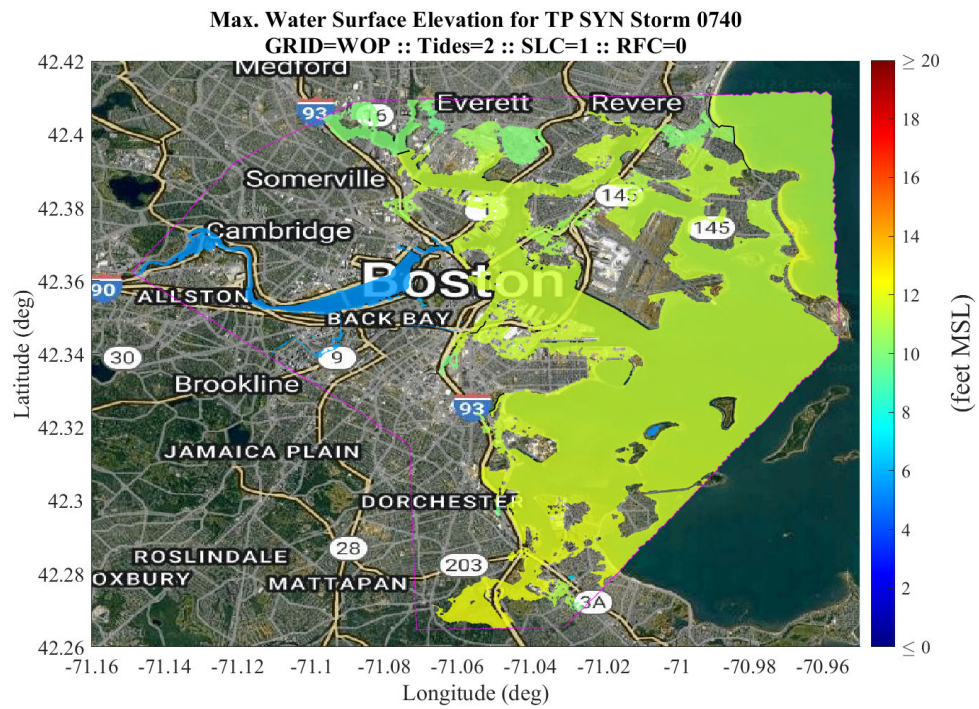


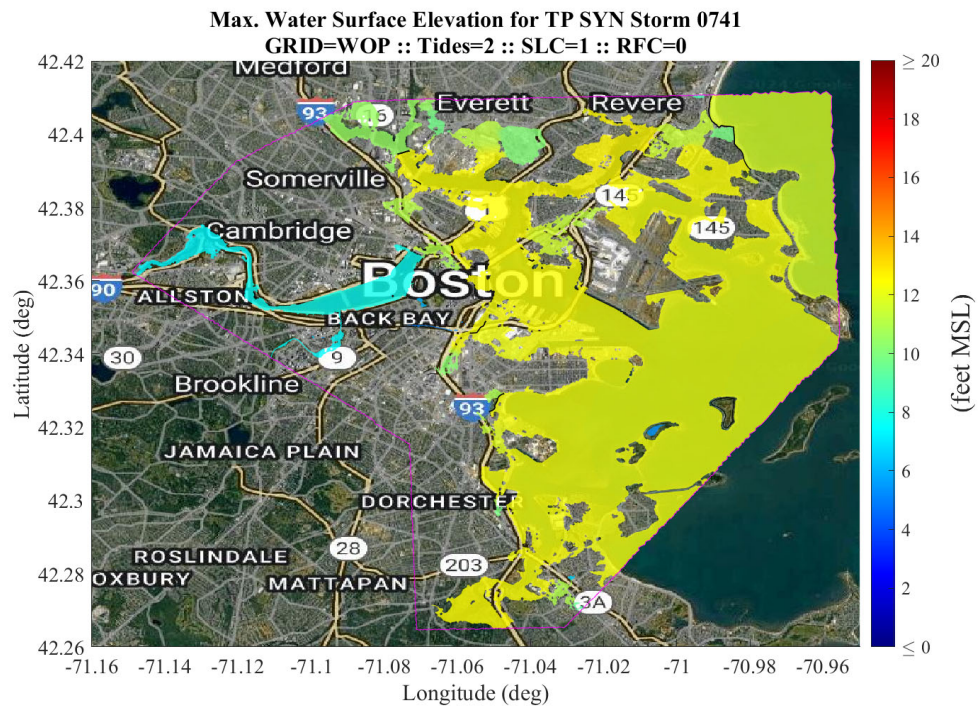


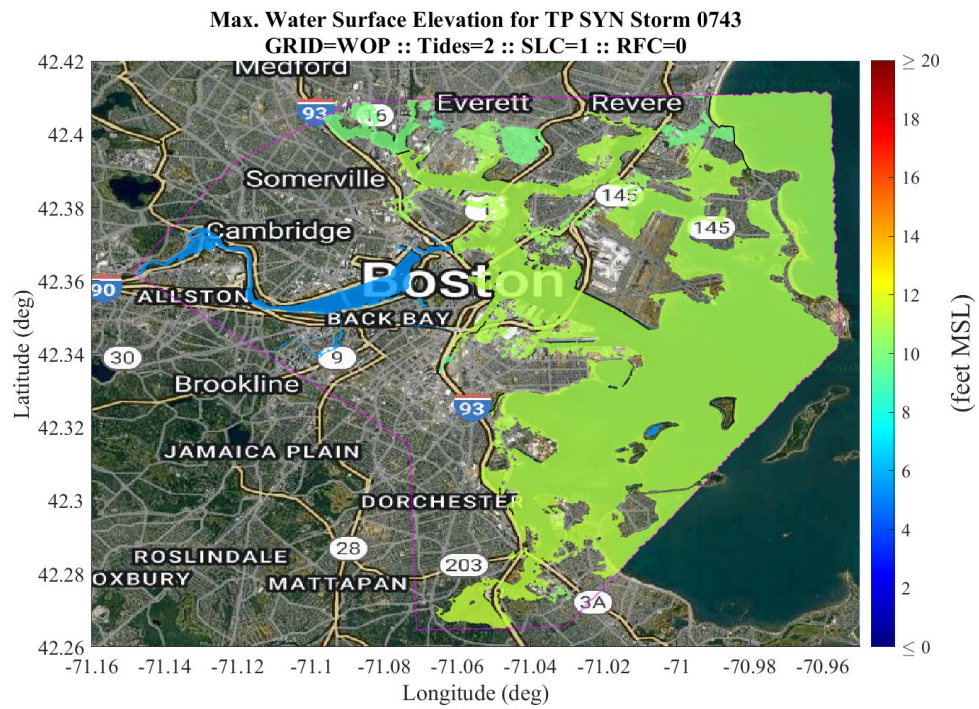


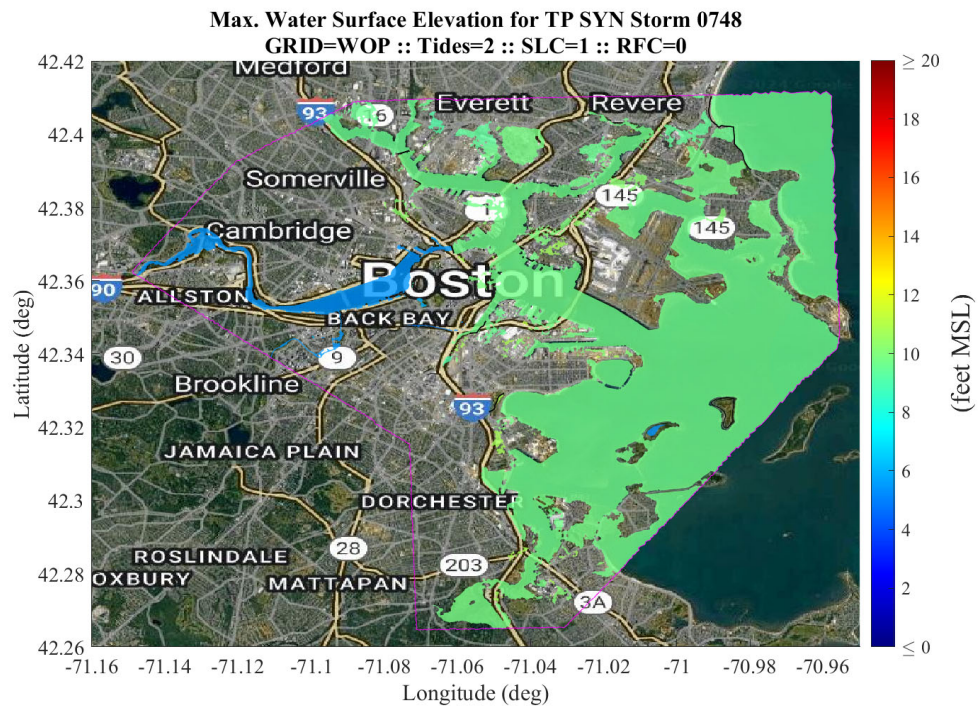


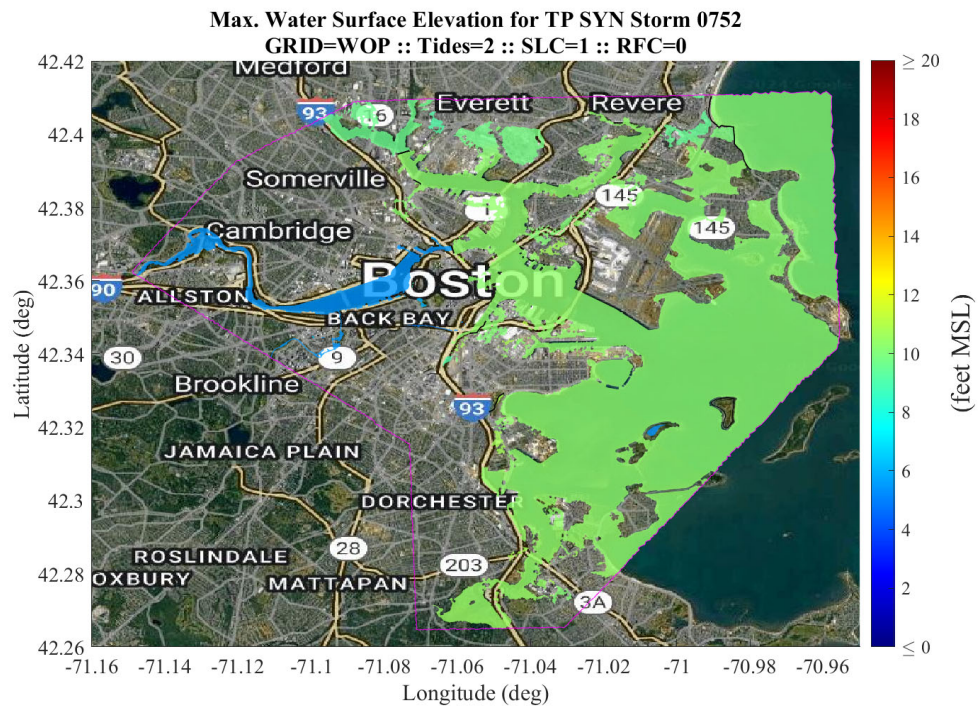


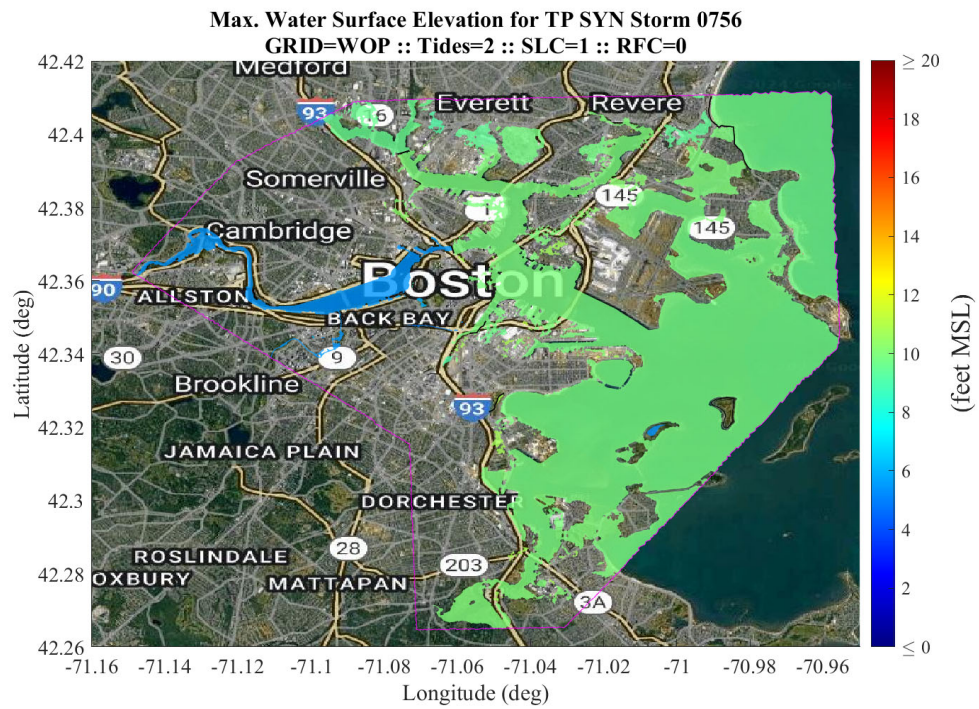


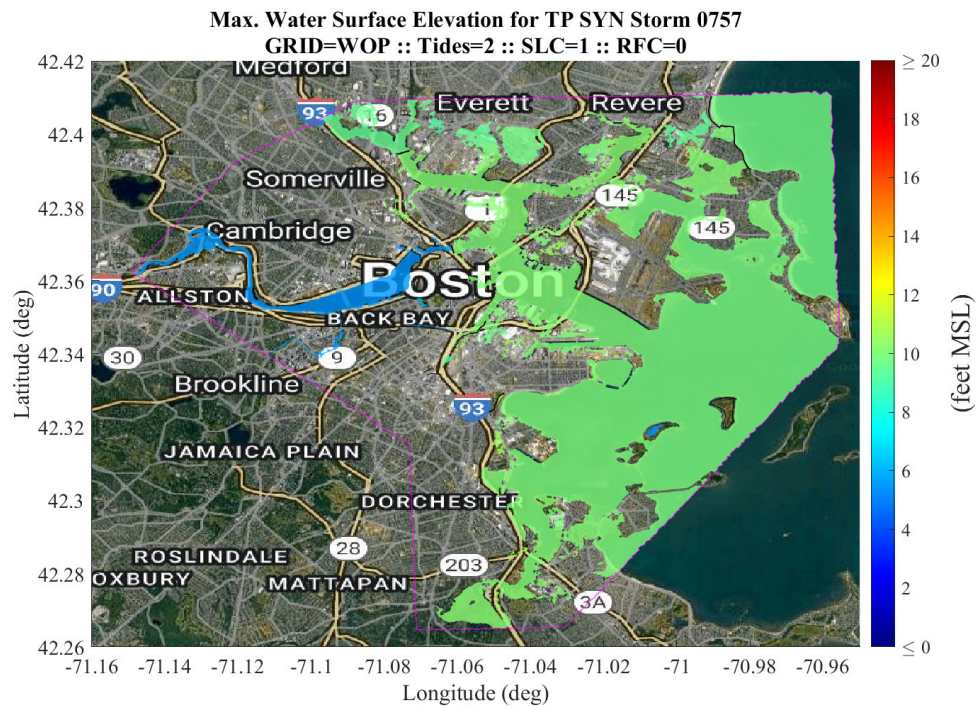


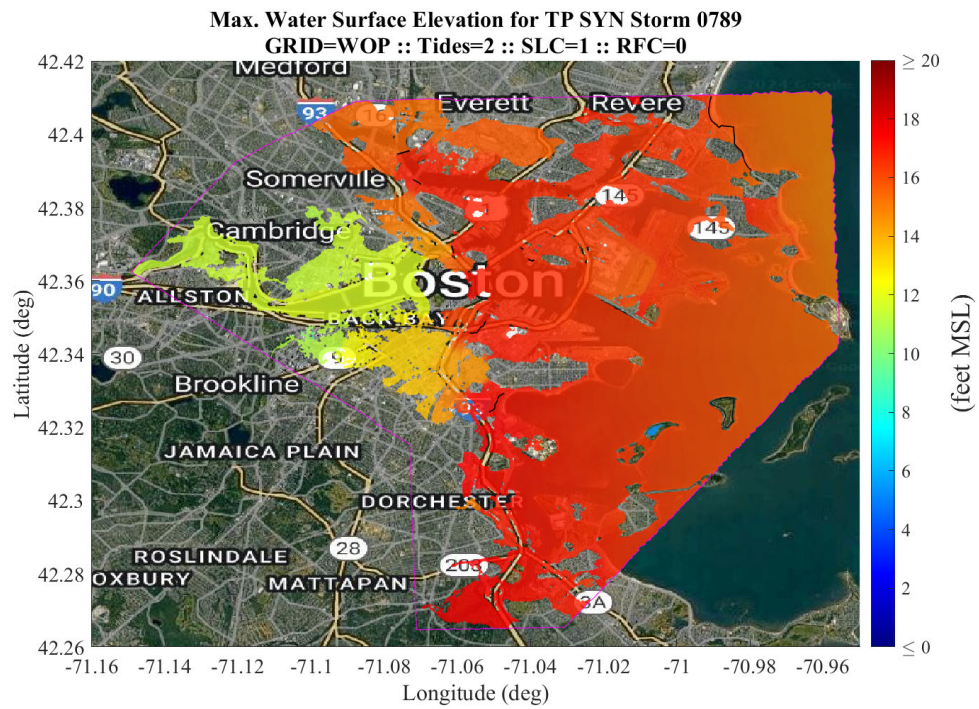


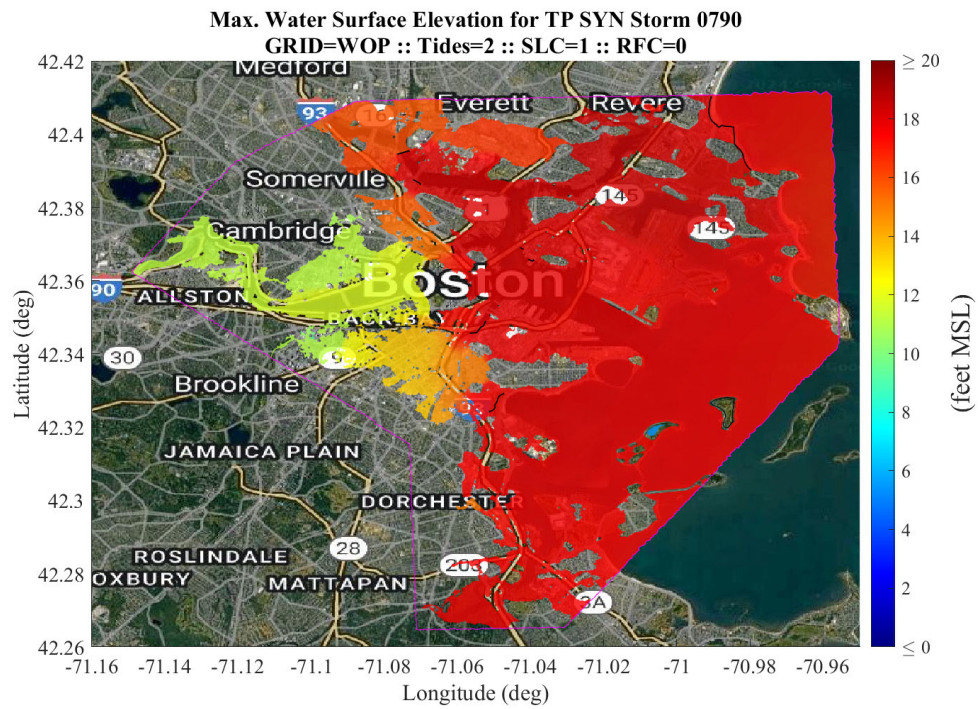


