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Rapid simulation of storm surge inundation for hurricane evacuation in Florida by multi-scale nested modeling approach

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ABSTRACT

Hurricane evacuations require fast updates of coastal inundation predictions based on the update of hurricane forecasting track. NOAA usually updates the hurricane track at about 6 h interval. This paper presents a multi-scale nested modeling method for faster simulations of storm surge and coastal inundations. A medium-resolution model with minimum mesh size of 1200 m for the Gulf of Mexico is used to simulate the storm surge in the Gulf of Mexico. A high-resolution model with 120m–150 m mesh sizes is used to predict coastal inundations in the area of potential hurricane landfall. A nested modeling method has been developed to transfer boundary conditions from the large-scale storm surge model to the nested local-scale high-resolution model. The nested models have been satisfactorily validated and applied in the case study of Hurricane Michael. Results indicate that, by applying the nested models, it takes about 85 min for the simulation of one hurricane track for a 5-day forecasting, which will provide sufficient time before the next NOAA forecast update of hurricane's track in 6 h interval. The nested model application to the case study of Hurricane Michael demonstrates the coastal inundation patterns in the city of Mexico Beach with the root-mean-square error of 0.12 m from all measurement stations. Results of the nested model inundations on coastal critical infrastructure and roadways are further used with models that investigate risk assessments to support hurricane mitigation planning and evacuation operations sufficiently in advance.

1. Introduction

Tropical storms especially hurricanes cause the most damage among weather related natural hazards in the United States each year, with an average cost of $22 billion per event for the last 40 years [1]. The expenses are projected to increase multifold due to many factors such as climate change and coastal infrastructure development [2]. It is expected that Florida, with a long coastline, would have to face an increasing number of hurricanes each year [3] and subsequently more mitigation or relief expenses. Martinez (2020) based on a data analytic study emphasized that a more accurate prediction of the track and intensity of a hurricane would reduce the damages and consequently associated expenses [4]. An accurate determination of zones affected by floodwater due to an impending storm is necessary for effective mitigation actions that can minimize the hazards. Economic impacts of storms were also studied by Wang et al. (2022) [5] and Yang et al. (2018) [6]. Integration of Geographic Information systems and numerical models to assess economic aspects of storm related disasters is a relatively new area of study. Moradi et al. (2020) [7] integrated GIS and system dynamics for assessment of the impacts of storm damage on coastal communities by applying ADCIRC model. Harris et al. (2022) [8] examined the dynamics of

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the hurricane-forecast-evacuation system. Wang and Yang (2019) [9] investigated the nonlinear effects of sea level rise on coastal inundations due to storm surge. An operational model based on CEST were developed by Zhang et al. (2013) for the east coast of USA [10].

Damages due to storm surge and waves [11], resulting in coastal flooding and associated damages to infrastructure. Disaster management agencies determine flood zones and evacuation zones using numerical models. For example, Florida Division of Emergency Management (FDEM) designate zones based on surge due to a large number of numerically simulated storms [12]. One limitation of surge zones is that a numerical model is not used to determine inundation in land. Instead, the oceanic storm surge model results are superimposed over a digital elevation map to describe inundation zones over land areas [13]. Therefore, a more reliable and accurate depiction of coastal inundation would be to numerically model coastal inundations and derive surge zones from the inundation model results.

Another limitation of inundation zones is that they are fixed for a given area because they are marked based on many storms. The zones may not accurately represent inundation due to a single hurricane. In other words, the FDEM evacuation zones do not change with individual hurricane track changes. This sometimes result in over-estimating damages and evacuations and complicates evacuation actions in a limited time frame of a few days [14]. A recent example is hurricane Irma (2017) which was predicted to hit the Miami area, resulting in millions of people evacuating. The storm eventually made landfall in the west coast of the peninsula, instead of Miami. A post storm assessment indicated only moderate flood damage to the actual land fall area and minimal damage to Miami [15]. Therefore, a dynamically changing hazard zone depending on the changing forecast track and intensity of a hurricane would enhance a coastal community's ability to streamline its preparation efforts. This study tries to address these two limitations of coastal inundation zones, which are subsequently used for disaster management actions such as evacuations. This paper describes ADCIRC numerical model applied to a coastal inland domain to model inundations resulting from storm surge. Results from this model can be used to determine surge zones more accurately. Additionally, the model can be used to determine dynamically changing storm surge and inundation zones with changes in forecast track and intensity of a hurricane. However, the numerical model that determines such dynamically changing inundation zones needs to be computationally faster than the forecast interval.

The motive of storm surge modeling is to provide information on how flooding and surge waves affect the morphology of the coastal region, and to delineate hazard zones due to flooding, in land [16]. Modeling coastal inundation therefore requires a mesh that covers land. As land-based features like small hills, barriers and sand dunes, alter the pattern of inundation a higher resolution mesh resolving these small-scale features becomes necessary. On the other hand, a large-scale oceanic mesh is required to model the surge and waves created by a storm in the ocean. In short, the ideal inundation model domain should cover a large area of the ocean as well as coastal land areas, with a high-resolution mesh.

A higher resolution mesh covering a large area of ocean has the following deficiencies. One is that the number of elements would be very large. This would lead to larger data being processed by the model at every time step, reducing the computational efficiency. In addition, a larger domain would take longer time to complete one time step. Secondly, higher resolution models need smaller time steps because higher the resolution, smaller the time step should be, to maintain computational stability of the ADCIRC model [17]. Thus, such a high-resolution, large-scale model would require days and sometimes weeks to run a storm surge simulation, making it not suitable for preparing dynamically changing surge and evacuation zones. In other words, a high-resolution model is necessary for coastal inland inundation but limited by a smaller domain size. Since we cannot avoid a large oceanic domain model as well, a number of small scale, high resolution meshes are developed for the Florida coast, which are nested within a coarse resolution, large scale oceanic mesh. The exchange of data between the large and nested domains is a critical aspect of this modeling technique. This article describes the nested modeling for faster coastal inundation modeling and a new method to transfer data from large-scale model to the nested model.

Previous studies employing nested domains for ADCIRC were mostly focused on long-term effects of surge on land or are for post storm assessment. A nested domain of the Bohai Sea in China was used in the long term analysis study by Wang et al. (2018) [18], but the nested domain was not on land. In another, very recent study, Liu et al. (2020) simulated street scale inundation of New York City and large scale storm surge and tide in the Mid-Atlantic Bight during hurricane Sandy using nested mesh covering land [19]. Studies involving very high-resolution meshes are sometimes referred to as street scale models. Kress et al. (2015) modeled inundation of Staten Island NY using a street scale model [20] and Marsooli and Wang (2020) applied a similar model on Manhattan NY [21]. Street scale modeling is more suited to models that capture wave dynamics in land such as FVCOM and WAVEWATCH. One such study used FVCOM model applied on Nemuro, Japan [22]. Another study by Blumberg et al. (2015) used the same technique with an ocean model called sECOM to model inundation of New Jersey-Hudson river water front [23]. In short, studies using nested modeling technique were used only in post storm analysis, not as a forecasting framework.

Coastal inundation is primarily due to the storm surge water levels, but higher frequency waves significantly contribute to the total water levels and destruction at the coast during a storm [24]. The third limitation of the FDEM surge zones is the absence of a wave numerical model to determine the additional threat posed by higher frequency waves at the coastal boundary. In effect, the resulting surge and evacuation zones do not account for the wave effects [12]. Therefore, in this study a coupled storm surge and wave model is ADCIRC and SWAN model is used in the large-scale oceanic model. The advantage of coupling is that the results are more accurate compared to the stand alone models, but results in an increase in computational time [25]. Moreover, the wave model cannot be used to model inland inundations due to its inadequacy in modeling crashing waves in land [26]. In short, this study uses the coupled model on an oceanic domain and then a higher resolution domain nested within the larger domain to simulate coastal inundations using an uncoupled model.

Total computational time becomes critical as this coupled, nested modeling framework is intended use is to produce dynamically changing inundation zones. Thus, a faster algorithm to transfer information between the large scale and nested models is discussed here, so that the framework can be used to generate dynamically changing inundation zones. The article first describes the large-scale coupled storm surge simulation. The large-scale model is validated using observations during Hurricane Michael (2018) in a previous study [27]. The focus area in this study is Mexico Beach, FL where Hurricane Michael made landfall. The nested regional mesh for this area of Florida coast is described next and the methodology used to transfer water level information between the domains is illustrated.

2. Multi-scale nested modeling methodology

2.1. Large-scale storm surge and wave model (ADCIRC + SWAN) for Gulf of Mexico

A storm usually forms in the ocean far away from land. As the storm intensifies, the winds generate water waves that travel to the shore and increases its amplitude when it enters shallower waters near shore, creating storm surge. A numerical model to simulate storm surge and waves therefore requires a large-scale mesh to generate the effects of a storm while it is in the ocean. Numerical models to study storm surge and waves, solve conservation equations of mass, momentum and energy numerically, by discretizing the domain under study. A large-scale domain covers a large area consisting of a marginal sea or an ocean basin whereas a small-scale model covers only a region usually a few hundred square kilometers. The resolution of a model domain is defined by the smallest size of the element in the domain mesh. In this section the coupled storm surge and wave model ADCIRC + SWAN on a large-scale domain with a medium resolution with minimum mesh size of 1.2 km shown in Fig. 1a.

