

DEVELOPMENT OF A TSUNAMI FORECAST MODEL FOR OCEAN CITY, MARYLAND (DRAFT)

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August, 2010

Abstract

As part of NOAA's tsunami forecast system, this study addresses the development, validation, and stability tests of the tsunami forecast model for Ocean City, Maryland. Based on the Method of Splitting Tsunami (MOST), the tsunami forecast model is constructed at a spatial resolution of approximately 36 m in the finest grid to accomplish a 4-hour simulation of wave inundation onto dry land within 20 minutes of CPU time. A reference inundation model is developed in parallel, using grid size up to eight meters to provide a reference for the forecast model. The present study conducted the sensitivity tests to optimize the grid extension and resolution of the forecast model. Due to lack of historical tsunami data, the Ocean City forecast model was carefully evaluated using the 1755 Lisbon earthquake, the source of which is still in debate within tsunami science community. The model validations show excellent agreement between the forecast model and reference model, suggesting that the forecast model is qualified to provide quantitative estimation of the inundation, runup and computed maximum values for potential threats posed by future tsunamis. The stability of the forecast model is further evaluated with eight synthetic scenarios generated in the Puerto Rico Trench, Hispaniola Trench, Cayman Trough, Los Muertos Trough and South Sandwich Island at magnitudes ranging from M_w 7.5 to M_w 9.3.

1. Background and Objectives

The National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami, Research (NCTR) at the NOAA Pacific Marine Environmental Laboratory (PMEL) has developed a tsunami forecasting capability for operational use by NOAA's two Tsunami Warning Centers located in Hawaii and Alaska (Titov *et al.*, 2005). The system is designed to efficiently provide basin-wide warning of approaching tsunami waves accurately and quickly. The system, termed Short-term Inundation Forecast of Tsunamis (SIFT), combines real-time tsunami event data with numerical models to produce estimates of tsunami wave arrival times and amplitudes at a coastal community of interest. The SIFT system integrates several key components: deep-ocean observations of tsunamis in real time, a basin-wide pre-computed propagation database of water level and flow velocities based on potential seismic unit sources, an inversion algorithm to refine the tsunami source based on deep-ocean observations during an event, and high-resolution tsunami forecast models.

Maryland's Atlantic coast features the barrier island beaches of Fenwick and Assateague Islands (**Figure 1a** and **Figure 1b**). Of the 40 miles of beaches in Maryland, only about 10 miles are maintained by the state. Ocean City, Maryland's only coastal resort, occupies the entire 8 miles of Fenwick Island within Maryland. Although it was founded

from a single beach-front cottage in 1869, Ocean City established itself as one of the world's greatest fishing ports when a powerful storm in 1933 helped to form the Ocean City Inlet, offering easy access to the fishing grounds of the Atlantic Ocean. Extending from the inlet northward, the strip of barrier island that constitutes Ocean City now supports hotels, motels, apartment houses and condominiums. Rapid expansion of Ocean City took place during the post-war boom. In 1952, with the completion of the Chesapeake Bay Bridge, Ocean City became easily accessible to people in the Baltimore-Washington corridor. In 1964, with the completion of the Chesapeake Bay Bridge tunnel, another new pathway to the south was opened. Ocean City became one of the largest vacation areas of the east. By the 1970s, big business flourished and created a spectacular sight of high-rise apartments. Today, Ocean City still remains as one of the most popular recreation barrier islands in the Atlantic coasts. Ocean City has a total area of 94.3 square kilometers. According to Census 2010, Ocean City has only 7,102 permanent residents (<http://2010.census.gov/2010census/index.php>). Most of the population in Ocean City comes from the tourists - the summer weekend population in Ocean City is estimated to be 320,000 to 345,000. Thus, the vulnerability of Ocean City to the potential coastal hazards poses challenging, yet long-standing, tasks for the coastal communities on how to protect their lives and properties.

Due to low land elevation, all properties in Ocean City, MD are in a flood hazard area and subject to flooding from the ocean, coastal bays and heavy rainfall. Minor flooding is not uncommon, and major flooding happens occasionally. On 26 April, 2010, Ocean City was designated as a National Weather Service Storm-Ready Community that is better prepared to save lives from the onslaught of severe weather through advanced planning, education and awareness (Ocean City Department of Emergency Services, 2010). In Ocean City, rapid shoreward erosion of the barrier islands jeopardizes both property and economy. Massive development of Fenwick Island has both increased the urgency for and complicated the process of beach restoration. Like many Atlantic coast communities, Ocean City has been under beach nourishment and dune management as the primary maintenance strategy since 1988. Currently utilized sand resources are located north of Ocean City Inlet, within the three-mile limit of state jurisdiction. These sands are committed to the reconstruction and periodic nourishment of Ocean City beaches (<http://www.mgs.md.gov/coastal/osr/ocsand2.html>). Titus et al. (1987) evaluated the potential impacts of sea level rise on the beach at Ocean City. They concluded that the sea level rise could double the rate of erosion at Ocean City in the next forty years. If no additional erosion control measures are taken, the shore will erode 85-153 feet by 2025, assuming current sea level trends. The projected rise in sea level would increase the quantity of sand necessary to maintain the current shoreline from 5-10 million cubic yards for the next 40 years at current trends to 11 – 15 million cubic yards for an accelerated sea level rise regime.

Since it is one of the largest barrier islands in the U.S. Atlantic coast that has been transformed into high-density year-round urban complexes, Ocean City has been evaluated and studied for various coastal hazards as mentioned above. However, the potential tsunami impact on the coast of Ocean City is significantly understudied, probably due to uncommon tsunami activities in the Atlantic and lack of historical tsunami data. The only reported tsunami height at the Ocean City tide gauge was the 0.3

m due to a large submarine slump triggered by a magnitude 7.2 earthquake in Grand Banks, Canada on 18 November 1929 (<http://earthquakescanada.nrcan.gc.ca/>). ten Brink et al. (2007) evaluated all tsunami sources with the potential to impact the U.S. Atlantic and Gulf Coasts. Their report indicated that earthquake sources located west of Gibraltar and in the Puerto Rico Trench are capable of generating trans-oceanic tsunamis. A large tsunamigenic earthquake taking place in the Puerto Rico trench may be destructive to many parts of the U.S. East Coast, although the ability of this plate boundary to generate earthquakes is being investigated. ten Brink et al. (2008) also speculated that landslides along the U.S. Atlantic margin have the potential to cause tsunamis locally. For instance, the Currituck Slide occurred less than 200 km southeast of Ocean City and is one of the major mass movements that have taken place on the Atlantic continental margin over the last 100,000 years (Prior et al., 1986) and could have caused a damaging tsunami to the East Coast of United States. The landslide modeling results of Geist et al. (2009) showed that the failure of Currituck landslide could trigger tsunami waves of up to 3 m in amplitude on the shelf offshore of Ocean City. Titov et al. (2009) employed high-resolution tsunami inundation forecast models to assess the potential tsunami hazards for coastal communities in U.S. Atlantic coasts due to distant earthquake- and landslide-generated tsunamis in the Atlantic. The development of the Ocean City tsunami forecast model in the present study is a valuable supplement to this assessment, and more importantly adds another essential contribution to the existing NOAA's tsunami forecasting system in the Atlantic.

2. Forecast Methodology

A high-resolution inundation model was used as the basis for development of a tsunami forecast model to operationally provide an estimate of wave arrival time, wave height, and inundation at Ocean City, Maryland following tsunami generation. All tsunami forecast models are run in real time while a tsunami is propagating across the open ocean. The Ocean City model was designed and tested to perform under stringent time constraints given that time is generally the single limiting factor in saving lives and property. The goal of this work is to maximize the length of time that the community of Ocean City has to react to a tsunami threat by providing accurate information quickly to emergency managers and other officials responsible for the community and infrastructure.

The general tsunami forecast model, based on the Method of Splitting Tsunami (MOST), is used in the tsunami inundation and forecasting system to provide real-time tsunami forecasts at selected coastal communities. The model runs in minutes while employing high-resolution grids constructed by the National Geophysical Data Center. The Method of Splitting Tsunami (MOST) is a suite of numerical simulation codes capable of simulating three processes of tsunami evolution: earthquake, transoceanic propagation, and inundation of dry land. The MOST model has been extensively tested against a number of laboratory experiments and benchmarks (Synolakis *et al.*, 2008) and was successfully used for simulations of many historical tsunami events. The main objective of a forecast model is to provide an accurate, yet rapid, estimate of wave arrival time, wave height, and inundation in the minutes following a tsunami event. Titov and

González (1997) describe the technical aspects of forecast model development, stability, testing, and robustness, and Tang *et al.* (2009) provide detailed forecast methodology

A basin-wide database of pre-computed water elevations and flow velocities for unit sources covering worldwide subduction zones has been generated to expedite forecasts (Gica *et al.*, 2008). As the tsunami wave propagates across the ocean and successively reaches tsunameter observation sites, recorded sea level is ingested into the tsunami forecast application in near real-time and incorporated into an inversion algorithm to produce an improved estimate of the tsunami source. A linear combination of the pre-computed database is then performed based on this tsunami source, now reflecting the transfer of energy to the fluid body, to produce synthetic boundary conditions of water elevation and flow velocities to initiate the forecast model computation.

Accurate forecasting of the tsunami impact on a coastal community largely relies on the accuracies of bathymetry and topography and the numerical computation. The high spatial and temporal grid resolution necessary for modeling accuracy poses a challenge in the run-time requirement for real-time forecasts. Each forecast model consists of three telescoped grids with increasing spatial resolution in the finest grid, and temporal resolution for simulation of wave inundation onto dry land. The forecast model utilizes the most recent bathymetry and topography available to reproduce the correct wave dynamics during the inundation computation. Forecast models, including the Ocean City model, are constructed for at-risk populous coastal communities in the Pacific and Atlantic Oceans. Previous and present development of forecast models in the Pacific (Titov *et al.*, 2005; Titov, 2009; Tang *et al.*, 2008; Wei *et al.*, 2008) have validated the accuracy and efficiency of each forecast model currently implemented in the real-time tsunami forecast system. Models are tested when the opportunity arises and are used for scientific research. Tang *et al.*, 2009 provide forecast methodology details.

3. Model development

The general methodology for modeling at-risk coastal communities is to develop a set of three nested grids, referred to as A, B, and C-grids, each of which becomes successively finer in resolution as they telescope into the population and economic center of the community of interest. The offshore area is covered by the largest and lowest resolution A-grid while the near-shore details are resolved within the finest scale C-grid to the point that tide gauge observations recorded during historical tsunamis are resolved within expected accuracy limits. The procedure is to begin development with large spatial extent merged bathymetric topographic grids at high resolution, and then optimize these grids by sub sampling to coarsen the resolution and shrink the overall grid dimensions to achieve a 4 to 10 hr simulation of modeled tsunami waves within the required time period of 10 min of wall-clock time. The basis for these grids is a high-resolution digital elevation model constructed by the National Geophysical Data Center and NCTR using all available bathymetric, topographic, and shoreline data to reproduce the wave dynamics during the inundation computation for an at-risk community. For each community, data are compiled from a variety of sources to produce a digital elevation model referenced to Mean High Water in the vertical and to the World Geodetic System 1984 in the horizontal (<http://ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html>). From these digital elevation models, a set of three high-resolution, 'reference' elevation

grids are constructed for development of a high-resolution reference model from which an 'optimized' model is constructed to run in an operationally specified period of time. The operationally developed model is referred to as the 'optimized tsunami forecast' model or 'forecast model' for brevity.

3.1 Forecast area

3.1.1 Ocean City as a barrier island

Barrier islands are dynamic landforms, subject to storm-surge flooding and sand transport processes. These coastal features are particularly vulnerable areas for human habitation, since they extend seaward of the mainland and are composed entirely of loose sediment (Leatherman, 1982). Like all ocean beaches, the beach at Ocean City exhibits a seasonal pattern. Winter storms erode the beach, while the calm waves of spring and summer rebuild it. In the long term, however, the shoreline has shown a slow but steady erosion trend. In the last 50 years, the beach has eroded over 30 meters (Titus et al., 1985). Studies by Leatherman (1985) and Everts (1985) have offered different explanation for the causes of this erosion, arguing the erosion is caused by either the long-term sea level rise or the substantial quantities of sand transported along the shore and old Fenwick Island. Leatherman (1985) identified another possible cause of the erosion due to the opening of Ocean City inlet, which was formed during a hurricane in 1933.

3.1.2 Ocean City Inlet and jetties

The Ocean City Inlet separated the Assateague Island into two sections at the southern end of Ocean City. Subsequent construction of two stone jetties to maintain the inlet for navigation interrupted the longshore transport of sand to the south. Since then, the jetties have trapped sand, building the Ocean City shores seaward by 250 meters by the mid-1970s (Dean and Perlin, 1977). In the contrast, the south of the inlet experienced sand starvation on the northern part of Assateague Island, which has migrated almost 700 meters landward and transformed the barrier into a low-relief, overwash-dominated barrier (Leatherman, 1979; 1984). Since 1988, the U.S. Army Corps of Engineers and National Park Service have been mechanically transferring sand from the inlet and the ebb and flood tide deltas, where the sand is trapped, to the shallow nearshore regions along the north end of Assateague Island, making the island barrier more robust. As this nourishment project continues, new sources of offshore sand are needed for future nourishment projects. However, the area of critical erosion caused by jetties continues to move southerly along the shoreline.

While trapping sands, the jetties also change the bathymetric features at the entrance of the Ocean City Inlet. A multibeam survey study by Buttolph et al. (2006) showed that the rehabilitation of the south jetty in 2002 has strengthened the ebb jet, causing the seaward ridge of the ebb shoal to migrate radially outward. Differences in measured bathymetry between the 2004 and 2005 surveys indicate that the shoal expansion may still be ongoing.

The width of Ocean City Inlet is about 340 m at its widest. Two jetties were constructed in 1934 and 1935, following the opening formed by the 1933 hurricane. The jetty on the

north side is about 335 m long with a crest elevation of 2.05 m above Mean High Water (MHW) and a crown width of 3.7 m. The total length of the dog-leg-shape jetty on the south side is about 730 m with a crest elevation of 1.15 m above MHW and a crown width of 2.7 m. Several repairs and rehabilitations were conducted on both jetties due to slope failures.

3.1.3 Ocean City tide gauge

The Ocean City tide gauge is located on a pier in a small boat basin (38.3282°N, 75.0917°W according to NOAA tides and currents), 350 m north of the inlet, on the west side of the Ocean City barrier island (**Figure 2**). Located at a water depth of 3.1 m (Mean High Water), the gauge is sheltered by a thin wall of piles that separate the boat basin from the inlet. This National Ocean Service (NOS) station was established on 5 June 1978, and upgraded to its present installation on 17 November 1997. The local mean tide range is about 0.65 m, and the diurnal range is 0.76 m.

3.2 Historical events and data

National Geophysical Data Center (NGDC)'s tsunami runup database (<http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=167&d=166>) shows that there have been a number of historical tsunamis affecting the coasts of Virginia, Maryland, Delaware, New Jersey and New York (**Figure 3** and **Table 1**). Only a small tsunami of 0.3-m wave amplitude was reported at Ocean City due to an earthquake-triggered submarine landslide in Grand Banks on the 18 November 1929.

The 1929 Grand Banks tsunami is notable for a number of reasons: this event is Canada's most tragic earthquake (M_w 7.2) with 28 lives lost (Ruffman, 1996); it was one of the very few catastrophic tsunamis, up to 27 m tsunami runup, to occur in the Atlantic; and it was one of the very few transoceanic tsunamis generated by a landslide (Pasad et al., 2009). Natural Resources Canada (2006) reported that "the earthquake triggered a large submarine slump (an estimated volume of 200 cubic kilometers of material was moved on the Laurentian slope), which ruptured 12 transatlantic cables in multiple places, and generated a tsunami. The tsunami was recorded along the eastern seaboard as far south as South Carolina and across the Atlantic Ocean in Portugal." Lockridge et al. (2002) reported that the Ocean City tide gauge recorded a change of approximately 0.3 m. Tide gauge records showed that it was also recorded at Atlantic City, New Jersey, with about the same height as Ocean City at these two locations, and on the tide gauge at Charleston, South Carolina.

Past tsunami waves that have affected the coasts from Virginia to New York had complex triggering mechanisms, including earthquake, landslide or meteorological events (**Table 1**). In some of these cases, shortly after the local earthquakes occurred, unusual tsunami-like waves were reported on coasts located within 200-kilometers distance from the earthquake location. Such earthquakes are the 1817 Philadelphia, 1840 Philadelphia, 1871 New York, 1884 New York, and 1895 New Jersey events. Some of the distant tsunamis that have impacted the Virginia-New York coasts were triggered by earthquakes in the Puerto Rico and the Hispaniola Trenches in the northeast of the Caribbean, such as the 1973 Mona Passage, 4 August 1946 Dominican Republic, and 8 August 1946

Dominican Republic events. Since they were all recorded by the tide gage in Atlantic City, NJ, where is only about 135 km northeast to Ocean City, Ocean City may have also been affected when these tsunami waves passed by. Except for the 1929 Grand Banks, trans-Atlantic tsunamis that may have produced impact on Ocean City is the 1755 Lisbon tsunami due to an M_w 8.5 – 9.0 earthquake (Barkan et al., 2008; Roger et al., 2009; Muir-Wood and Mignan, 2009). Runup reports from the 1755 Lisbon tsunami were documented in the Caribbean, Brazil and Newfoundland (Canada), and no reports were documented along the U.S. East Coast (Barkan et al., 2009). A model simulation of the Lisbon tsunami (see section 4.1 of this report) shows that the computed maximum wave amplitudes are about 30 cm along the Ocean City's shoreline and about 10 cm at the tide gage inside the inlet. The global reach of the catastrophic 26 December 2004 Indian Ocean tsunami was also recorded on the East Coast of United States, with 0.11 m at Atlantic City, NJ and 0.06 m at Cape May, NJ (Titov et al., 2005). Although Ocean City may not have detected distinct waves during the 2004 Indian Ocean tsunami, it is worth noting that large tsunamis can propagate substantial and damaging wave energy to distant coasts, including different oceans, through a combination of source focusing and topographic waveguides, and local resonant effects, which may strongly amplify the arriving waves too (Titov et al., 2005).

Other than confirmed earthquake-generated tsunamis, tsunami-like waves have also been recorded at tide gages in U.S. East Coast with unclear generation mechanisms. Some of them have been associated with passing hurricanes or meteorological pressure changes. For instances, tsunami-like waves were observed in Virginia when a category 4 hurricane passed over on 3 September 1821. When "heavy tides" were observed in Atlantic City on 10 June of 1913, they were unable to be linked to either storms or earthquakes (Lockridge et al., 2002). These types of waves were frequently seen on the coast of New Jersey and New York in 1923, 1924, 1931, 1932, 1938, 1944, and 1964. Some of them were attributed to either submarine landslides or abnormal weather events. Whether or not Ocean City has historically been affected by these tsunami-like waves remains unclear. Therefore, an inundation model is needed to equip the Ocean City area with the capability of tsunami forecasting and hazard assessment.

3.3 Model setup

3.3.1 Grid boundary and resolution

The wide continental shelf on the East Coast of United States complicates the modeling of tsunami waves approaching the shoreline. When a tsunami reaches continental shelf and begins to shoal, it will slow down and increase in height while introducing model diffusion and dispersion. Burwell et al. (2007) studied the diffusion and dispersion characterization of MOST model, and concluded that the nature of the scheme, at all resolvable wave numbers, is diffusive and dispersive for $\beta = (gd)^{1/2} \Delta t / \Delta x \neq 1$, where Δt is the temporal step and Δx is the space step. Diffusive effects are stronger for poorly resolved waves (large space step compared to wave length). As β decreases, diffusive effects are reduced and dispersion continues to increase. Thus, numerical dispersion can be an issue closer to shore, but can be controlled through a careful choice of β , or in other words, the ratio between Δt and Δx . The tsunami propagation database (Gica et al., 2008)

was developed at a grid spacing of 4-arc-minute (about 7.2 km at the equator) and saved at 16-arc-minute (about 28.8 km at the equator) resolution. This resolution may introduce large model diffusion effects if applied directly to continental shelf, where water depth is generally less than 100 m. The telescoped grids adopted in the MOST model are thus critical for wave transformation over the continental shelf, and for the inundation modeling at the coastline. Ideally, manipulation of β value may reduce the effects of diffusion and mimic the real-world dispersion through numerical dispersion.

The outmost grid (A grid as referred hereafter) provides a smooth transition from tsunami propagation database to the inundation forecast model. As stated above, this boundary connection must not occur over the continental shelf, and must extend further beyond the continental shelf, where the numerical diffusion can be significantly reduced during the transition. **Figure 4** shows a sensitive study of the wave amplitude difference between a 1-arc-min (~ 1.5 km at latitude 38 degree) and 30-arc-sec (~ 750 m at latitude 38 degree) grid resolutions along different transects for the synthetic tsunami scenario ATSZ 46-55. When the eastern boundary of A grid is placed at 71.5°W (section A-A'), the wave amplitude difference is mostly negligible over time (**Figure 4**) with a root-mean-square of 0.53 cm after 7-hours of model run time between the two resolutions. As the boundary is moved closer to the coastline, the difference increases as more shelf area is taken into account, with most of the differences occurring in the portion over the shelf along the transects. When the eastern boundary is placed at 75°W , the root-mean-square of the difference is 18.2 cm, nearly 35 times the amplification of the differences when the deep-ocean boundary is placed at 71.5°W . To save model computational time, the entire eastern boundary of the intermediate grid (B grid as referred hereafter) is located on the shelf between transects E-E' and F-F', where differences were up to 50 cm. A 30-arc-second (~ 750 m at latitude 38 degree) resolution was implemented for grid A to provide more accurate boundary conditions for grid B. The eastern boundary of grid A is also placed at longitude 71°W , beyond the continental shelf, in order to minimize the numerical diffusion, as discussed above.

3.3.2 Digital Elevation Model of Ocean City

Medley et al. (2009) at the National Geophysical Data Center (NGDC) developed a 1/3-arc-sec (~ 8 m at latitude 38 degree) digital elevation model of Ocean City, Maryland. The bathymetry was developed based on the hydrographic survey data from NGDC's NOS Hydrographic Survey Database and US Army Corps of Engineers (USACE) survey. The topographic datasets incorporated the Coastal Service Center (CSC) Lidar data since 2000. Medley et al. (2009) also evaluated but did not use the Shuttle Radar Topographic Mission (SRTM) Elevation 1-arc-second DEM from USGS. The Ocean City Inlet jetty on Assateague Island was digitized using ArcMap, based on USGS jetty shapefile, and was included in the final coastline. Medley et al. (2009) also stated that many of the inlets and harbors in Ocean City Harbor had not been surveyed, and therefore do not have accurate depths. These have been manually assigned a water depth of 2 m for the inlets and 3 m for the harbor.

The bathymetry and topography used in the development of this forecast model was based on a digital elevation model provided by the National Geophysical Data Center and

the author considers it to be an adequate representation of the local topography/bathymetry. As new digital elevation models become available, forecast models will be updated and report updates will be posted at http://nctr.pmel.noaa.gov/forecast_reports/.

As aforementioned, the Ocean City tide gage is located in a small boat basin in the inlet, and is protected by a thin-wall of piles, which cannot be seen in the 1/3-arc-sec grid. **Figure 5a** shows the shoreline at the boat basin, which was clearly missing from the 1/3-arc-sec grid. In the present development, these piles were manually constructed to mimic the real-world sheltering of the tide gage (**Figure 5b**), although they may have been enlarged to fit the grid points.

3.3.3 Development of model grids

Development of an optimized tsunami forecast model for Ocean City began with the spatial extent merged bathymetric/topographic grids shown in **Figure 6-10**. A significant portion of the modeled tsunami waves, typically 4 to 10 hr of modeled tsunami time, pass through the model domain without appreciable signal degradation. **Table 2** provides specific details of both reference and tsunami forecast model grids, including extents and complete input parameter information for the model runs is provided in **Appendix 1**.

Figure 6 shows the coverage of the A grid, which has a spatial resolution of 30 arc seconds (~ 750 m at 38°N). It is used in both the optimized tsunami forecast model and the reference model. This grid is obtained from the Pacific 30-sec database. For the reasons that were laid out in section 3.3.1, the eastern boundary of the A grid is specified at 71°W , where the water depth ranges from 2,000 m to more than 4,000 m. The northeastern corner of the grid almost reaches the toe of the shelf. One can see the abrupt depth change, from 2,000 m to less than 100 m, along the continental slope. The continental shelf extends more than 100 km offshore, typically with water depths of less than 100 m and with 80% of the shelf shallower than 50 m. This grid entirely encompasses two large water bodies, Delaware Bay and Chesapeake Bay, in order to reduce the artificial effects introduced by un-natural model boundaries.

Figure 7 and **Figure 8** show the bathymetry and topography of B grid for the optimized forecast model and the reference model. The two grids have the same model extent (**Table 2**) but different grid resolutions, 12 arc second (~ 290 m at latitude 38°) for the forecast model and 3 arc second (~ 73 m at latitude 38°) for the reference model. Both grids were obtained from the Ocean City 1/3-arc-sec DEM developed by NGDC (Medley et al., 2009). The eastern boundary of the B grid is located about 40 km offshore of Ocean City with a maximum water depth of 40 m. Fenwick Island and the Assateague Island are also fully entirely encompassed, and Ocean City is located at the center of B grid to reduce the numerical errors introduced by the boundary between A and B grids. The high grid resolution clearly shows the sand ripples offshore, caused by the long-term longshore sediment transport, and these may be important bathymetric features affecting tsunami propagation within the continental shelf.

To satisfy the model computing time requirement, the C grid of the optimized forecast model has a smaller coverage than that of the reference model. Although the south boundary of the forecast model includes only the northern part of Assateague Island, where there are no residents, the forecast model covers the entire 13-kilometer barrier island of Ocean City to the north. To adequately describe the Ocean City inlet jetties and the boat basin hosting the tide gage, a 1.5-arc-sec (~ 36 m at latitude 38 degree) spatial resolution was employed in the forecast model, while a 1/3-arc-sec (~ 8 m at latitude 38 degree) space resolution is used in the reference model. Both grids were based on the Ocean City 1/3-arc-sec DEM developed by NGDC (Medley et al., 2009). The eastern boundary of the forecast model is located about 8 km offshore of the Ocean City coastline with a maximum water depth of 20 m (**Figure 9**). Other than the noticeable sand ripples formed by the longshore sediment transport, Figure 8 and 9 shows the DEM clearly describes the ebb shoal at the inlet entrance due to the rehabilitation of the south jetty (Buttolph et al., 2006). The reference model has broader boundaries on the southern, eastern and northern sides than the forecast model (**Figure 10**), which provides accurate model reference to confirm whether the boundary selection of forecast model affects the modeling results.

The boat basin hosting the tide gage has a fairly small dimension of 35 m (east-west) by 70 m (south-north), which can barely be represented by one grid node (~ 36 m in east-west dimension and 50 m in south-north dimension) in the forecast model. The thin wall of piles (less than 1-m wide) separating the boat basin from the inlet is therefore ignored at this level of grid resolution. However, this wall is manually added in the reference model, to be of the same length but wider than the real size (**Figure 5**). This way, the reference model can be used to evaluate the forecast model by comparing model results both at the entrance and inside the boat basin; this will be discussed in the next section.

4. Results and Discussion

4.1 Model validation

Lack of tsunami measurements in the Atlantic is a major issue of model validation for the tsunami forecast models developed for U.S. East Coast and Caribbean. An alternative approach is to employ model-to-model comparison. Unfortunately, other than this study, no known tsunami modeling for Ocean City has been conducted by any tsunami modeling or research group. Another crude validation technique is to test the model with a historical case where tsunami impact is well known at the modeling site or its vicinity, and consider the model is validated if this model gives no “surprising” results. The 1755 Lisbon tsunami is a representative case for such a model validation for Ocean City.

The earthquake source of the 1755 Lisbon tsunami is not fully understood. Previous studies have proposed several source mechanisms that may have potentially produced this basin-wide tsunami. The magnitude of the proposed earthquakes ranges from 8.0 to 9.0 (Barkan et al., 2009; Muir-Wood, 2009; Titov et al., 2009; Roger et al., 2009), while the rupture area varies between 6000 km² and 480000 km². Titov et al. (2009) compared five tsunami scenarios for different earthquake sources, and they all indicate that the tsunami impact on U.S. East Coast is minor, and is not reported or documented anywhere in United States. The preferred scenario is that of Barkan et al. (2009), which produced

very similar result after comparing the tsunami records at many places in the Atlantic, particularly in the Caribbean (**Figure 11** and **Figure 12**).