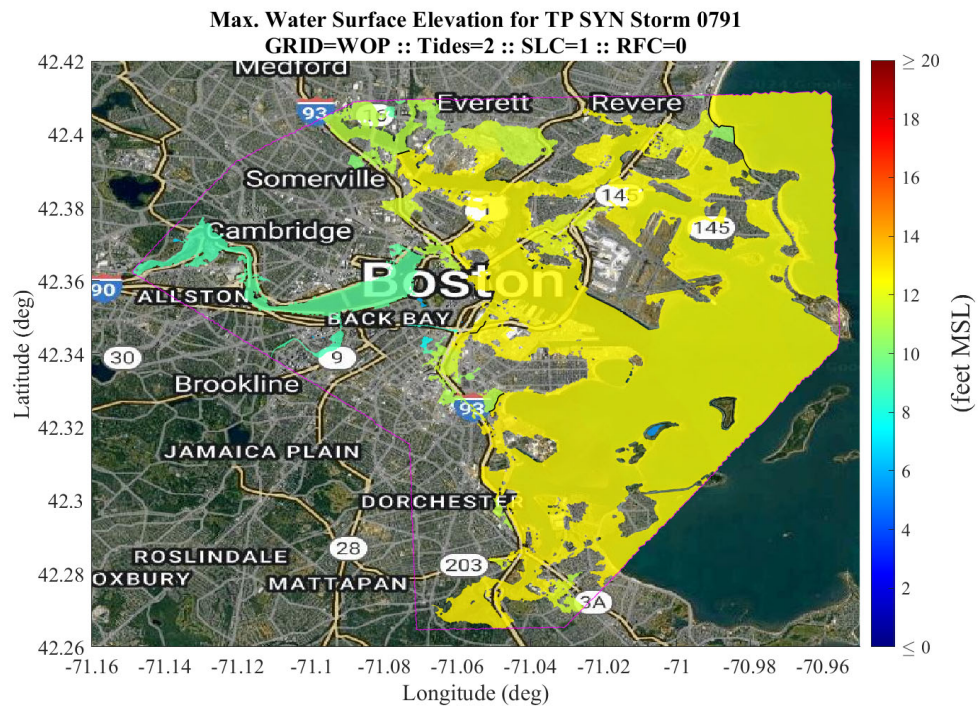


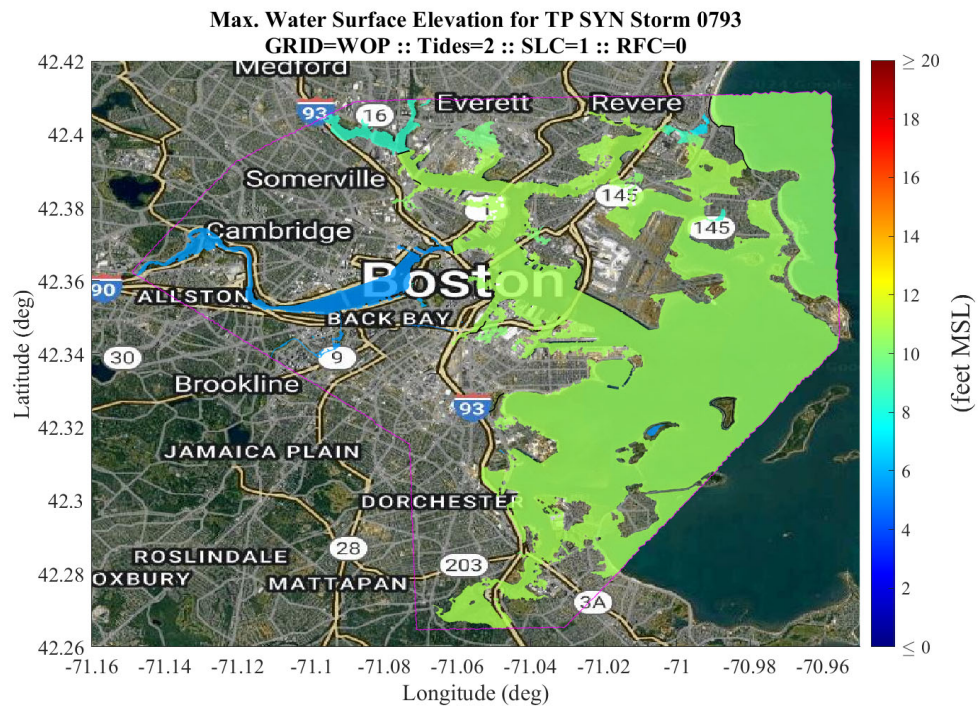


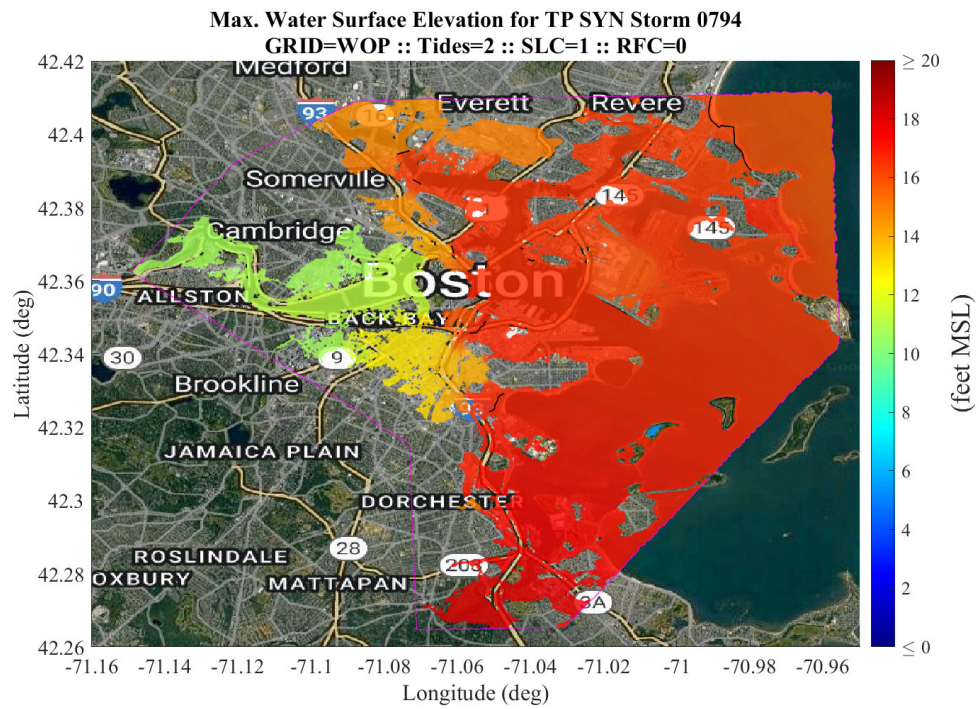


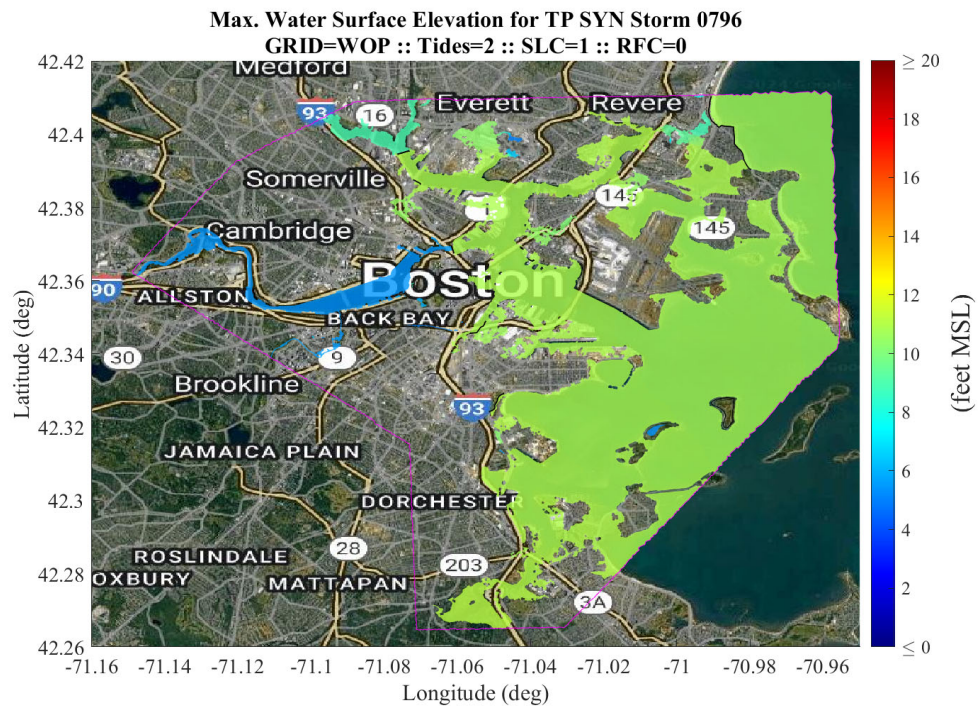


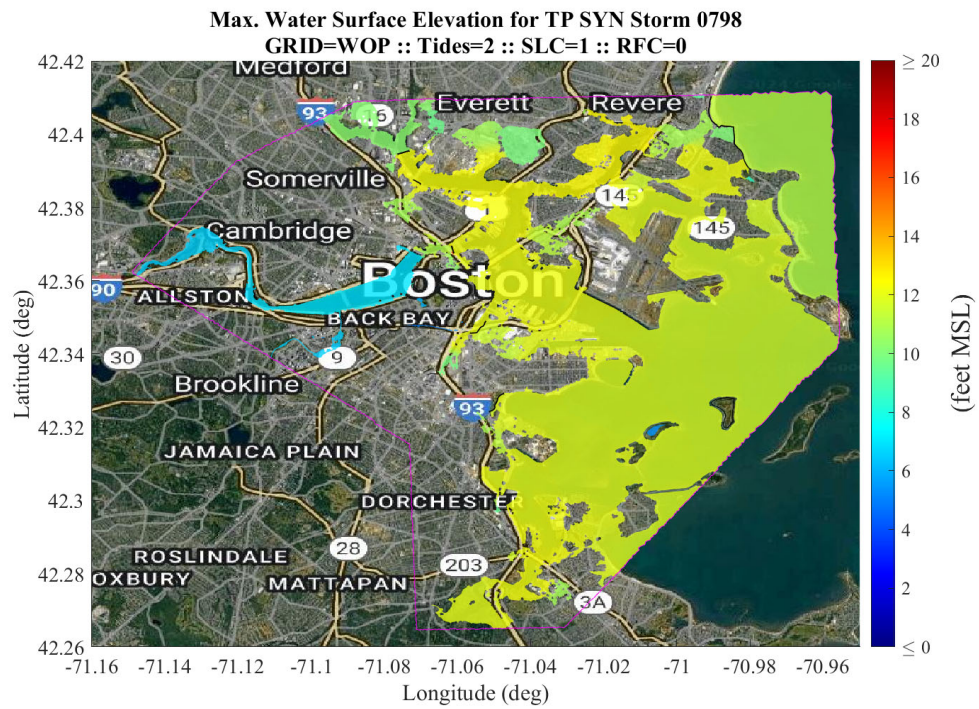


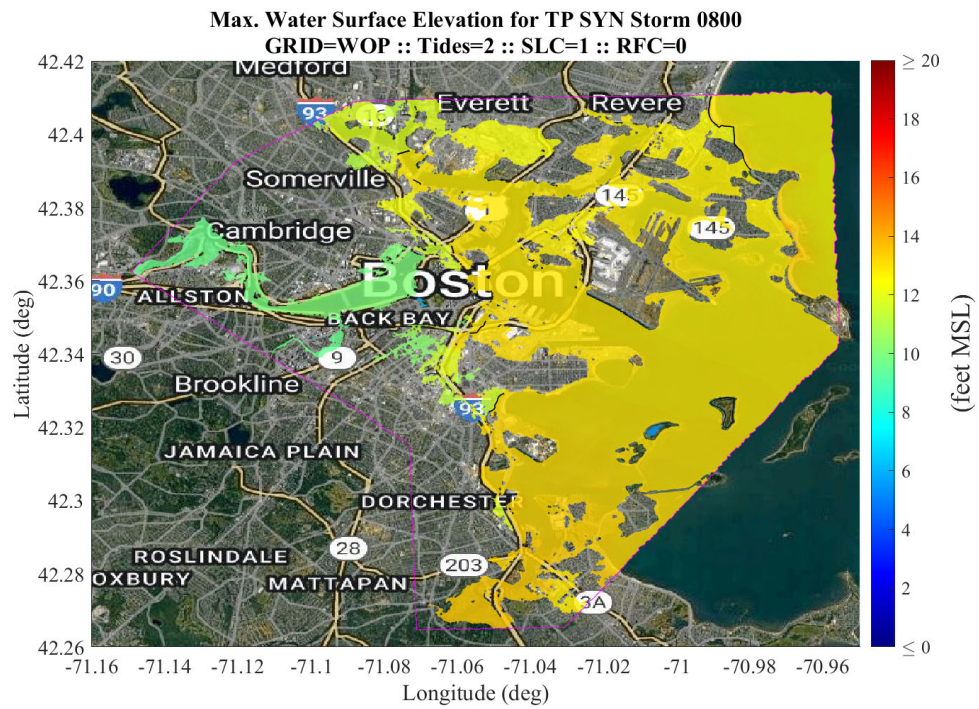


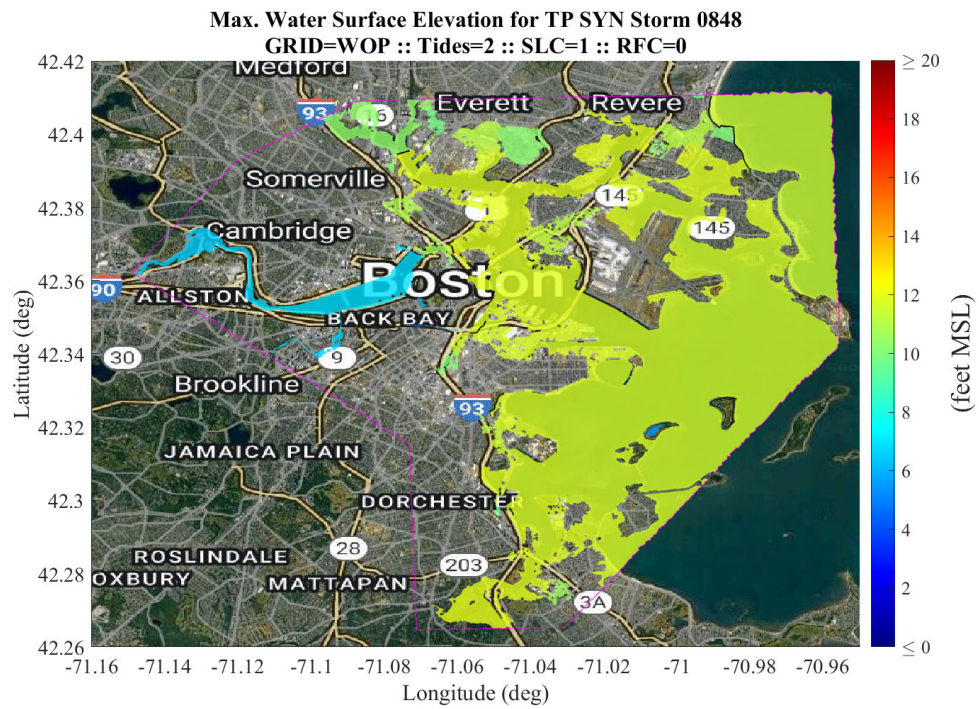


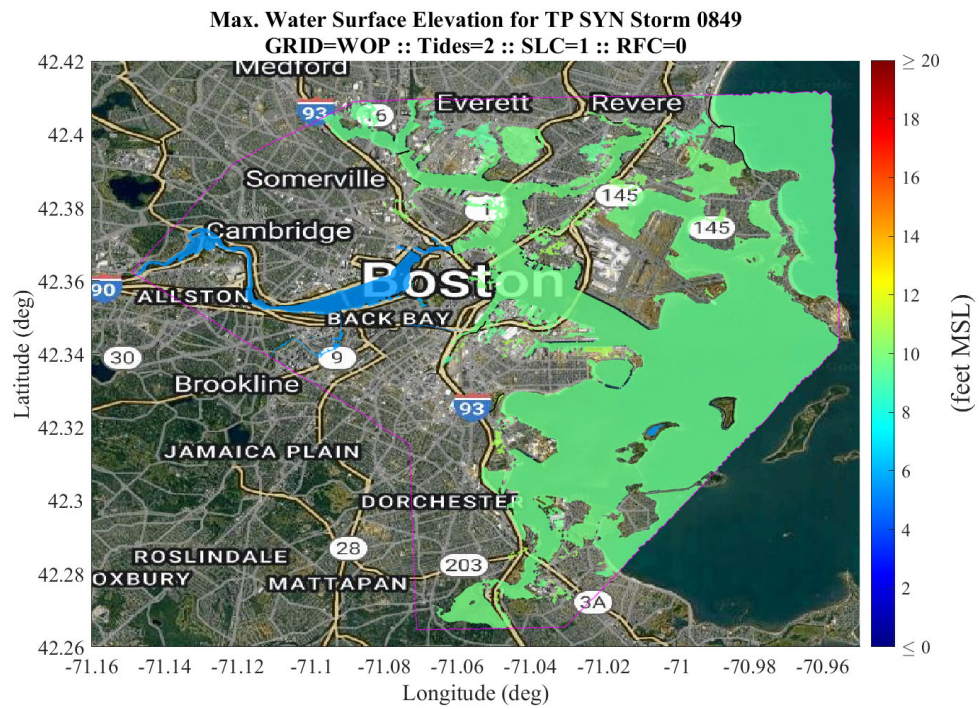