ADCIRC is a finite element hydrodynamic model that uses an irregular mesh made of triangular shaped element. a model developed by Luettich et al. (1992) [28] capable of modeling storm surge and tide effectively. Since storm surge is caused by momentum exchange between hurricane force winds and the surface of the ocean, the model is forced with a previously calibrated hurricane wind field. Waves generated in the open ocean travel to the coast and parameters like wave height and speed get modified as the waves enter shallow waters near the shore. In other words, wave characteristics change with topography, that is, they reflect, refract, or break depending on the near shore topography and slope [26]. In addition to these, waves interact among themselves and with currents in a highly non-linear manner. SWAN (Simulating Waves Nearshore) is a spectral wave model that captures the dynamics of such high-frequency waves when they are nearshore [29]. In short, the coupled ADCIRC + SWAN model is used on the coarse resolution

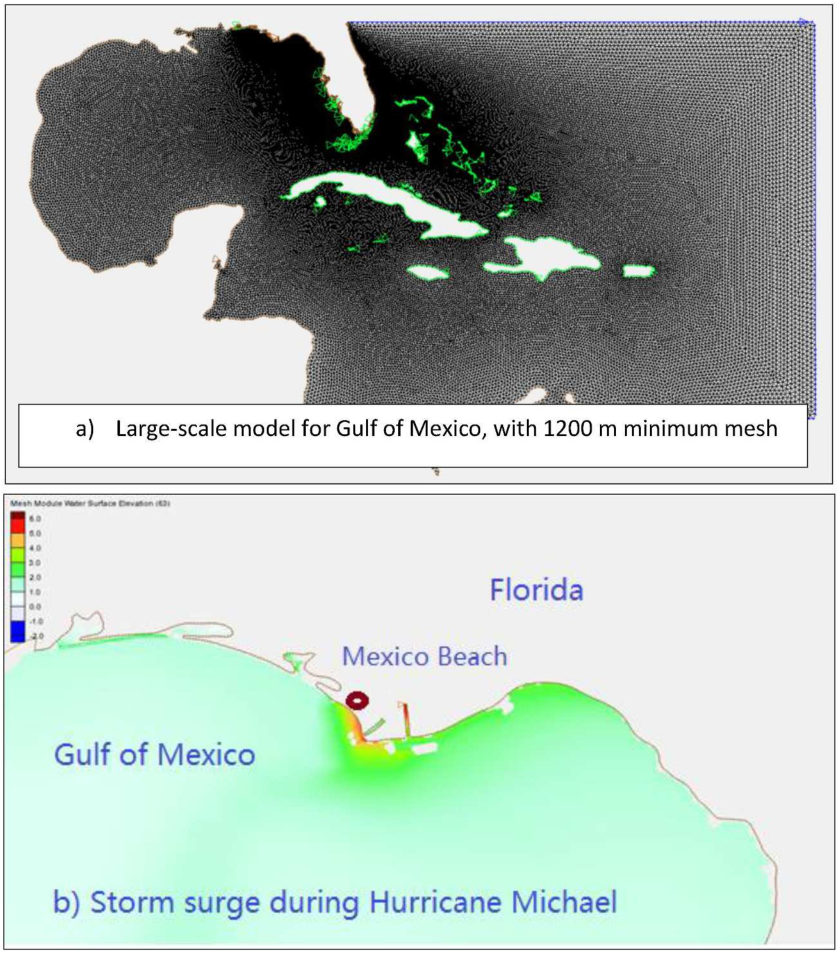

Fig. 1. a) Large-scale model mesh for Gulf of Mexico with 1200 m minimum mesh, and, b) model simulated storm surge along Florida coast during Hurricane Michael.

mesh to simulate the effects of both storm surge and higher frequency waves generated by the storm.

The large-scale, medium resolution model domain is shown in Fig. 1a. The mesh resolution ranges from 1200 m for near shore elements to 10 km for deep ocean elements. The model is run for a period of 5 days close to the landfall of a hurricane using a model time step of 10 s for ADCIRC. The time step value is determined by the smallest element size in the domain, that is, for a smaller mesh size, the time step would be less than 10 s. In our initial numerical experiments, a high-resolution mesh model (with minimum size of 100 m) took a few days or a week to run in our GPU workstation, making it unacceptable to provide timely coastal inundation for real-time evacuation. For this reason, a medium resolution mesh as shown in Fig. 1 was developed for a faster storm surge simulation to provide boundary condition to a local-scale high-resolution nested model.

SWAN, on the other hand, is numerically stable and can have larger time steps of 240 s. Storm surge water levels, surface velocity, wind field and Manning coefficient for bottom friction after every 240 s are transferred to the SWAN computational core. Here the output of significant wave height, spectral frequencies and mean wave period are transferred back to ADCIRC for further calculations. The results of the coupled model are, therefore, significant wave height, spectral wave frequency and time period from SWAN, in addition to the storm surge water levels and velocities from ADCIRC. This is repeated for the model run time of 5 days. A successful large scale, coarse resolution coupled ADCIRC + SWAN model run produces the water surface elevation in m, at every node for the period of model run. In order to get the total water surface elevation or the maximum level of water from the coupled model, we need to use the relationship between significant wave height and the maximum wave height. The significant wave height (H_S) is the average height of the highest 1/3rd waves of the spectrum. The spectral distribution follows a Raleigh distribution and the maximum wave height that can be expected in the spectrum is approximately 2*$H_{S.}$ ADCIRC transfers the storm surge water levels to SWAN using which it calculates Hs. Therefore, in order to get an estimate of the total water level, the following formula was used.

$$H_{Total} = \xi_{ADCIRC} + 0.5H_{max} = \xi_{ADCIRC} + 0.5 * 2 * H_s = \xi_{ADCIRC} + H_s \tag{1}$$

This is the total height of water felt at the shoreline boundary of the larger mesh, flooding the coastal areas. The total water level will be provided to the local-scale model as boundary condition to simulate coastal inundations in the study area. The large-scale model has been validated in previous study by Vijayan et al. (2021) [27]. Model simulations of storm surge during Hurricane Michael is given in Fig. 1b.

The dynamically coupled ADCIRC and SWAN model code is used in this study. There is only one shared executable program to run both the models. ADCIRC calculates wind velocities, surface velocities (currents) and water surface elevations at every time-step. After

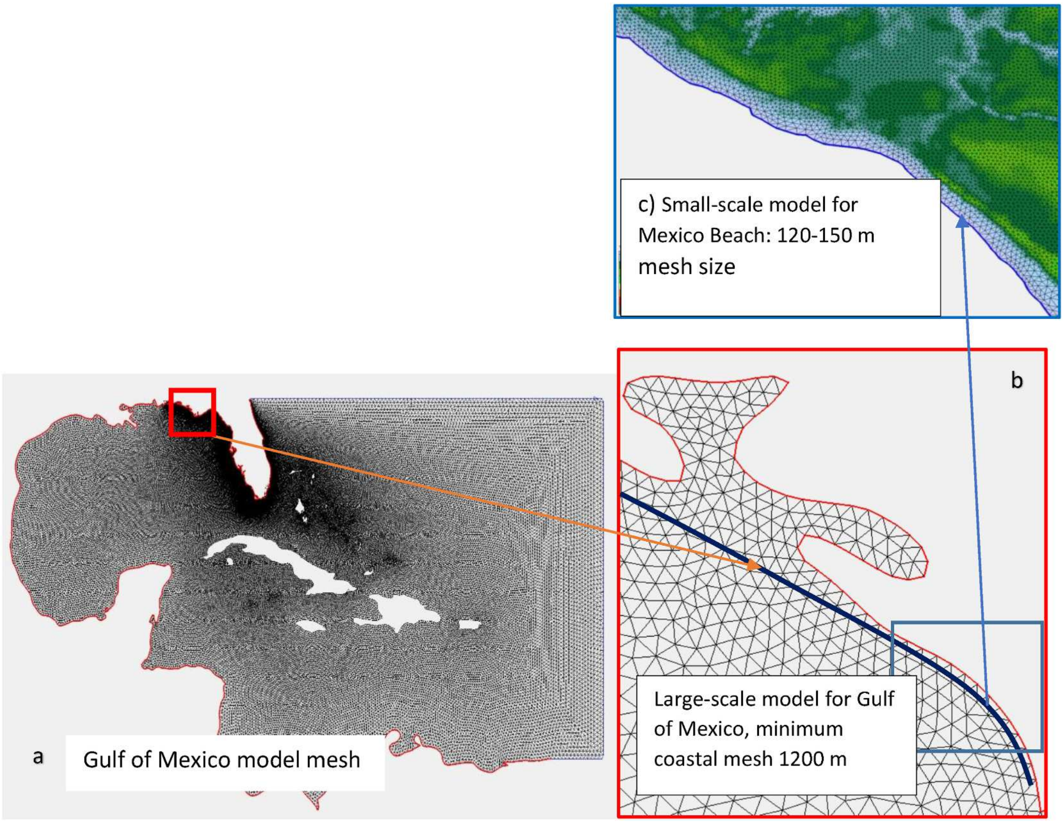

Fig. 2. (a) Large scale model mesh for Gulf of Mexico, (b) Zoomed-in large-scale mesh in the coast with minimum size of 1200 m, (c) nested high resolution mesh (120–150 m) for the city of Mexico Beach.

a prescribed SWAN time step, wind speed, currents and water elevations are transferred to SWAN, where wave heights, frequencies and directions are calculated. These are transferred back to ADCIRC as forcing for the next time-step [30]. It is obvious that the coupling is computationally expensive than the individual models [31]. An important parameter in the numerical model is the open ocean boundary condition. Since the storm surge water levels are influenced by the tidal waves, the model is forced with the tide boundary condition. The Le Provost tidal database, available with ADCIRC is used in the present study, where the tidal amplitude and frequency are specified at all boundary nodes for the date and time of the simulation. There will be a land boundary in the domain as well which is not open for flow. This can also be open on some elements to represent rivers and other water sources that flow into the domain.