This report uses the Barkan et al. (2009) scenario as a model “validation” case study for the Ocean City models. **Figure 13** shows the computed time series at the tide gage location of Ocean City. One can see that the maximum wave amplitude is about 10 cm, and the maximum wave height is about 25 cm. A tsunami of this amplitude or height, along with a 15 to 20 minutes wave period, cannot produce a significant coastal impact on the Ocean City and should be considered as a “no surprise” result. The computed maximum wave amplitude and maximum current speed in **Figure 14** indicates two offshore areas where the highest wave amplitudes of 40 cm occur: the northern part of Assateague Island up to the south jetty of the Ocean City Inlet, and the central-north of Ocean City. Both models indicate no tsunami inundation. The computational results show high-speed currents up to 50 cm/sec (about 1 knot) in the Ocean City inlet, which provides the only access point for tsunami waves to enter through the barrier islands. The currents induced by tsunami waves move faster when they pass by the offshore ripples and the ebb shoals at the inlet entrance. As the forecast model was tested for a 24-hour run, one can see that the tsunami energy has largely reduced after it passes the narrow channels and enters the ambient water body behind the barrier islands.

However, as mentioned in 3.1.1, the shoreline of Assateague Island and Fenwick Island has experienced significant changes - the two barrier islands were connected before 1850 (and before 1933 when the inlet was formed, **Figure 15**). It is noted here that to achieve a realistic model validation, the 1755 Lisbon tsunami should have been modeled based on the shoreline before 1850. However, we used the present model setup of Ocean City for this “validation” here since there are no measurements with which a comparison can be made. It may be more meaningful to evaluate the potential tsunami impact with the present model setup when struck by the 1755 Lisbon event or a similar tsunami in the future.

The results obtained from both the optimized forecast model and the reference model, when compared to each other, show a close match in wave amplitude, wave period, arrival time, and current speed. The computed time series at the tide gage (**Figure 13**) obtained from the reference model shows slightly deeper troughs than those from the forecast model, probably due to the different grid resolutions implemented for the small boat basin. **Figure 14** shows that the forecast model represents the reference model very well despite the former computing the tsunami dynamics over a smaller domain and with coarser grid resolution. The error introduced from the boundary of C grid is negligible.

4.2 Model stability testing using synthetic scenarios

Model stability testing using synthetic scenarios provides important case studies to test the robustness, durability, and efficiency of the developed models in the following ways:

1. Synthetic scenarios that examine the developed models' dynamics under extreme tsunami conditions. Scenarios are, usually generated by mega earthquakes or landslides, to check model stability under these conditions, and to ensure the efficiency of the forecast model during a catastrophic event.

2. Synthetic scenarios that also examine the developed models with tsunamis of medium size (amplitude and velocities). Scenarios are generated by intermediate-size earthquakes, to check model stability under small wave conditions, and to ensure the efficiency of the forecast model during a moderate event.
3. Synthetic scenarios that examine the developed models with tsunami forcing of negligible size (amplitude and velocities). Such scenarios are generated by insignificant earthquakes in distance, to guarantee the modeling results are not interfered with by the numerical noise.
4. The synthetic scenarios were selected in such a way that there is at least one test from each potential tsunami source zone. These cases are used to examine the reliability of the developed models in response to the directionality of tsunami waves.

Table 3 summarizes the synthetic scenarios (plotted in **Figure 12**) used in the model testing. Except for the 1755 Lisbon (used as a model validation in section 4.1), other scenarios were artificially constructed from the combination of the unit sources, shown as black boxes. Table 3 gives the details of the unit sources used and their scaling coefficient for a total of eight scenarios, six with magnitude 9.3, one with magnitude 7.5 and one no-wave. Five of the magnitude-9.3 cases were selected in the Puerto Rico Trench and Hispaniola Trench since they are considered the most dangerous tsunamigenic earthquake zones in the Atlantic (ten Brink et al., 2007). The earthquake zones between the Caribbean and South American plates have been relatively inactive, and tsunami waves generated there have minor impact on the U.S. East Coast, based on the tsunami hazard assessment study by Titov et al. (2009, Chapter 2). Therefore, no synthetic scenarios were selected from this area. The magnitude-9.3 scenario from South Sandwich source zone was used as a stability test in response to different tsunami directionalities.

The synthetic scenario ATSZ 48-57, generated by an M_w 9.3 earthquake from Puerto Rico Trench that is akin to the 2004 Indian Ocean tsunami, would create catastrophic impact to Ocean City. The modeling results in **Figure 16** show that Fenwick Island and Assateague Island would be almost entirely flooded by waves up to 6 meters at the coastline. Occurring between four and five hours after the tsunami waves are generated, the flood waters impact upon the two barrier islands with strong currents at speeds of more than 5 to 6 m/s on land. After rushing into the inlet, the waves further inundate part of the coastline of West Ocean City on west bank of the inlet (**Figure 16 b**). The jetties at the inlet are both overtopped by the incoming waves. Figure 16 shows the waves amplified grow rapidly (indicated by the red and purple color) within the five-km shallow shelf seaward from the shoreline, reaching their maximum at the shoreline. The time series indicates a dominant first wave up to 1.4 m high at the tide gage followed by a series of smaller waves with a maximum trough of 1 m (**Figure 17**). The modeled time series after 12 hours demonstrates a lengthening wave period from 20 minutes to two hours, indicating possible wave resonance in the inlet. The time series computed by forecast model agrees with that of the reference model, except it shows shallower troughs.

The synthetic scenario ATSZ 38-47, despite having the same magnitude as synthetic scenario ATSZ48-57, has minor impact on the coastline of Ocean City with maximum wave amplitudes up to 2 m. The northern tip of the Assateague Island and south to the southern jetty show minor flooding at the shoreline. After passing the jetties, the induced tsunami waves enter the inlet with attenuated wave amplitudes up to 0.8 m but high current speeds up to 3 m/s (**Figure 18 c** and **Figure 18 d**). Except for the inlet entrance near where the ebb shoal is located, the current speed along the shoreline is less than 1 m/s. The wave amplitude near the inlet entrance is generally larger than that everywhere else. The maximum tsunami amplitude is about 0.5 m at the tide gage. Also in contrast to ATSZ 48-57, there is no obvious wave resonance computed in the train of late waves after 12 hours (**Figure 19**).

With similar fault orientation and location, the synthetic scenarios ATSZ 58-67 and ATSZ 82-91 give analogous computational results at Ocean City. Both scenarios show minor inundation on the west side of Assateague Island and south of Ocean City harbor. **Figure 20** and **Figure 22** indicate in both scenarios waves up to 1 m in amplitude and current flows up to 0.2 m/s along the coastline. The narrow opening at the inlet entrance speeds the flow to about 2 m/s, which, in turn, affect the current fields in the south and north channels of the inlet on the west of the barrier islands, including the small boat basin hosting the tide gage. A notable feature of the time series at the tide gage in both scenarios (**Figure 21** and **Figure 23**) is the leading depression N-waves (Tadepalli and Synolakis, 1994), which propagates from the tsunami source. Unlike the Puerto Rico Trench and the Hispaniola Trench, where the North America plate was subducting southwesterly beneath the Caribbean plate, the geological setting at ATSZ 58-67 and ATSZ 82-91 features submarine troughs – the Cayman Trough at ATSZ 58-67 and Los Muertos Trough at ATSZ 82-91. The Cayman Trough is a complex transform fault zone bounded by strike-slip faults, while the Los Muertos trough is formed by northerly dipping Caribbean Plate and associated seismic zones (in contrast to the south-dipping Puerto Rico – Lesser Antilles subduction zone described in LaForge and McCann (2005)). The northerly dipping of the Los Muertos Trough results in an uplift at its south, but a subsidence at the north, which corresponds to the leading depression when the tsunami waves propagate in the Atlantic. ATSZ 58-67 in the Cayman Trough disturbs the water surface in a similar, but more conservative way by simulating these faults using a subducting mechanism rather than a strike-slip mechanism.

The synthetic scenario of ATSZ 68-77 is a special case that highlights two important characteristics of tsunami waves: wave period and late waves. The computed time series at the Ocean City tide gage shows that the wave period of ATSZ 68-77 scenario, approximately one and half to two hours in length, is considerably longer than most other tsunami waves. The wave amplitude did not reach its maximum until almost 20 hours after the tsunami was generated, while the first wave had arrived about six hours into the event. When comparing the modeling results between the forecast model and the reference model for the first nine hours, one can see excellent match in both the computed wave amplitude and flow speed (**Figure 24** and **Figure 25**), although the latter was only computed up to nine hours after the tsunami was generated. **Figure 26** shows the computed maximum wave amplitude and flow speed after a 24-hour model run, which indicates greater tsunami impact in the coast of Ocean City due to larger late

waves that are obviously not present in the nine-hour modeling results. The synthetic scenario of ATSZ 68-77 stresses the need of retaining the tsunami warning or watch for more than 24 hours for the coasts of Ocean City during a real tsunami event.

Excellent agreement was also found between the forecast model and reference model for the synthetic scenario of SSSZ 1-10 (**Figure 27** and **Figure 28**), which represents a Mw 9.3 earthquake-generated tsunami waves from South Sandwich source zone. The model results show wave amplitudes of 50 to 80 cm along the coastline and the flow speeds in the inlet of approximately 1 m/s. The maximum wave amplitude at the tide gauge is only of the order of 25 cm and there is very limited impact to the coastline. Similar to ATSZ 68-77, the largest wave arrives about five hours later than the first wave, probably due to the reflected waves from Africa.

The synthetic scenario of magnitude 7.5, ATSZ b52, produces wave amplitudes up to 5 cm along the shoreline of Ocean City, and 1 cm at the tide gauge. Both the forecast model and reference model show good agreement and stability in terms of maximum wave amplitudes, flow speed (**Figure 29**) and the time series at the tide gauge (**Figure 30**).

5. Summary and conclusions

Ocean City of Maryland is a city built on a strip of barrier islands in the Atlantic. While providing popular recreation to attract tourists from all over the world, Ocean City is also known for its vulnerability to potential coastal hazards such as beach erosion, sea level change, storm surge and tsunamis, which pose challenging, yet long-standing tasks for the Ocean City community on how to protect lives and property. Previous studies for Ocean City have assessed the hazards posed by, and developed forecast methodologies for beach erosion, sea level change and storm surge. However, tsunami forecast and hazard assessment in Ocean City remains significantly understudied, probably due to the minor impact and infrequent occurrence of tsunamis throughout Ocean City's history.

The tsunami forecast model developed in this study for the community of Ocean City, Maryland is being implemented into NOAA's tsunami forecast system. It will provide real-time modeling forecasts of tsunami wave characteristics, runup and inundation along Ocean City's coastline. Discussion of the details of each of the individual components of the forecast model, including the bathymetry and topography, the basic model setup, and the model parameters are provided in the report. The forecast model employs grids as fine as 36 m and can accomplish a four-hour simulation after tsunami arrival in 20 minutes of computer CPU time. A reference model was developed in parallel using grids as fine as 8 m to provide a basis for evaluating the performance of the forecast model.

Due to a lack of historical tsunami records, the 1755 Lisbon tsunami is used as a model validation case to show the Ocean City models do not produce "surprising" results. Based on the Barkan et al. (2009) source of the 1755 tsunami, the modeling results showed a 40 cm maximum wave amplitude in the nearshore of Ocean City and 10 cm at the tide gauge, with no tsunami inundation. The highest current speed was about 50 cm/sec in the Ocean City inlet. It is noted that the modeling in Ocean City of 1755 Lisbon tsunami was based on present bathymetric and topographic features, instead of those present at that time, when Fenwick Island and Assateague Island were connected before the storm opened an

inlet between them in 1933. The results from both the forecast model and the reference model showed excellent agreement in wave amplitude, wave period, arrival time, and current speed.

A total of eight synthetic scenarios, including six of catastrophic and one of small-size, were used to examine the stability of the developed forecast model and reference model for Ocean City. The synthetic scenarios were selected in such a way that at least one from each of the Puerto Rico Trench, Hispaniola Trench and South Sandwich source zones were tested. Both the forecast model and reference model give stable, and consistent between the two models. The results for the synthetic scenarios encompass tsunami waves emanating from different source locations and different directionalities. Other than testing the model stability, these synthetic scenarios are also useful in summarizing some of the characteristics common to tsunami waves generated from these source zones.

1. A magnitude of 9.3 earthquake in Puerto Rico Trench, represented by ATSZ 48-57 in this report, may generate a catastrophic tsunami for many communities in the Atlantic coast of United States. The modeling results show such a tsunami inundated most of the barrier islands, upon which Ocean City is built on, with a maximum wave amplitude of 6 m along the coastline and 5 to 6 m/s current speed on land.
2. Tsunamis caused by a magnitude of 9.3 earthquake from other source zones pose less threatening impacts on Ocean City. These source zones include the Lesser-Antilles (scenario ATSZ 38-47), Hispaniola Trench (scenario ATSZ 58-67), Cayman Trough (scenario ATSZ 68-77), Los Muertos Trough (scenario ATSZ 82-91) and South Sandwich source zone (scenario SSSZ 1-10).
3. Tsunamis generated from submarine troughs display a leading depression when propagating in the Atlantic toward U.S. East Coast. The northerly dipping of the Los Muertos Trough (scenario ATSZ 82-91) results in uplift at its south, but subsidence at the north, which corresponds to the leading depression. The faults in Cayman Trough (scenario ATSZ 68-77) were simulated using a subducting mechanism rather than a strike-slip mechanism.
4. For tsunamis generated in the Cayman trough or in South Sandwich source zone, the model simulations show the late waves are higher than the first waves and may pose larger impact to Ocean City's coastline. Along with these waves are longer wave period up to one and half hours. This demonstrates the need of retain the tsunami warnings or watches for more than 24 hours for the coasts of Ocean City during a real tsunami event.

All model validation and stability tests demonstrated that both the forecast and reference models for Ocean City, Maryland, are robust and efficient in their application towards both the short-term real-time forecasting of tsunami and the long-term investigation of the tsunami inundation, although model accuracy still requires validation using future real events. The optimized forecast model developed for Ocean City, Maryland provides a four-hour forecast of first wave arrival, amplitudes, and inundation within 20 minutes based on the testing presented in this report.

6. Acknowledgements

The author wish to thank Edison Gica and Jean Newman for their work with the propagation database, Burak Uslu for providing propagation database tabular unit source information and graphics, and the entire modeling group of NCTR for helpful suggestions and discussion. The author especially acknowledges and thanks Marie C. Eble for providing invaluable technical assistance and for editorial review. Collaborative contribution of the National Weather Service, the National Geophysical Data Center, and the National Data Buoy Center were invaluable.

Funding for this publication and all work leading to development of a tsunami forecast model for Kodiak, Alaska was provided by the National Oceanic and Atmospheric Administration. This publication was partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement NO. NA17RJ1232, JISAO Contribution No. 1763. This is PMEL Contribution No. 3343.

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Tables:

Table 1: Historical tsunami events that have affected the central north of the U.S. East Coast, including Ocean City, Maryland.

Table 2: MOST setup parameters for the reference and forecast models for Ocean City, Maryland.

Table 3: Synthetic tsunami events – Atlantic.

Table 1. Historical tsunami events that have affected central north of U.S. East Coast, including Ocean City, Maryland

Event	Date, Time (UTC), Epicenter	Magnitude	Earthquake source area
1755 Lisbon	01 Nov. 10:16:00, 36.0°N 11.0°W	8.5 – 9.0	Portugal: Lisbon
1817 Philadelphia	08 Jan, 39.95°N 75.1°W	?	Philadelphia
1821	03 Sep	/	Meteorological
1840 Philadelphia	11 Nov, 39.8°N 75.2°W	5.2	Philadelphia
1871 New York	18 Jun, 40.5°N 73.9°W	?	New York
1884 New York	10 Aug 10:07:00, 40.6°N 73.75°W	5.5	New York
1895 New Jersey	1 Sep 11:09:00, 40.667°N 74.883°W	4.3	New Jersey
1913	9 Jun	/	Unknown
1918 Puerto Rico	11 Oct 14:14:00 18.5°N 67.5°W	7.3	Atlantic (ATSZ)
1923	6 Aug	/	Unknown
1924	8 Aug	/	Unknown
1929 Grand Banks	18 Nov 20:32:00, 44.69°N 56.0°W	7.2	Canada: Grand Banks
1931	19 Aug	/	Meteorological
1932	10 Nov	/	Meteorological
1938	21 Sep	/	Meteorological
1944	14 Sep	/	Meteorological
1946 Dominican Republic	4 Aug 17:51:6.0, 19.3°N 68.9°W	7.8	Atlantic (ATSZ)
1946 Dominican Republic	8 Aug 13:28:0.0, 19.71°N 69.51°W	7.4	Atlantic (ATSZ)
1964	19 May	/	Possibly a submarine landslide
2004 Sumatra	26 Dec 00:58:53.4, 3.295°N 5.982°E	9.0 - 9.3	Indian Ocean (IOSZ)

Table 2: MOST setup parameters for reference and forecast models for Ocean City, Maryland.

		Reference Model				Forecast Model			
Grid	Region	Coverage Lat. [°N] Lon. [°W]	Cell Size [“]	nx x ny	Time Step [sec]	Coverage Lat. [°X] Lon. [°X]	Cell Size [“]	nx x ny	Time Step [sec]
A	Central north of U.S. East Coast	36.5 - 39.7 77.5 - 71.0	30”	781 × 385	3.2	36.5 - 39.7 77.5 - 71.0	30”	781 × 385	3.6
B	East of Maryland and Delaware	37.75-38.85 75.5 - 74.75	3”	901 × 1321	2.8	37.75-38.85 75.5 - 74.75	12”	226 × 331	12.6
C	Ocean City	75.1749878 - 74.9500122	1/3”	2431 × 2809	0.4	38.30 -38.42 75.175 - 75.0	1.5”	421 × 289	1.8
Minimum offshore depth [m]				1.0		1.0			
Water depth for dry land [m]				0.1		0.1			
Friction coefficient [n ²]				0.0009		0.0009			
CPU time for 4-hr simulation				~ 37 hours		~ 20 minutes			
Computations were performed on a single Intel Xeon processor at 3.6 GHz, Dell PowerEdge 1850.									

Table 3. Synthetic tsunami events – Atlantic

Sce. No	Scenario Name	Source Zone	Tsunami Source	α (m)
Mega-tsunami scenario				
1	ATSZ 38-47	Atlantic	A38-A47, A38-A47	25
2	ATSZ 48-57	Atlantic	A48-A57, B48-B57	25
3	ATSZ 58-67	Atlantic	A58-A67, B58-B67	25
4	ATSZ 68-77	Atlantic	A68-A77, B68-B77	25
5	ATSZ 82-91	Atlantic	A82-A91, B82-B91	25
6	SSSZ 1-10	South Sandwich	A1-A10, B1-B10	25
Mw 7.5 Scenario				
7	ATSZ B52	Atlantic	B52	1
Micro-tsunami Scenario				
8	SSSZ B11	South Sandwich	B11	0.01

Figures:

Figure 1. (a) Aerial view of Fenwick Island, upon which Ocean City is built, and Assateague Island; (b) Closer aerial view of Ocean City Inlet.

Figure 2. Location of Ocean City tide gauge. (a) Google aerial view of south end of Ocean City and the Ocean City Inlet; (b) Location of the Ocean City tide gauge - area indicated by the red box in (a); (c) Location of Ocean City tide gauge within the boat basin (photo courtesy of <http://tideandcurrents.noaa.gov>).

Figure 3. Historical tsunami events that have affected central north of U.S. East Coast, The earthquake location are indicated by ● and The meteorological tsunamis are indicated by 'M'. The black boxes are the tsunami propagation unit sources (Gica et al., 2008).

Figure 4. Computed wave amplitude difference between 1-arcmin and 30 arcsec resolutions along transects in the A grid.

Figure 5. (a) Comparison of the shoreline from the DEM developed by NGDC with an aerial photo by Google. Note how the boat basin is missing from the NGDC DEM. (b) Shoreline comparison after the piles of the boat basin were manually constructed in the 1/3-arc-second grid.

Figure 6. A-grid bathymetry and topography for both the forecast model and the reference model, where the black boxes indicate the coverage of B grid and C grid. The red circle indicates the location of Ocean City tide gauge.

Figure 7. B-grid bathymetry and topography for the forecast model, where the black box indicate coverage of the C grid in forecast model. The red circle indicates the location of Ocean City gauge.

Figure 8. B-grid bathymetry and topography for the reference model, where the black box indicate coverage of C grid in forecast model. The red circle indicates the location of Ocean City tide gauge.

Figure 9. C-grid bathymetry and topography for the forecast model, where the red circle indicates the location of Ocean City tide gauge.

Figure 10. C-grid bathymetry and topography for the reference model, where the red circle indicates the location of Ocean City tide gauge.

Figure 11. Tsunami energy projection (or computed maximum wave amplitude) of the 1755 Lisbon tsunami in the Atlantic.

Figure 12. Model scenarios used in model validation and model stability testing. Parameters of the model scenarios are listed in Table 3.

Figure 13. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for 1755 Lisbon tsunami. The upper panel is a enlarged view of eight to 16 hours in the lower panel.

Figure 14. Computed maximum wave amplitude and maximum current speed in the C grid for the 1755 Lisbon tsunami. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 15. Aerial photo of northern Assateague Island and Ocean City, Maryland showing former barrier positions. Note that in 1850, a single barrier island, shown in outlined in yellow, occupied this stretch of coast. In 1933, Ocean City inlet was created by a hurricane. By 1942, the barrier south of the inlet had migrated landward (show as a green shaded region). Courtesy: Titus et al. (2009).

Figure 16. Computed maximum wave amplitude and maximum current speed in the C grid for the ATSZ 48-57 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in C grid computed with the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 17. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for the ATSZ 48-57 scenario. The upper panel is an enlarged view of two to ten hours in the lower panel.

Figure 18. Computed maximum wave amplitude and maximum current speed in the C grid for the ATSZ 38-47 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 19. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for the ATSZ 38-47 scenario. The upper panel is an enlarged view of two to ten hours in the lower panel.

Figure 20. Computed maximum wave amplitude and maximum current speed in the C grid for the ATSZ 58-67 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the

computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 21. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for the ATSZ 58-67 scenario. The upper panel is an enlarged view of two to ten hours in the lower panel.

Figure 22. Computed maximum wave amplitude and maximum current speed in the C grid for the ATSZ 82-91 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 23. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for the ATSZ 82-91 scenario. The upper panel is an enlarged view of two to ten hours in the lower panel.

Figure 24. Comparison of computed time series between forecast and reference models at the Ocean City tide gauge for the ATSZ 68-77 scenario. The upper panel is an enlarged view of three to 11 hours in the lower panel.

Figure 25. Computed maximum wave amplitude and maximum current speed of the first nine hours after tsunami arrival in the C grid for the ATSZ 68-77 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 26. Computed maximum wave amplitude and maximum current speed of 24 hours after tsunami arrival in the C grid for the ATSZ 68-77 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

Figure 27. Computed maximum wave amplitude and maximum current speed in the C grid for the SSSZ 1-10 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

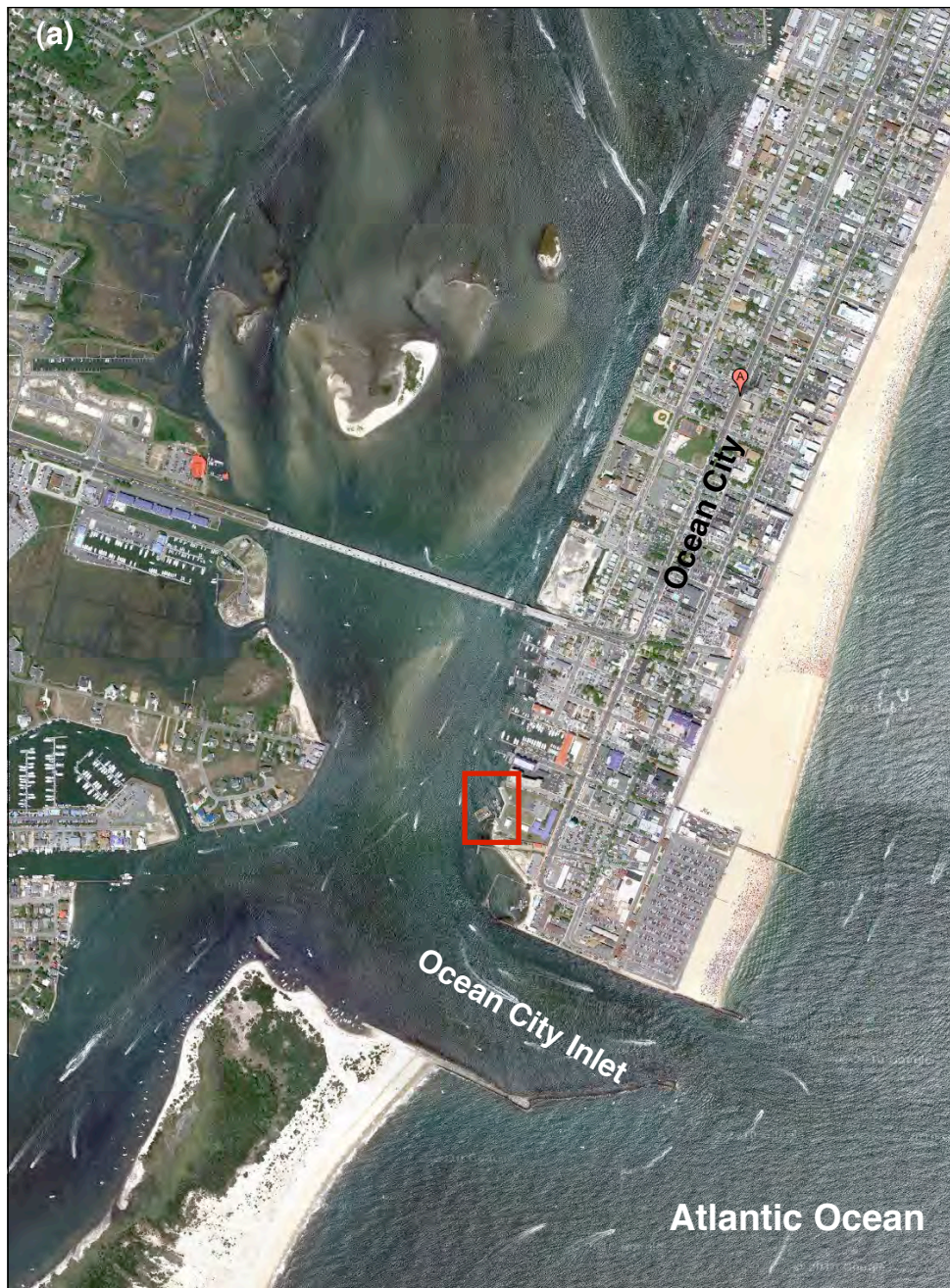
Figure 28. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for the SSSZ 01-10 scenario. The upper panel is an enlarged view of 16 to 24 hours in the lower panel.