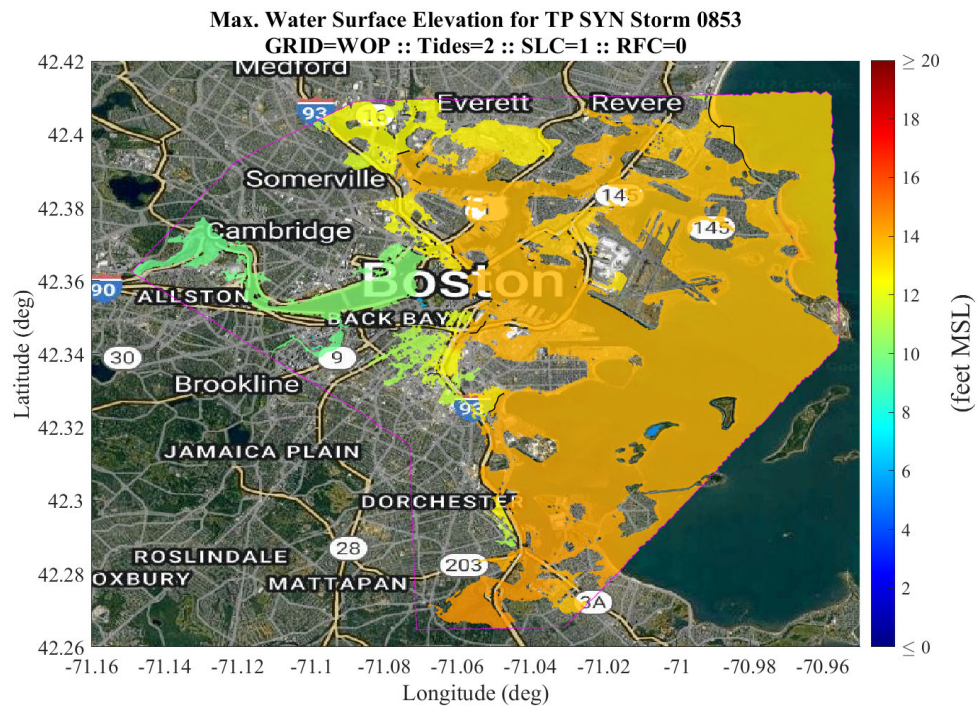


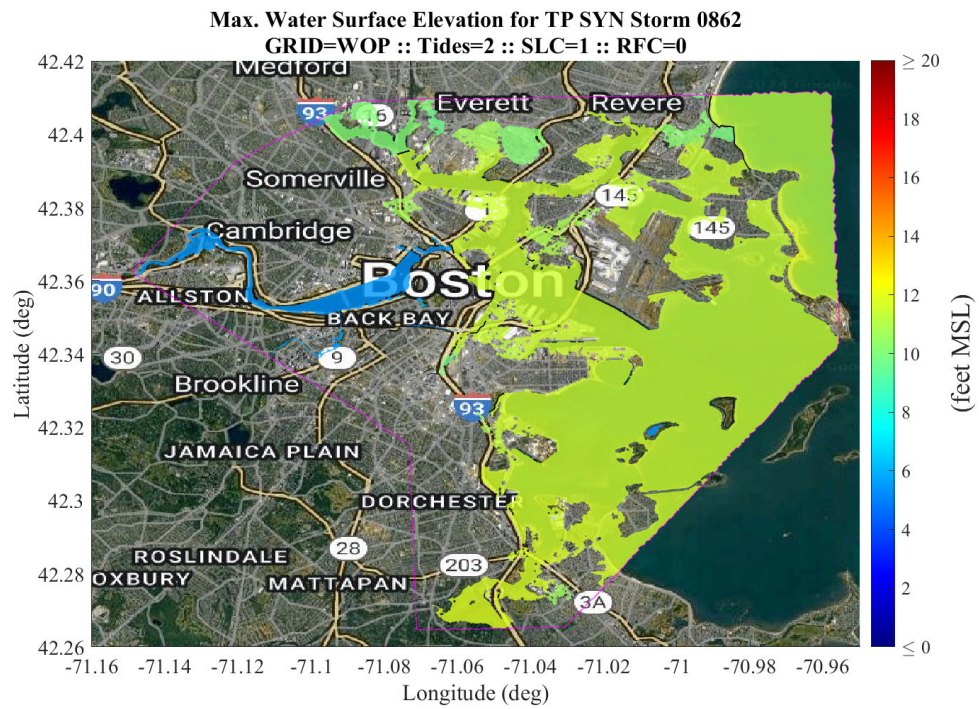


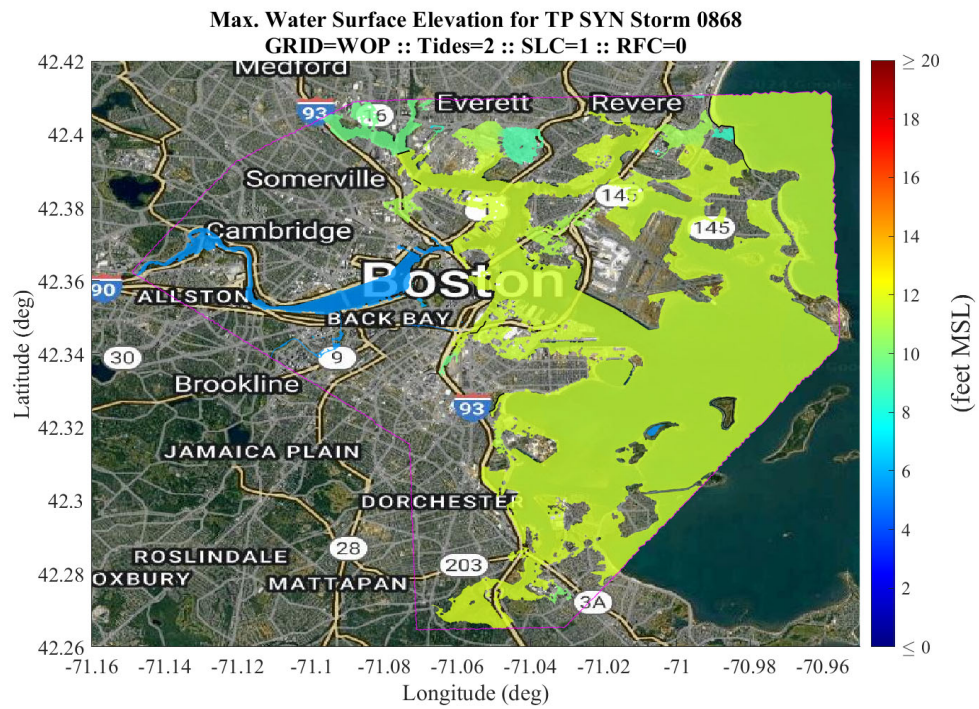


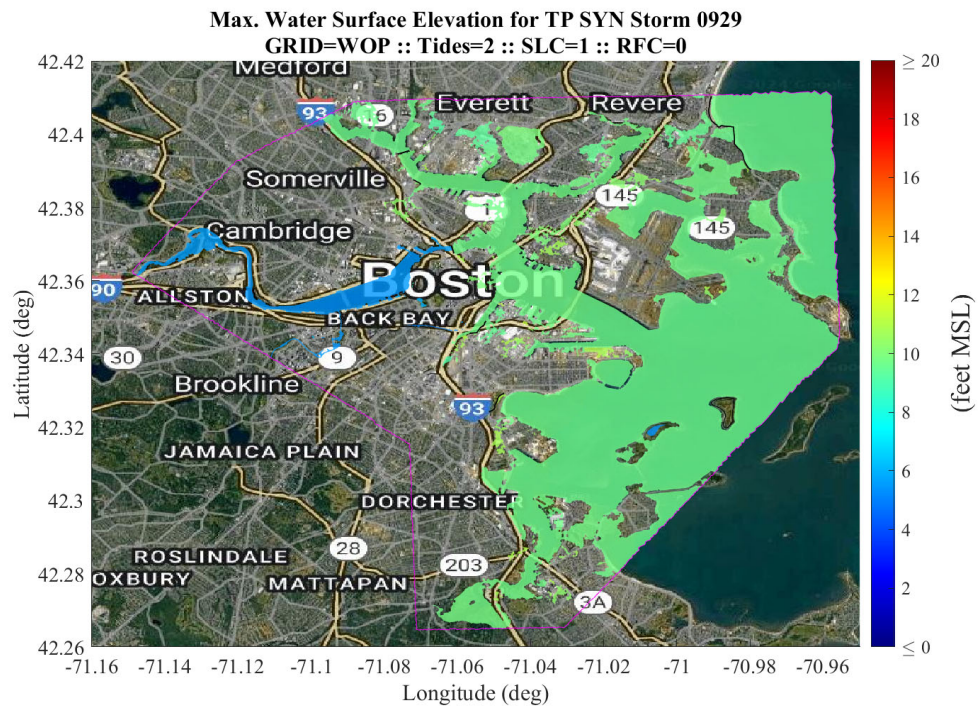


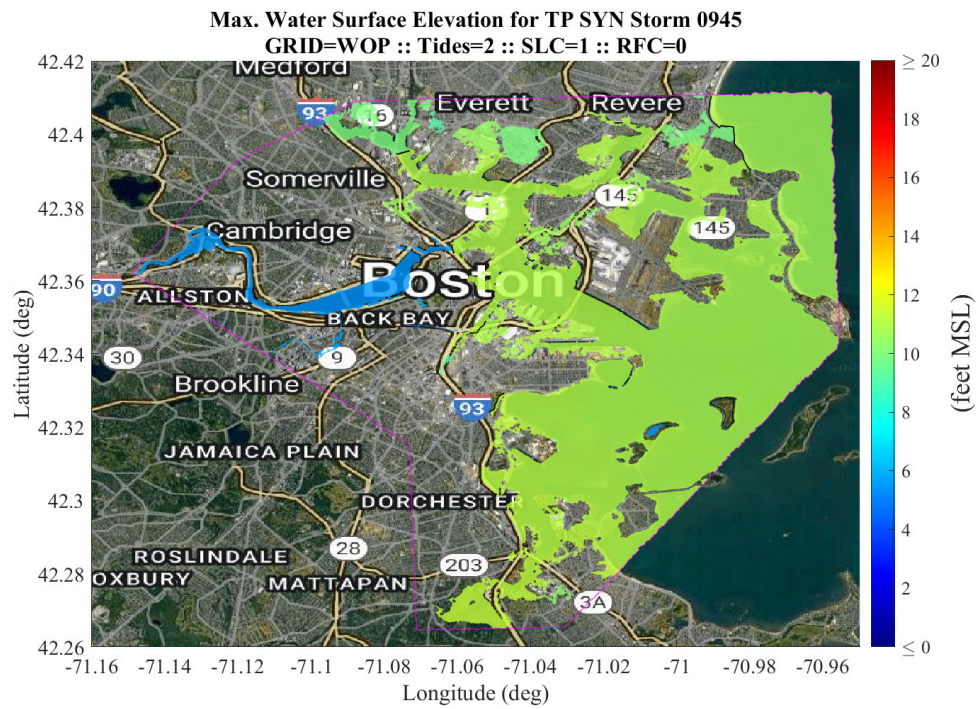


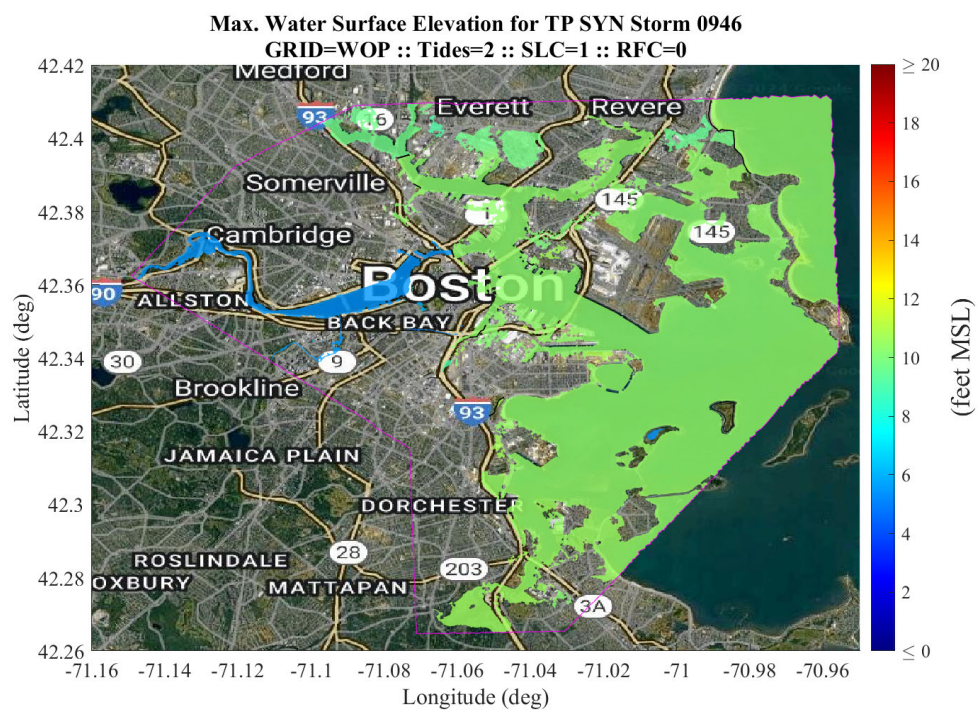


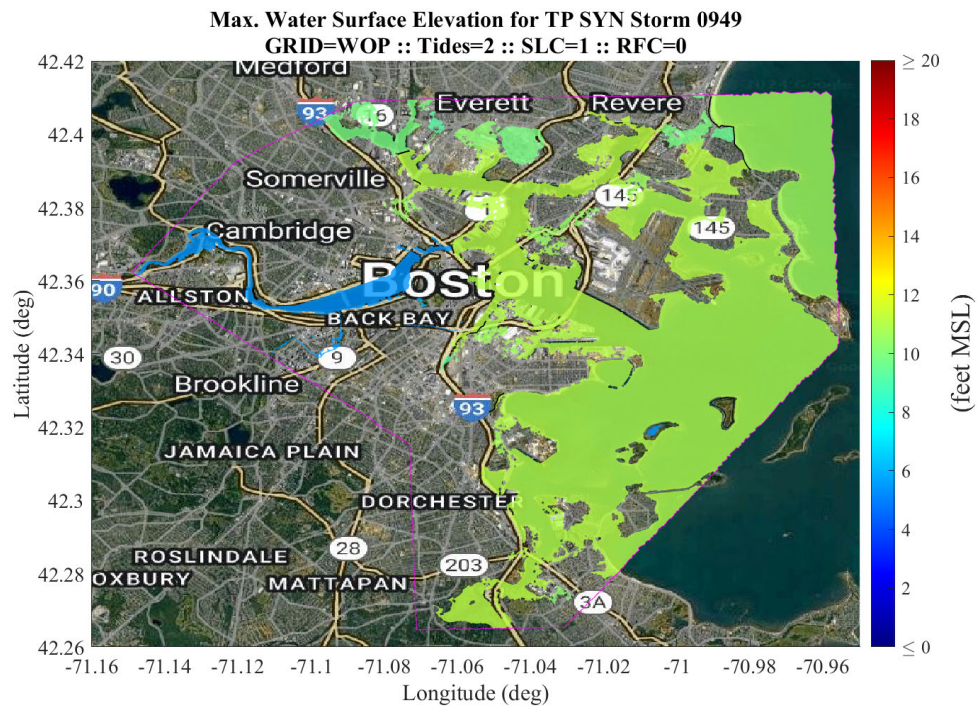


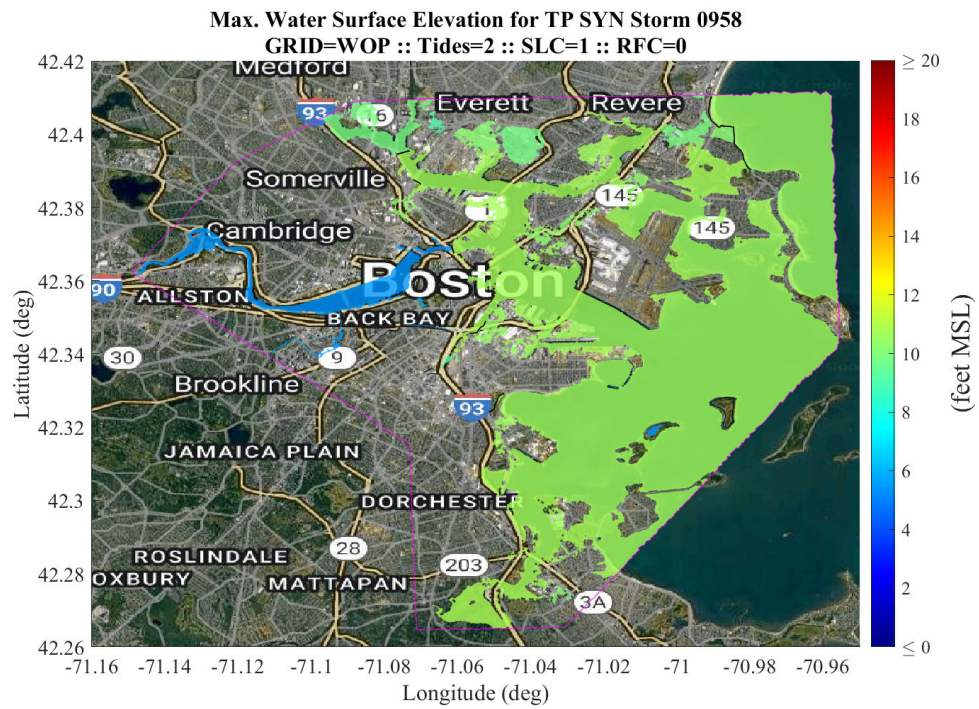


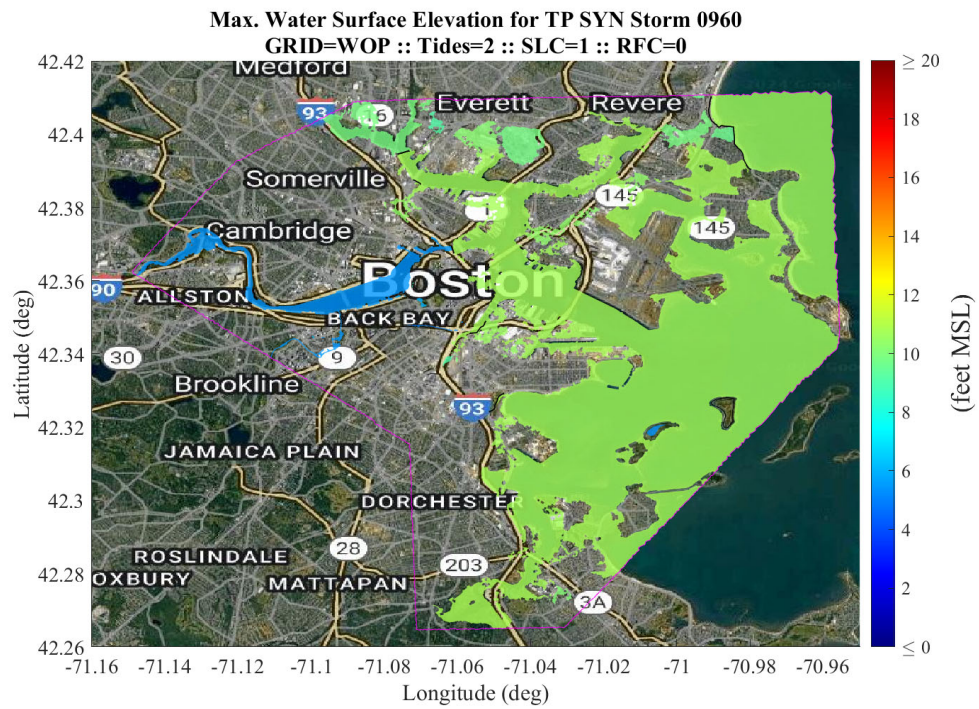