2.2. Local scale nested storm surge model (ADCIRC) for coastal inundation

The large-scale storm surge model results are processed so that the surge water levels, and wave heights are used as open boundary conditions for the nested high-resolution model. The large-scale mesh covers the entire Gulf of Mexico and part of the Atlantic Ocean (Fig. 2a). We have generated a number of regional meshes covering land areas around population centers along the coast of Florida. These regional meshes are nested within the large-scale mesh, at their corresponding locations along the coast. The large-scale mesh has a lower spatial resolution (minimum 1200 m mesh) compared to the regional mesh (minimum 120 m mesh). Fig. 2b shows the area of Mexico Beach and Panama City in the large-scale mesh. One high-resolution mesh is nested here. The red curve in the figure shows the coarse mesh boundary of the region. The thick blue curve represents approximately, the open boundary of the nested mesh. A close-up of the nested regional mesh is shown in Fig. 2c. The blue arrow points from the location of Mexico Beach in Fig. 2b to that in Fig. 2c. In contrast to the large mesh, the nested mesh covers mostly land. The boundary of this mesh is shown in thick blue (Fig. 2c). The nested mesh boundary does not follow coarse resolution boundary shown in red, instead goes in its general direction.

The open boundary of the nested mesh is shown in blue corresponding to the blue outline in Fig. 2 (b). Due to the difference in the resolution, there are 6–10 nodes in the nested mesh boundary, between two boundary nodes of the coarse resolution mesh. Water surface elevation values obtained in the large-scale simulation (Eqn (1)) need to be used as a non-periodic open ocean boundary condition on the nested boundary (Fig. 1c). Because of the difference in resolution in the large-scale and the nested small-scale models, a numerical interpolation method has been developed to transfer data from the large-scale model to the small-scale model.

2.3. Data transfer in boundary between large-scale and small-scale nested models

A numerical method has been developed in this study to transfer boundary storm surge data from the large-scale model to the small-scale model to speed up the numerical simulations. As shown in Fig. 3, the red straight line represents the large-scale boundary line and the 5 boundary nodes on it have hourly values of water surface elevation from the large-scale simulation. The blue curve represents the nested mesh boundary. The nodes on this curve require hourly values of water surface elevation as boundary condition for the nested model. As there are many blue nodes between two red nodes, some interpolation of values is required.

Both large scale and the nested boundaries can be represented as functions of longitude and latitude (x and y respectively). Similarly, water surface elevation output from the large-scale model simulation is also a function of x and y. However, we can see the fact that the y co-ordinates of both these boundaries can be explicitly expressed as functions of x alone. For example, large scale boundary in Fig. 3 can be represented using the equation $y = a + bx$ and nested boundary as $y = a + bx + c\sin(n\pi x)$. This idea is extended to the case of water surface elevation output as well. For water surface elevation $= f(x, y)$, we can substitute $y = g(x)$ into the above function gives

$$\eta = f(x, g(x)) = \varphi(x) \tag{2}$$

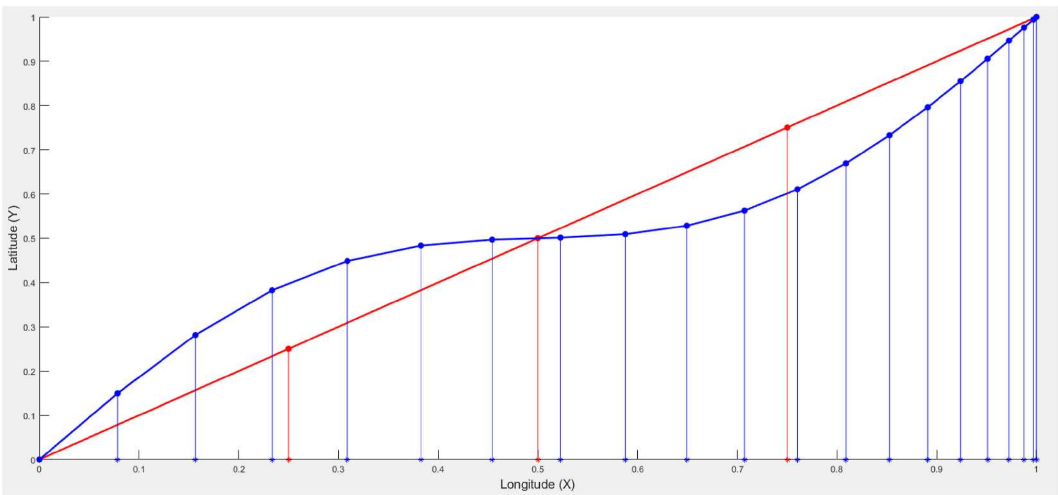

Fig. 3. Large-scale model boundary mesh shown as red line, and small-scale model mesh in blue.

This is equivalent to projecting all nodes to the x-axis and the process of interpolation is based on these projected points. In other words, interpolation is carried out based on the nodes on x-axis and not on the real boundary lines of the two domains. The points with available data (large-scale nodes) and the query points where the data is required (nested nodes) are both on the x-axis represented by red and blue asterisks respectively. The water surface elevation values projected on to x axis is illustrated on Fig. 4 as well.

A cubic spline interpolation is carried out on the water surface elevation function η(x). We need to construct a spline $\eta : [x_1 to x_n]$ where n is the number of nested boundary nodes. This requires n-1 third degree polynomials. In order to derive a smooth interpolation curve, the first and second derivatives of the two polynomials common to a point should be the same. Lastly, the second derivatives of the first and last points are set to zero as a natural curvature condition. Fig. 5 shows the water surface elevation on the projected longitudinal axis, data and query points on the x-axis. The smooth curve of interpolated water surface elevation is the result of the cubic interpolation.

Next the interpolated curve is projected back onto the nested boundary line as shown in Fig. 6. It is to be noted that such an interpolation is carried out for all hourly value of the large-scale model. The numerical model ADCIRC + SWAN requires a grid information input file for it to run. This file consists of node IDs, their spatial co-ordinates and IDs of the nodes constituting the different boundaries. The model writes its output (surge water levels and significant wave heights) based on the node ID. In the grid information file, grids on the boundary node-string are numbered from 1 to n which varies from mesh to mesh. In the present nested mesh in our study area, the ocean boundary nodes are numbered from 1 to 745. The large-scale domain land boundary is the Florida coastline, which is not at all straight. When generating grids for the nested domains, open ocean boundaries are generated parallel to the general coastline direction of the region. In other words, interpolation is carried out by projecting the boundaries on to a longitudinal axis (X) or latitudinal axis (Y), depending on the orientation of the nested mesh. As the present case, the nested mesh boundary is generally oriented in the east-west direction, the projection axis is longitudinal. The first step here is to extract data from the large-scale mesh. Following a successful run of the large-scale coupled model, water surface elevation (which includes tidal signals and storm surge from ADCIRC) and significant wave height (from SWAN) values of large-scale nodes in the list are extracted using a MATLAB script. The extracted data is for 6 h around landfall when the maximum water levels are experienced. Total water level is computed using equation (1) for each of these large-scale nodes.

During the nested mesh generation stage, a list was created connecting the boundary node IDs of the large-scale mesh (minimum 1200 m mesh size) and the nearest open boundary nodes of the nested mesh. For example, the list links node ID #1 of the nested mesh with the nearest boundary node ID of the larger mesh, node ID #7 of the nested mesh to the ID of its nearest node in the larger mesh and so on. Spatial interpolation is carried out as described before, which results in estimation of hourly water surface elevation values on all 745 nodes of the nested boundary. Regional meshes, even though encompasses small scale features like barrier islands, have a simple open ocean boundary. This spatial interpolation is done for each of the hourly values. These values are written as a single column non-periodic boundary information file given as an input to the nested ADCIRC model.

2.4. Multi-scale nested model simulation procedure

The nested model is different from the large-scale model in two aspects. One is that the domain consists largely of land-based nodes and elements. The ocean boundary is very close to the shoreline where we impose the storm surge water elevation as the boundary

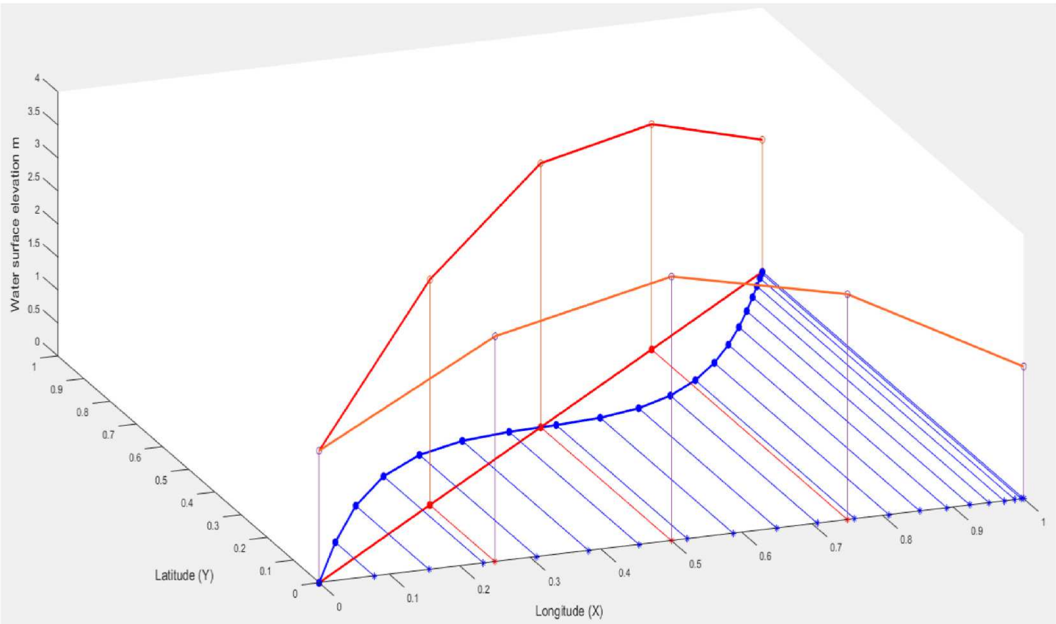

Fig. 4. 3D illustration of the projection of model boundary to longitudinal axis which is the general direction of the coastal line in Mexico Beach.