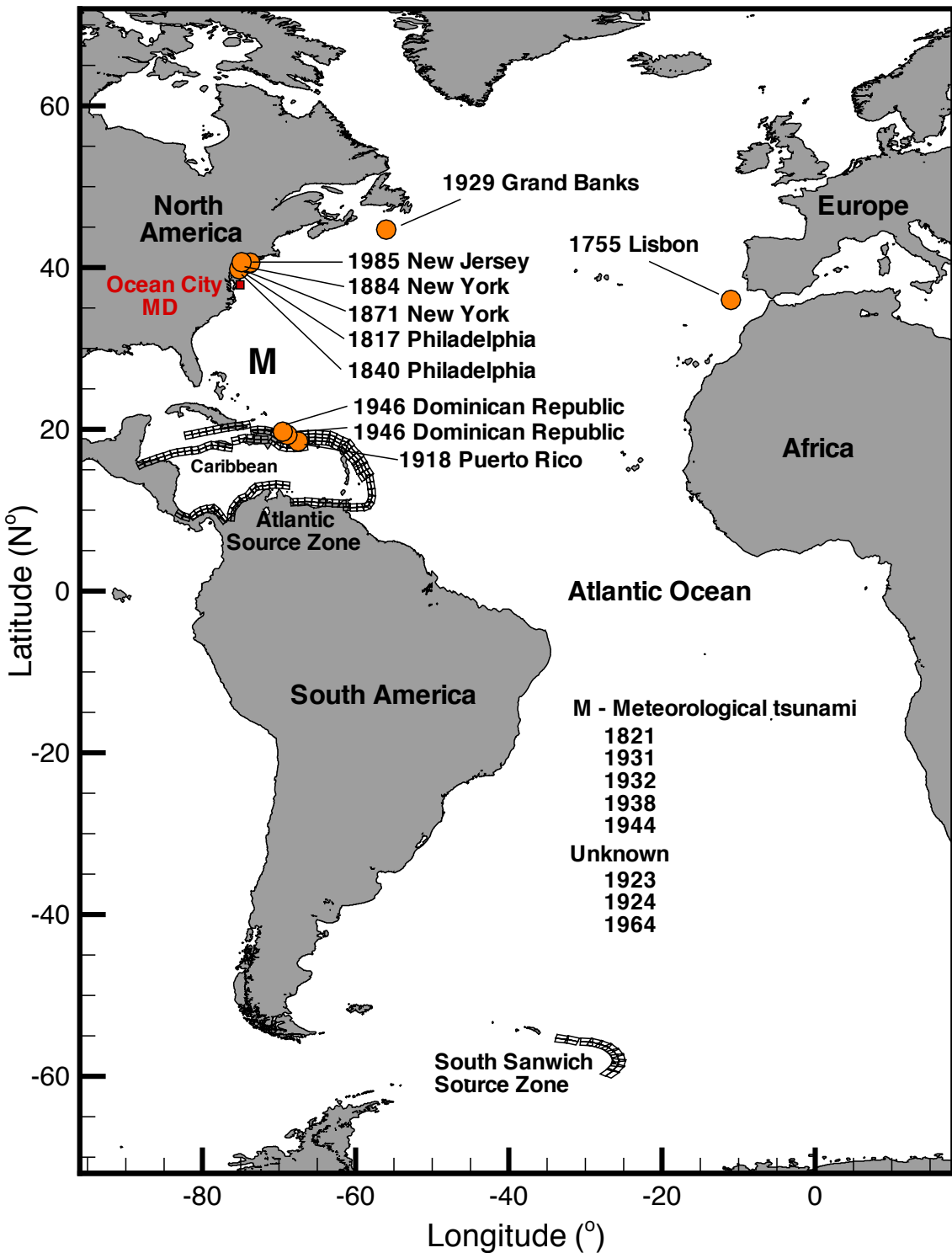
Figure 29. Computed maximum wave amplitude and maximum current speed in the C grid for the ATSZ B52 scenario. (a) Maximum wave amplitude in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (b) maximum wave amplitude in the C grid for the forecast model; (c) maximum current speed in the C grid for the reference model, where the black box indicates the computational domain of the forecast model; (d) maximum current speed in the C grid for the forecast model.

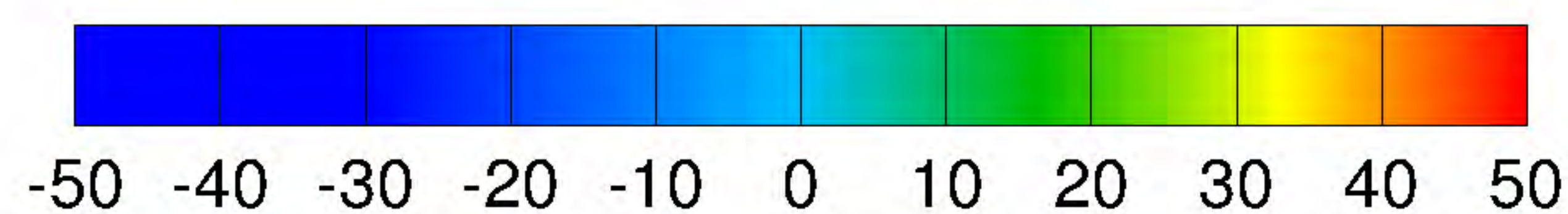
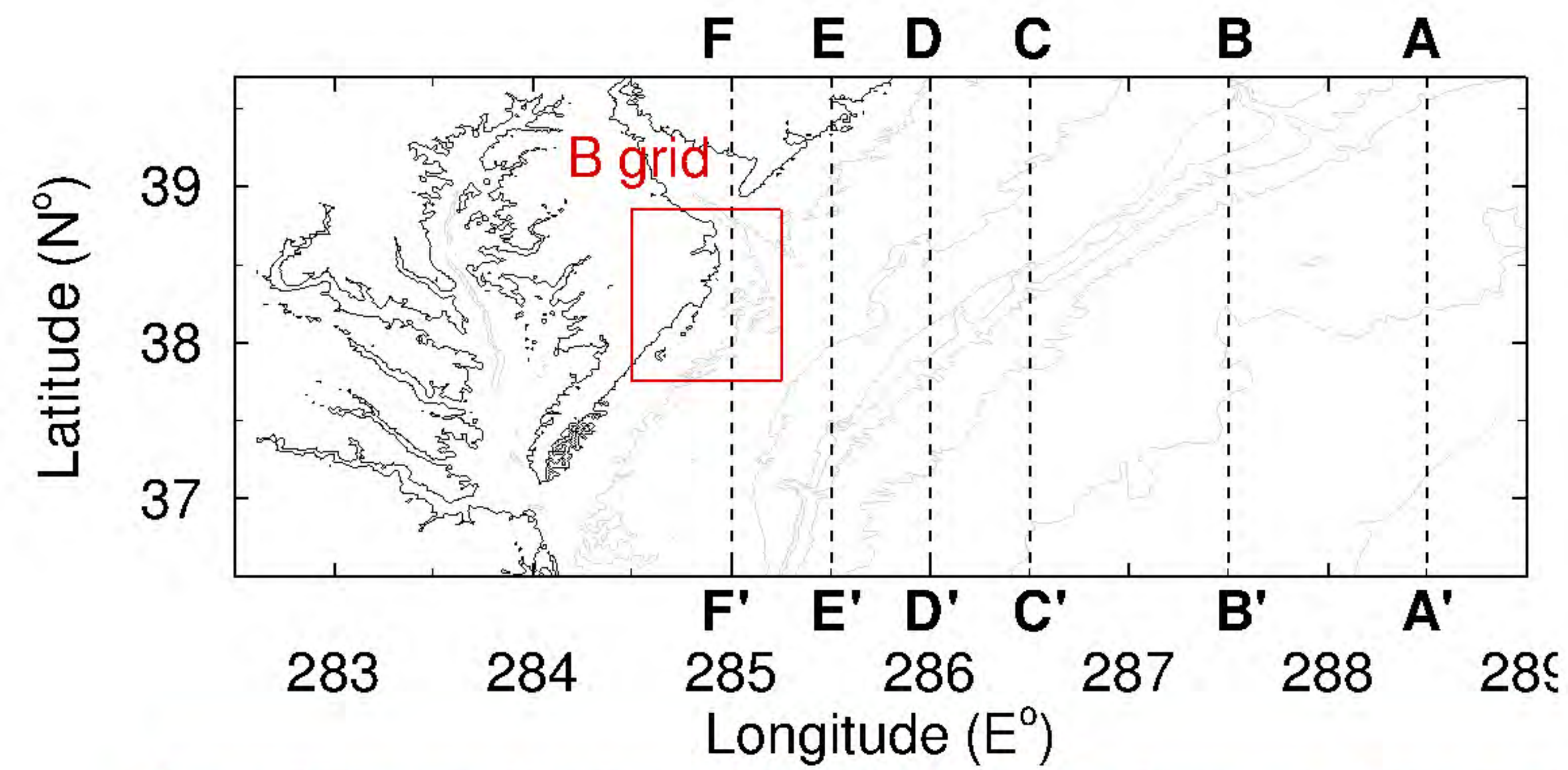
Figure 30. Comparison of computed time series between the forecast and reference models at the Ocean City tide gauge for the ATSZ B52 scenario. The upper panel is an enlarged view of three to 11 hours in the lower panel.



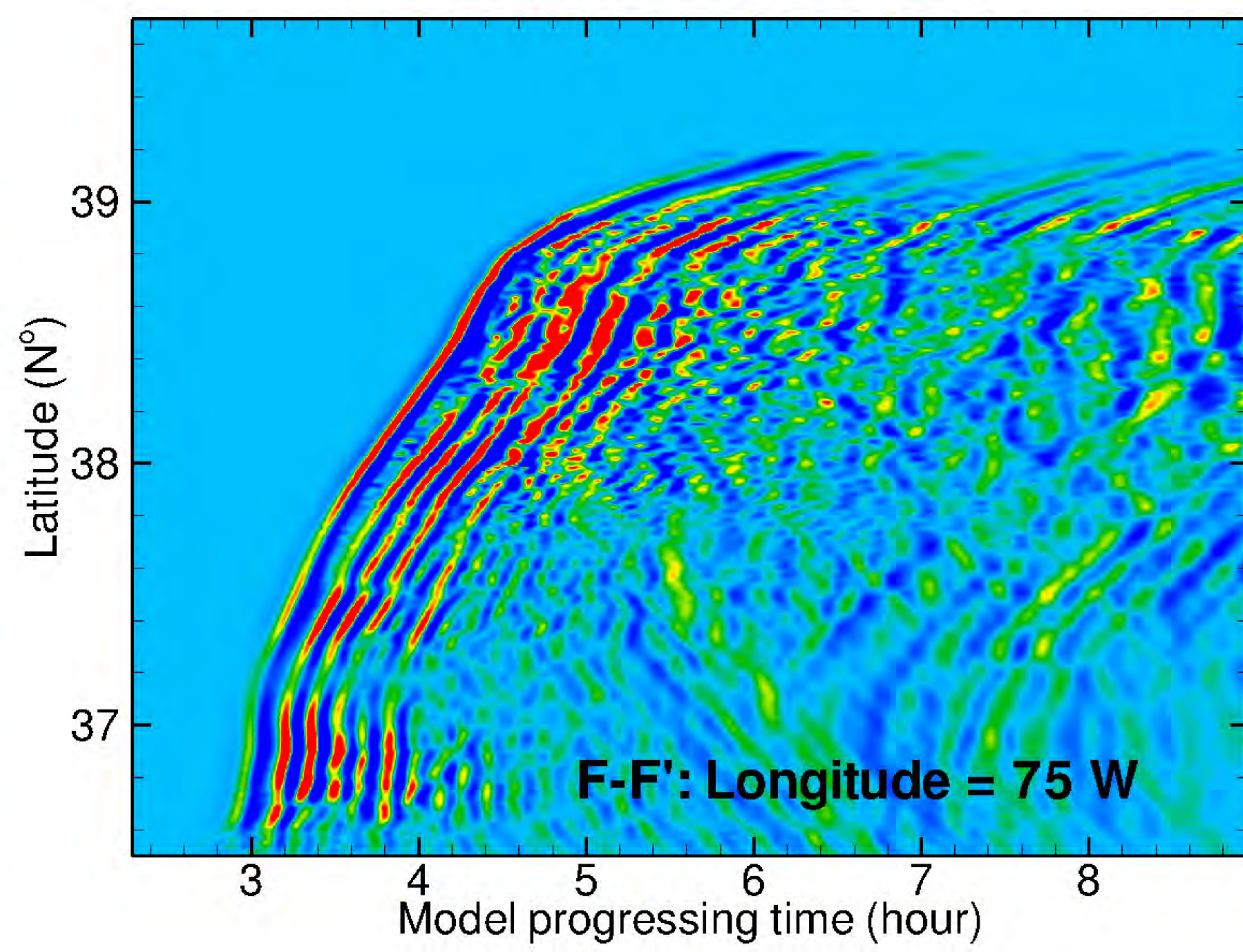
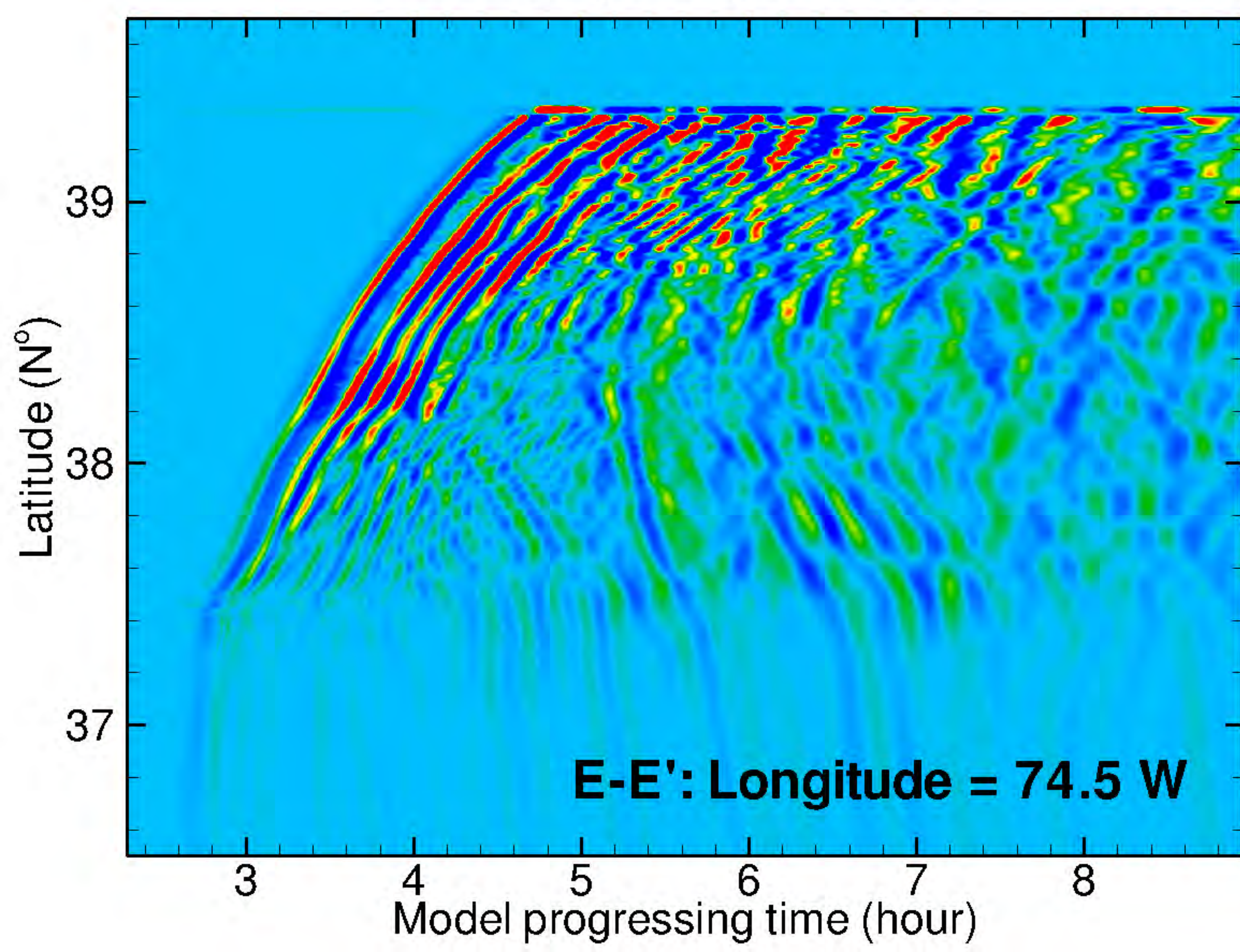
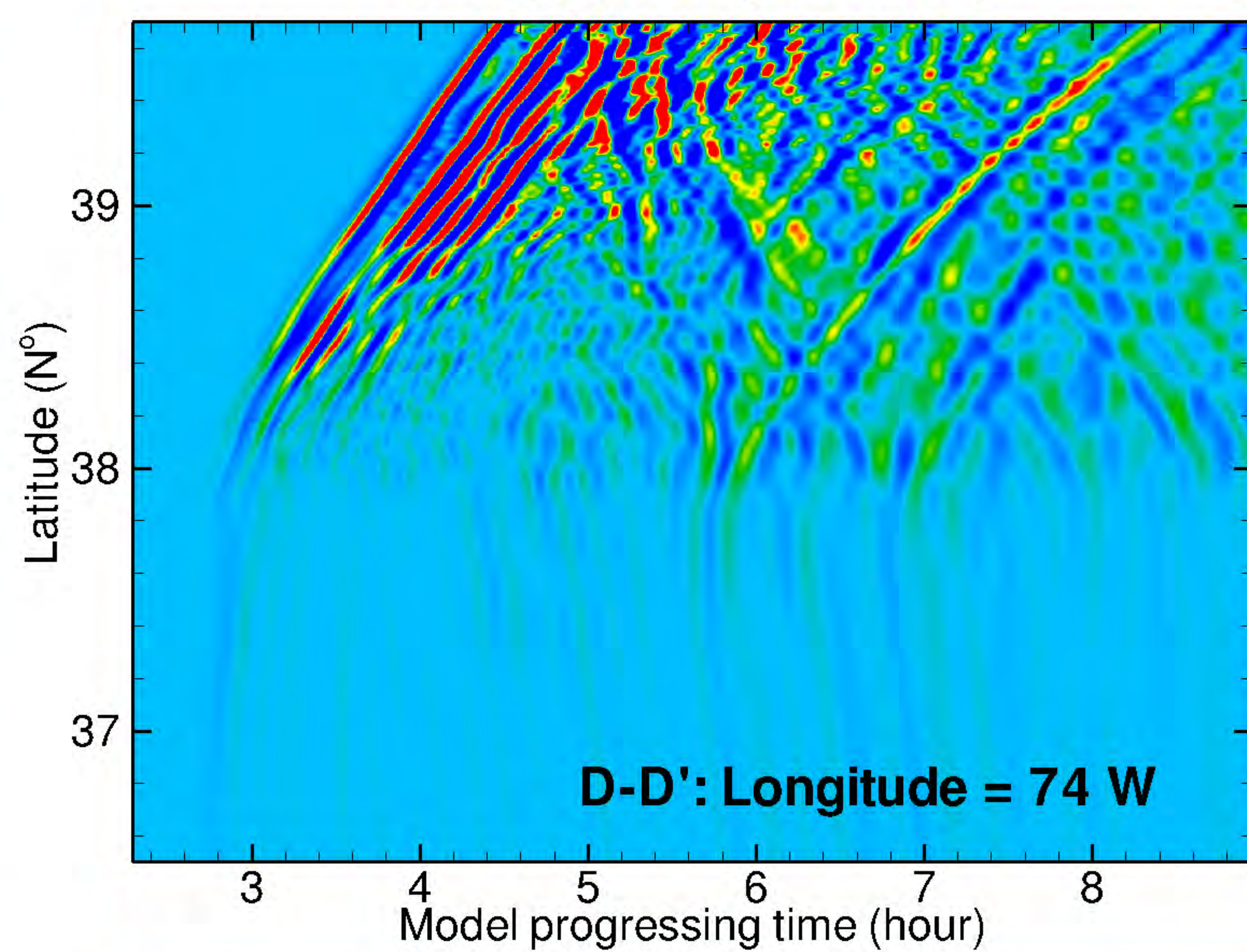
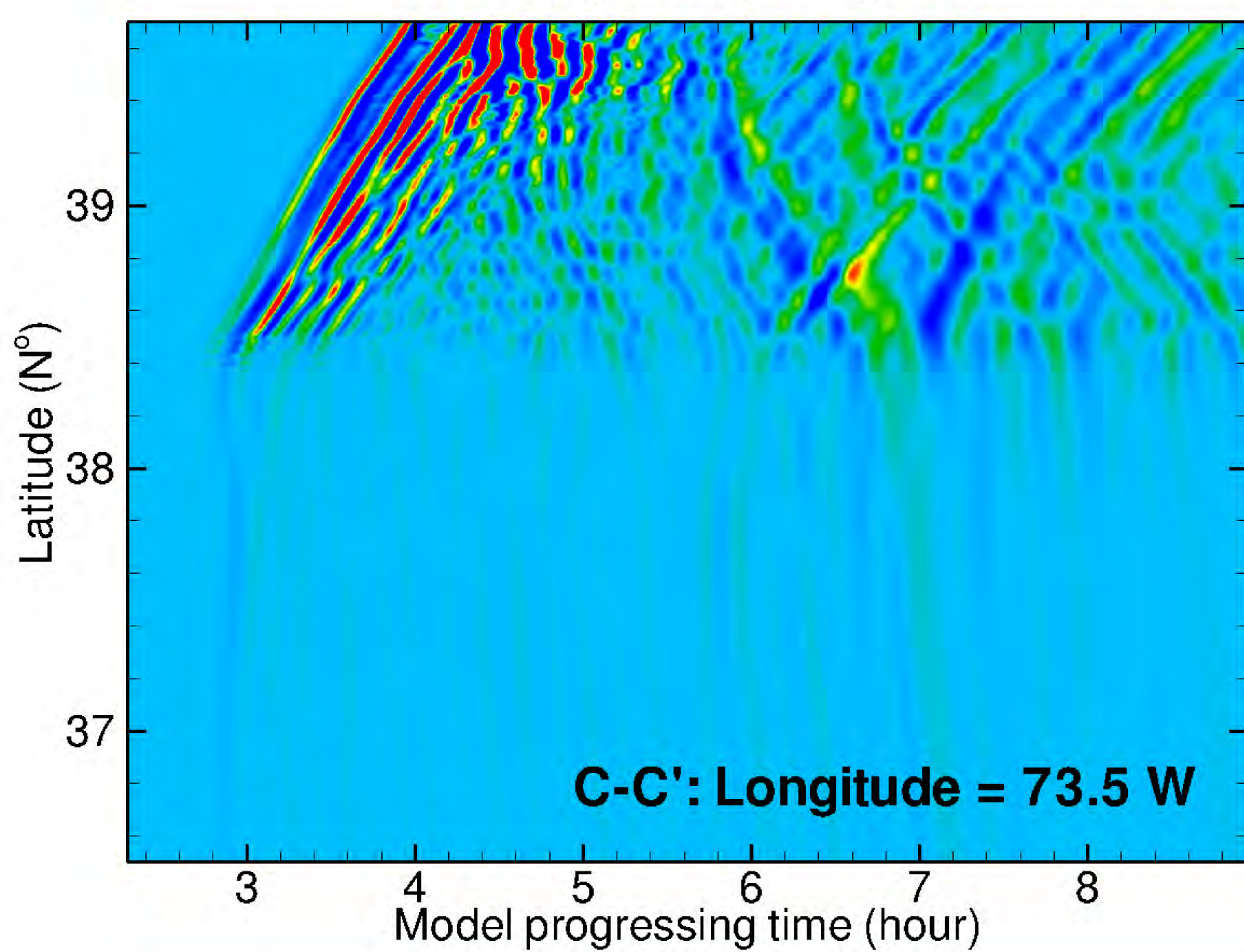
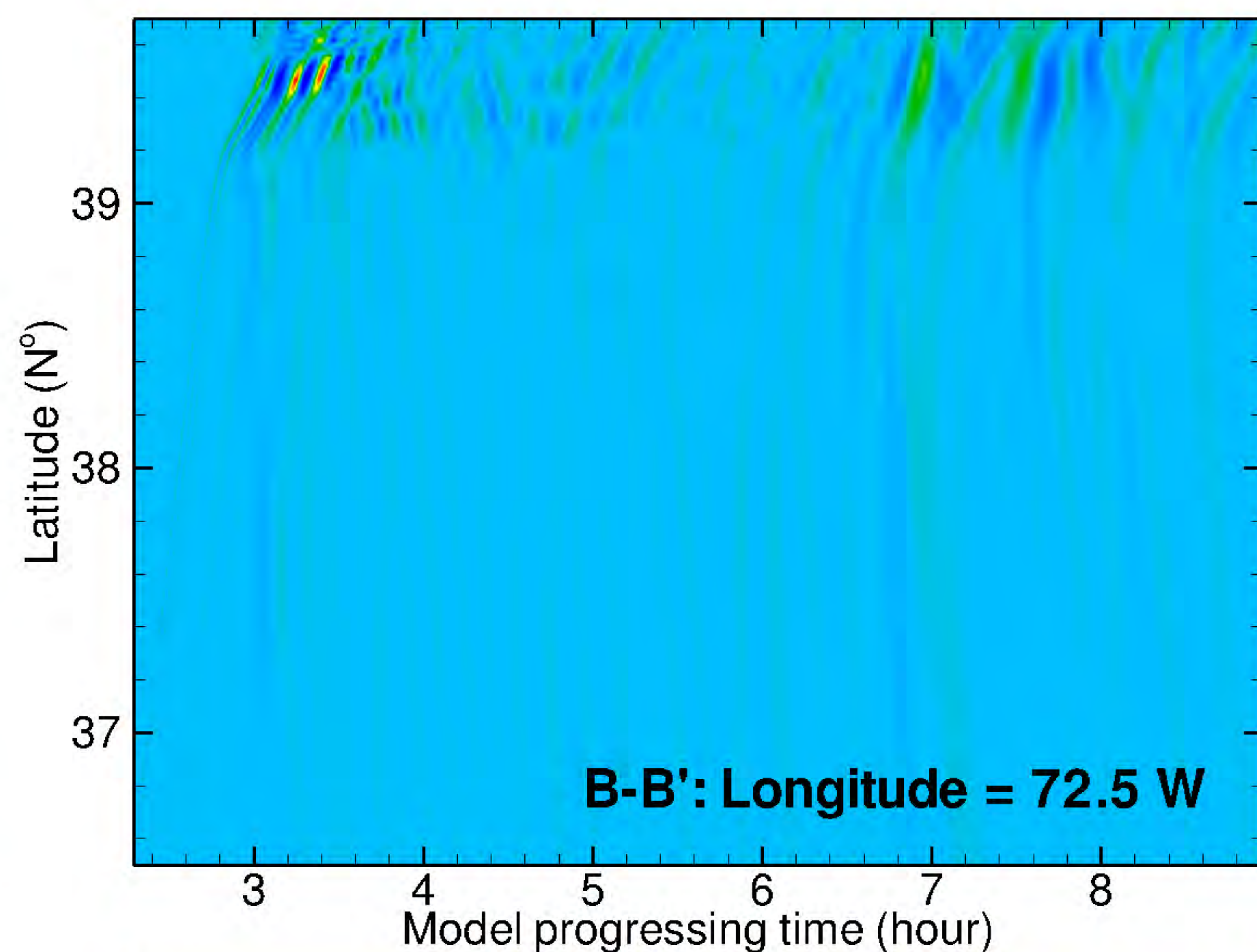
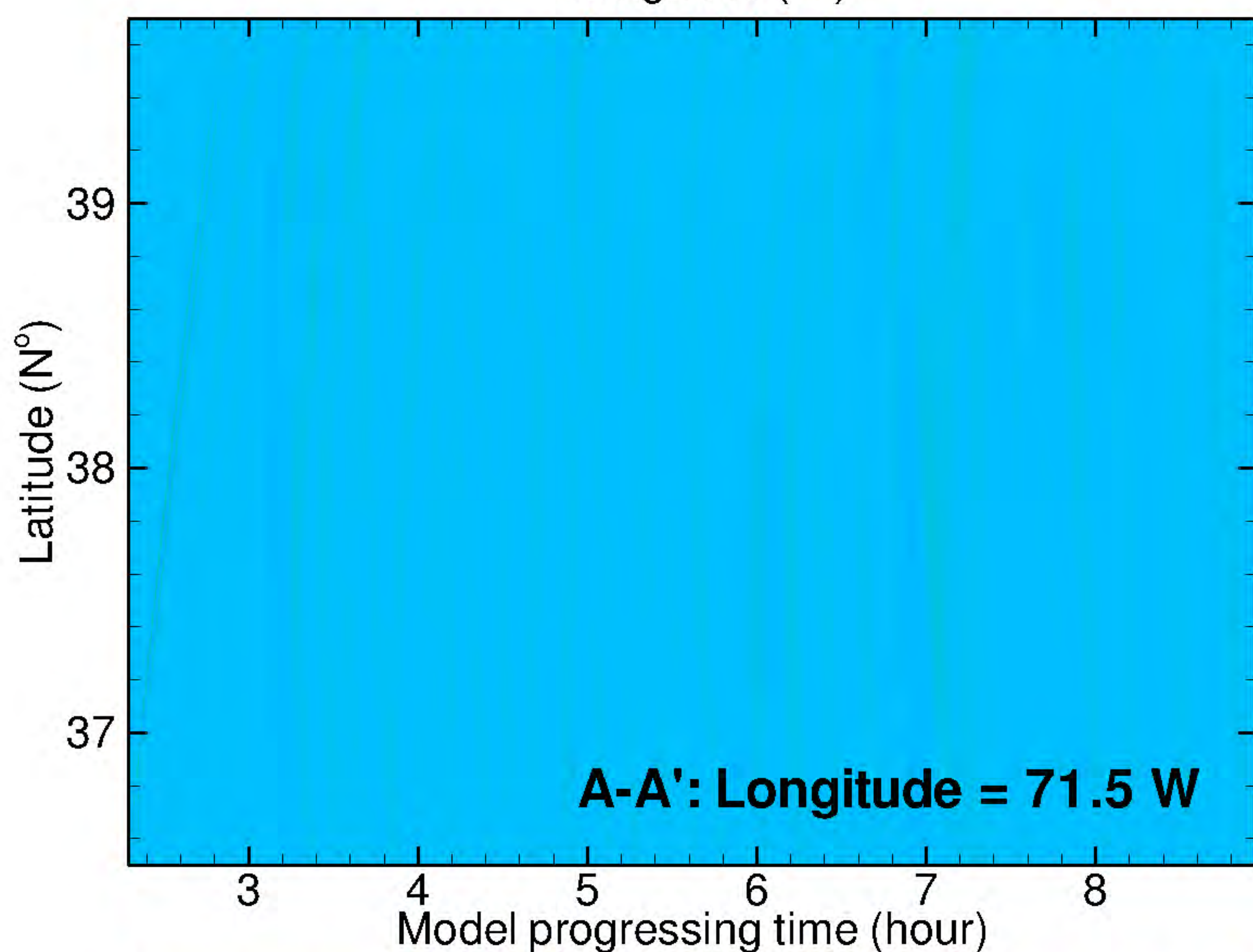