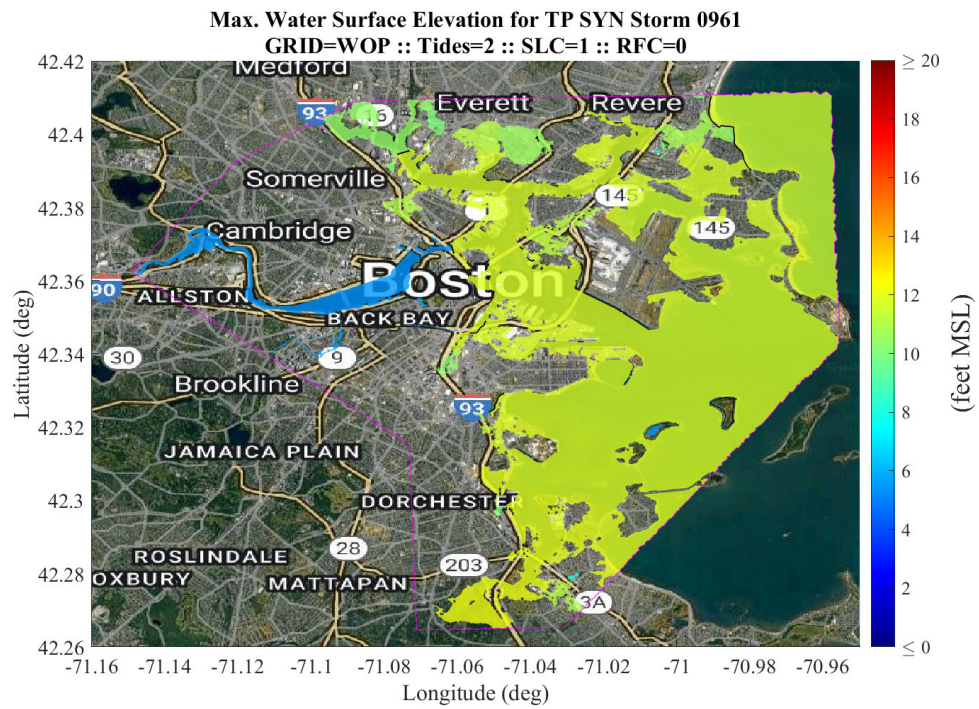


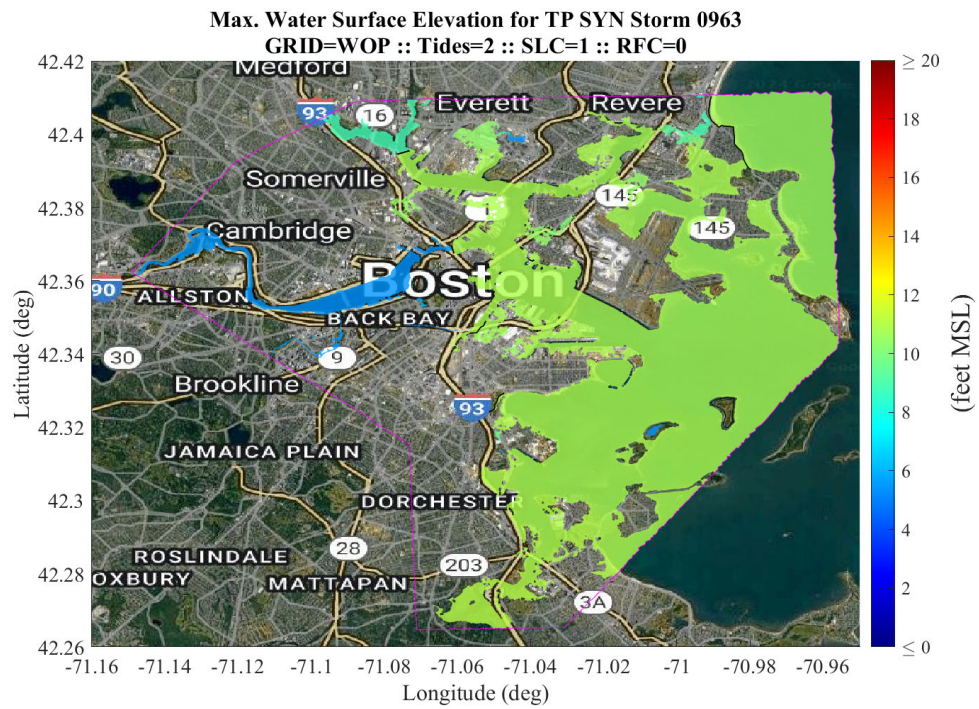


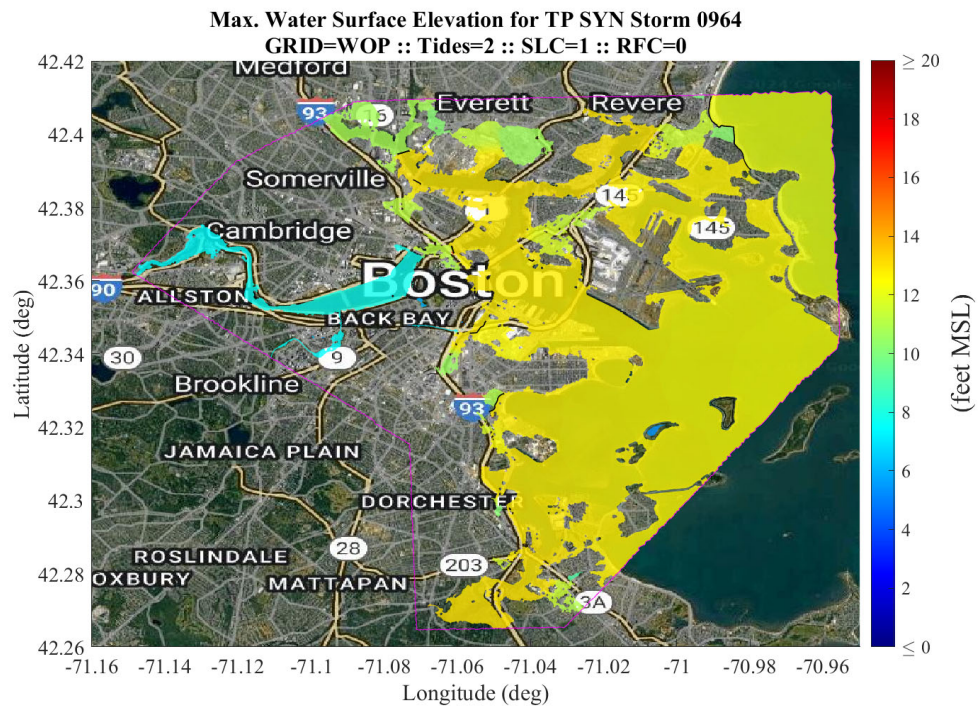


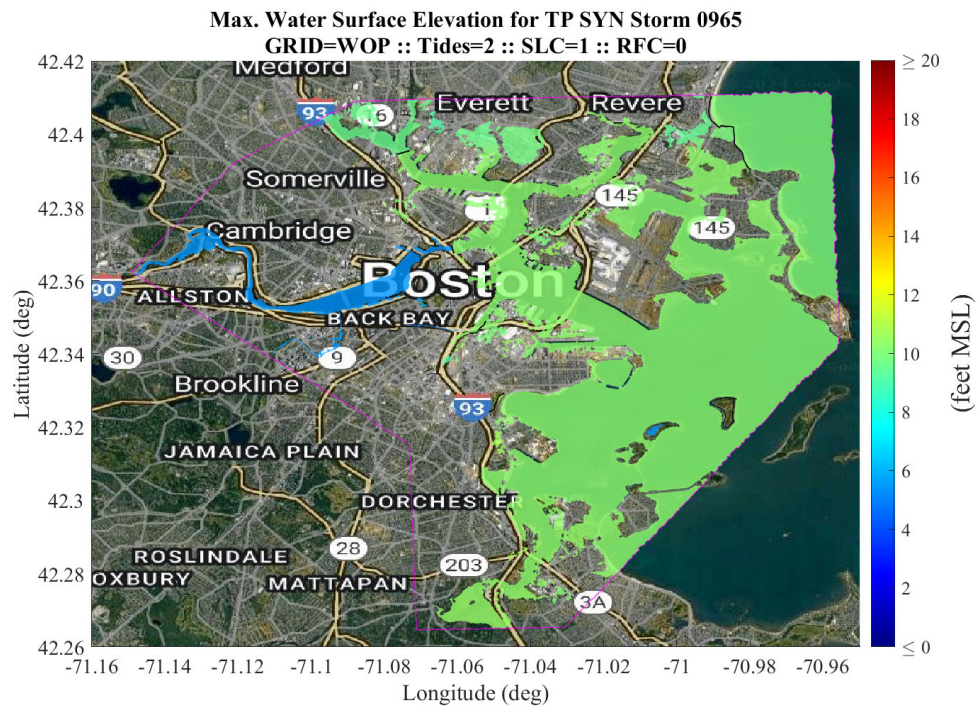


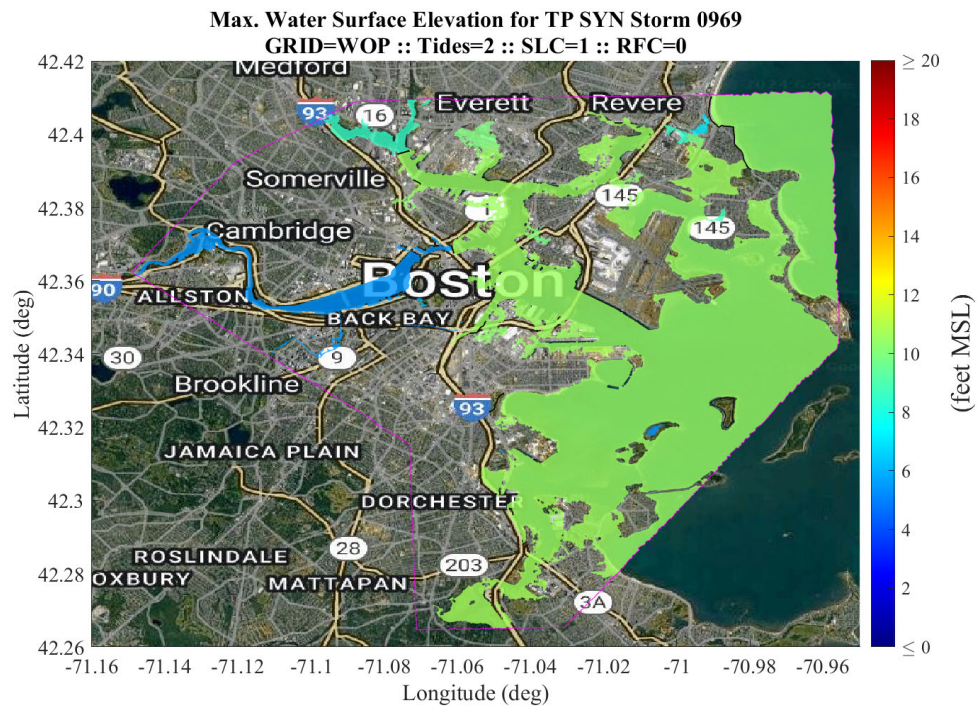


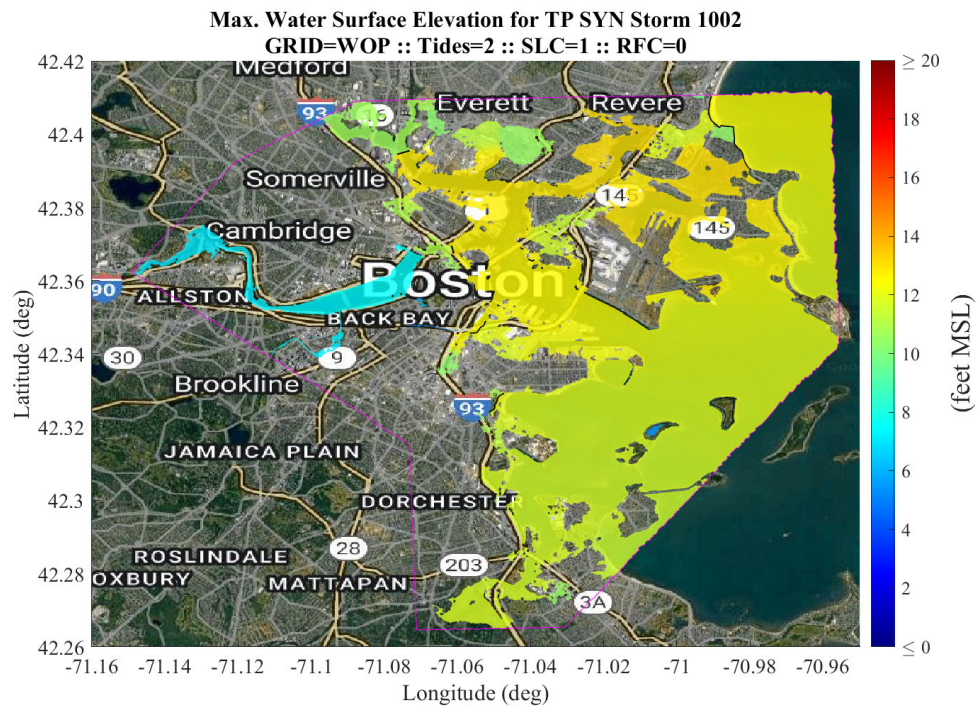


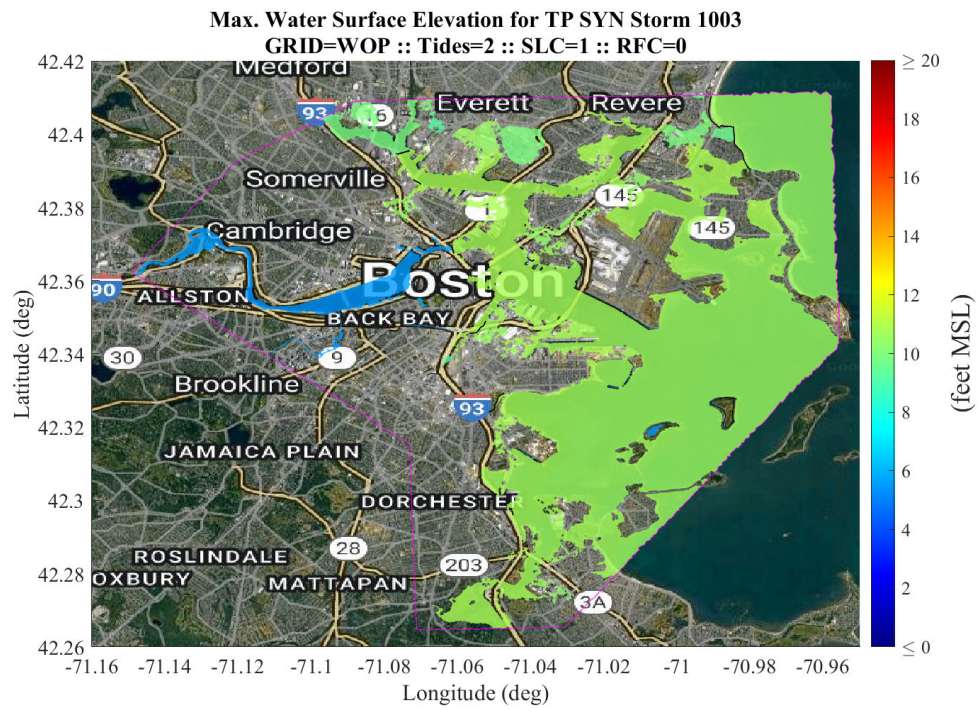


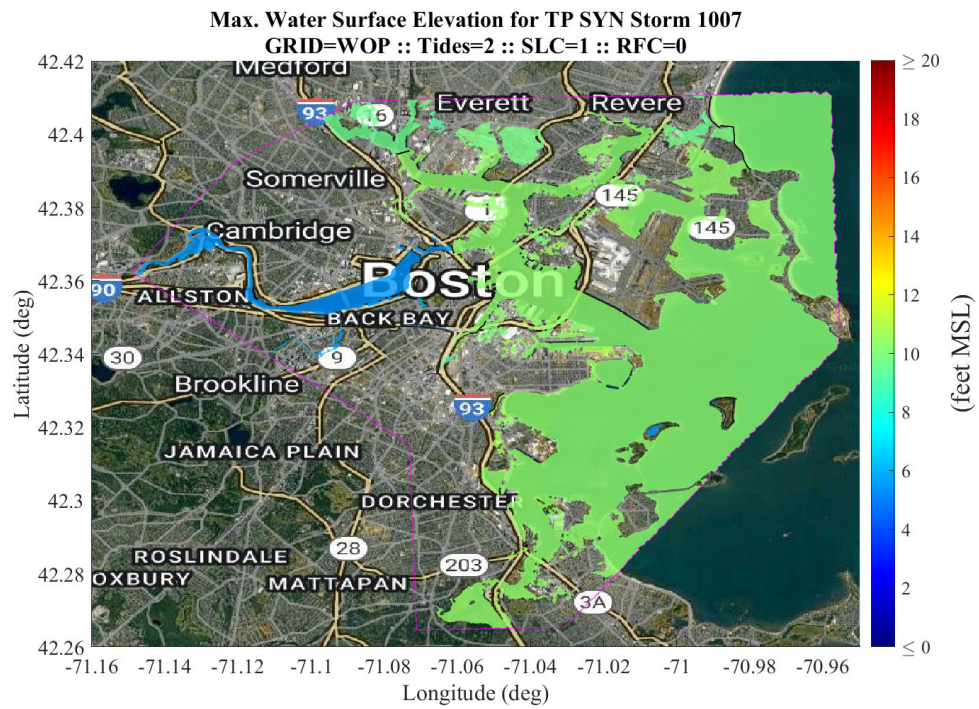