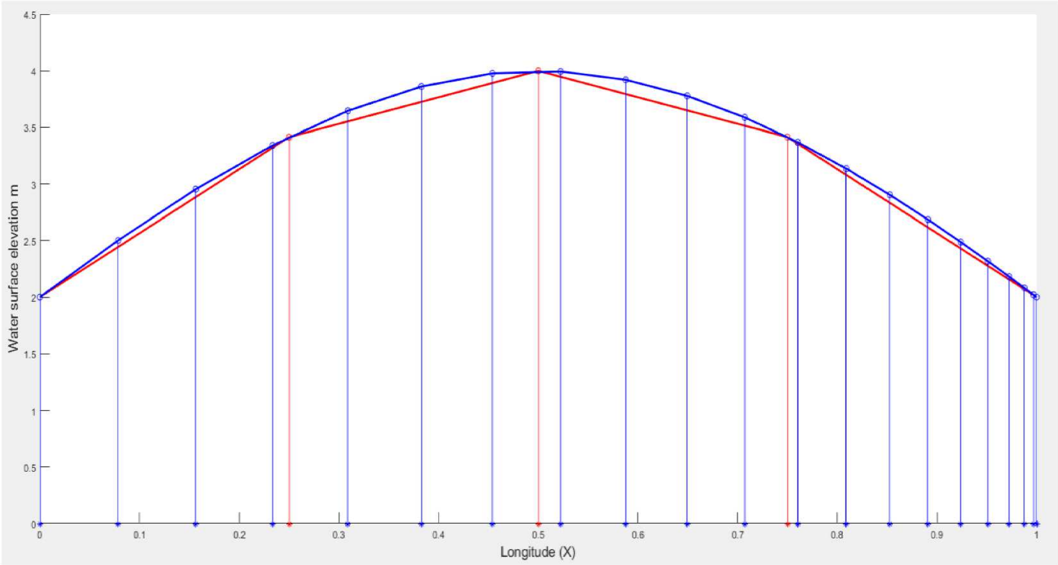

Fig. 5. Interpolation between large mesh (red) and small mesh (blue) based on the projected points on the longitudinal (x) axis which is the general direction of the coastal line in Mexico Beach.

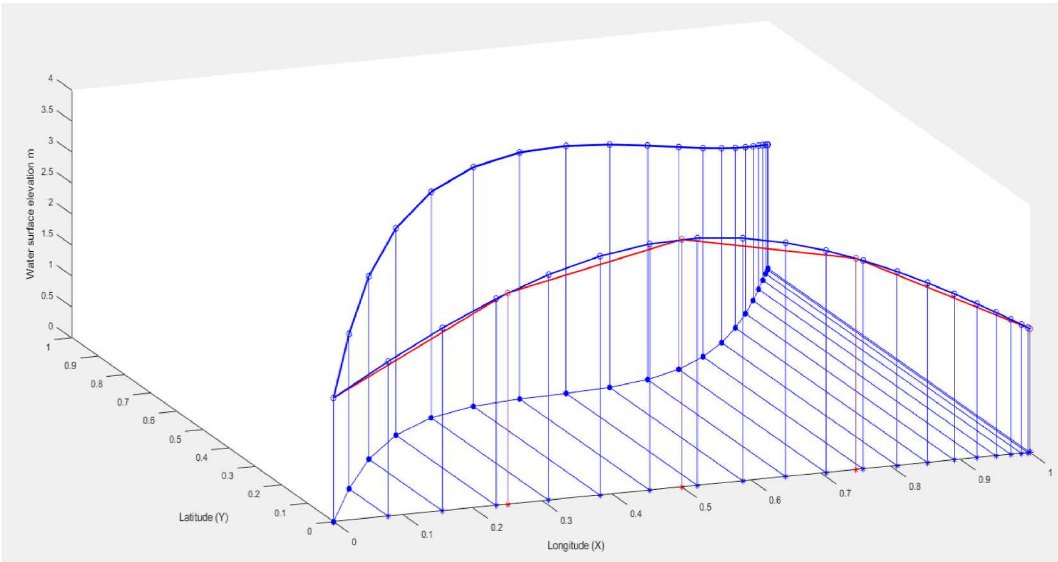

Fig. 6. Projection of the interpolated values in small-scale model back to the nested boundary line after interpolations have been done along longitudinal axis.

condition as described in the previous section. Since SWAN is unable to accurately model wave breaking into land, the nested run is not coupled. Secondly, the model has no wind forcing by default. If needed a wind field can be separately written for this smaller domain. A higher resolution mesh demands a smaller time step to maintain computational stability. The time step typically employed in nested runs is around 0.5 s. In some meshes, due to the topography (sharp changes in elevation) we employed 0.1 s for a stable run.

A flowchart depicting the overall procedure summarizing the procedure is given below. (Fig. 7). The first step is to prepare the hurricane wind field based on the track and intensity forecast provided by the National Hurricane Center. The forecast intervals vary from 12 h when the storm is far away from the US coast to 6 h when it is near the coast. In the next step the large scale coupled model is run and the total water surface elevation is retrieved, interpolated and written as a boundary information file for the nested domain. Since the nested run can only afford a very small time-step, it usually takes more time than the 5-day large scale run. The results from the nested model are exported to GIS as shape files to geo-processing which results in marking the inundation zones.

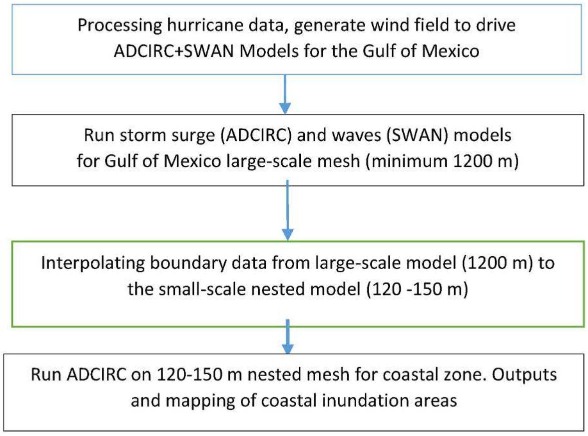

Fig. 7. Flow chart of model simulations in the nested large-scale and small-scale models to speed up model simulations.

3. Validation of multi-scale nested models

In this section, the inland inundation model validation is described. As we use a large-scale mesh and a nested regional mesh, both need to be validated. Because we use a simplified, symmetric hurricane wind field, it is more rational to validate the large-scale model using observations at the land fall location. Therefore, large scale model results are compared using storm surge and wave heights at the Mexico Beach area first. Fig. 8 shows Mexico Beach Pier (red diamond marker) where a water level data is recorded during Hurricane Michael.

Storm surge and significant wave height water levels from the large-scale model are applied to the nested domain as boundary condition to get inland inundations. The nested model's runtime is usually 5–6 h around land fall time where maximum water levels are measured. Therefore, the storm surge and wave height results of the large-scale model during the same period is used in this validation. Since the large-scale model domain consists only of oceanic nodes, the observation station closest to the ocean, is used here. Additionally, this is the only station where a time-series water level data is available in the vicinity. Other stations in Fig. 8 (brown diamond markers) have only one water level data.

Validation of the nested model is described next based on observations of water level in Mexico Beach, where Hurricane Michael impact was maximum. The reason behind using this location is that model results of Mexico Beach were used to calibrate the coupled surge and wave model. Therefore, it is reasonable to use inland observations of water level at this location to test the accuracy of the nested inundation model. The nested mesh is created from Florida Digital Elevation Model database and the ocean bathymetry from the GEBCO (General Bathymetric Chart of the Oceans) database. In the vertical, positive elevation indicate depth, and the mesh node with positive elevation during the simulation is considered to be in water or always wet. The mainland boundary was specified roughly 10 km inlands where the maximum height encountered was 20 m. This height is specified as negative in the model and consequently the node is termed as dry if the elevation remains negative during the model simulation. This means that a location is said to be inundated if the elevation of a node initially in land becomes positive or wet during simulation. The wetting and drying capability of

Fig. 8. USGS water mark locations in Mexico Beach used for validation.

ADCIRC enables it to simulate inundation processes very well. The algorithm treats an element in the mesh as dry when its depth is negative and wet when the depth is positive which helps in identifying the areas which are inundated at any instant during the model run.