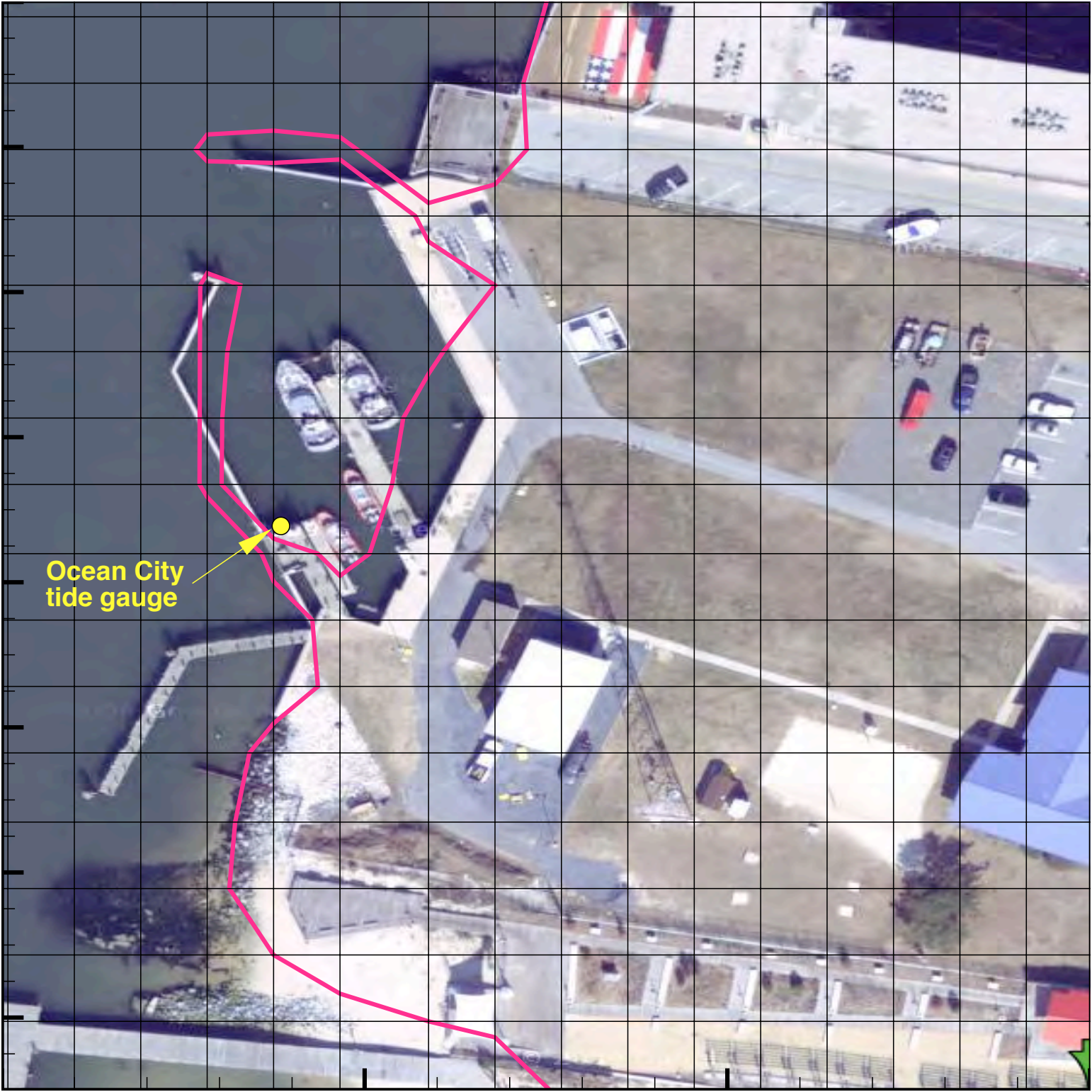


Wave amplitude difference (cm) along transects in A grid between 1-min and 30-sec resolution



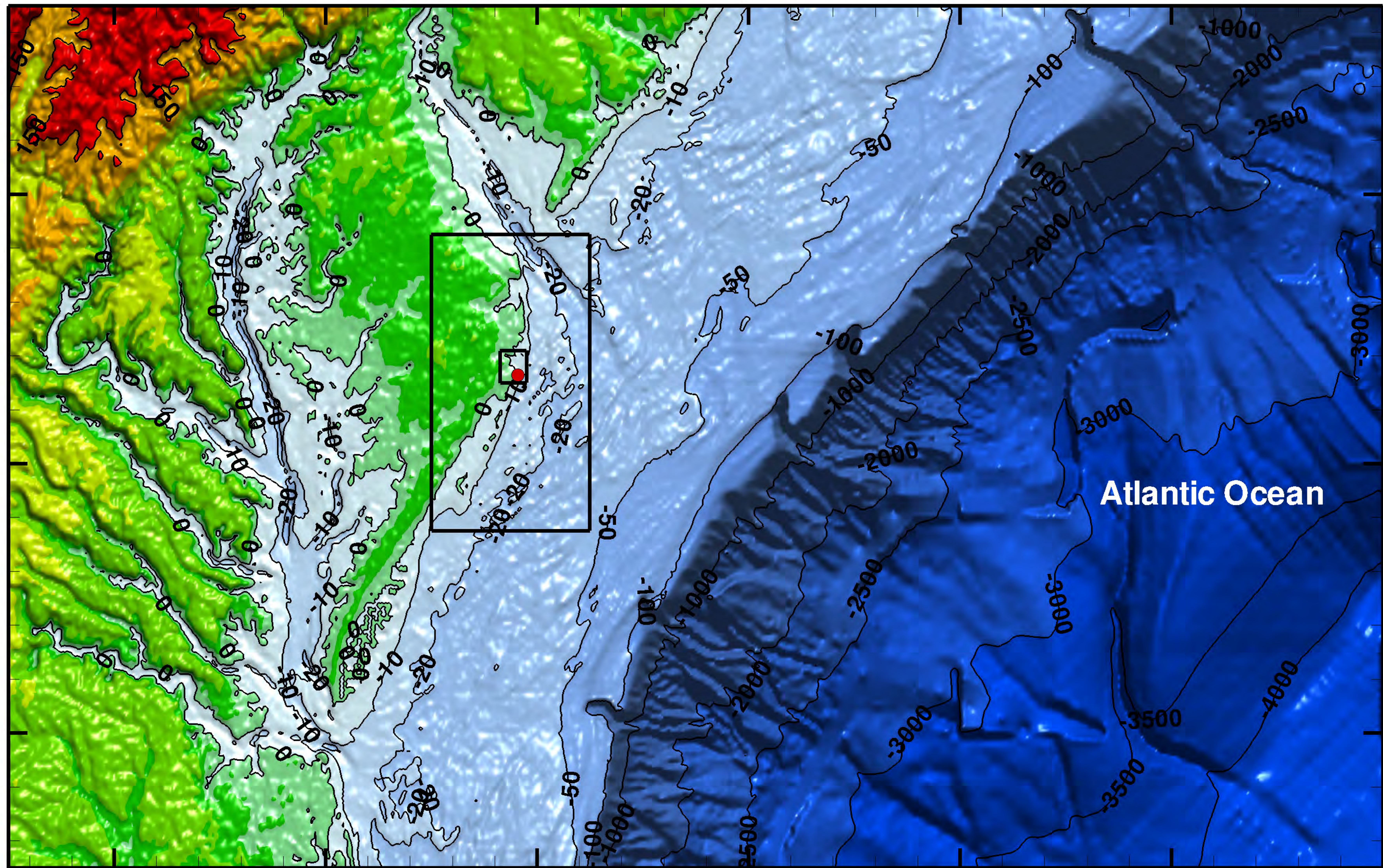


Ocean City
tide gauge



Latitude (N°)

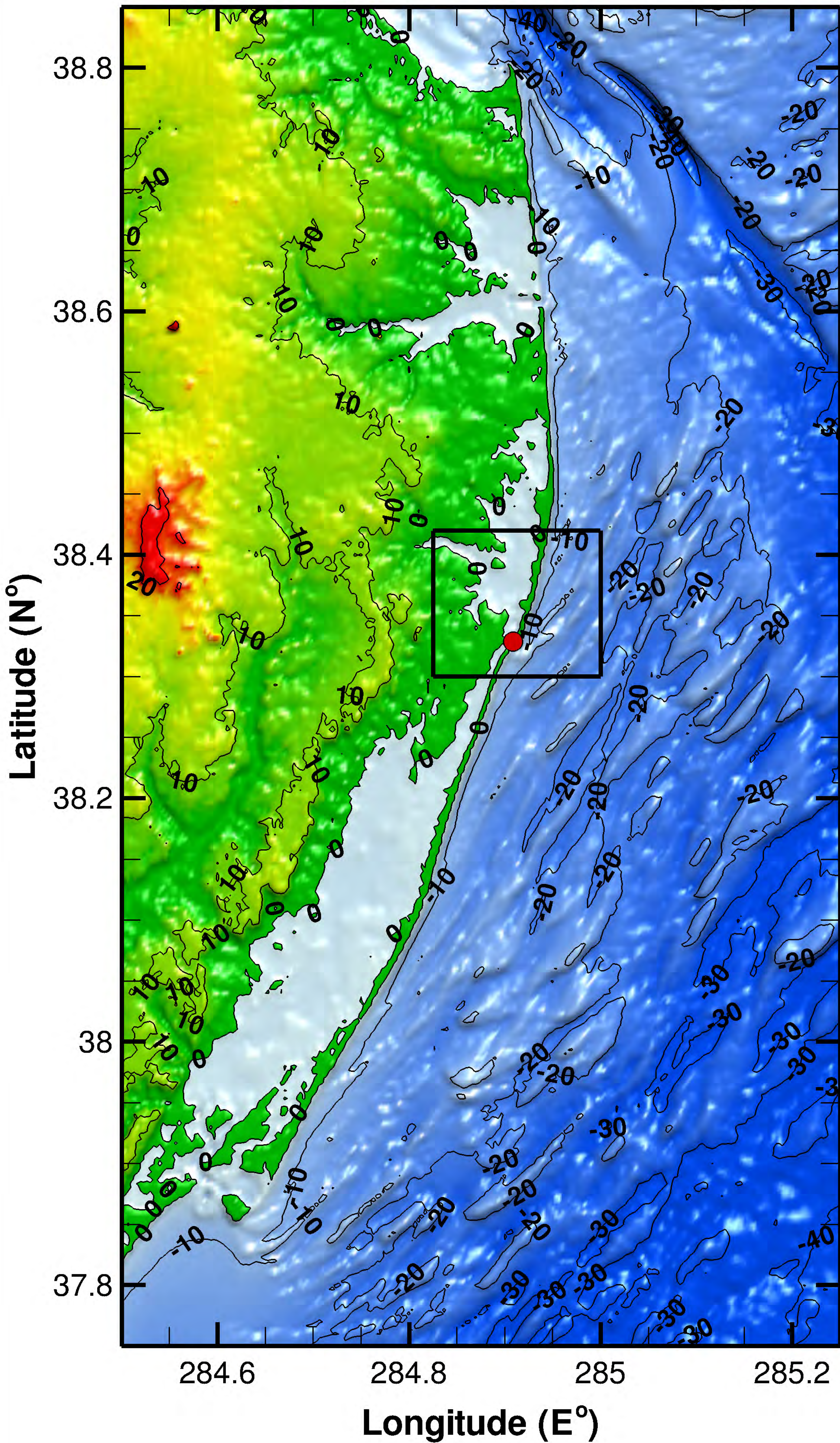
39
38
37

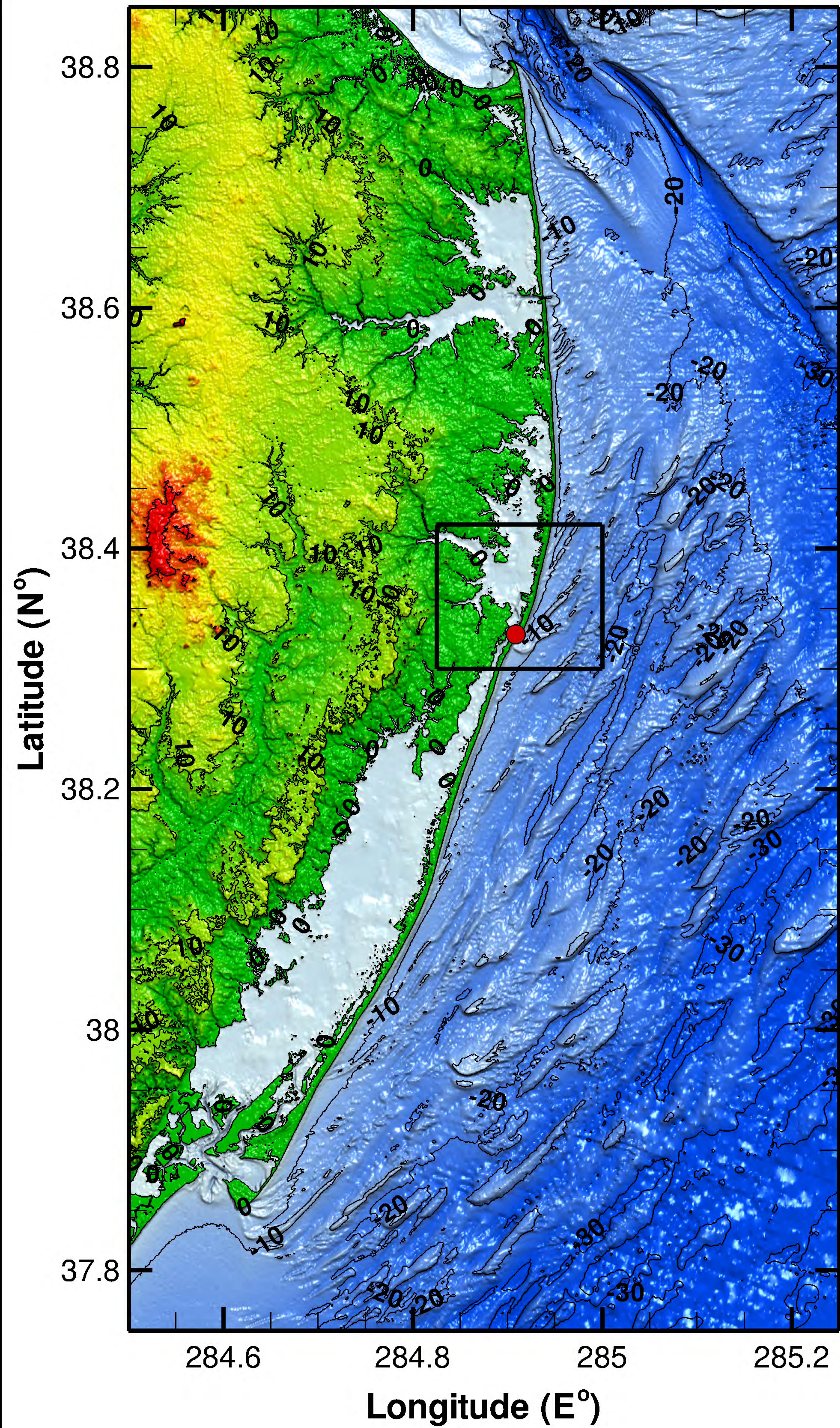


Atlantic Ocean

Longitude (E°)

283 284 285 286 287 288 289



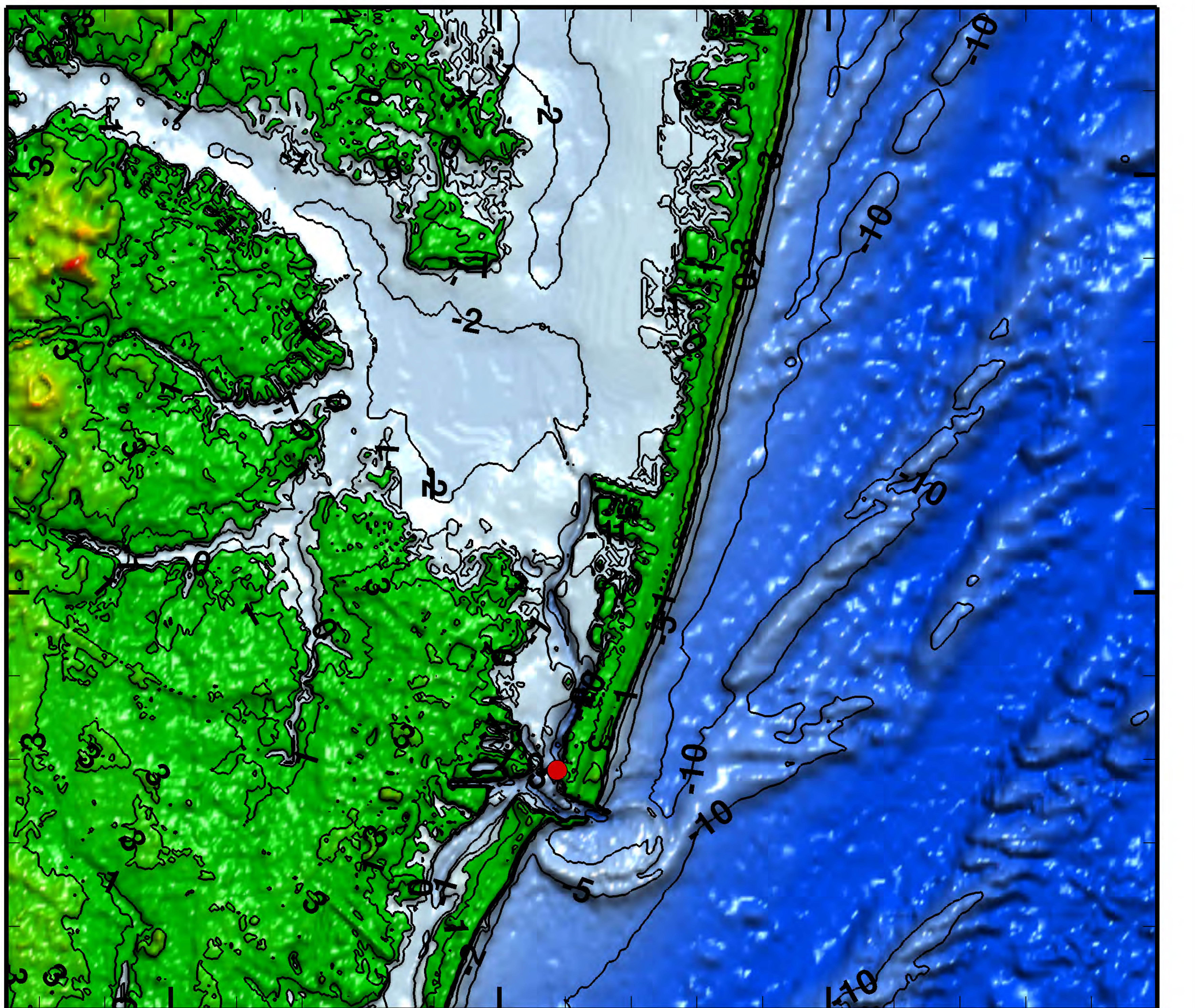


Latitude (N°)

38.4

38.35

38.3



284.85

284.9

284.95

285

Longitude (E°)

Latitude (N°)

38.45

38.4

38.35

38.3

38.25

Forecast Model
Coverage

284.85

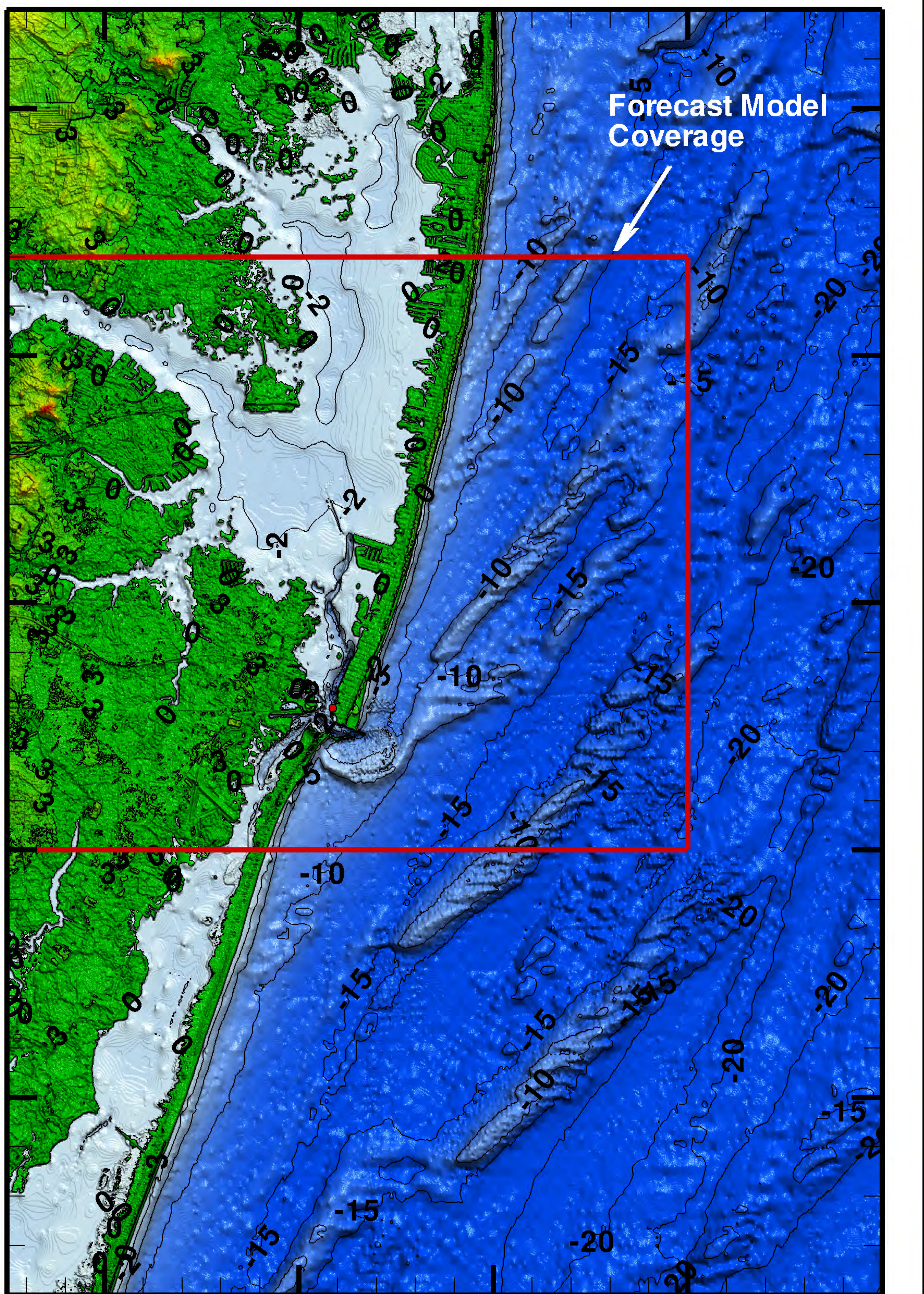
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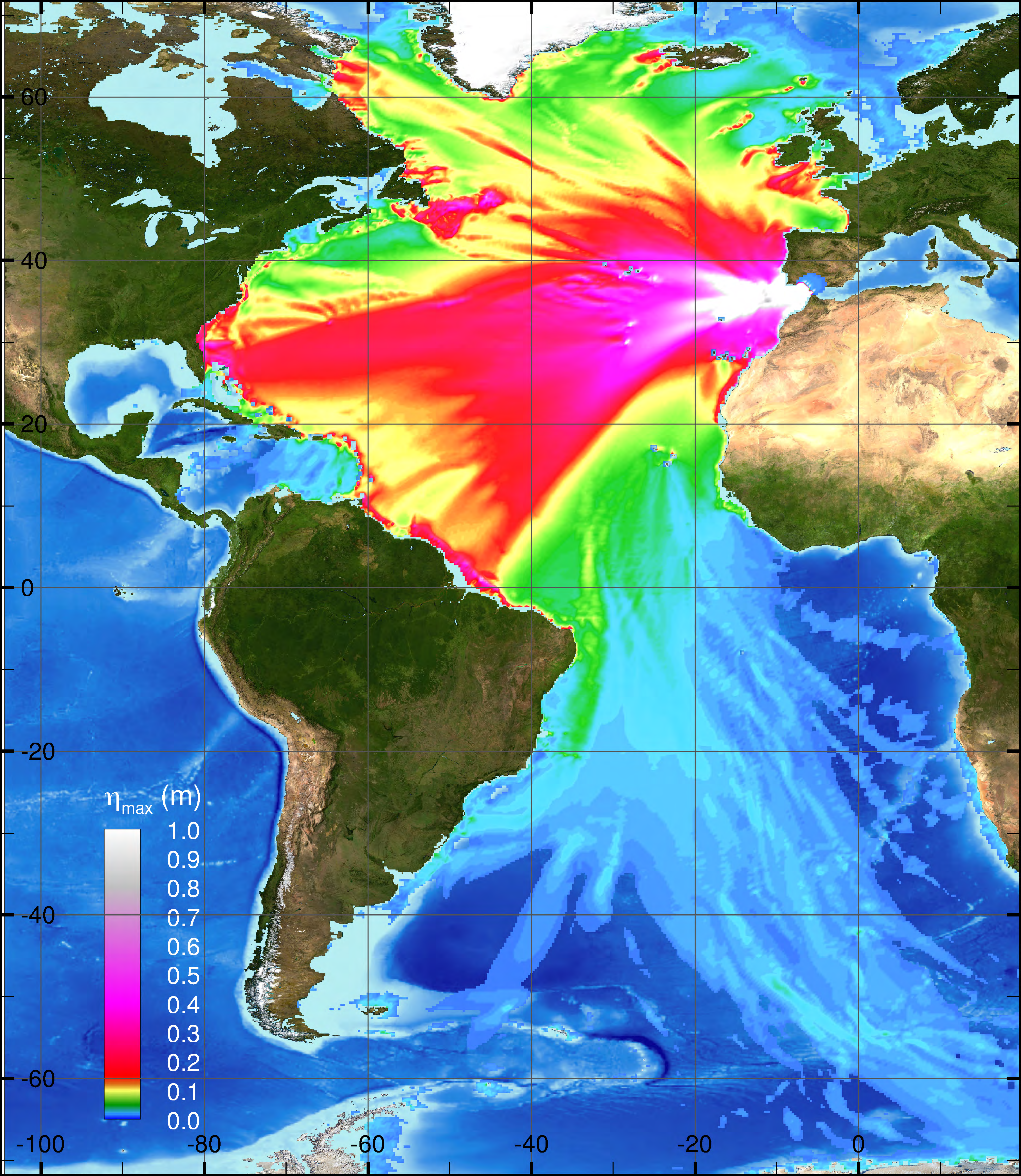
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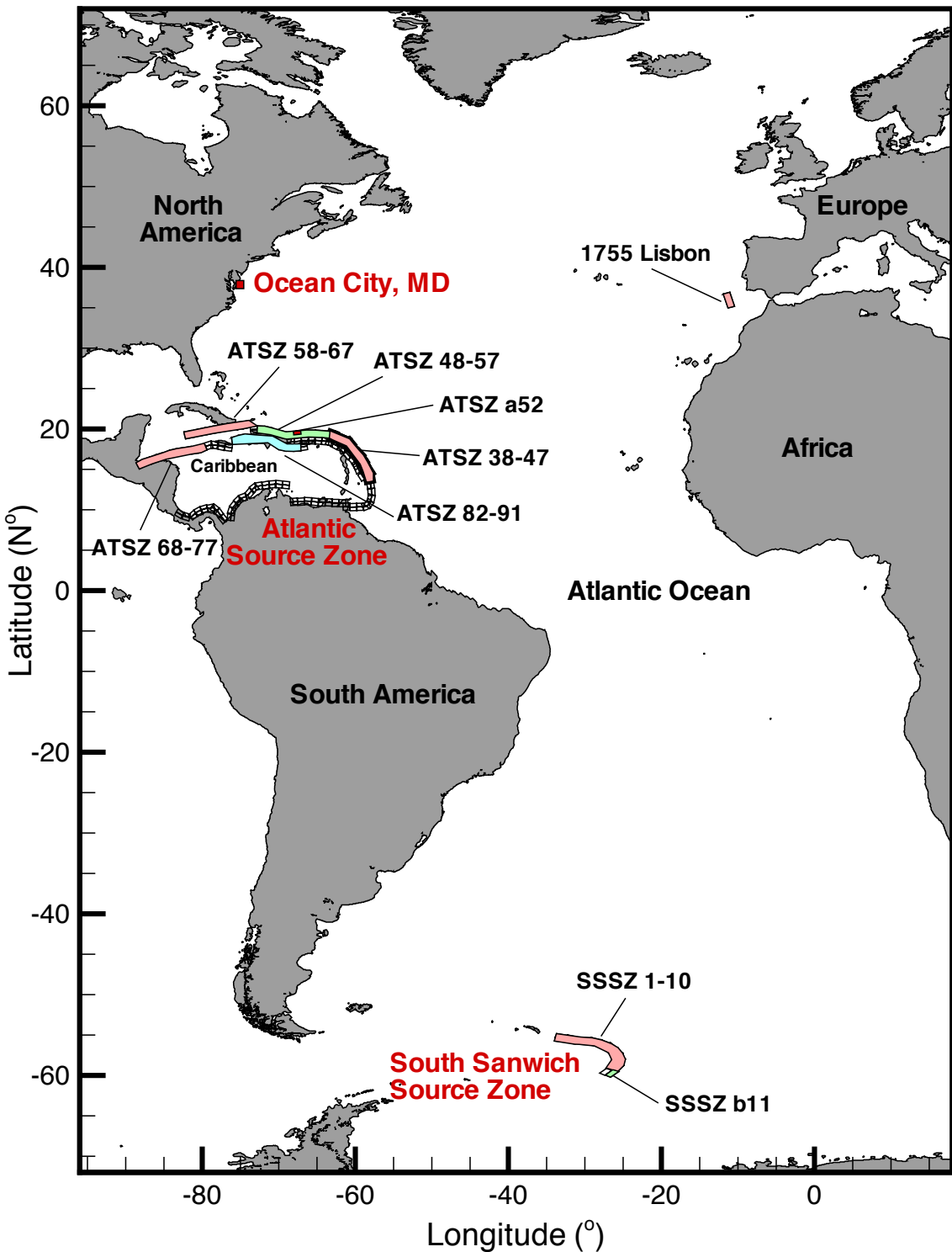
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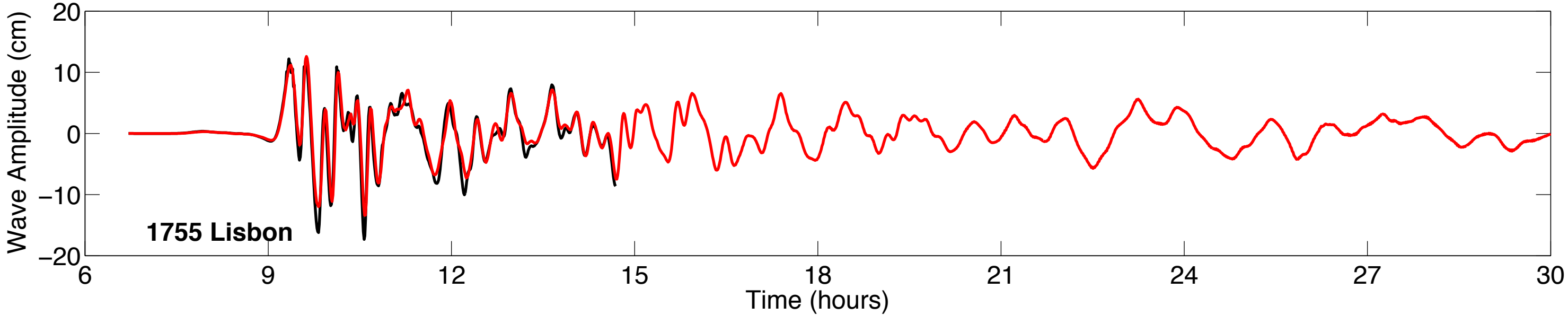
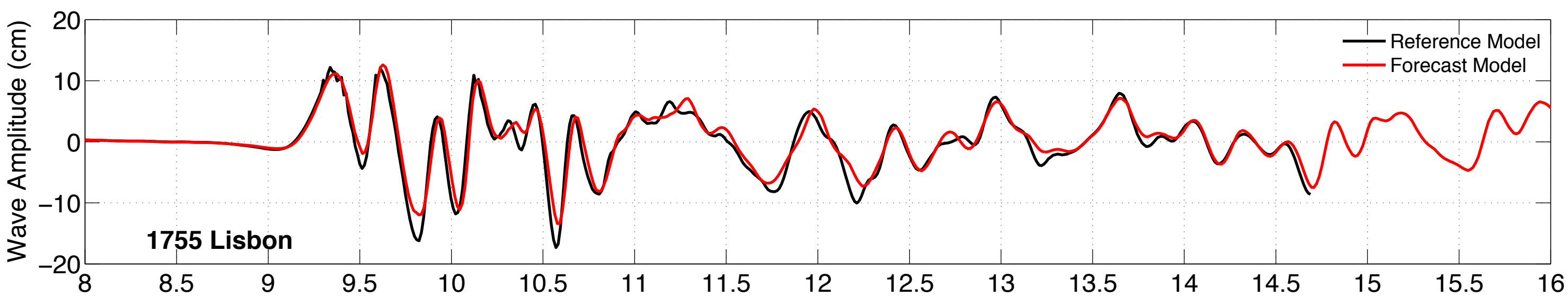
285.05