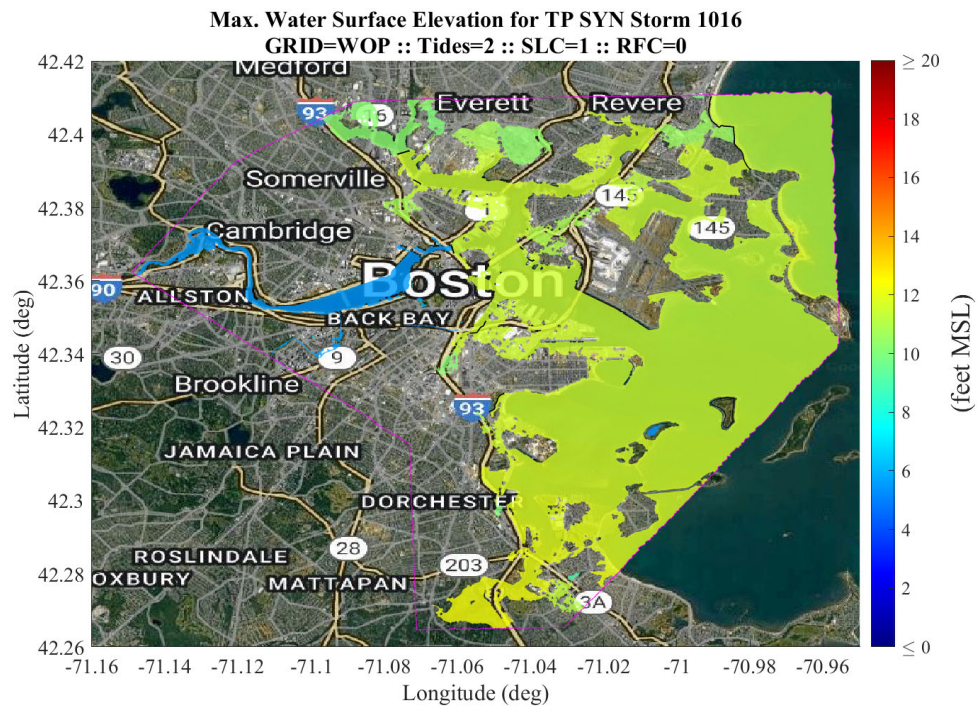


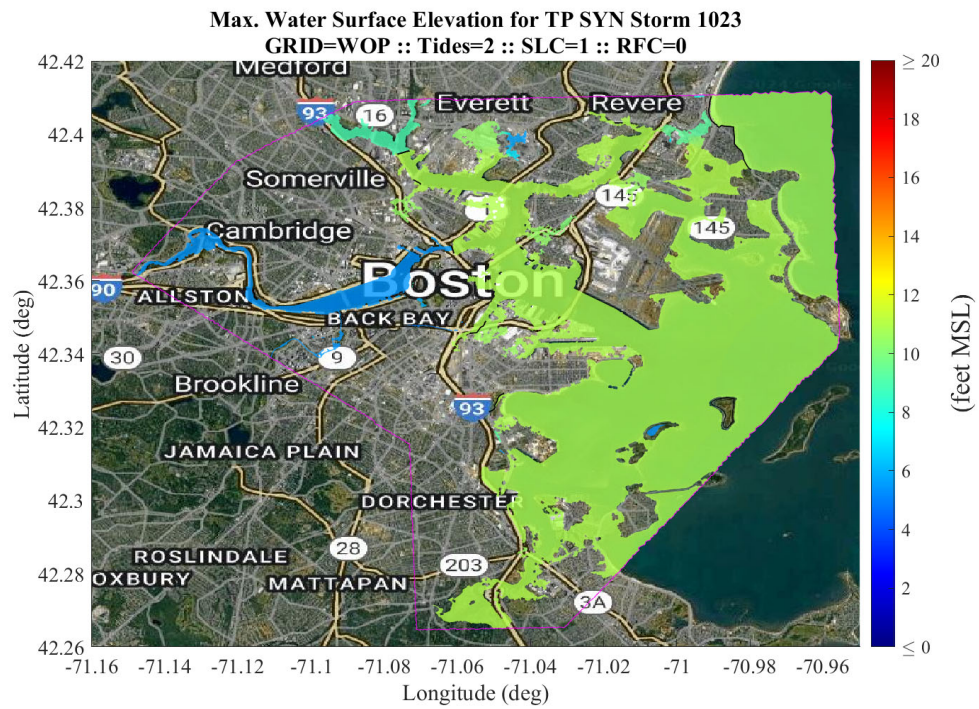


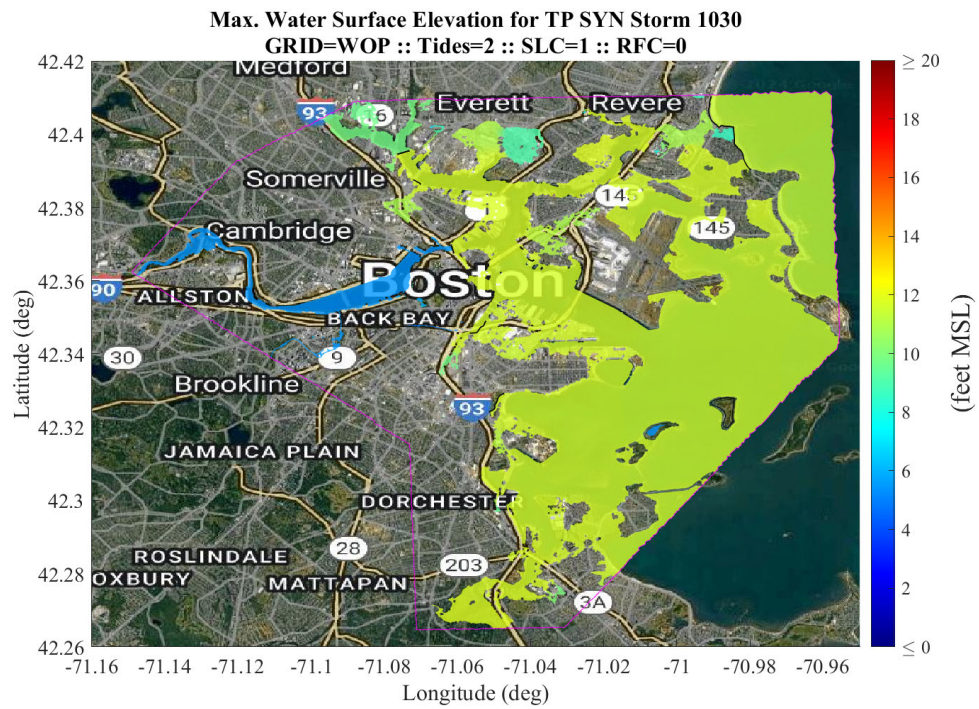


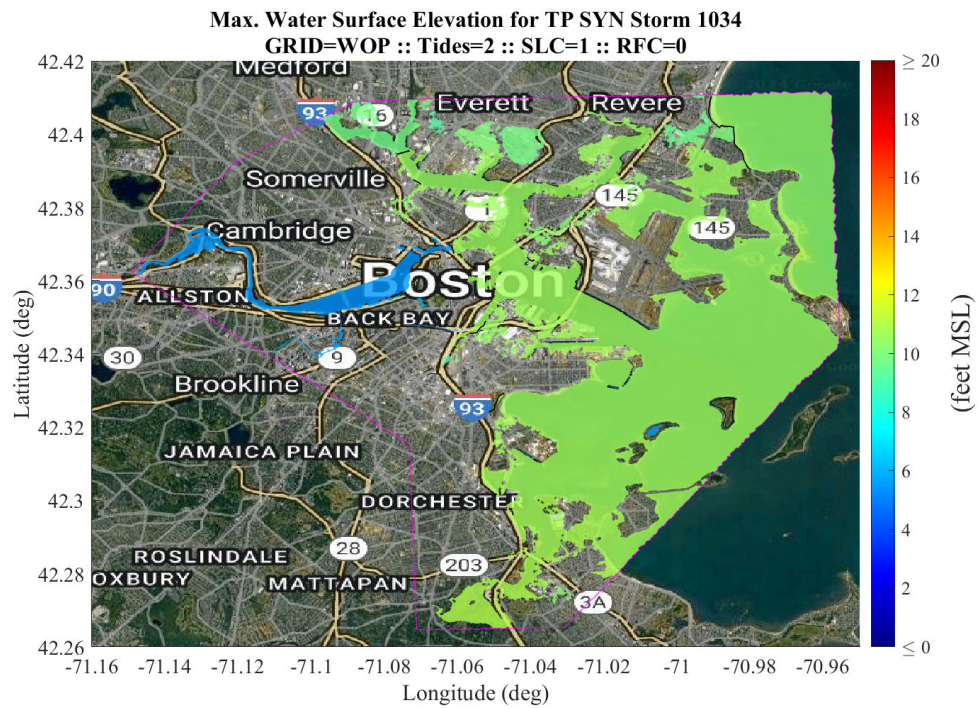


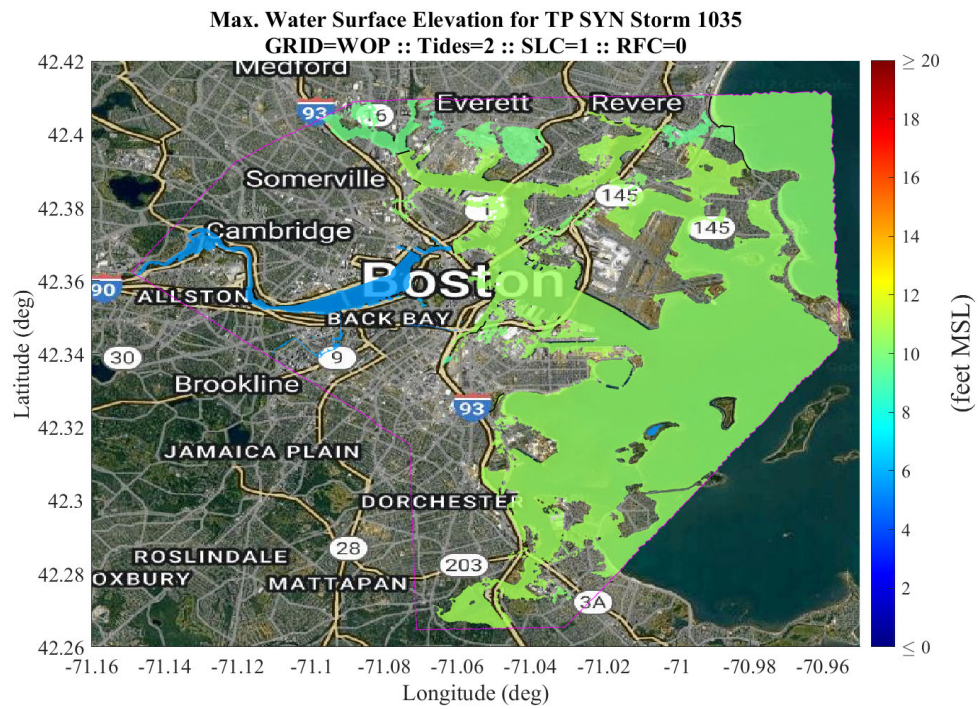














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24 April 2026

MEMORANDUM FOR RECORD

SUBJECT: Pre Decision Point 2 Risk Informed Design Discussion

1. References.

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2. The meeting held on 24 March 2026 was not a risk assessment. There was not a high enough level of design maturity to analyze the project at that time. The meeting was for the Project Delivery Team (PDT) and the Risk Informed Design (RID) Team to discuss preliminary assumptions, analysis, and design decisions. The RID Team was provided with the PowerBI Dashboard for the project showing the G2CRM model results; a web-based GIS Viewer loaded with some of the inundation maps generated by the costal modeling; terrain files on the district MinuteMan server; and early draft copies of plan sets showing conceptual designs for the Dorchester and Charlestown neighborhoods.