Time discretization in ADCIRC is by an explicit finite difference scheme, and this makes numerical stability an important consideration when prescribing model parameters. In order to maintain numerical stability, a very small time-step of 0.5 s was employed in the small scale model, owing to its very small spatial element size. The oceanic boundary is roughly 300 m off the coastline and has a maximum depth of 3 m, forced with the storm surge water surface elevation prescribed in each time step. The boundary condition on the mainland boundary for the model was prescribed as essential with no slip. The model extent was chosen so that flood water does not reach the rigid mainland boundary any time during the simulation, preventing unnatural accumulation of water at the mainland boundary.

3.1. Validation of the large scale model at a coastal measurement station

The water level observations were obtained from the USGS station on the Mexico Beach Pier station. USGS provides the filtered water surface elevation data from the station. This can be used to compare the storm surge water levels produced by the model. As shown in Fig. 9, the model data correlates very well with the observations of storm surge.

There is only one station that provides data of both significant wave heights and water levels. The observed water levels from the station is used to determine the significant wave height for the period using the formula [26].

$$Hs = 1.62 * 4\sqrt{\sigma^2} \tag{3}$$

The maximum significant wave height from the coupled ADCIRC + SWAN model was close to the observed significant wave height obtained using Eq. (3). (Table 1). The absolute error at Mexico Beach Pier station was only 4 cm. The model errors of the order of 10 cm were obtained for other stations along the panhandle coast.

3.2. Validation of the small-scale inundation model in the city of Mexico beach

Observation data from four water mark stations as shown in Fig. 8 in the city of Mexico Beach were compared with the observed water surface elevation. The inundation results from the model are compared to these observations in Table 2.

As shown in Table 2, absolute errors at the four stations ranged from 0.02 m to 0.19 m, with the root-mean-square error of 0.12 m. Errors of similar order of magnitude were present in other nearby watermark stations along the coast as well. In short, the local-scale nested model validation is satisfactory in modeling inundation water levels in the Mexico Beach area, and the model results can be further used in the framework.

4. Simulation of storm surge inundation in the city of Mexico beach

4.1. Spatial inundation pattern in Mexico beach area

In order to more understand the spatial coverage of flood water incrementally in the Mexico Beach area, ADCIRC inundation model output was exported to ArcGIS for visualization and analysis. The inundation layers are superimposed over the satellite image of the region. Fig. 10 a-h shows the incremental inundation of the Mexico Beach area. It is worth noting that features smaller in horizontal dimension than 150 m were not resolved in the model and as such did not influence the flooding pattern of the region. Fig. 10a represents the area that would be under water if a storm surge of 1/8th strength of that of Michael was incident on the area. The water levels (m) in this figure roughly corresponds to the levels shown on Fig. 10. There is no significant difference in spatial coverage of

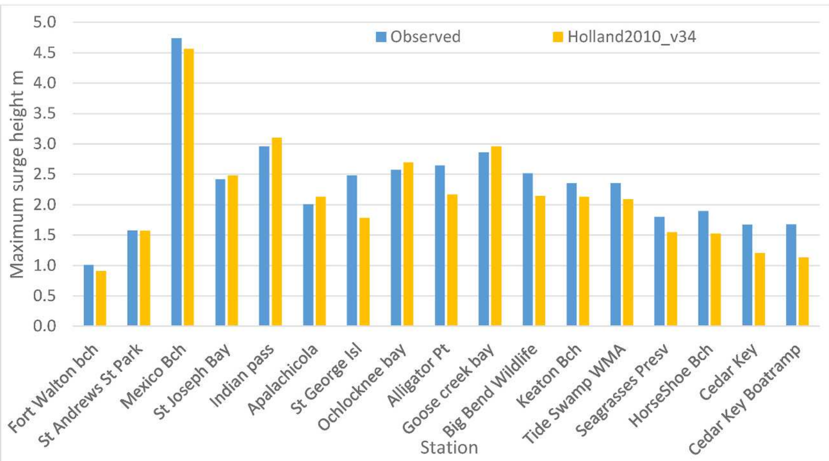

Fig. 9. Comparison of large-scale model simulated and observed of storm-surge water elevation along coastal stations of Gulf of Mexico with details described in Vijayan et al. (2021) [26].

Table 1
Comparison of modeled and observed significant wave height (Hs) in the coastal station in the large-scale ADCIRC-SWAN model for the Gulf of Mexico.

Station	Observed Hs (m)	Modeled Hs (m)	Abs Error in m
Mexico Beach	2.69	2.73	0.04

Table 2
Model vs Observed inundation levels at stations in Mexico Beach.

ID	Latitude ^{0}N	Longitude ^{0} W	Observed	Modeled	error (m)	% error
FLBAY27701	29.9533	85.4286	5.22	5.24	0.02	0.38
FLBAY27706	29.9517	85.4261	5.46	5.27	0.19	3.60
FLBAY27709	29.9511	85.4236	5.36	5.40	0.04	0.71
FLABY27713	29.9492	85.4203	5.61	5.46	0.15	2.79
RMSE					0.12	2.31

Note: RMSE is the root mean square error.

Fig. 10b and c, but it is inferred that in the second case water levels in the inundated areas increased even though spatial coverage remained the same. A storm surge of 1–1.5 m would be enough to flood the western end of the Mexico Beach near the inverted L shaped cut. This area seems to be more susceptible to flood water. Another cut south of 12th street makes a network of marinas in the town. The southern cut would hold against a surge of approximately 2 m (Fig. 10d). These two were the fronts where floodwater breached over the weak barrier offered by US 98. A stronger surge however would have made most of the town under water subsequently. A category 3 hurricane would be enough to inundate most of the Mexico Beach area (Fig. 10e and f). The low elevation further inlands caused flood water to reach as far as 3 km inlands (Fig. 10g–h) as per the model. This lower elevation might have helped drain the flood water from the area, but further study is needed to confirm this.

4.2. *Comparing maximum inundation from Hurricane Michael to FEMA 100-yr inundation*

Fig. 11 shows inundation zone derived from the model compared with the FEMA flood zone VE of Mexico Beach. Results from the inland inundation model are exported to GIS as polygonal shapefiles. Large scale storm surge model results, in the form of maximum water surface elevations (that includes wave heights as well) along the coast, were used to force the small-scale high-resolution model. The results of the high-resolution model can be taken as the flood water levels at an instant during the model simulation. Since Mexico Beach and the vicinity suffered the most damage, this discussion focuses on the area.

The inundation levels were around 5.85 m at the Mexico Beach town by the side of US highway 98 which is lower than the maximum water surface elevations at the shoreline. This shows the model can simulate attenuation of water levels further inlands. However, flood water reached as far as 2-mile inlands according to the model, due to the lower elevation of the marsh land or agricultural land north of the Mexico Beach area. The canals or cuts made to access the marinas north of the city were not resolved in the model and consequently, did not affect the model results in the area. The background image is taken after hurricane Michael and the inflicted damage is evident, which is due to the combined action of flooding, water wave, erosion and extreme winds. Design and fabrication standards based on flood zones may have some effect on the vulnerability of these structures.

5. Inundation of critical coastal infrastructure

One advantage of integration with GIS is an improved quantification of the infrastructure damage due to water and wind hazards of a hurricane. Federal Emergency Management Agency (FEMA) defines flood hazard zones according to the 1 % annual chance of flood (called a 100-year flood). In the focus area, high risk areas with 1 % chance of flooding and a 26 % chance of over a period of 30 years are designated zone A. If base flood elevations are provided, such zones are designated AE. Similarly, for coastal areas the letters V and VE are provided, because of additional hazard from storm waves. The blue areas in Fig. 11b represent FEMA high hazard zone VE. It is noteworthy that most of the facilities are outside the high-risk zones, even though some of them are enveloped by high-risk zones. Fig. 11a shows the maximum water surface elevation in Mexico Beach and nearby areas from the model framework during hurrincane Michael. where elements which are wet are shown in the figure in color. The shoreline inundation levels were around 5.85 m.

Observed flood water heights and significant wave heights during hurricane Michael's landfall well exceeded the base flood elevations provided by FEMA in zones AE and VE. For example, the beach front in the Mexico Beach area is designated VE with 4.27 m flood elevation and 3 ft (1 m) wave height for a 100-year flood. (Fig. 9b). This is the highest risk category as per FEMA standards, but the maximum flood level in the area was 5.66 m with a significant wave height of 6.2 ft (2 m), from the measurements of FLBAY03283 [32]. These values are well-validated by the model results as well, with a mean absolute error of 10 cm. In short, both model and observations point to the fact that the flood levels were much higher than expected. Even though the model output and observations do not show significant variation in the water levels in the area, especially near shore, the damage states of adjacent structures vary appreciably in reality.