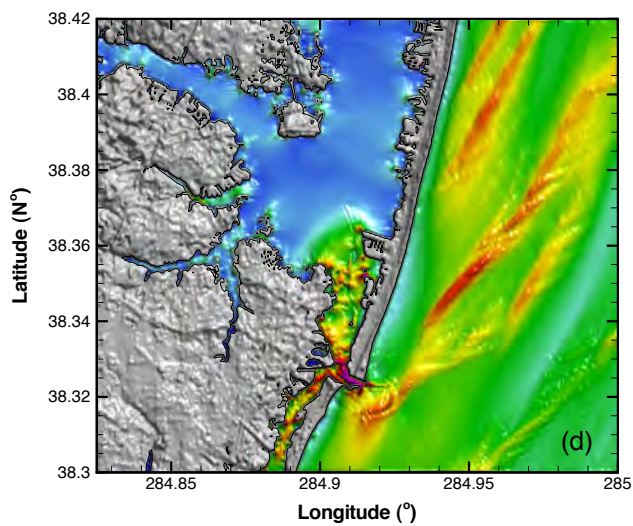
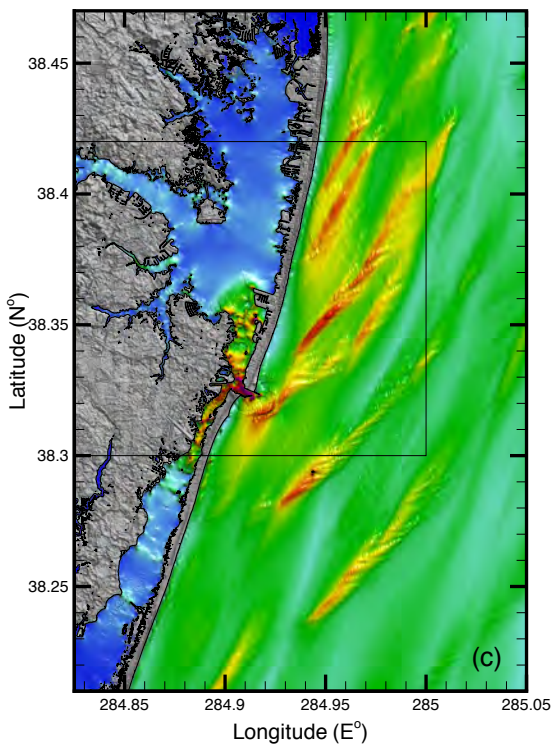
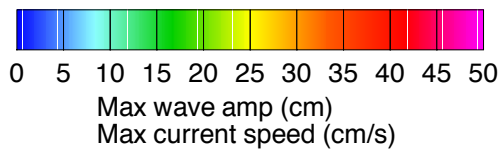
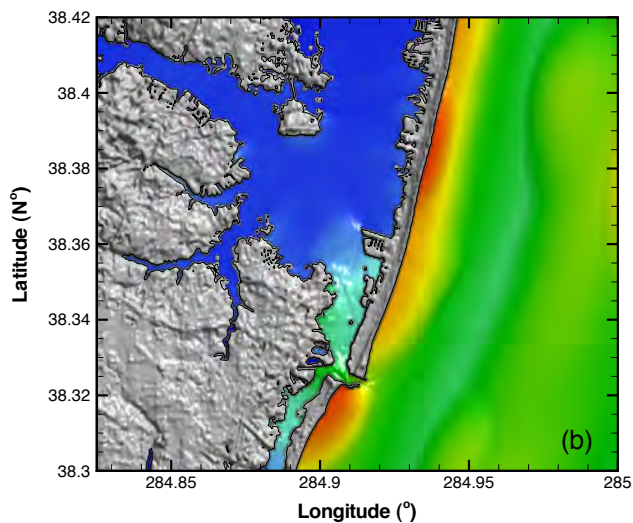
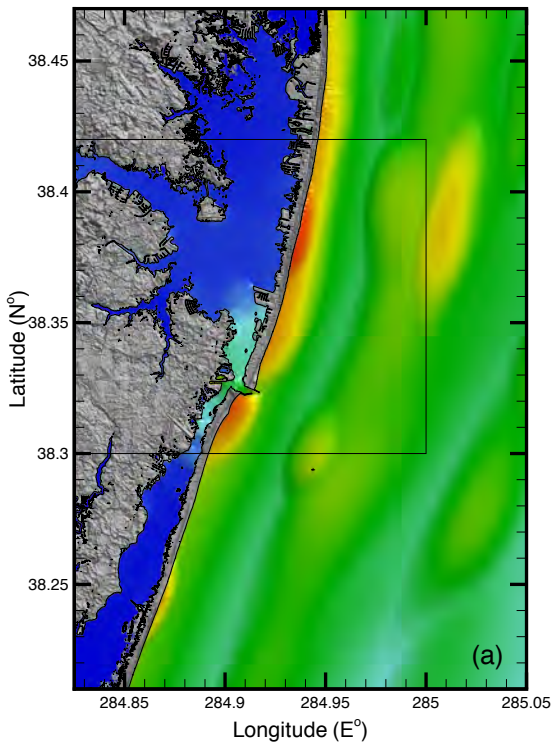
Longitude (E°)

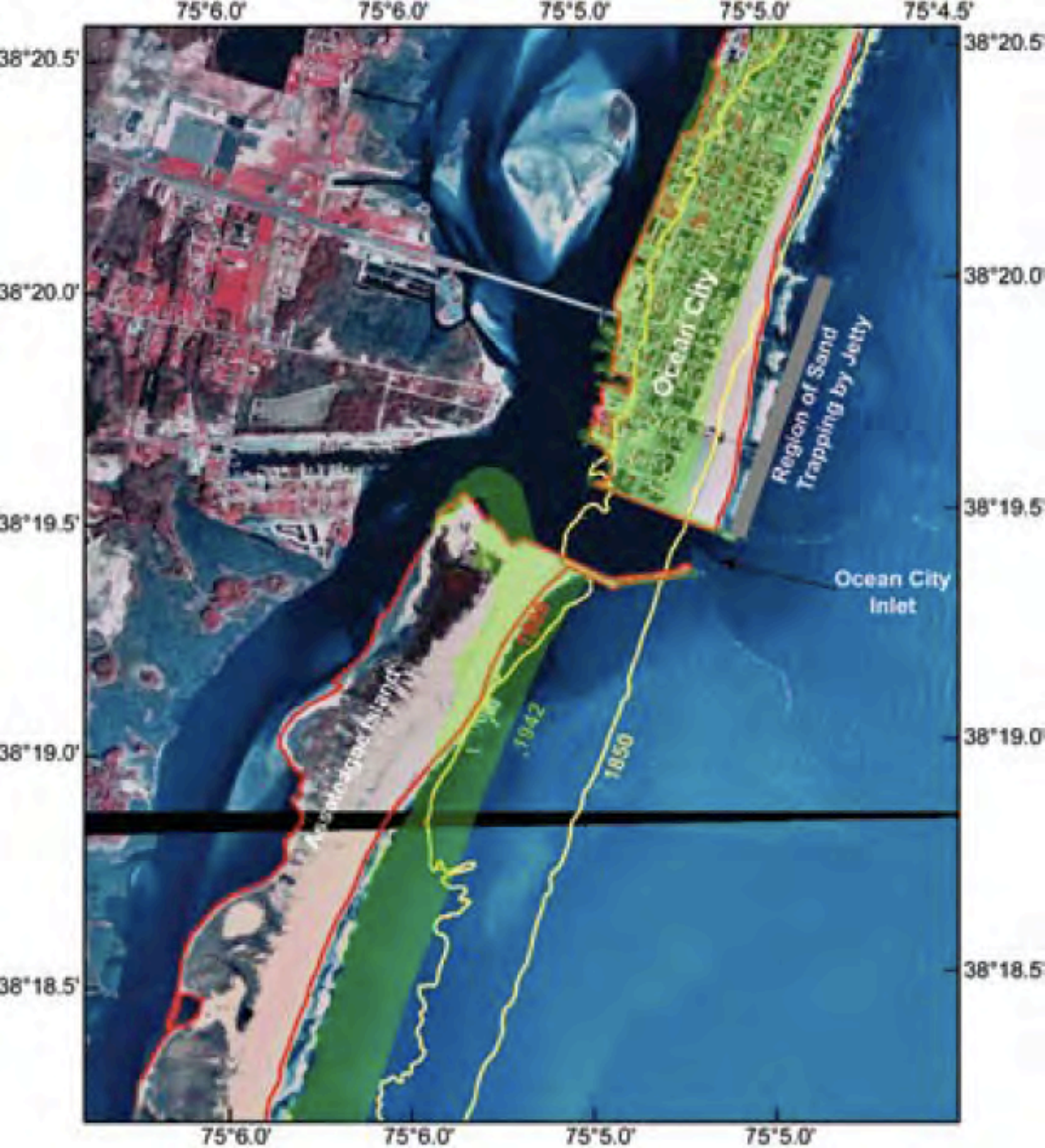


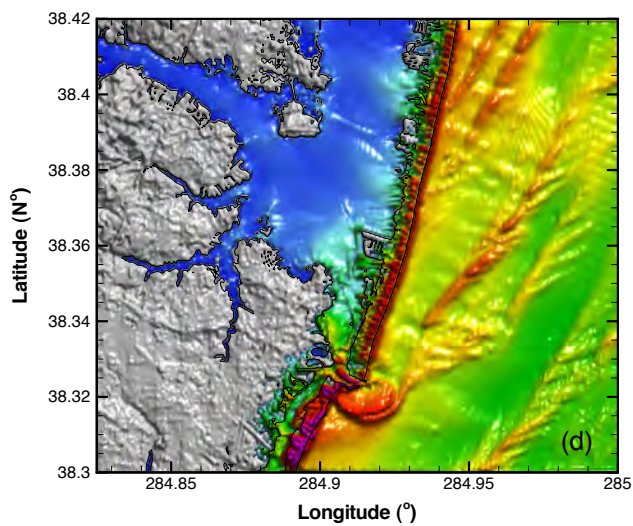
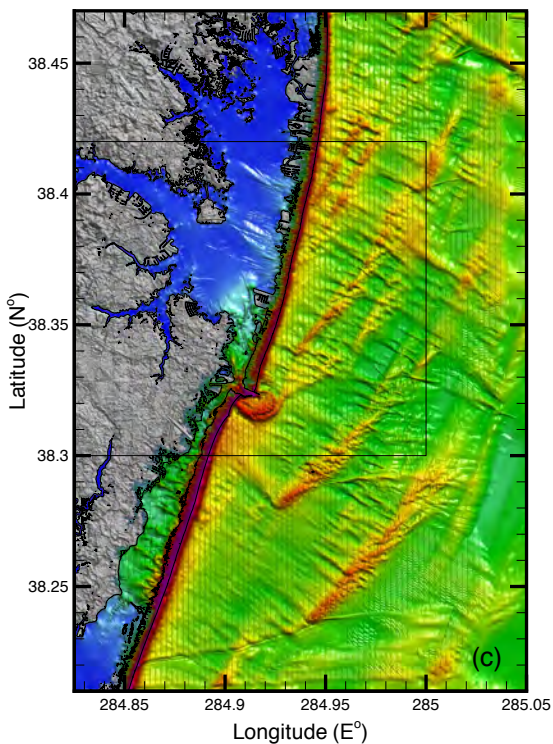
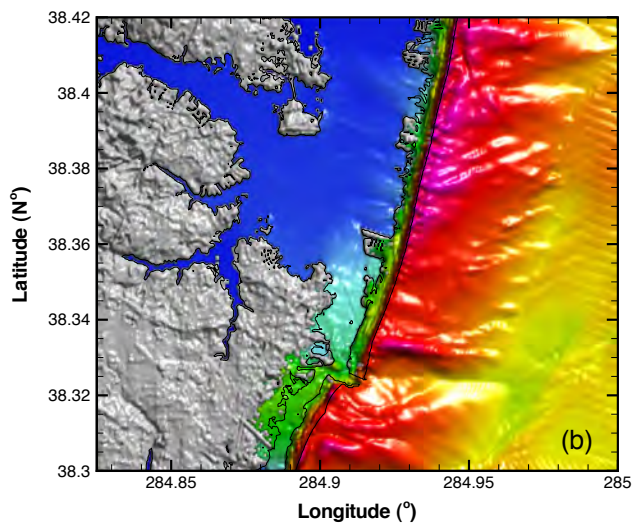
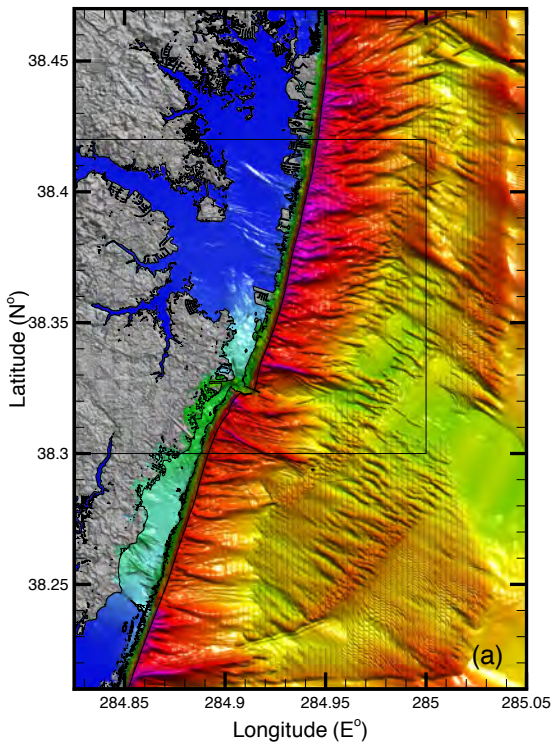


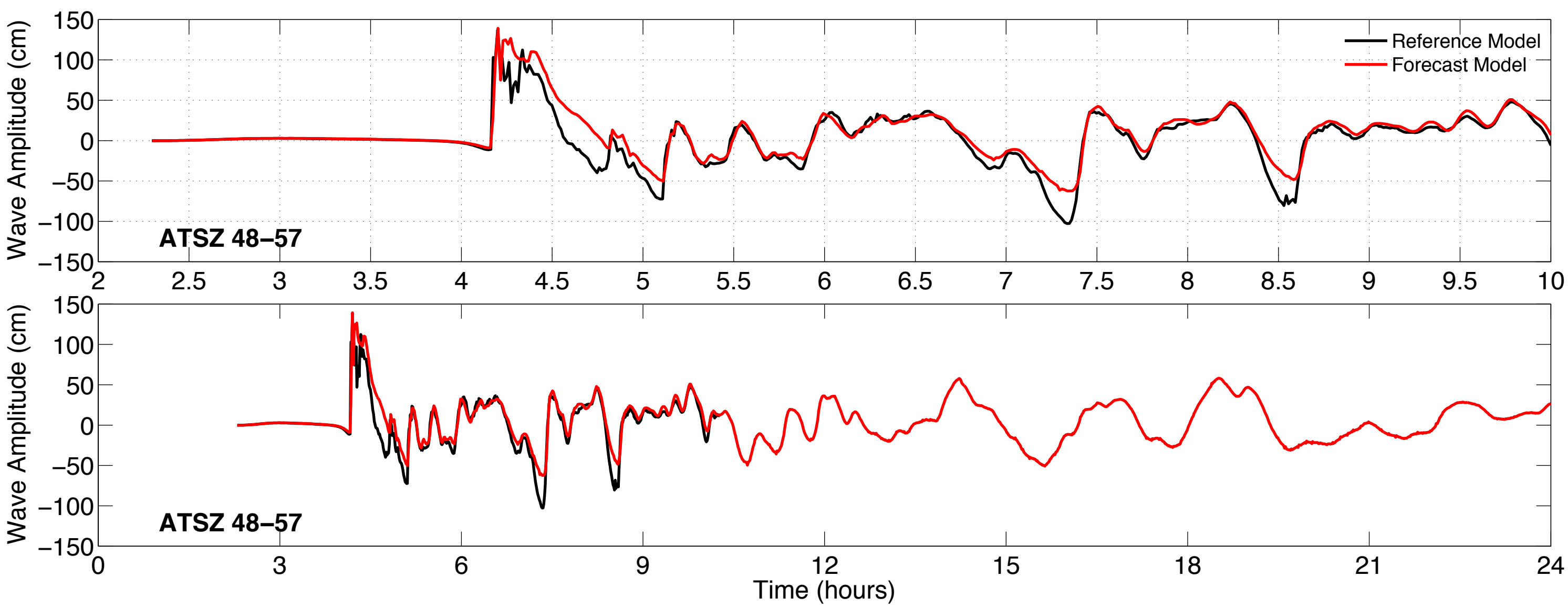


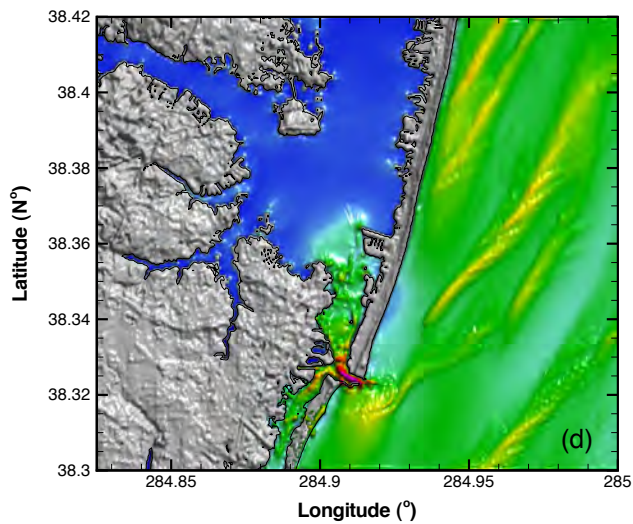
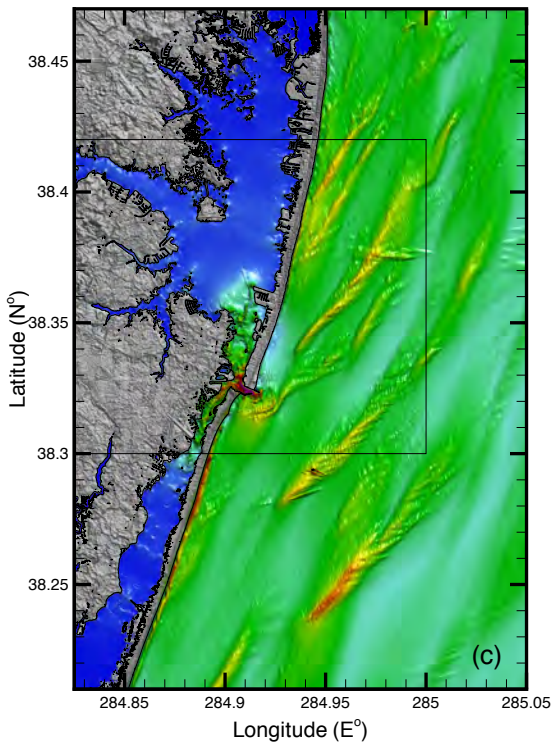
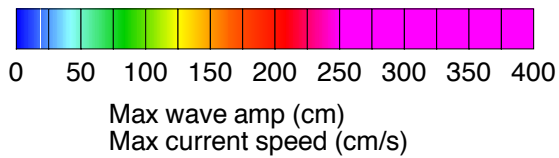
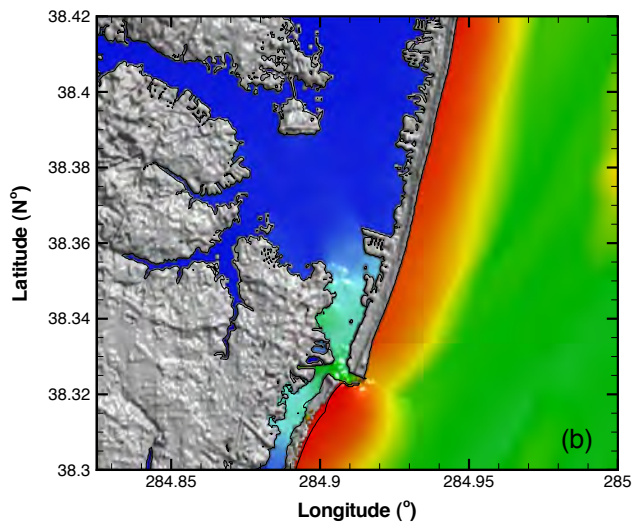
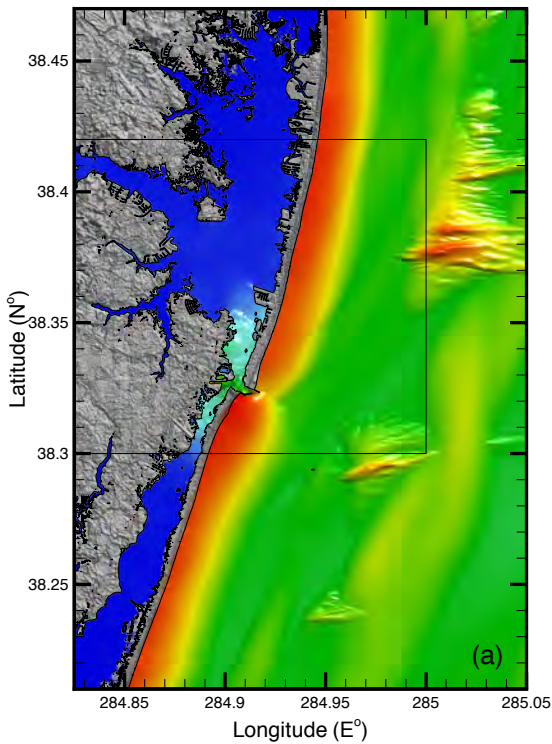