3. The first topic of the meeting was a definition of "risk" as the Dam and Levee Safety Program defines it (USBR and USACE 2019, USACE 2022, USACE 2023a, USACE 2023b, and USACE 2025b).

a. Flood Risk of a leveed area is defined as the probability of water getting into an area multiplied by the consequences of that water getting in. The risk is subdivided into two parts: Levee (formerly “Incremental”) Risk and Background (formerly “Non-Breach”) Risk. Levee Risk encompasses all scenarios where the system does not perform as designed. Common general scenarios counted in Levee Risk include Breach Prior to Overtopping, Component Malfunction or Improper Operation, and Overtopping with Breach. Background Risk represents the risk posed by a flood event that would overwhelm the system even if it performs as designed, i.e. Overtopping without Breach.

b. Risk assessments use the term “potential failure mode” (PFM) when discussing the specific scenarios that could lead to failure. PFMs can be thought of as either Risk Drivers or Non-Risk Drivers. Risk Drivers, as the name implies, are expected to contribute substantially to the levee risk. Non-Risk Drivers would be PFMs that could happen but are physically implausible or do not result in incremental consequences. Incremental consequences are consequences above the amount expected if the system performed as designed, i.e. when discussing the consequences of an overtopping breach, we only count the consequences in excess of those that had already occurred from overtopping flows.

4. After discussing how life safety risk is calculated, the group shifted focus to discuss the seven (7) typical cross-sections currently being considered across the project.

a. The shorter typical earthen structure, called “earthen berm” in the drawings provided before the meeting, has 2H:1V side-slopes, a 3-foot crest, variable height (generally not to exceed 3 feet), a 10-foot deep sheetpile cutoff, and sod cover for surface treatment. The homogeneous embankment fill is expected to have a hydraulic conductivity (K) of 1E-04 cm/s. This K would be representative of silts or silty sands commonly available in the region. One recommendation (Paragraph 8.a) was promptly discussed regarding the sheetpile. Looking at the PFMs commonly considered for earthen structures most were considered non-credible based on the design of the structure or duration of loading. Two PFMs were discussed further and led to recommendations (Paragraphs 8.b and 8.c) but were also screened due to expected structure geometry. The variability of subsurface conditions was noted and could be addressed by recommendation Paragraph 8.e.

b. For areas where a taller structure was needed and an embankment could be constructed the typical section was different. It was labeled “Typical Levee Section” in the drawings provided before the meeting. The embankment would have 3H:1V side-slopes, a 10-foot crest, variable height, a 10-foot deep sheetpile cutoff, and sod cover for surface treatment. The homogeneous embankment fill is the same $K=1E-04$ cm/s material, likely silts or silty sands. The same (Paragraph 8.a) sheetpile recommendation was made for this cross section. Looking at the PFMs commonly considered for earthen structures all were

considered non-credible based on the assumption of adequate design of the structure and duration of loading. The variability of subsurface conditions was noted and could be addressed by recommendation Paragraph 8.e.

c. For areas where the levee structure would be on the water, a third typical earthen structure section was discussed. It was labeled “Armored Coastal Levee Section” in the drawings provided before the meeting. The embankment would have 2H:1V side-slopes, a 10-foot crest, and variable height with a crest elevation of El. 17 ft NAVD88 on the typical section. There is no sheetpile cutoff in the design, but it is shown as being constructed over a stone slab wall with a top of wall elevation of approx. El. 10 ft NAVD88. The surface treatment is sod cover for the landside slope, asphalt/concrete on the crest, and armor stone ($D_{50} = 1.7$ -foot) on the waterside slope. There is no bedding layer shown between the 1.7-foot diameter stone and the low permeability embankment fill. A recommendation (Paragraph 8.d) is being made to add a layer to the cross section. Looking at the PFMs commonly considered for earthen structures all were considered non-credible based on the assumption of adequate design of the structure and duration of loading. The same two PFM specific recommendations (Paragraphs 8.b and 8.c) as for the short landward embankment section were also made for this section. The variability of subsurface conditions was noted and could be addressed by recommendation Paragraph 8.e.

d. A typical pile-supported T-wall section was discussed for segments where embankment levee would not be viable due to space constraints. In the drawings provided before the meeting, the wall has:

- A subsurface cutoff, possibly a sheetpile cutoff;
- A 1.5ft thick stem of variable height, the floodside embedment depth is shown to be 2 ft;
- A 2.5ft thick footing which is 2.5 ft wide on the floodside and 7 ft wide on the landside; and
- A vertical pile on the floodside of the pile cap / footing and a batter pile (1H:5V) on the landside.

The PFMs commonly considered for floodwalls were reviewed but none were considered credible based on the assumption of adequate design of the structure and duration of loading. The variability of subsurface conditions was noted and could be addressed by recommendation Paragraph 8.e.

e. Two variations of an L-wall section were discussed. The L-wall sections were to be placed waterward of existing vertical structures at the water’s edge. In the drawings provided before the meeting, both sections had:

- A pile and sheetpile “combo-wall” using the landward (vertical) pile. The depth of seepage cutoff provided by combo-wall, if any, is unclear from the drawings;

- A 2 ft thick stem of variable height;
- A 3 ft thick footing / pile-cap; and
- Gravel fill filling the minimum 3 ft gap between the “combo-wall” and existing structures.

The difference between the L-wall sections was the opportunity to accommodate a batter pile on the waterside of the floodwall for resisting lateral pressures. Where a batter pile can be accommodated, there is a batter pile (1H:5V) on the waterside of the pile cap / footing which would extend 6 ft landward of the stem. Where no batter pile can be accommodated, there are two vertical piles waterward of the combo-wall and the pile cap / footing would extend 14 ft landward of the stem. The PFMs commonly considered for floodwalls were reviewed but none were considered credible based on the assumption of adequate design of the structure and duration of loading. The variability of subsurface conditions was noted and could be addressed by recommendation Paragraph 8.e.

f. The final levee cross section discussed was a type of modified, buttressed I-wall, also to be placed waterward of existing vertical structures at the water's edge. In the drawings provided before the meeting, the landside exposed height for this type of levee would be no more than 3 ft. The wall is composed of a 6-inch thick precast concrete sheetpile supported laterally by alternating outboard vertical and batter (1H:5V) piles. Gravel fill filling the minimum 3 ft gap between the I-wall and the existing structures. The variability of subsurface conditions was noted and could be addressed by recommendation Paragraph 8.e0.

5. System-wide hydraulics represent the largest source of uncertainty at this time. The RID Team is making a recommendation (Paragraph 8.f) that would significantly reduce these uncertainties. However, the RID Team also understands that limited budget and schedule may require a qualitative assessment be conducted during the feasibility study to comply with guidance.

a. Based on discussions in the RID meeting and afterward, the RID Team understands that there was no Advanced Circulation (ADCIRC) model run which incorporated the proposed structures. Meaning that there is no quantified non-breach consequences value. The assumption is being made for the feasibility study that the coastal flooding is from an infinite-volume source and that no significant directional effects exist. And that from these assumptions two conclusions can be drawn: 1) if water is prevented from crossing the levee centerline, the leveed area will be protected and 2) the existence of the structure does not transmit loading to another area. Without more rigorous modeling available a risk assessment conducted “on the tentatively selected plan” (Paragraph 5.d, USACE 2019) would be, at best, a discussion of the terrain.

b. There are technical reservations about the ability of the ADCIRC model to describe the overland flows. The RID Team is concerned that there may be other sources of water and that overland flows may not be fully understood. It is unclear how well the ADCIRC model is capturing vertical terrain variation due to cell size and levees/walls, including those being designed as part of this project. It is also unlikely that ADCIRC can capture the bridges, dams/weirs (including Charles River dams), closure structures and roughness (blocked obstructions/buildings) experienced in an urban environment.

6. Current engineering guidance (Paragraph 8.b, USACE 2025a) says that the risk assessment “would focus on the incremental risk associated with the [...] levee” but there are no quantified non-breach consequences. The same document goes on to specify two paths to satisfying Tolerable Risk Guidelines 1 and 4 (Paragraphs 8.b.4, USACE 2025a). Neither outcome would be achievable with the current level of analytical rigor in the hydraulic & consequences modeling. The RID Team is making two recommendations to address these issues (Paragraph 8.g)

7. The project is focused on inundation due to coastal storms. Therefore, the flows from Chelsea Creek, the Mystic, Charles, and Bass Rivers have not been considered in the modeling conducted. While an interior drainage analysis is not always required as part of a risk assessment, it is relevant in situations where closures cut off existing flow paths or precipitation would accumulate due to flood protection structures. While this work is underway, it is not yet available and has not yet been discussed. When complete, impacts from interior drainage may need to be included in an existing conditions model. The RID Team have included a recommendation that would help to minimize that uncertainty (Paragraph 8.f); namely, modeling that includes all sources of loading and statistical analysis as needed to account for the loading sources’ interaction (joint/coincident frequency analysis). This is particularly relevant in places that are likely to be affected by multiple loading sources during an event, such as areas impacted by both coastal and riverine flow, and areas that would be susceptible to interior drainage from precipitation or cut off riverine flows when closures are shut.

8. Following the Risk-Informed Design discussion on 24 March 2026, the RID Team would like the PDT to consider the following recommendations.

a. The 10-foot sheetpile cutoff shown on the two homogeneous embankments should extend up into the embankment. This would significantly extend the seepage pathway or introduce a significant tortuosity to the pathway of internal erosion potential failure modes.

b. The material strengths associated with likely embankment fill materials (silts and silty sands) may be low for a 2H:1V slope. EM 1110-2-1913 Chapter 6, *Slope Design and Settlement*, indicates that 2H:1V is the steepest slope that can easily be constructed. For embankments where slopes are currently shown to be 2H:1V consider flattening the slopes or zoning the embankment to allow for stronger but more permeable materials to be used. Alternatively, conducting and documenting slope stability analyses once design parameters for the fill material are selected could be a path to document the adequacy of the design.

c. Sod cover can be adequate slope protection if well-maintained. For slopes where regular vehicle or significant pedestrian traffic is expected consider a surface treatment other than grass, such as pavement or articulating concrete blocks. For all waterside slopes that are not already armored with riprap, consider surface treatment more robust than grass to minimize the probability of the initiation of erosion.

d. The armored coastal levee typical section does not show a bedding layer between the 1.7-foot diameter stone and the low permeability embankment fill. Based on the assumed materials these are unlikely to be filter compatible. The RID team recommends a bedding layer be added to the design. If a material cannot be selected which is filter compatible with both the embankment fill and the armor stone, a multi-layer filter system is recommended.

e. The subsurface conditions are always a source of uncertainty. Many common risk driving prior-to-overtopping PFMs develop wholly in the subsurface and not in the designed material of the structure. The RID Team recommends that, as budgetary and scheduling constraints allow, borings and other subsurface investigations are conducted along the alignment of the proposed structure to reduce the uncertainty regarding material parameters such as permeability and strength. EM 1110-2-1913 Chapter 2, *Field Investigations*, recommends spacing borings at 200 to 1000 feet along the alignment based on available subsurface information.

f. The RID Team, for the previously discussed reasons, recommends creating a HEC-RAS model for the project including all intended structures and sources of loading. We further recommend that it is completed before the risk assessment is completed. The RID Team suspects that there may be other sources of water than are included in the current hydraulic model and that overland flows may not be fully understood. The cell sizes in the ADCIRC model are likely too large to fully capture vertical terrain variation and manmade structures. It is unclear whether the ADCIRC did or could capture the structures or surface roughness that would exist in the urban environment. Additionally, interior drainage analysis which is in progress may need to be included in the risk assessment modelling because closures or surge barriers cut off existing flow paths to the harbor.

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g. The RID Team recommends that a LifeSim model be created based on a complete hydraulic model to inform the discussion of breach, non-breach, and incremental consequences during the risk assessment.

h. The RID Team understands the current planning guidance requires a risk assessment before the end of feasibility (USACE 2019). Any risk assessment conducted using only the results of the models that have already been run would be extremely limited and would not include incremental consequences. There is neither any failure modeling nor non-breach modeling, incremental consequences cannot be quantified at all. Since the design and construction are likely to follow USACE guidance, system response probability analysis alone would provide relatively minimal value. In summary, the RID Team concludes that conducting a risk assessment without additional hydraulic and consequences modeling in the feasibility study would be an ineffective use of time and budget. We recommend a more comprehensive assessment in the Pre-Construction Engineering and Design phase of elements that move forward for design and construction.

9. The point of contact for this memorandum is Ms. Jennifer Todd, Acting NAE Risk Advisor, at Jennifer.F.Todd@usace.army.mil or (978) 318-8792.

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