Assessment of damage states of structures is based on performance evaluation of 6 structural components (roof, foundation, walls, attachments like stairways and sheds, windows and interiors). Damage states are rated from DS0 if no damages are visible, to DS6 if the structure is missing or an irreparable foundation is found. Post storm surveys in Mexico Beach showed that most of the structures on the

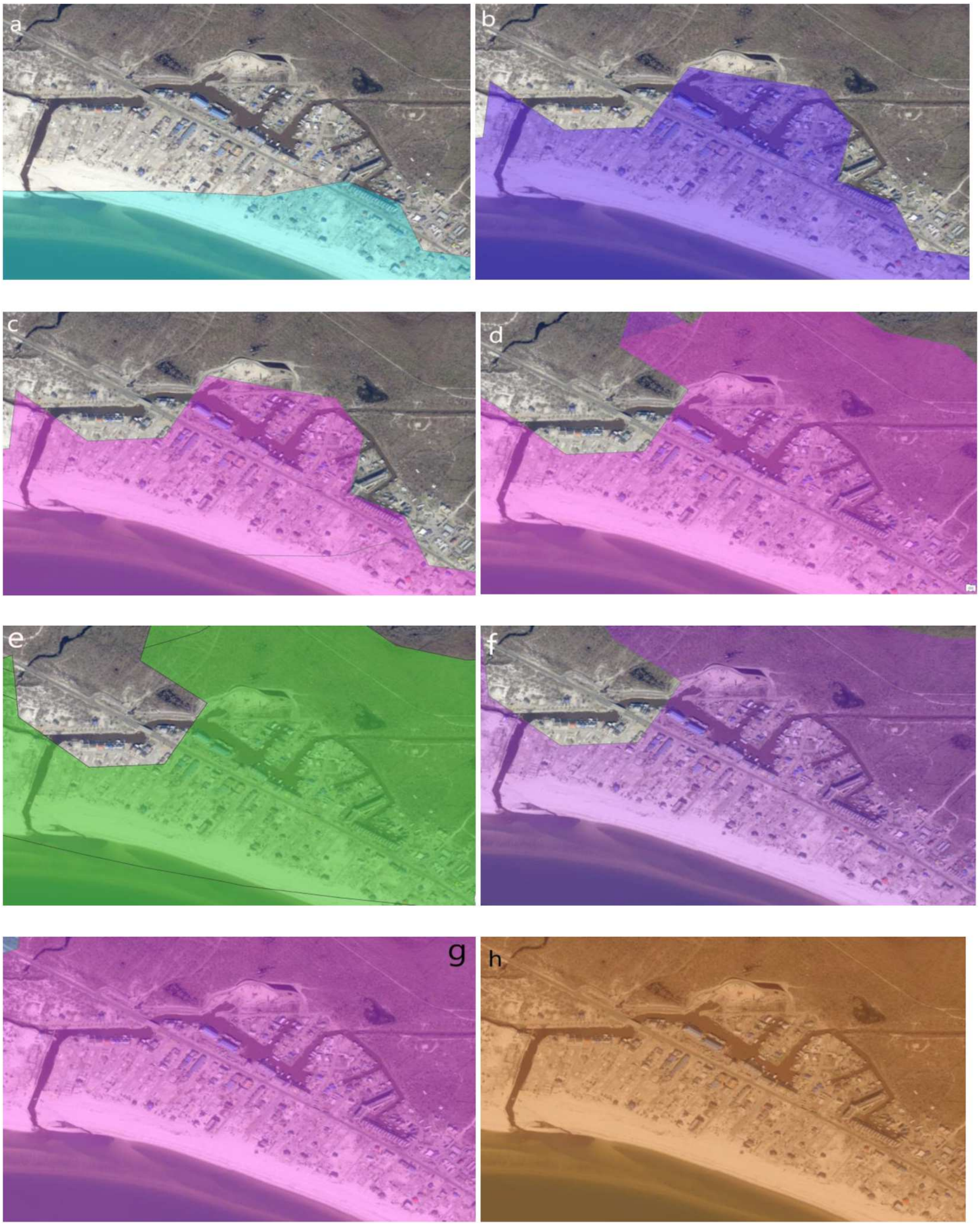

Fig. 10. a–h: Inundation patterns as storm surge rises at 1/8 interval of peak storm surge elevation in the city of Mexico Beach.

near shore side of US 98 were on DS6 and DS5 while only 4 to 5 were DS1. The lowest horizontal member (LHM) elevation of most DS6 and DS5 structures were less than 3 m while DS1-DS4 structures had average LHM of 5 m. (Kennedy et al., 2019). It is therefore inferred that serious damage to structures in the area were due to storm surge and water waves while lower damage states were due to wind and rain. Another factor that influenced the damage state might be the design standards adopted by individual structures. Older structures built on older building codes sustained multiple component damages. In other words, older buildings with a higher LHM were at a higher DS due to wind and rain rather than inundation. A same pattern can be expected for older structures away from the shoreline as well. As the inundation model resolution is much larger than the average building size, such variations in the damage states between adjacent structures would not be visible in the model. However, the general pattern of damage states can be confirmed by the model such as most of the DS6 structures were near shore while those with lower damage states were either inlands or had a higher LHM.

Inundation levels above 1.5 m were observed all along the Florida panhandle coast 2–3 h before landfall of hurricane Michael and

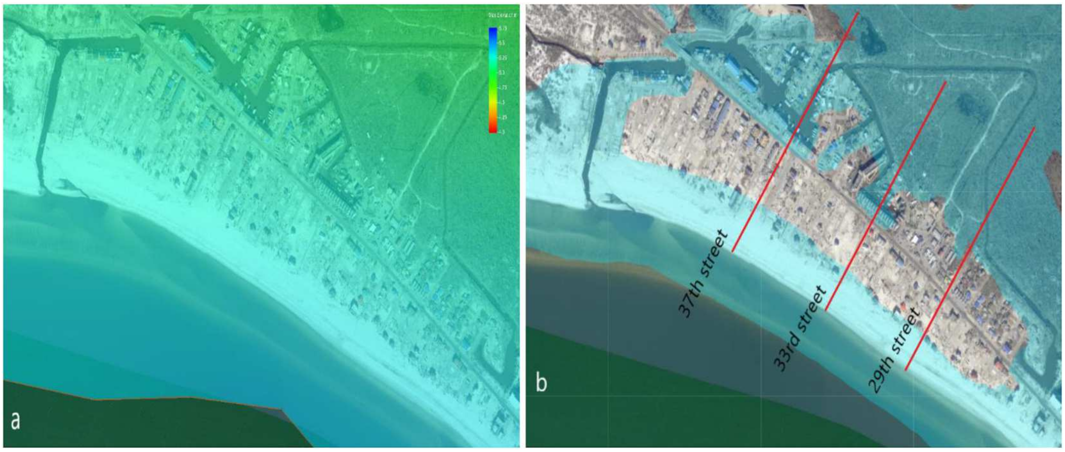

Fig. 11. Comparison between: a) maximum from Hurricane Michael, and b) FEMA 100-yr flood zone VE at Mexico Beach.

therefore, the model domain spanned from Fort Walton beach in the west to St. Marks wildlife refuge in the east. There were a number of facilities whose operations are critical to the emergency management close to the shorelines under the threat of flooding. Most of these facilities were outside the FEMA flood hazard zones, but as the flood levels exceeded all expectations, some of them might have experienced flooding. This section describes performance of critical infrastructure over this area including roadways based on our model results, against flooding and its effects on evacuation efforts.

Evacuation shelters, Hospitals, nursing homes, Fire/EM services, Power plants and Solid Waste landfill locations were considered here along with Major and some minor roads of the region. Evacuation shelters, hospitals and assisted living facilities could not be evacuated and therefore require actions to improve their system resilience such as uninterrupted power, food and medical supplies, structural enhancements to endure flood water and wind damages and so on. Fire and emergency medical services are critical services due to the fact that evacuation of the population was only 75 % effective. Power plants and waste management facilities are critical components in deciding the resilience of a region. The percentage of reduction in performance of these systems impact the robustness component while the time taken by a community to resume normal operation influence the rapidity component of quantifying resilience of a community.

Fig. 12 shows the critical infrastructure affected by floodwater obtained from the coastal inundation model. Fig. 12a covers areas from Panama City to Port St Joe while Fig. 12b shows areas from Apalachicola City to St Marks Wildlife refuge. There were a few hospitals and number of assisted living centers or nursing homes in the vicinity of Panama City. One nursing home each at Mexico Beach area and Port St Joe were very close to the beach front. Approximately 14 EMS and fire service units were deployed close to the beach. Two such stations in St George Island (Fig. 12b) were not considered in this analysis as the island was not resolved in the model and no flood levels were available. Only two power plants were operating in the region whereas many solid-waste land fill sites were present.

Emergency management systems anticipated and prepared well against Hurricane Michael even though it was not expected to be of category 5 intensity. Evacuation plans were well underway days before, along with other mitigation actions. The road network in the region is divided into major roads (US highways and State Roads) and minor roads. The highway US 98 is running parallel to the coastline. Even though it is at a higher elevation in most places this highway is susceptible to flooding due to its closeness to the shoreline. US highway 30 from Panama City Beach to Laguna Beach in the west is a few feet from the coastline. Highways 77, 71, 231 and 391 start from a city or town on the coast and go inland. A network of county roads and state roads also can be flooded due to its closeness with a waterbody.

One important benefit of integration of the model with ArcGIS is the use of geo-processing tools. Inundation levels obtained from the ADCIRC model is intersected with the spatial data of infrastructure facilities in ArcGIS for the analysis. A tolerance level of 100 m is set for the intersection. In other words, if the maximum flood levels reached within 100 m of the facility, it is considered flooded. Vertically, a facility is considered affected by flooding if the water levels were at least 0.1 m. Fig. 13a and b shows such facilities affected by flood water as shown in model simulations.

As shown in Fig. 13, one hospital each in the Tyndall area and Port St Joe were flooded as per the model when the maximum elevation levels were reached. Two nursing homes at Port St Joe and Mexico Beach were affected by flooding as per the model. These healthcare facilities were flooded due to their proximity to the beach even though they were resilient up to a surge height of 3–4 m. More importantly, as the structures were at a higher elevation, the maximum surge height translates to 0.5–0.75 m of flood water only. This means that the facilities could have functioned during the storm with some reduced capacity. All hospitals and nursing homes in Panama City area were safe against storm surge with resulting maximum inundation levels of 3 m. Floods of higher intensity (4–5 m) might have affected more facilities as these are situated near a bay and further modeling studies are needed to confirm this. This low number of affected entities in this segment indicate strong, well designed healthcare infrastructure, despite a large number operated in an apparently vulnerable area, against the most powerful hurricane to hit the area.