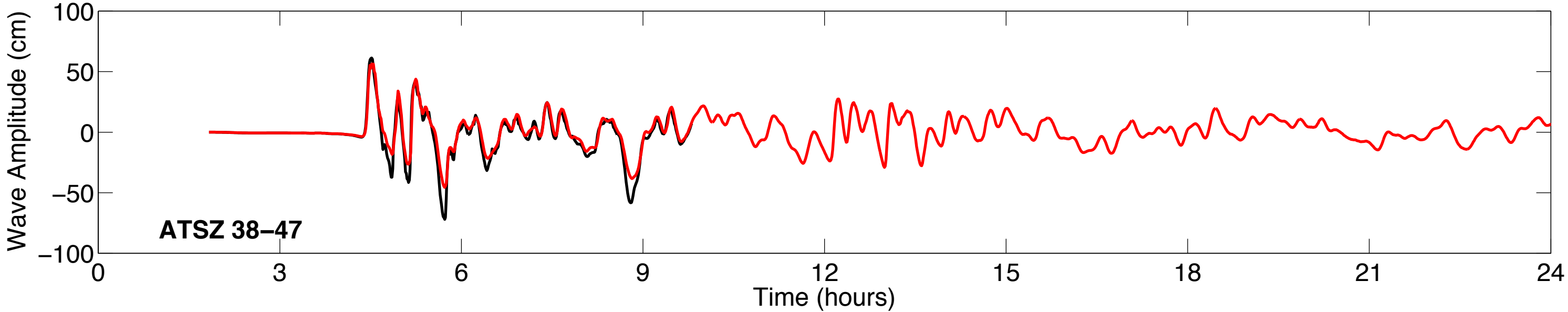
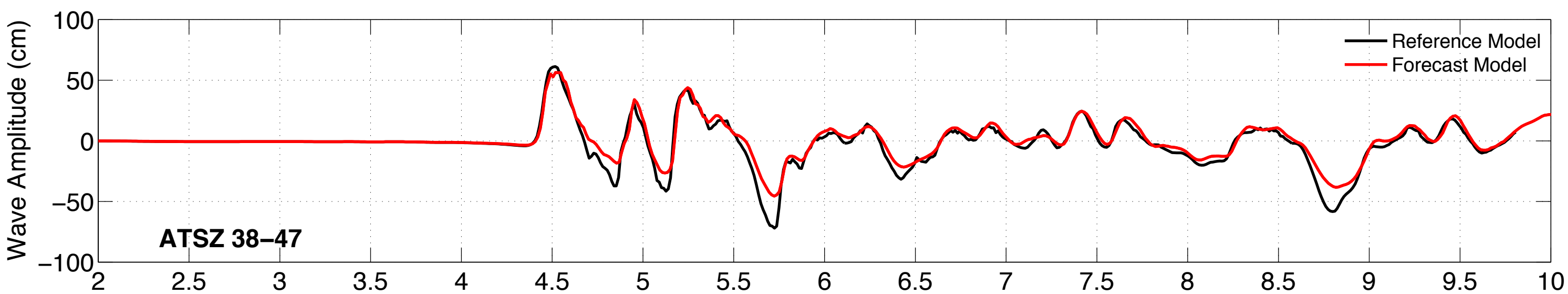


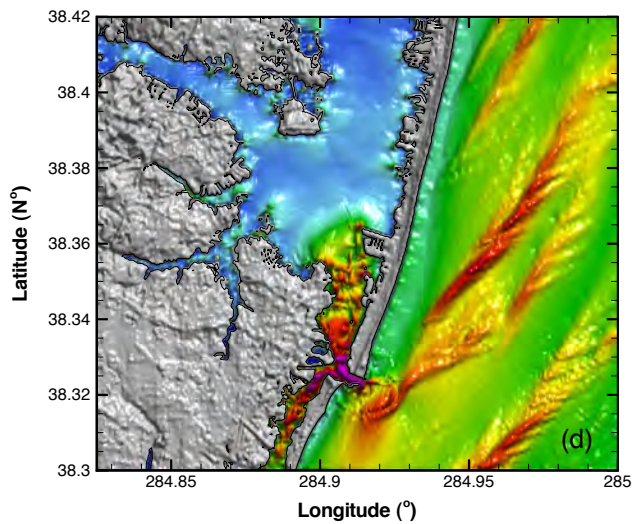
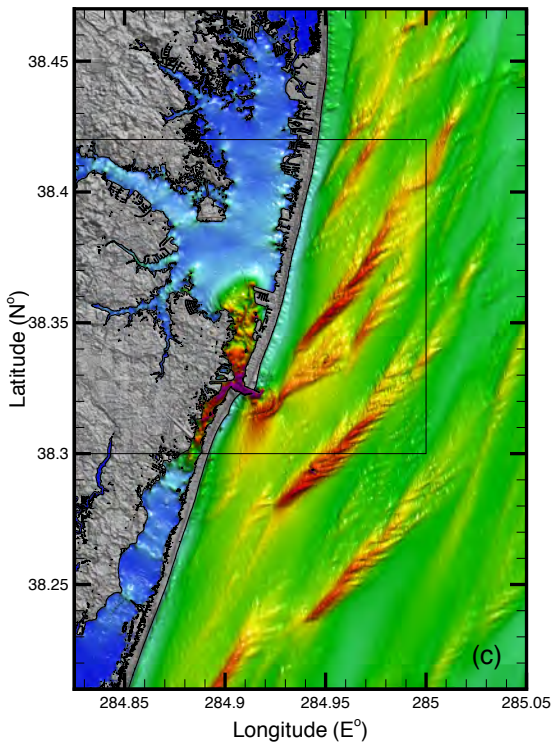
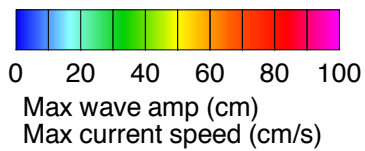
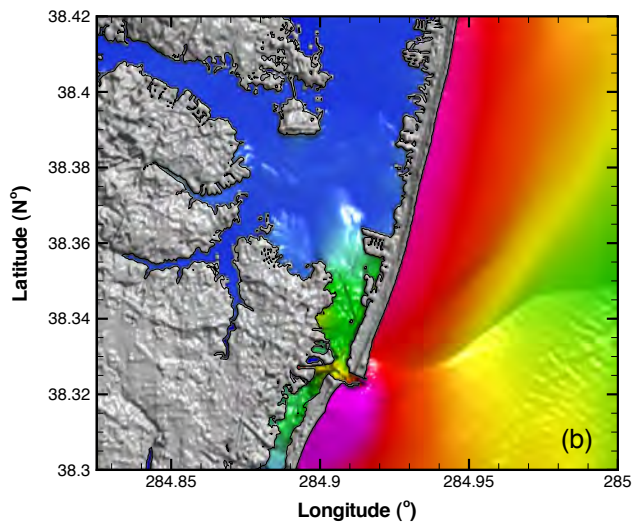
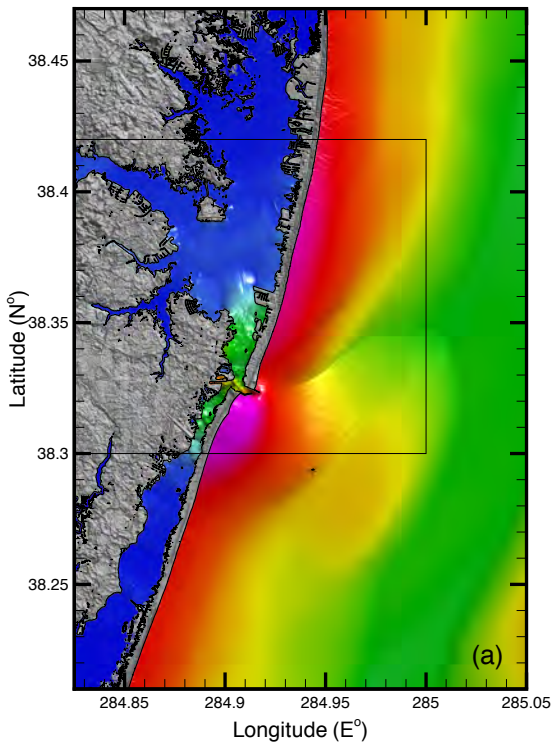


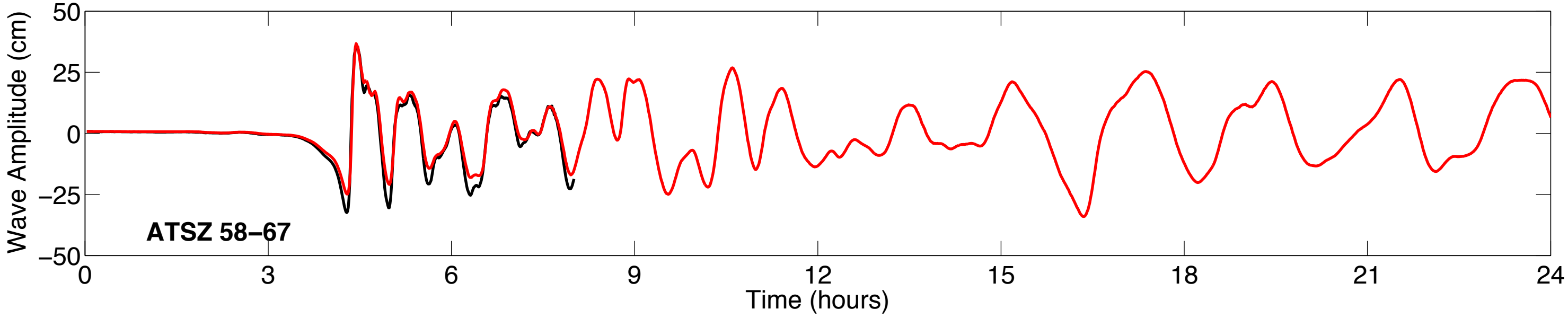
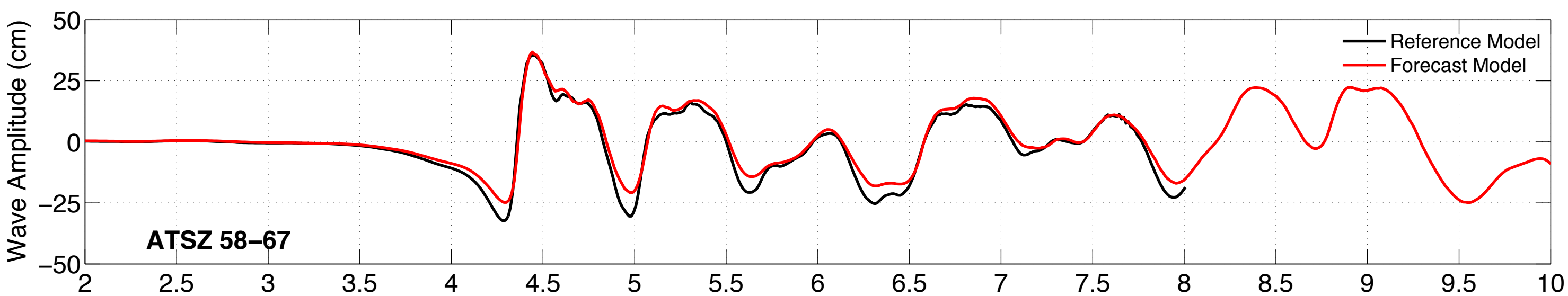


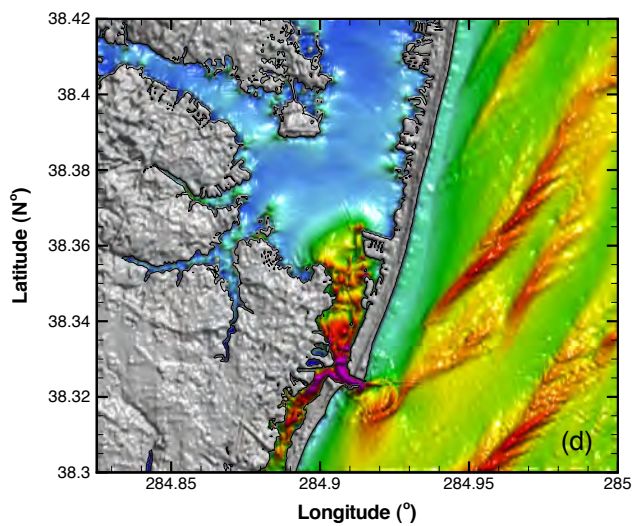
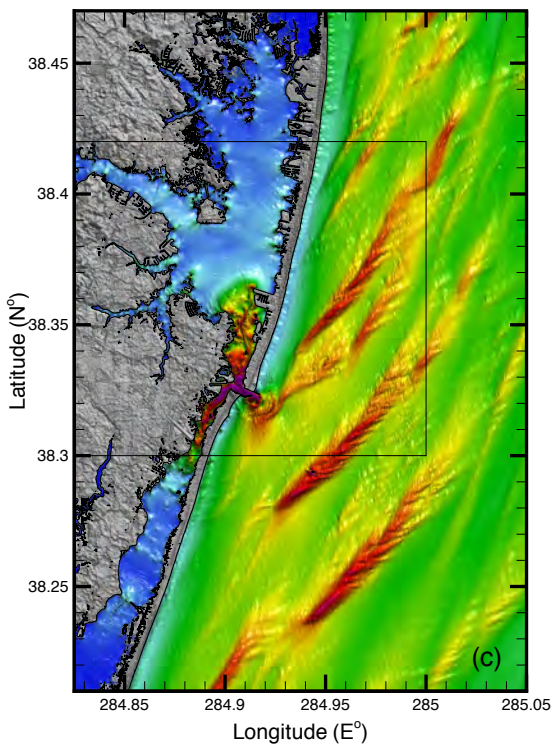
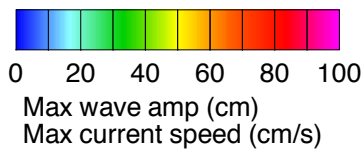
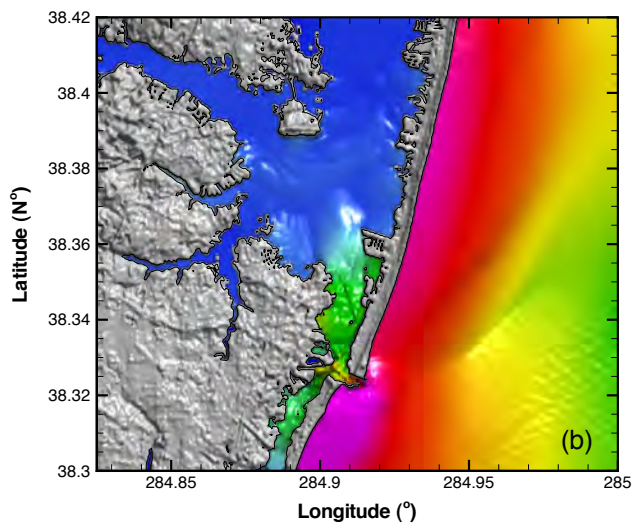
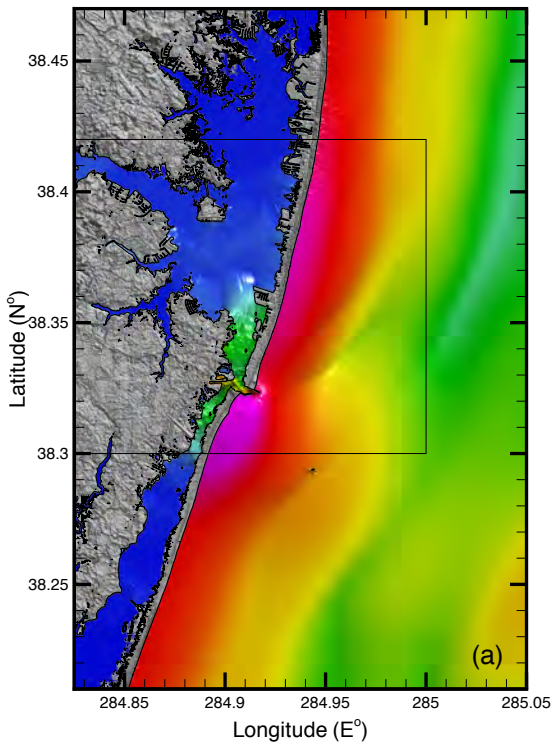


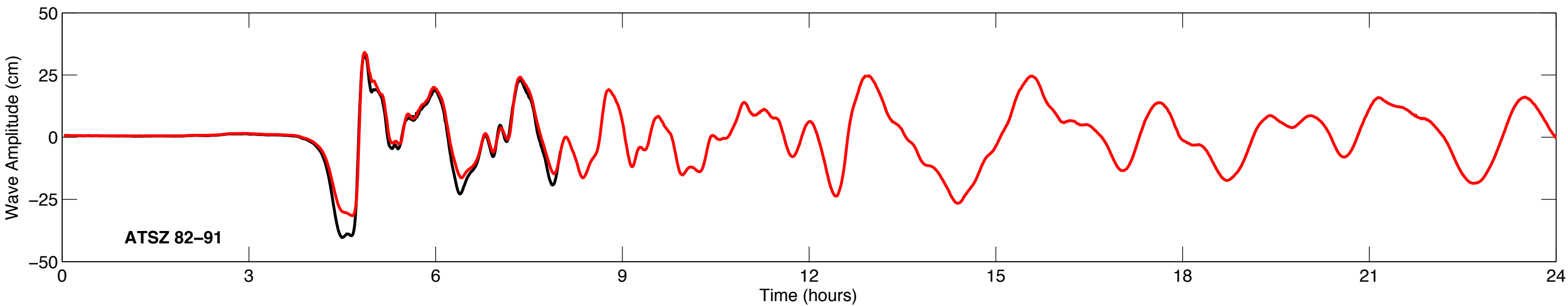
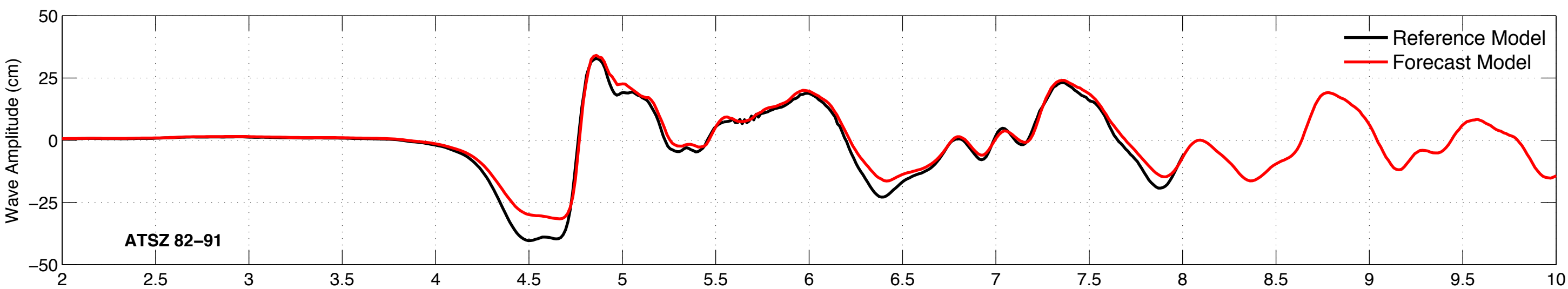


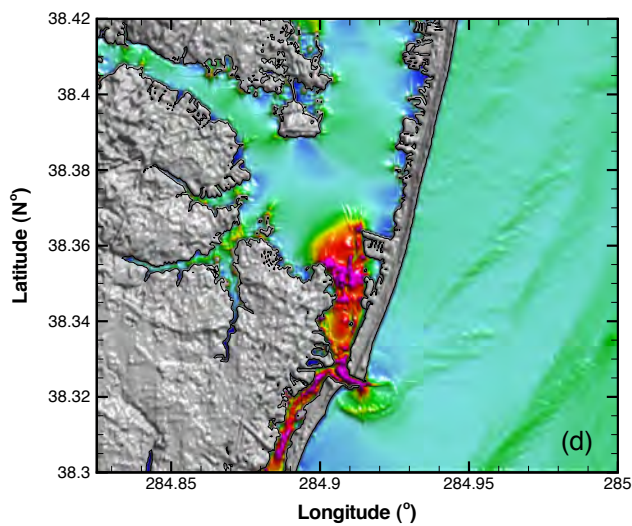
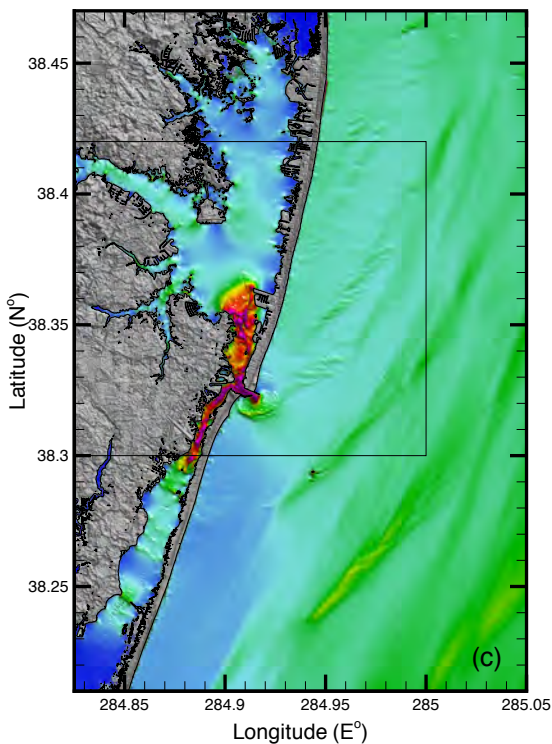
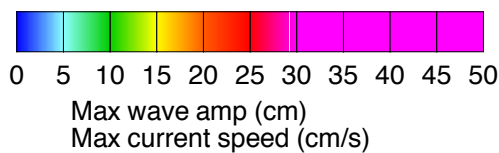
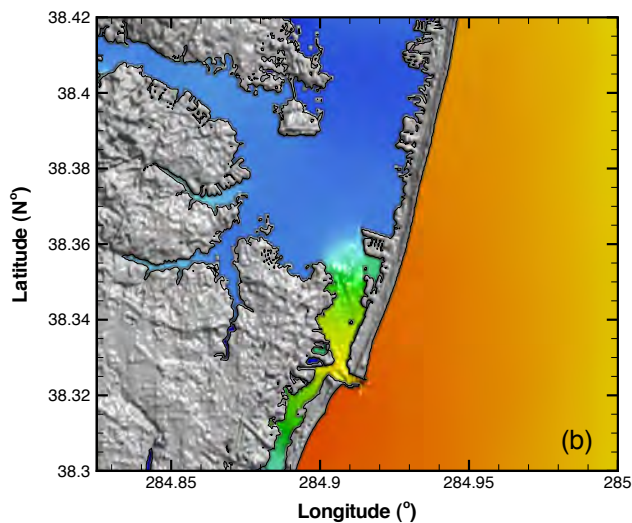
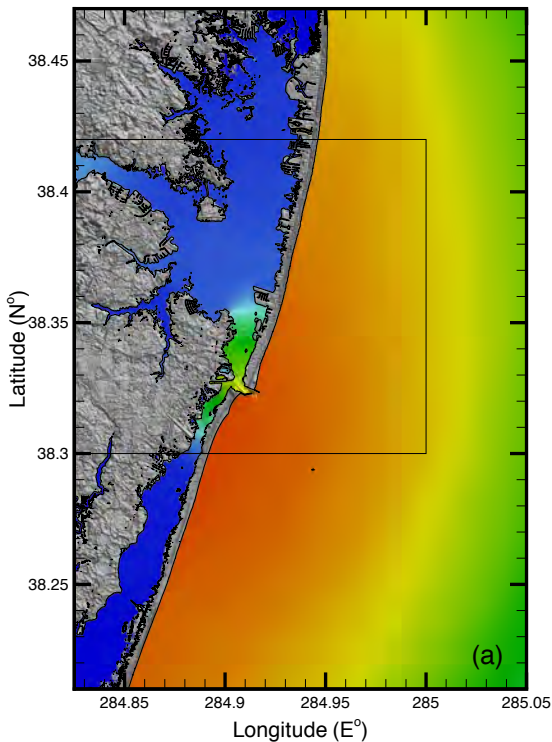


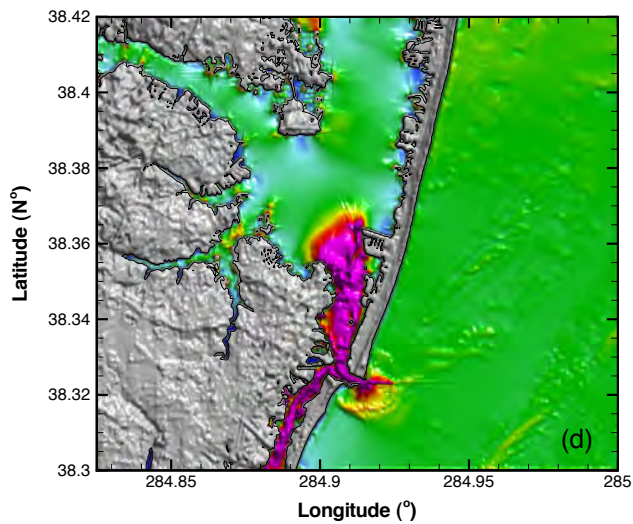
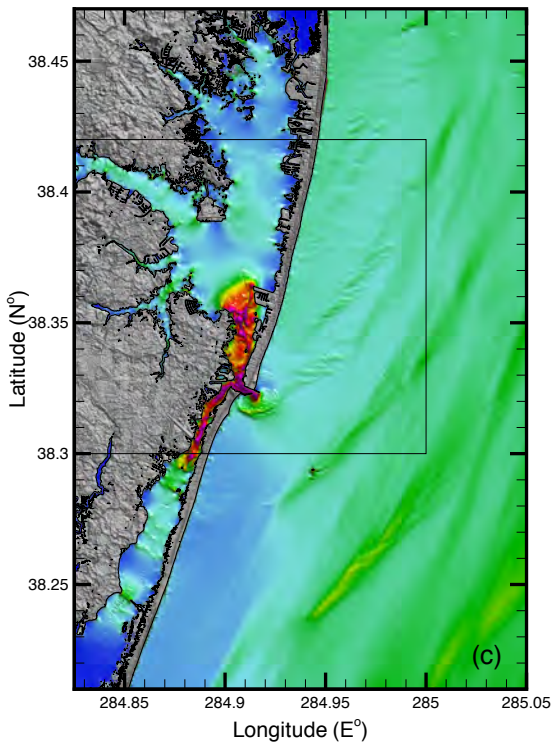
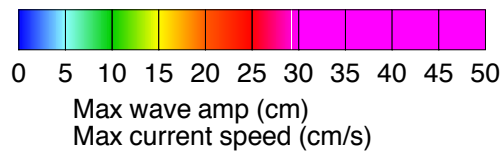
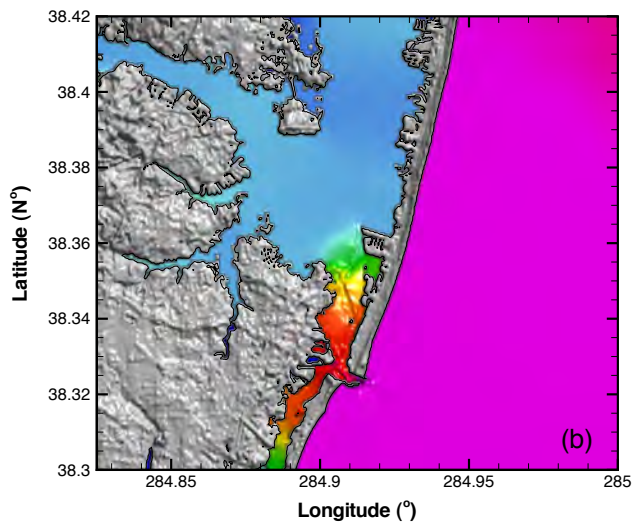
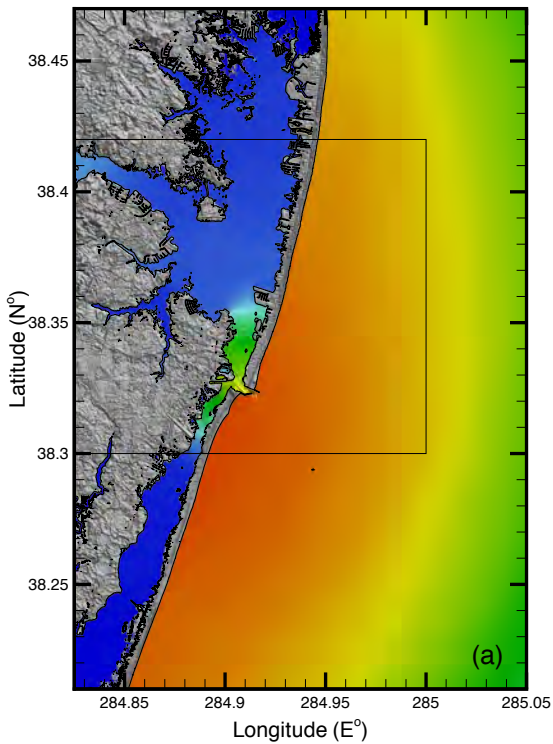