Fig. 13 also shows that a few Emergency Medical Services (EMS) and Fire stations were flooded which were all close to the beach

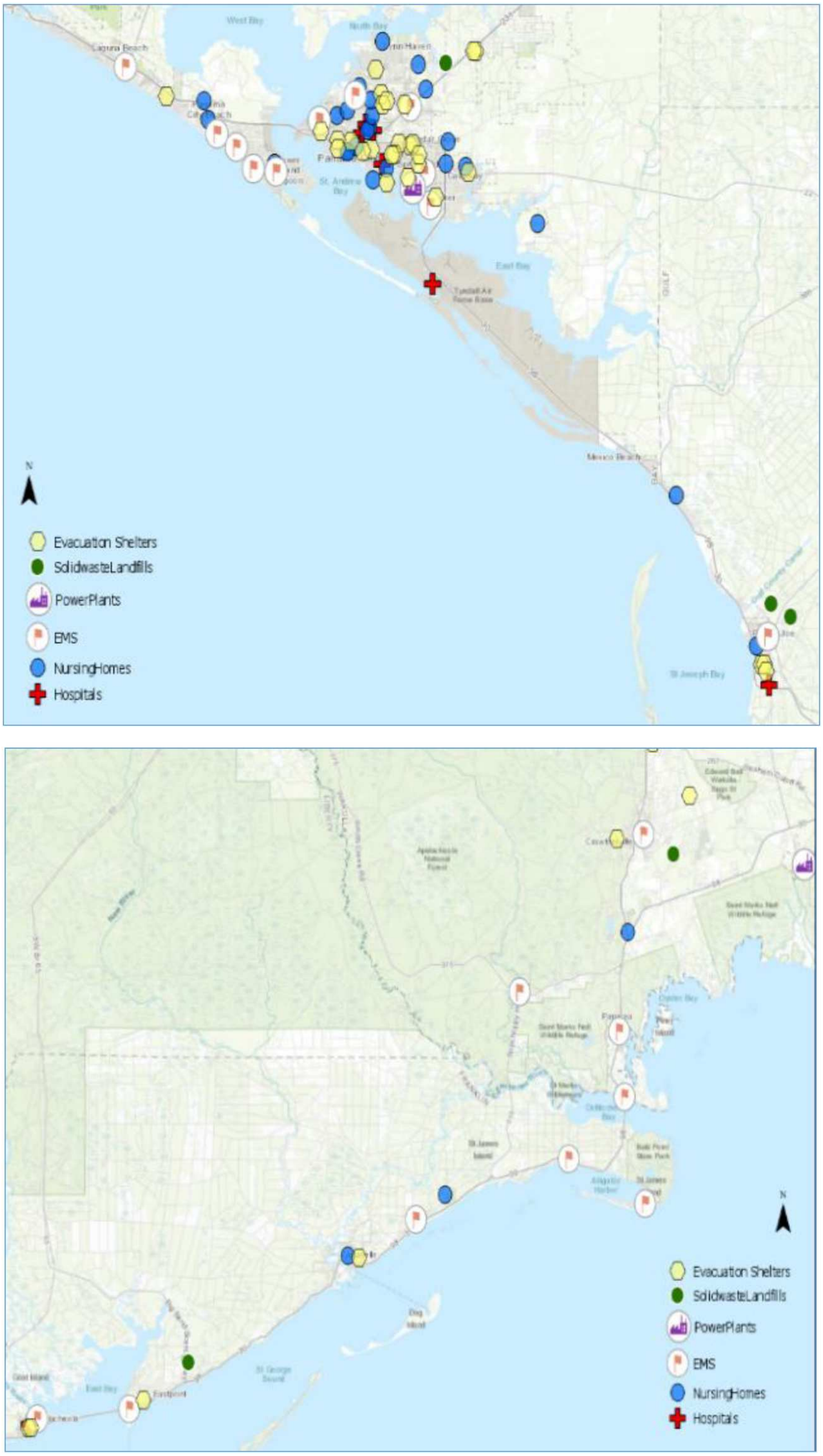

Fig. 12. Critical Infrastructure in the region a) from Panama City to Port St Joe (upper panel), b) Apalachicola to St Marks (lower panel).

front. Two in the Panama City Beach, One each in Apalachicola, Alligator Point and Ochlockonee Bay. There were 53 such stations in the model region and this points to good redundancy in the system. FEMA regulations assert that such services would be unavailable during and after the arrival of the storm for those who did not comply with the evacuation orders and therefore the overall system functionality is not affected by a few stations flooded. No Power plants and Solid waste land fill sites were affected by hurricane Michael's storm surge as they were sufficiently away from the shoreline or were at a higher elevation.

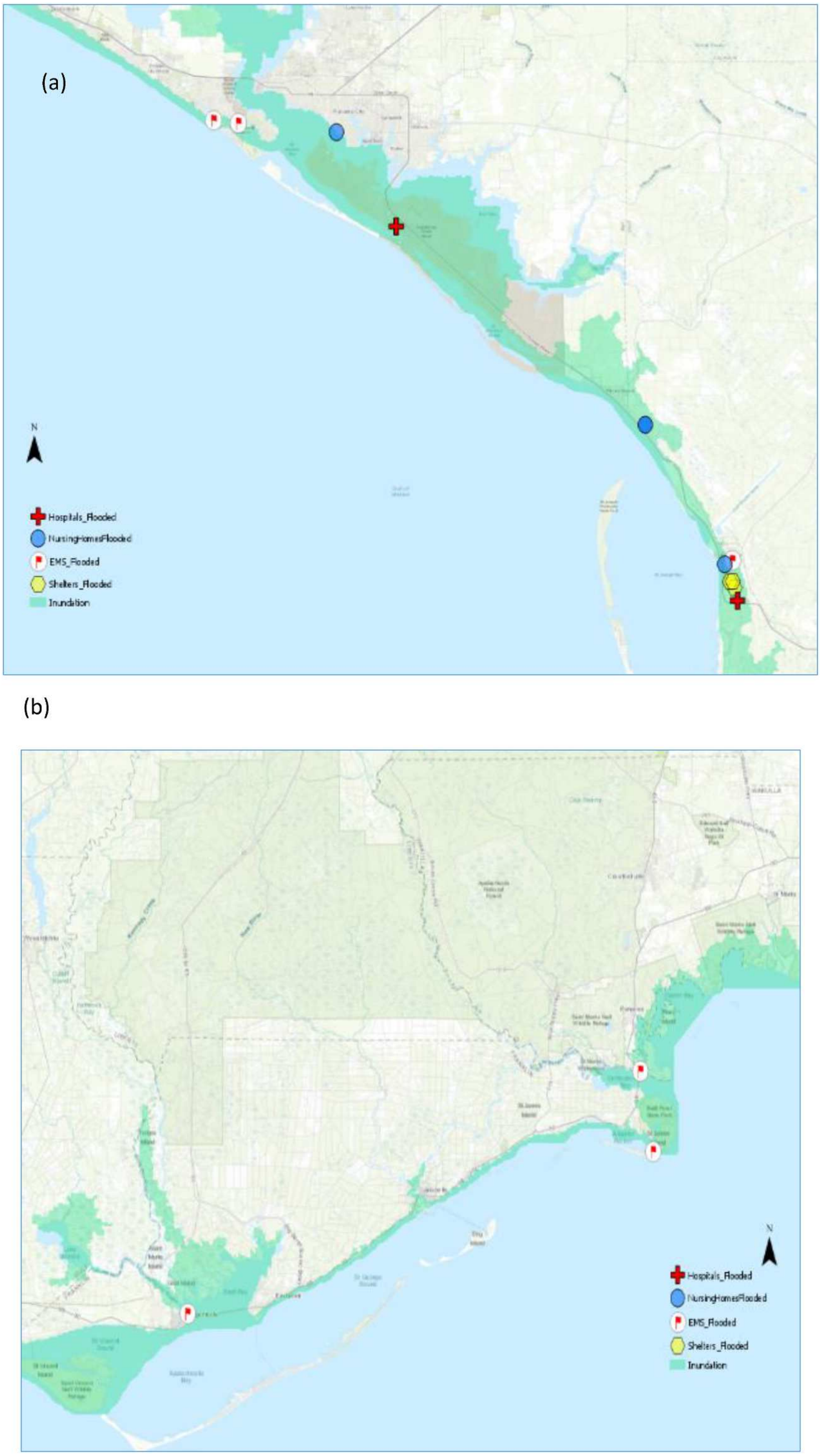

Fig. 13. Flooded facilities (Hospitals, Nursing homes, EMS, Evacuation shelters) during Hurricane Michael in the area of a) Panama City to Port St Joe b) Apalachicola to St Marks.

5.1. Inundation of coastal roadways

Prediction of roadway inundation by storm surge is important for hurricane evacuation operations. A more important benefit of integration with GIS is the quantification of roadways that would become ineffective due to the inland flooding. Fig. 14 shows the inundated road sections based on model results. A significant percentage of road network in the Florida Panhandle is vulnerable to flooding due to its proximity to coastline. Sections of US highway 98 in the Panama City, Mexico Beach, Port St Joe and Apalachicola area were observed to be inundated as a result of Hurricane Michael. Stretches of US highway 98 from Mexico Beach area (b) to Port St Joe (c) is completely inundated and is in good agreement with observations.

On Panama City Beach, Highway 31 was also flooded for a few miles although intermittently. Evidence of flooding in the area in Apalachicola area only indicated intermittent flooding of highways and minor roads, whereas the model results (Fig. 12d) shows more continuous sections under water. This may be due to the grid resolution used in the model being approximately 150 m. Most of the highways got flooded only when the surge was at its maximum. Some protection was offered by buildings or sand dunes for some sections of the high way while roads exposed directly to the ocean were susceptible to surge. An example to this is US-98 between Mexico Beach and Tyndall AFB, which was ruined even though it was at a higher elevation. These results are useful as the first step in evacuation planning ahead of an impending hurricane, particularly for such areas where no previous history of category 5 hurricanes are available.

6. Improving model simulation speed by multi-scale nested modeling approach to support real-time hurricane evacuation

A high-resolution mesh is necessary to accurately model coastal inland inundations. The results of the model are used to determine the flood water coverage in land, near the coast and subsequently to determine surge and evacuation zones. A coupled storm surge and wave model is necessary to accurately determine the effect of surge water along the coastline. The coupled model needs to cover a large area of the ocean for the model because the surge is due to the storm pushing water towards the coast from the ocean. In short, a large-scale high-resolution model is necessary. However, such a model would be very slow due to many elements and time steps. Nested models are developed to speed up the computation without compromising on accuracy, so that the modeling framework can be used to produce dynamically changing surge and evacuation zones, in response to the changes in track and intensity of a storm between successive forecasts. In this section the computational speed of the nested mesh model is discussed. In order to test the framework, we changed Hurricane Michael's track three times and simulated the time taken for each of these tracks. The results are summarized in Table 3.

ADCIRC + SWAN is run first with the hurricane wind field derived using symmetric Holland 1980 parametrization, based on a forecast, 5 days close to the land fall of a storm are modeled using the large-scale medium resolution mesh. The model takes approximately 40 min to run (Table 3) with ADCIRC time-step of 10 s and SWAN time step of 240 s [33]. The output storm surge height and significant wave height are extracted and interpolated into a higher resolution nested mesh. A fast linear interpolation technique using distances to a projected axis, either on a latitudinal or longitudinal axis was employed. All models are run on a parallel machine using 8 nodes.

A number of nested high resolution meshes covering the entire coastline of Florida were developed for this purpose. Depending on the forecasted land-fall location, an appropriate regional mesh is selected for nesting. ADCIRC model runs on the nested mesh, resulting in coastal inundation water levels. The model is run for 6–7 h around landfall, when maximum surge is experienced. Here the time step is 0.5 s due to the higher resolution. This model takes 30–45 min to run depending on the size of the nested mesh. In short, the time taken to prepare dynamically changing inundation zones is approximately 90 min, or in the worst-case scenario 150 min. This in turn help emergency managers to take informed decisions that minimize effects on critical infrastructure.

7. Discussions

For comparison purpose, in early stage of the study, a single high resolution (200 m minimum grid resolution) ocean-coastal land mesh model for northern Gulf of Mexico was also run for a period of 5 days. ADCIRC time step was reduced to 0.5 s due to the smaller mesh size. In comparison the time step for medium resolution mesh was 10 s. Other run time parameters were the same as that of the nested model. Both nested and single high-resolution models were run on the same high-performance computer using 8 nodes in parallel to make the comparison justified. The total run time for the high-resolution model was approximately two days. This was due to the very small-time step and due to the larger number of elements in the mesh resulting in a longer processing time per time step. In short, there is significant increase in speed from 2 days to less than 2 h by using nested models instead of the single high-resolution model. As the National Hurricane Center predicts a new track or intensity of a hurricane every 6 h, the inundation model needs to have a run time of less than 6 h. Therefore, the nested-mesh models can provide dynamically changes of storm surge and evacuation zones within 2–3 h to update the coastal hazard zone within the forecast interval of 6 h by NOAA National Hurricane Center. There are some limitations in this study. One of the limitations for the nested-modeling method is that it requires good mathematical and computer programing skills to understand and implement the method to nest the large-scale and fine-scale model together. Another limitation is that compound flooding from rainfall runoff is not included in the case study because no streams or rivers in Mexico Beach. For other study areas where rivers exist, river flood from storm runoff may need to be included and finer meshes may need to be developed in the nested fine scale model.

8. Conclusions

The NOAA National Hurricane Center generally updates its hurricane track forecasting at about 6-hr interval. Therefore, for hurricane evacuations, it is expected that the update of forecasting of coastal inundation by storm surges under the forecasting hurricane track can be completed within the 6-hr interval. To accomplish this task, a nested modeling method has been developed and validated to speed up coastal storm surge and inundation simulations in the Gulf of Mexico and Florida coast with computation and

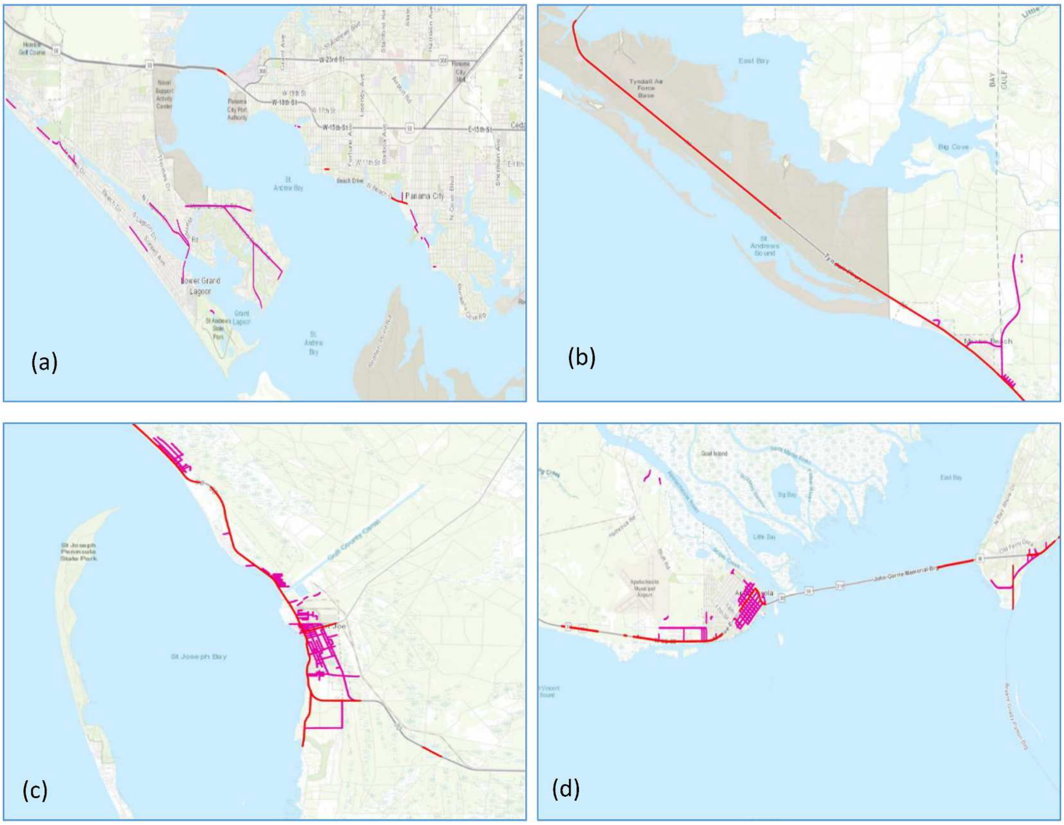

Fig. 14. Inundated sections of major and minor roads in a) Panama City b) Mexico Beach and c) Port St Joe, and d) Apalachicola.

Table 3
Computational time in minutes for simulations of Hurricane Michael.

Simulation	Large-scale modeling for Gulf of Mexico for 5-day simulation period	Nested local-scale model for one storm surge period
Time	40 min	45 min

Note: 1) Model simulations were conducted on Dell Workstation in parallel computation: AMD Ryzen Threadripper 3990 × 2.9 GHz. 256 GB DDR4 ram. 128 GB RadeonX GPU; 2) Additional 30 min are required for preparing GIS mapping of model outputs for coastal inundation.

data processing time completed within 2–3 h. A large scale coupled model ADCIRC + SWAN for the Gulf of Mexico is run on the medium resolution meth (minimum 1200 m) to predict the 5-day forecasting of storm surge based on the 5-day hurricane forecasting track. The outputs of storm surge height and significant wave height are extracted from the large-scale model and interpolated into small-scale nested model with high resolution (120–150 m) storm surge model (ADCIRC) to resolve the changes of local coastal line and topography. The numerical method for the nested modeling has been presented and validated in the case study of Hurricane Michael, which landed near Mexico Beach. The modeled water levels showed very small errors when compared with observations. The root-mean-square error for four locations in Mexico Beach was 0.12 m while the maximum error was 0.19 m for the case study of Hurricane Michael. The output water levels were then exported to Arc GIS for quantification of impacted infrastructure. The inundation model was very much in agreement with observations in the location. Results indicate that, peak water level during Hurricane Michael exceeds the FEMA 100-yr flood water level. Quantifications of infrastructure damage have produced results that agree with observations, especially sections of inundated roadways along the coast. While the nested modeling method can benefit coastal hazard modeling community, the validated nested model for Florida coast can be used to support hurricane mitigation planning and evacuation operations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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