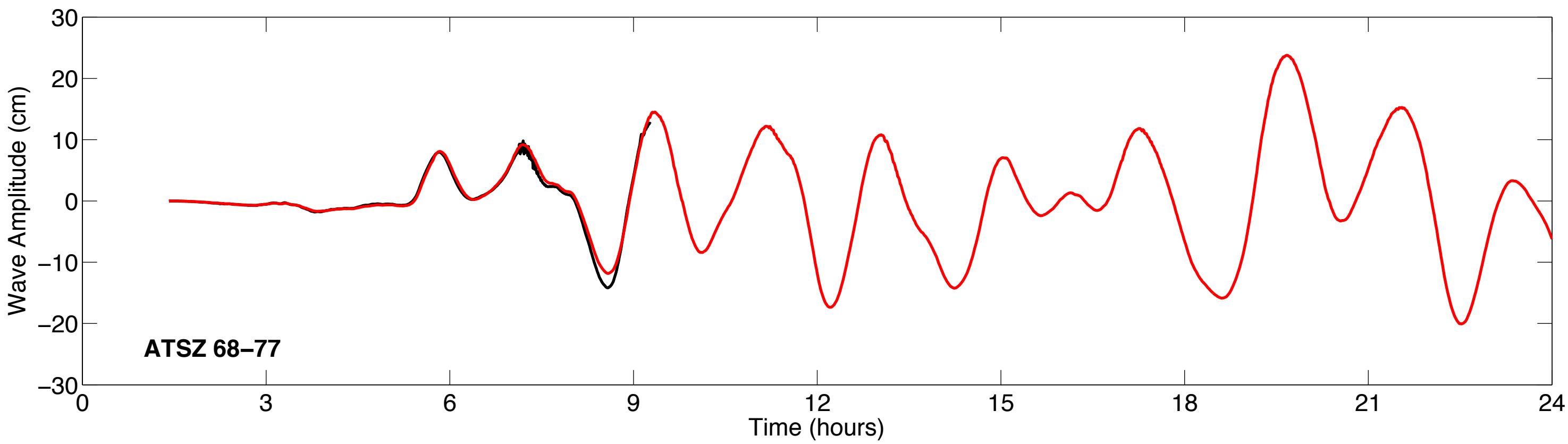
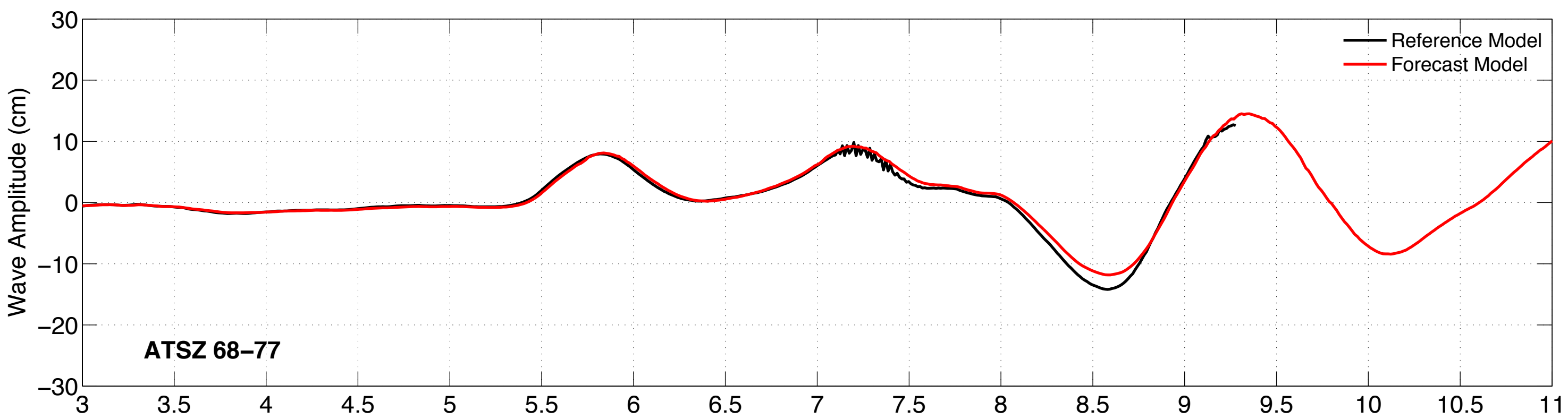


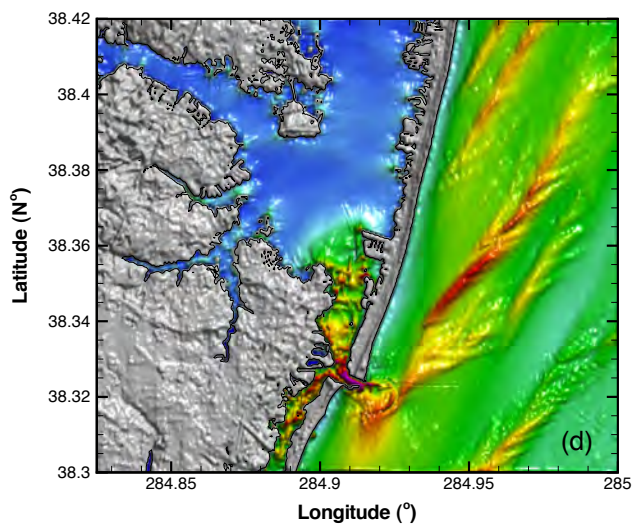
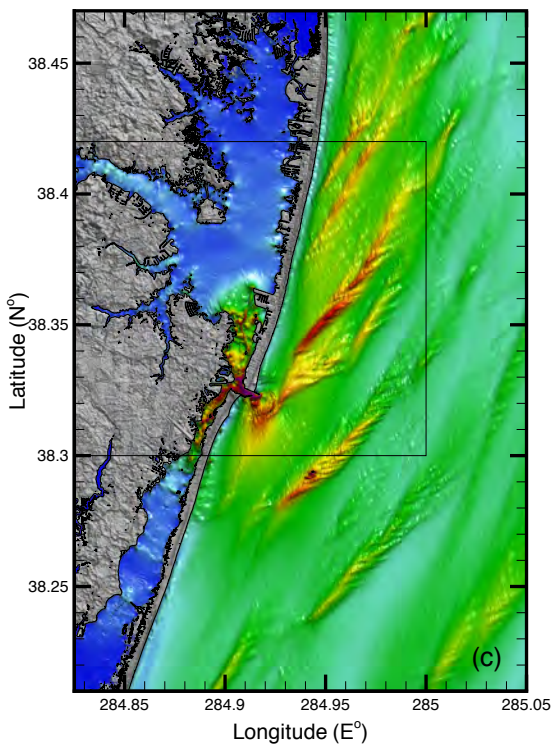
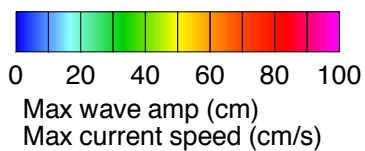
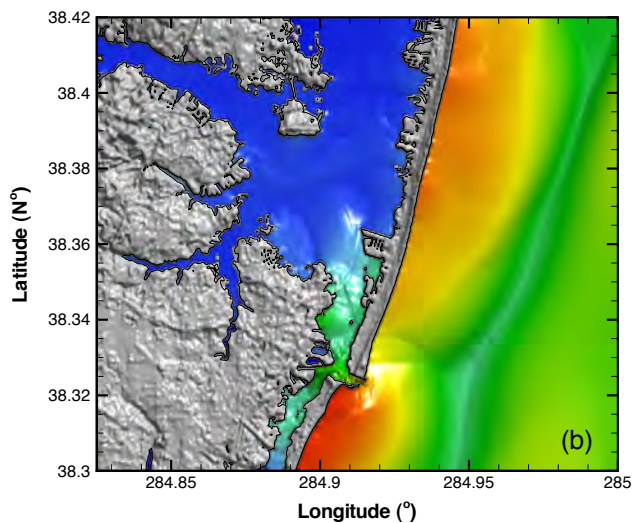
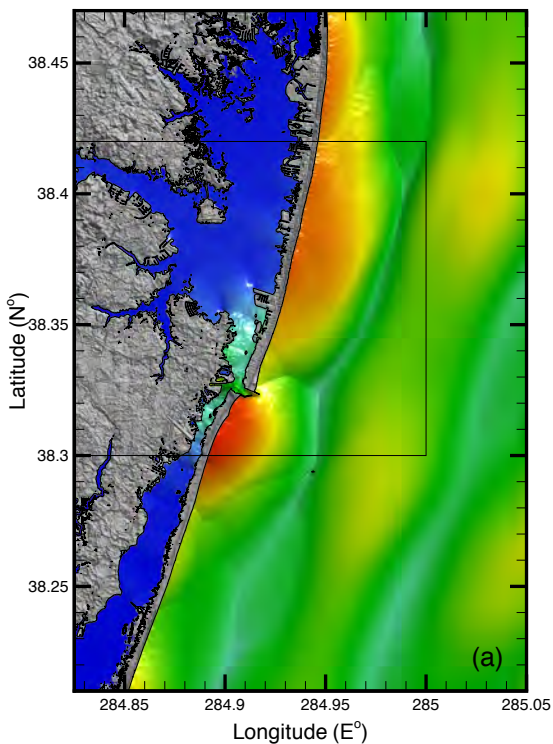


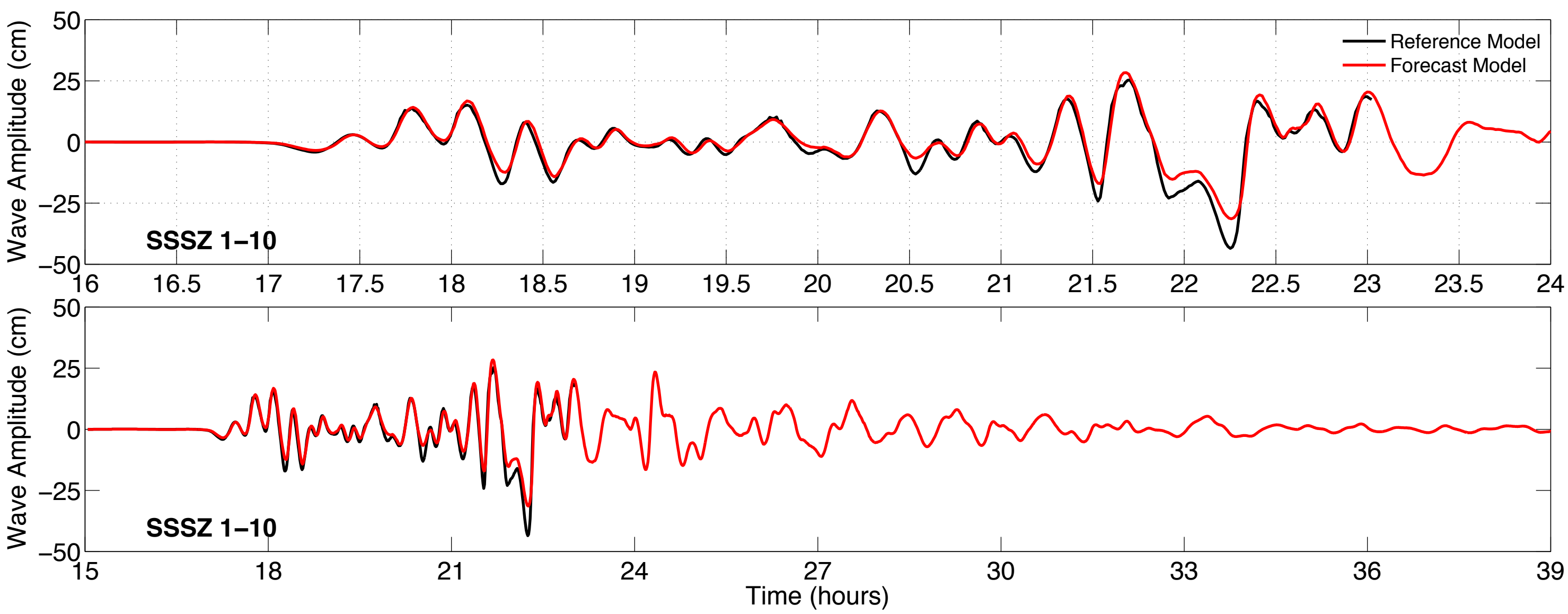


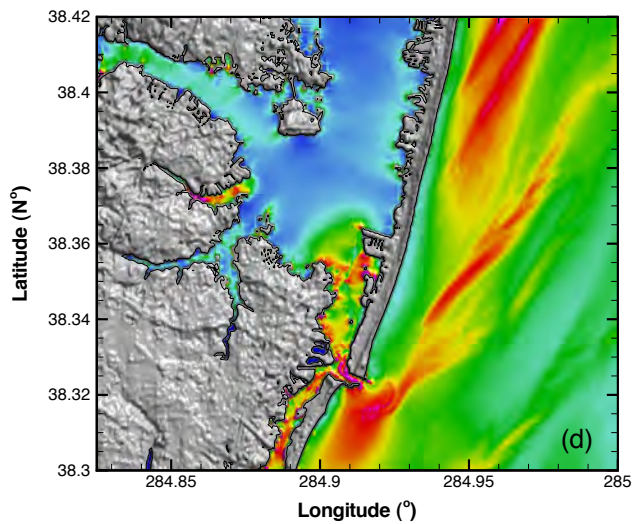
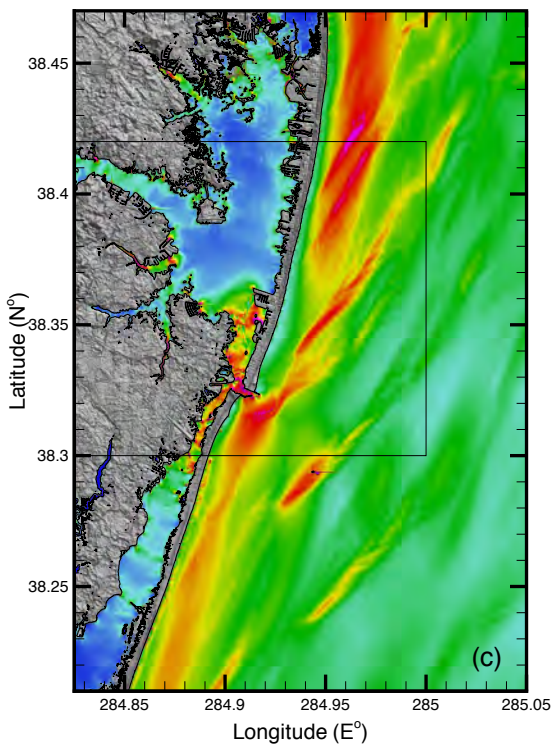
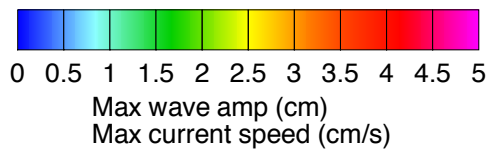
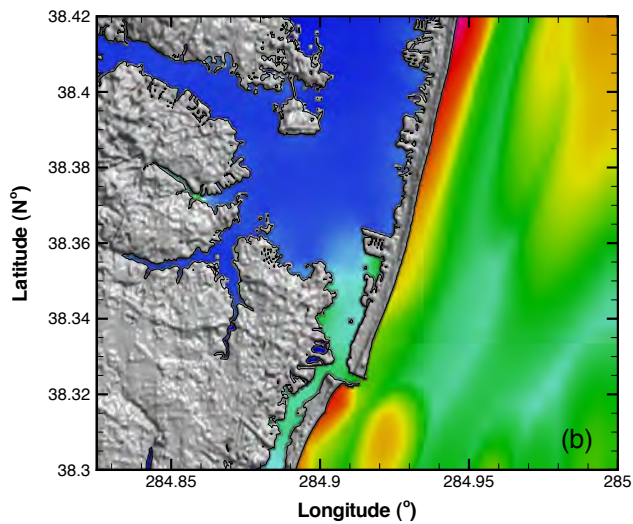
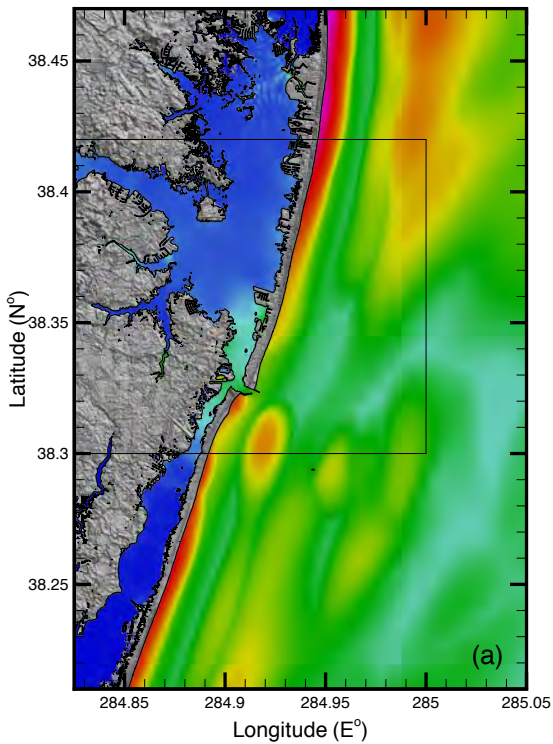


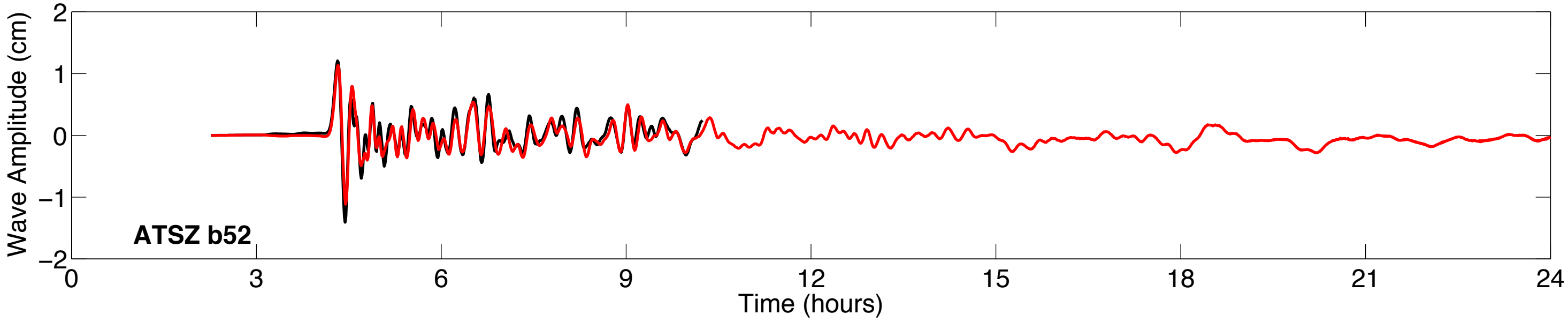
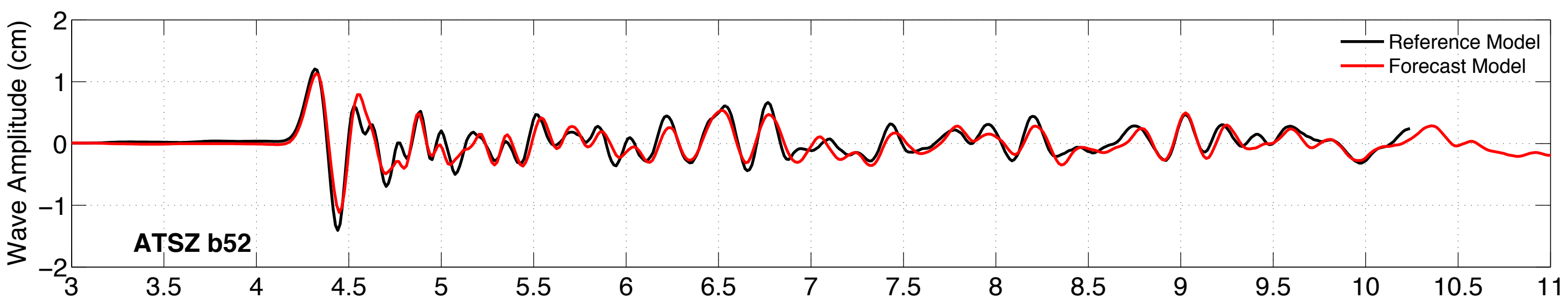












Appendix A.

Development of the Ocean City, Maryland, tsunami forecast model occurred prior to parameters changes that were made to reflect modification to the MOST model code. As a result, the input file for running both the optimized tsunami forecast model and the high-resolution reference inundation model in MOST have been updated accordingly. Appendix A1 and A2 provide the updated files for Ocean City, Maryland.

A1. Reference model *.in file for Ocean City, Maryland

```
1.0E-4 Minimum amplitude of input offshore wave (m)
1.0   Input minimum depth for offshore (m)
0.1   Input "dry land" depth for inundation (m)
0.0009 Input friction coefficient (n**2)
1     let a and b run up
90.0 blowup limit
1.8   input time step (sec)
16000 input amount of steps
2     Compute "A" arrays every n-th time step, n=
7     Compute "B" arrays every n-th time step, n=
14    Input number of steps between snapshots
0     ...Starting from
1     ...saveing grid every n-th node, n=
```

A2. Forecast model *.in file for Ocean City, Maryland

```
1.0E-4 Minimum amplitude of input offshore wave (m)
1.0   Input minimum depth for offshore (m)
0.1   Input "dry land" depth for inundation (m)
0.0009 Input friction coefficient (n**2)
1     let a and b run up
90.0 blowup limit
0.4   input time step (sec)
72000 input amount of steps
8     Compute "A" arrays every n-th time step, n=
7     Compute "B" arrays every n-th time step, n=
56    Input number of steps between snapshots
0     ...Starting from
1     ...saving grid every n-th node, n=
```


Appendix B. Propagation database:

Atlantic Ocean Unit Sources

These propagation source details reflect the database as of February 2013, and there may have been updates in the earthquake source parameters after this date.

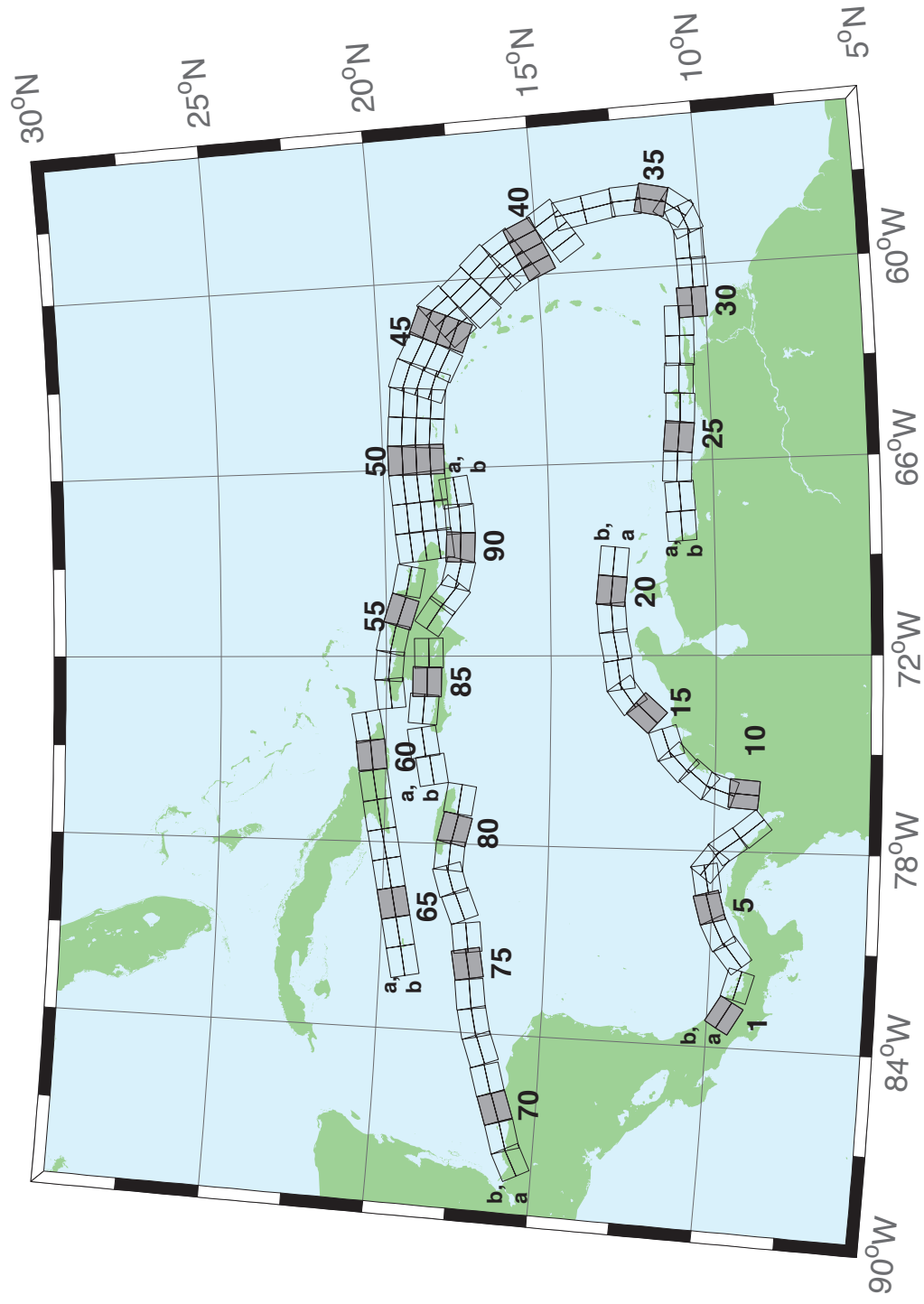


Figure B.1: Atlantic Source Zone unit sources.

Table B.1: Earthquake parameters for Atlantic Source Zone unit sources.

Segment	Description	Longitude(°E)	Latitude(°N)	Strike(°)	Dip(°)	Depth (km)
atsz-1a	Atlantic Source Zone	-83.2020	9.1449	120	27.5	28.09
atsz-1b	Atlantic Source Zone	-83.0000	9.4899	120	27.5	5
atsz-2a	Atlantic Source Zone	-82.1932	8.7408	105.1	27.5	28.09
atsz-2b	Atlantic Source Zone	-82.0880	9.1254	105.1	27.5	5
atsz-3a	Atlantic Source Zone	-80.9172	9.0103	51.31	30	30
atsz-3b	Atlantic Source Zone	-81.1636	9.3139	51.31	30	5
atsz-4a	Atlantic Source Zone	-80.3265	9.4308	63.49	30	30
atsz-4b	Atlantic Source Zone	-80.5027	9.7789	63.49	30	5
atsz-5a	Atlantic Source Zone	-79.6247	9.6961	74.44	30	30
atsz-5b	Atlantic Source Zone	-79.7307	10.0708	74.44	30	5
atsz-6a	Atlantic Source Zone	-78.8069	9.8083	79.71	30	30
atsz-6b	Atlantic Source Zone	-78.8775	10.1910	79.71	30	5
atsz-7a	Atlantic Source Zone	-78.6237	9.7963	127.2	30	30
atsz-7b	Atlantic Source Zone	-78.3845	10.1059	127.2	30	5
atsz-8a	Atlantic Source Zone	-78.1693	9.3544	143.8	30	30
atsz-8b	Atlantic Source Zone	-77.8511	9.5844	143.8	30	5
atsz-9a	Atlantic Source Zone	-77.5913	8.5989	139.9	30	30
atsz-9b	Atlantic Source Zone	-77.2900	8.8493	139.9	30	5
atsz-10a	Atlantic Source Zone	-75.8109	9.0881	4.67	17	19.62
atsz-10b	Atlantic Source Zone	-76.2445	9.1231	4.67	17	5
atsz-11a	Atlantic Source Zone	-75.7406	9.6929	19.67	17	19.62
atsz-11b	Atlantic Source Zone	-76.1511	9.8375	19.67	17	5
atsz-12a	Atlantic Source Zone	-75.4763	10.2042	40.4	17	19.62
atsz-12b	Atlantic Source Zone	-75.8089	10.4826	40.4	17	5
atsz-13a	Atlantic Source Zone	-74.9914	10.7914	47.17	17	19.62
atsz-13b	Atlantic Source Zone	-75.2890	11.1064	47.17	17	5
atsz-14a	Atlantic Source Zone	-74.5666	11.0708	71.68	17	19.62
atsz-14b	Atlantic Source Zone	-74.7043	11.4786	71.68	17	5
atsz-15a	Atlantic Source Zone	-73.4576	11.8012	42.69	17	19.62
atsz-15b	Atlantic Source Zone	-73.7805	12.0924	42.69	17	5
atsz-16a	Atlantic Source Zone	-72.9788	12.3365	54.75	17	19.62
atsz-16b	Atlantic Source Zone	-73.2329	12.6873	54.75	17	5
atsz-17a	Atlantic Source Zone	-72.5454	12.5061	81.96	17	19.62
atsz-17b	Atlantic Source Zone	-72.6071	12.9314	81.96	17	5
atsz-18a	Atlantic Source Zone	-71.6045	12.6174	79.63	17	19.62
atsz-18b	Atlantic Source Zone	-71.6839	13.0399	79.63	17	5
atsz-19a	Atlantic Source Zone	-70.7970	12.7078	86.32	17	19.62
atsz-19b	Atlantic Source Zone	-70.8253	13.1364	86.32	17	5
atsz-20a	Atlantic Source Zone	-70.0246	12.7185	95.94	17	19.62
atsz-20b	Atlantic Source Zone	-69.9789	13.1457	95.94	17	5
atsz-21a	Atlantic Source Zone	-69.1244	12.6320	95.94	17	19.62
atsz-21b	Atlantic Source Zone	-69.0788	13.0592	95.94	17	5
atsz-22a	Atlantic Source Zone	-68.0338	11.4286	266.9	15	17.94
atsz-22b	Atlantic Source Zone	-68.0102	10.9954	266.9	15	5
atsz-23a	Atlantic Source Zone	-67.1246	11.4487	266.9	15	17.94
atsz-23b	Atlantic Source Zone	-67.1010	11.0155	266.9	15	5
atsz-24a	Atlantic Source Zone	-66.1656	11.5055	273.3	15	17.94
atsz-24b	Atlantic Source Zone	-66.1911	11.0724	273.3	15	5
atsz-25a	Atlantic Source Zone	-65.2126	11.4246	276.4	15	17.94
atsz-25b	Atlantic Source Zone	-65.2616	10.9934	276.4	15	5
atsz-26a	Atlantic Source Zone	-64.3641	11.3516	272.9	15	17.94
atsz-26b	Atlantic Source Zone	-64.3862	10.9183	272.9	15	5
atsz-27a	Atlantic Source Zone	-63.4472	11.3516	272.9	15	17.94

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Table B.1 – continued from previous page

Segment	Description	Longitude(°E)	Latitude(°N)	Strike(°)	Dip(°)	Depth (km)
atsz-27b	Atlantic Source Zone	-63.4698	10.9183	272.9	15	5
atsz-28a	Atlantic Source Zone	-62.6104	11.2831	271.1	15	17.94
atsz-28b	Atlantic Source Zone	-62.6189	10.8493	271.1	15	5
atsz-29a	Atlantic Source Zone	-61.6826	11.2518	271.6	15	17.94
atsz-29b	Atlantic Source Zone	-61.6947	10.8181	271.6	15	5
atsz-30a	Atlantic Source Zone	-61.1569	10.8303	269	15	17.94
atsz-30b	Atlantic Source Zone	-61.1493	10.3965	269	15	5
atsz-31a	Atlantic Source Zone	-60.2529	10.7739	269	15	17.94
atsz-31b	Atlantic Source Zone	-60.2453	10.3401	269	15	5
atsz-32a	Atlantic Source Zone	-59.3510	10.8123	269	15	17.94
atsz-32b	Atlantic Source Zone	-59.3734	10.3785	269	15	5
atsz-33a	Atlantic Source Zone	-58.7592	10.8785	248.6	15	17.94
atsz-33b	Atlantic Source Zone	-58.5984	10.4745	248.6	15	5
atsz-34a	Atlantic Source Zone	-58.5699	11.0330	217.2	15	17.94
atsz-34b	Atlantic Source Zone	-58.2179	10.7710	217.2	15	5
atsz-35a	Atlantic Source Zone	-58.3549	11.5300	193.7	15	17.94
atsz-35b	Atlantic Source Zone	-57.9248	11.4274	193.7	15	5
atsz-36a	Atlantic Source Zone	-58.3432	12.1858	177.7	15	17.94
atsz-36b	Atlantic Source Zone	-57.8997	12.2036	177.7	15	5
atsz-37a	Atlantic Source Zone	-58.4490	12.9725	170.7	15	17.94
atsz-37b	Atlantic Source Zone	-58.0095	13.0424	170.7	15	5
atsz-38a	Atlantic Source Zone	-58.6079	13.8503	170.2	15	17.94
atsz-38b	Atlantic Source Zone	-58.1674	13.9240	170.2	15	5
atsz-39a	Atlantic Source Zone	-58.6667	14.3915	146.8	15	17.94
atsz-39b	Atlantic Source Zone	-58.2913	14.6287	146.8	15	5
atsz-39y	Atlantic Source Zone	-59.4168	13.9171	146.8	15	43.82
atsz-39z	Atlantic Source Zone	-59.0415	14.1543	146.8	15	30.88
atsz-40a	Atlantic Source Zone	-59.1899	15.2143	156.2	15	17.94
atsz-40b	Atlantic Source Zone	-58.7781	15.3892	156.2	15	5
atsz-40y	Atlantic Source Zone	-60.0131	14.8646	156.2	15	43.82
atsz-40z	Atlantic Source Zone	-59.6012	15.0395	156.2	15	30.88
atsz-41a	Atlantic Source Zone	-59.4723	15.7987	146.3	15	17.94
atsz-41b	Atlantic Source Zone	-59.0966	16.0392	146.3	15	5
atsz-41y	Atlantic Source Zone	-60.2229	15.3177	146.3	15	43.82
atsz-41z	Atlantic Source Zone	-59.8473	15.5582	146.3	15	30.88
atsz-42a	Atlantic Source Zone	-59.9029	16.4535	137	15	17.94
atsz-42b	Atlantic Source Zone	-59.5716	16.7494	137	15	5
atsz-42y	Atlantic Source Zone	-60.5645	15.8616	137	15	43.82
atsz-42z	Atlantic Source Zone	-60.2334	16.1575	137	15	30.88
atsz-43a	Atlantic Source Zone	-60.5996	17.0903	138.7	15	17.94
atsz-43b	Atlantic Source Zone	-60.2580	17.3766	138.7	15	5
atsz-43y	Atlantic Source Zone	-61.2818	16.5177	138.7	15	43.82
atsz-43z	Atlantic Source Zone	-60.9404	16.8040	138.7	15	30.88
atsz-44a	Atlantic Source Zone	-61.1559	17.8560	141.1	15	17.94
atsz-44b	Atlantic Source Zone	-60.8008	18.1286	141.1	15	5
atsz-44y	Atlantic Source Zone	-61.8651	17.3108	141.1	15	43.82
atsz-44z	Atlantic Source Zone	-61.5102	17.5834	141.1	15	30.88
atsz-45a	Atlantic Source Zone	-61.5491	18.0566	112.8	15	17.94
atsz-45b	Atlantic Source Zone	-61.3716	18.4564	112.8	15	5
atsz-45y	Atlantic Source Zone	-61.9037	17.2569	112.8	15	43.82
atsz-45z	Atlantic Source Zone	-61.7260	17.6567	112.8	15	30.88
atsz-46a	Atlantic Source Zone	-62.4217	18.4149	117.9	15	17.94
atsz-46b	Atlantic Source Zone	-62.2075	18.7985	117.9	15	5
atsz-46y	Atlantic Source Zone	-62.8493	17.6477	117.9	15	43.82
atsz-46z	Atlantic Source Zone	-62.6352	18.0313	117.9	15	30.88

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Table B.1 – continued from previous page

Segment	Description	Longitude(°E)	Latitude(°N)	Strike(°)	Dip(°)	Depth (km)
atsz-47a	Atlantic Source Zone	-63.1649	18.7844	110.5	20	22.1
atsz-47b	Atlantic Source Zone	-63.0087	19.1798	110.5	20	5
atsz-47y	Atlantic Source Zone	-63.4770	17.9936	110.5	20	56.3
atsz-47z	Atlantic Source Zone	-63.3205	18.3890	110.5	20	39.2
atsz-48a	Atlantic Source Zone	-63.8800	18.8870	95.37	20	22.1
atsz-48b	Atlantic Source Zone	-63.8382	19.3072	95.37	20	5
atsz-48y	Atlantic Source Zone	-63.9643	18.0465	95.37	20	56.3
atsz-48z	Atlantic Source Zone	-63.9216	18.4667	95.37	20	39.2
atsz-49a	Atlantic Source Zone	-64.8153	18.9650	94.34	20	22.1
atsz-49b	Atlantic Source Zone	-64.7814	19.3859	94.34	20	5
atsz-49y	Atlantic Source Zone	-64.8840	18.1233	94.34	20	56.3
atsz-49z	Atlantic Source Zone	-64.8492	18.5442	94.34	20	39.2
atsz-50a	Atlantic Source Zone	-65.6921	18.9848	89.59	20	22.1
atsz-50b	Atlantic Source Zone	-65.6953	19.4069	89.59	20	5
atsz-50y	Atlantic Source Zone	-65.6874	18.1407	89.59	20	56.3
atsz-50z	Atlantic Source Zone	-65.6887	18.5628	89.59	20	39.2
atsz-51a	Atlantic Source Zone	-66.5742	18.9484	84.98	20	22.1
atsz-51b	Atlantic Source Zone	-66.6133	19.3688	84.98	20	5
atsz-51y	Atlantic Source Zone	-66.4977	18.1076	84.98	20	56.3
atsz-51z	Atlantic Source Zone	-66.5353	18.5280	84.98	20	39.2
atsz-52a	Atlantic Source Zone	-67.5412	18.8738	85.87	20	22.1
atsz-52b	Atlantic Source Zone	-67.5734	19.2948	85.87	20	5
atsz-52y	Atlantic Source Zone	-67.4781	18.0319	85.87	20	56.3
atsz-52z	Atlantic Source Zone	-67.5090	18.4529	85.87	20	39.2
atsz-53a	Atlantic Source Zone	-68.4547	18.7853	83.64	20	22.1
atsz-53b	Atlantic Source Zone	-68.5042	19.2048	83.64	20	5
atsz-53y	Atlantic Source Zone	-68.3575	17.9463	83.64	20	56.3
atsz-53z	Atlantic Source Zone	-68.4055	18.3658	83.64	20	39.2
atsz-54a	Atlantic Source Zone	-69.6740	18.8841	101.5	20	22.1
atsz-54b	Atlantic Source Zone	-69.5846	19.2976	101.5	20	5
atsz-55a	Atlantic Source Zone	-70.7045	19.1376	108.2	20	22.1
atsz-55b	Atlantic Source Zone	-70.5647	19.5386	108.2	20	5
atsz-56a	Atlantic Source Zone	-71.5368	19.3853	102.6	20	22.1
atsz-56b	Atlantic Source Zone	-71.4386	19.7971	102.6	20	5
atsz-57a	Atlantic Source Zone	-72.3535	19.4838	94.2	20	22.1
atsz-57b	Atlantic Source Zone	-72.3206	19.9047	94.2	20	5
atsz-58a	Atlantic Source Zone	-73.1580	19.4498	84.34	20	22.1
atsz-58b	Atlantic Source Zone	-73.2022	19.8698	84.34	20	5
atsz-59a	Atlantic Source Zone	-74.3567	20.9620	259.7	20	22.1
atsz-59b	Atlantic Source Zone	-74.2764	20.5467	259.7	20	5
atsz-60a	Atlantic Source Zone	-75.2386	20.8622	264.2	15	17.94
atsz-60b	Atlantic Source Zone	-75.1917	20.4306	264.2	15	5
atsz-61a	Atlantic Source Zone	-76.2383	20.7425	260.7	15	17.94
atsz-61b	Atlantic Source Zone	-76.1635	20.3144	260.7	15	5
atsz-62a	Atlantic Source Zone	-77.2021	20.5910	259.9	15	17.94
atsz-62b	Atlantic Source Zone	-77.1214	20.1638	259.9	15	5
atsz-63a	Atlantic Source Zone	-78.1540	20.4189	259	15	17.94
atsz-63b	Atlantic Source Zone	-78.0661	19.9930	259	15	5
atsz-64a	Atlantic Source Zone	-79.0959	20.2498	259.2	15	17.94
atsz-64b	Atlantic Source Zone	-79.0098	19.8236	259.2	15	5
atsz-65a	Atlantic Source Zone	-80.0393	20.0773	258.9	15	17.94
atsz-65b	Atlantic Source Zone	-79.9502	19.6516	258.9	15	5
atsz-66a	Atlantic Source Zone	-80.9675	19.8993	258.6	15	17.94
atsz-66b	Atlantic Source Zone	-80.8766	19.4740	258.6	15	5
atsz-67a	Atlantic Source Zone	-81.9065	19.7214	258.5	15	17.94

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Table B.1 – continued from previous page

Segment	Description	Longitude(°E)	Latitude(°N)	Strike(°)	Dip(°)	Depth (km)
atsz-67b	Atlantic Source Zone	-81.8149	19.2962	258.5	15	5
atsz-68a	Atlantic Source Zone	-87.8003	15.2509	62.69	15	17.94
atsz-68b	Atlantic Source Zone	-88.0070	15.6364	62.69	15	5
atsz-69a	Atlantic Source Zone	-87.0824	15.5331	72.73	15	17.94
atsz-69b	Atlantic Source Zone	-87.2163	15.9474	72.73	15	5
atsz-70a	Atlantic Source Zone	-86.1622	15.8274	70.64	15	17.94
atsz-70b	Atlantic Source Zone	-86.3120	16.2367	70.64	15	5
atsz-71a	Atlantic Source Zone	-85.3117	16.1052	73.7	15	17.94
atsz-71b	Atlantic Source Zone	-85.4387	16.5216	73.7	15	5
atsz-72a	Atlantic Source Zone	-84.3470	16.3820	69.66	15	17.94
atsz-72b	Atlantic Source Zone	-84.5045	16.7888	69.66	15	5
atsz-73a	Atlantic Source Zone	-83.5657	16.6196	77.36	15	17.94
atsz-73b	Atlantic Source Zone	-83.6650	17.0429	77.36	15	5
atsz-74a	Atlantic Source Zone	-82.7104	16.7695	82.35	15	17.94
atsz-74b	Atlantic Source Zone	-82.7709	17.1995	82.35	15	5
atsz-75a	Atlantic Source Zone	-81.7297	16.9003	79.86	15	17.94
atsz-75b	Atlantic Source Zone	-81.8097	17.3274	79.86	15	5
atsz-76a	Atlantic Source Zone	-80.9196	16.9495	82.95	15	17.94
atsz-76b	Atlantic Source Zone	-80.9754	17.3801	82.95	15	5
atsz-77a	Atlantic Source Zone	-79.8086	17.2357	67.95	15	17.94
atsz-77b	Atlantic Source Zone	-79.9795	17.6378	67.95	15	5
atsz-78a	Atlantic Source Zone	-79.0245	17.5415	73.61	15	17.94
atsz-78b	Atlantic Source Zone	-79.1532	17.9577	73.61	15	5
atsz-79a	Atlantic Source Zone	-78.4122	17.5689	94.07	15	17.94
atsz-79b	Atlantic Source Zone	-78.3798	18.0017	94.07	15	5
atsz-80a	Atlantic Source Zone	-77.6403	17.4391	103.3	15	17.94
atsz-80b	Atlantic Source Zone	-77.5352	17.8613	103.3	15	5
atsz-81a	Atlantic Source Zone	-76.6376	17.2984	98.21	15	17.94
atsz-81b	Atlantic Source Zone	-76.5726	17.7278	98.21	15	5
atsz-82a	Atlantic Source Zone	-75.7299	19.0217	260.1	15	17.94
atsz-82b	Atlantic Source Zone	-75.6516	18.5942	260.1	15	5
atsz-83a	Atlantic Source Zone	-74.8351	19.2911	260.8	15	17.94
atsz-83b	Atlantic Source Zone	-74.7621	18.8628	260.8	15	5
atsz-84a	Atlantic Source Zone	-73.6639	19.2991	274.8	15	17.94
atsz-84b	Atlantic Source Zone	-73.7026	18.8668	274.8	15	5
atsz-85a	Atlantic Source Zone	-72.8198	19.2019	270.6	15	17.94
atsz-85b	Atlantic Source Zone	-72.8246	18.7681	270.6	15	5
atsz-86a	Atlantic Source Zone	-71.9143	19.1477	269.1	15	17.94
atsz-86b	Atlantic Source Zone	-71.9068	18.7139	269.1	15	5
atsz-87a	Atlantic Source Zone	-70.4738	18.8821	304.5	15	17.94
atsz-87b	Atlantic Source Zone	-70.7329	18.5245	304.5	15	5
atsz-88a	Atlantic Source Zone	-69.7710	18.3902	308.9	15	17.94
atsz-88b	Atlantic Source Zone	-70.0547	18.0504	308.4	15	5
atsz-89a	Atlantic Source Zone	-69.2635	18.2099	283.9	15	17.94
atsz-89b	Atlantic Source Zone	-69.3728	17.7887	283.9	15	5
atsz-90a	Atlantic Source Zone	-68.5059	18.1443	272.9	15	17.94
atsz-90b	Atlantic Source Zone	-68.5284	17.7110	272.9	15	5
atsz-91a	Atlantic Source Zone	-67.6428	18.1438	267.8	15	17.94
atsz-91b	Atlantic Source Zone	-67.6256	17.7103	267.8	15	5
atsz-92a	Atlantic Source Zone	-66.8261	18.2536	262	15	17.94
atsz-92b	Atlantic Source Zone	-66.7627	17.8240	262	15	5

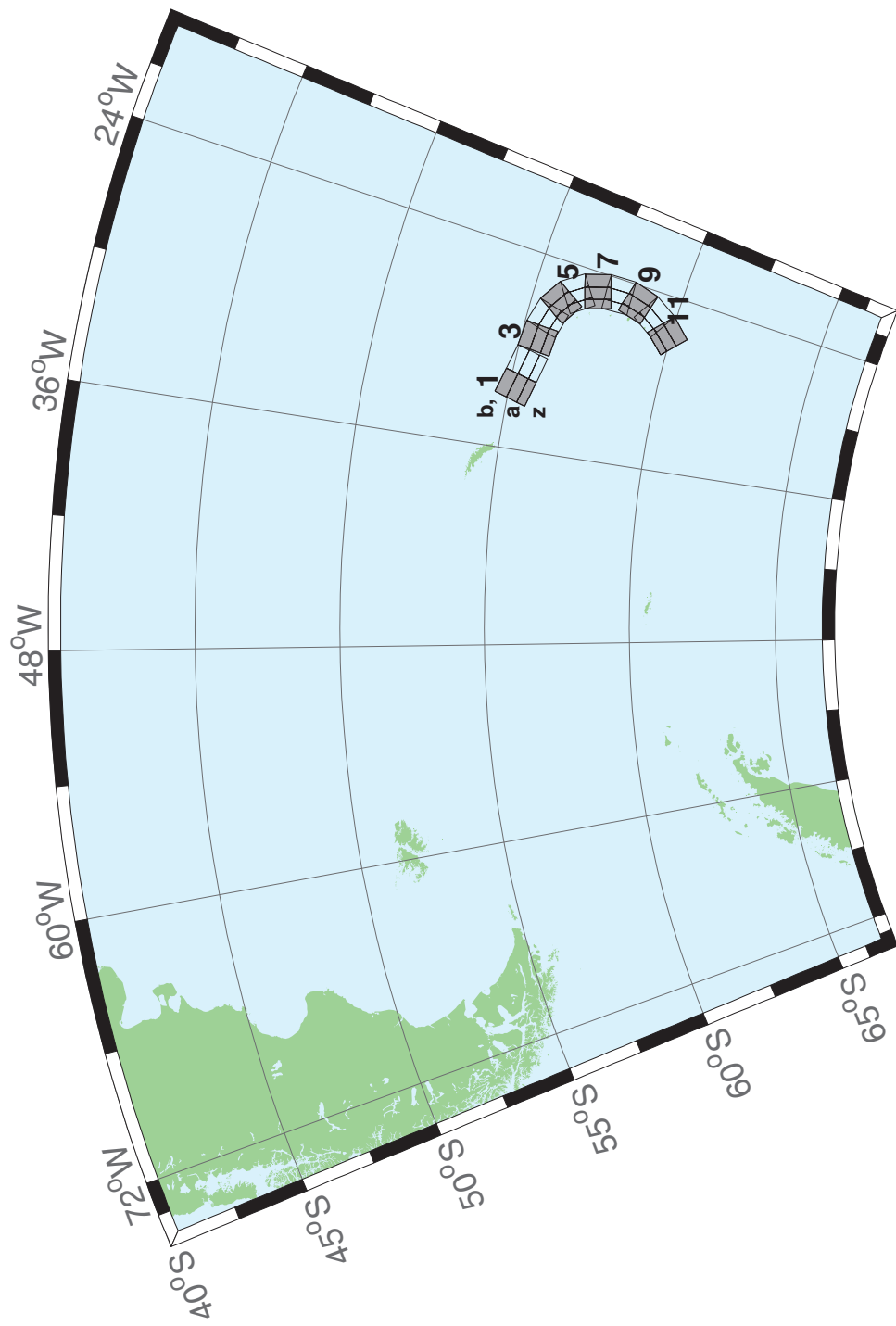


Figure B.2: South Sandwich Islands Subduction Zone.

Table B.2: Earthquake parameters for South Sandwich Islands Subduction Zone unit sources.

Segment	Description	Longitude(°E)	Latitude(°N)	Strike(°)	Dip(°)	Depth (km)	
sssz-1a	South Sandwich Islands Subduction Zone	-32.3713	-32.3713	-55.4655	104.7	28.53	17.51
sssz-1b	South Sandwich Islands Subduction Zone	-32.1953	-32.1953	-55.0832	104.7	9.957	8.866
sssz-1z	South Sandwich Islands Subduction Zone	-32.5091	-32.5091	-55.7624	104.7	46.99	41.39
sssz-2a	South Sandwich Islands Subduction Zone	-30.8028	-30.8028	-55.6842	102.4	28.53	17.51
sssz-2b	South Sandwich Islands Subduction Zone	-30.6524	-30.6524	-55.2982	102.4	9.957	8.866
sssz-2z	South Sandwich Islands Subduction Zone	-30.9206	-30.9206	-55.9839	102.4	46.99	41.39
sssz-3a	South Sandwich Islands Subduction Zone	-29.0824	-29.0824	-55.8403	95.53	28.53	17.51
sssz-3b	South Sandwich Islands Subduction Zone	-29.0149	-29.0149	-55.4468	95.53	9.957	8.866
sssz-3z	South Sandwich Islands Subduction Zone	-29.1353	-29.1353	-56.1458	95.53	46.99	41.39
sssz-4a	South Sandwich Islands Subduction Zone	-27.8128	-27.8128	-55.9796	106.1	28.53	17.51
sssz-4b	South Sandwich Islands Subduction Zone	-27.6174	-27.6174	-55.5999	106.1	9.957	8.866
sssz-4z	South Sandwich Islands Subduction Zone	-27.9659	-27.9659	-56.2744	106.1	46.99	41.39
sssz-5a	South Sandwich Islands Subduction Zone	-26.7928	-26.7928	-56.2481	123.1	28.53	17.51
sssz-5b	South Sandwich Islands Subduction Zone	-26.4059	-26.4059	-55.9170	123.1	9.957	8.866
sssz-5z	South Sandwich Islands Subduction Zone	-27.0955	-27.0955	-56.5052	123.1	46.99	41.39
sssz-6a	South Sandwich Islands Subduction Zone	-26.1317	-26.1317	-56.6466	145.6	23.28	16.11
sssz-6b	South Sandwich Islands Subduction Zone	-25.5131	-25.5131	-56.4133	145.6	9.09	8.228
sssz-6z	South Sandwich Islands Subduction Zone	-26.5920	-26.5920	-56.8194	145.6	47.15	35.87
sssz-7a	South Sandwich Islands Subduction Zone	-25.6787	-25.6787	-57.2162	162.9	21.21	14.23
sssz-7b	South Sandwich Islands Subduction Zone	-24.9394	-24.9394	-57.0932	162.9	7.596	7.626
sssz-7z	South Sandwich Islands Subduction Zone	-26.2493	-26.2493	-57.3109	162.9	44.16	32.32
sssz-8a	South Sandwich Islands Subduction Zone	-25.5161	-25.5161	-57.8712	178.2	20.33	15.91
sssz-8b	South Sandwich Islands Subduction Zone	-24.7233	-24.7233	-57.8580	178.2	8.449	8.562
sssz-8z	South Sandwich Islands Subduction Zone	-26.1280	-26.1280	-57.8813	178.2	43.65	33.28
sssz-9a	South Sandwich Islands Subduction Zone	-25.6657	-25.6657	-58.5053	195.4	25.76	15.71
sssz-9b	South Sandwich Islands Subduction Zone	-24.9168	-24.9168	-58.6127	195.4	8.254	8.537
sssz-9z	South Sandwich Islands Subduction Zone	-26.1799	-26.1799	-58.4313	195.4	51.69	37.44
sssz-10a	South Sandwich Islands Subduction Zone	-26.1563	-26.1563	-59.1048	212.5	32.82	15.65
sssz-10b	South Sandwich Islands Subduction Zone	-25.5335	-25.5335	-59.3080	212.5	10.45	6.581
sssz-10z	South Sandwich Islands Subduction Zone	-26.5817	-26.5817	-58.9653	212.5	54.77	42.75
sssz-11a	South Sandwich Islands Subduction Zone	-27.0794	-27.0794	-59.6799	224.2	33.67	15.75
sssz-11b	South Sandwich Islands Subduction Zone	-26.5460	-26.5460	-59.9412	224.2	11.32	5.927
sssz-11z	South Sandwich Islands Subduction Zone	-27.4245	-27.4245	-59.5098	224.2	57.19	43.46

Appendix C. SIFT testing results

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1.0 PURPOSE

Forecast models are tested with synthetic tsunami events covering a range of tsunami source locations. Testing is also done with selected historical tsunami events when available.

The purpose of forecast model testing is three-fold. The first objective is to assure that the results obtained with NOAA's tsunami forecast system, which has been released to the Tsunami Warning Centers for operational use, are identical to those obtained by the researcher during the development of the forecast model. The second objective is to test the forecast model for consistency, accuracy, time efficiency, and quality of results over a range of possible tsunami locations and magnitudes. The third objective is to identify bugs and issues in need of resolution by the researcher who developed the Forecast Model or by the forecast software development team before the next version release to NOAA's two Tsunami Warning Centers.

Local hardware and software applications, and tools familiar to the researcher(s), are used to run the Method of Splitting Tsunamis (MOST) model during the forecast model development. The test results presented in this report lend confidence that the model performs as developed and produces the same results when initiated within the forecast application in an operational setting as those produced by the researcher during the forecast model development. The test results assure those who rely on the Ocean City tsunami forecast model that consistent results are produced irrespective of system.

2.0 TESTING PROCEDURE

The general procedure for forecast model testing is to run a set of synthetic tsunami scenarios through the forecast system application and compare the results with those obtained by the researcher during the forecast model development and presented in the Tsunami Forecast Model Report. Specific steps taken to test the model include:

1. Identification of testing scenarios, including the standard set of synthetic events and customized synthetic scenarios that may have been used by the researcher(s) in developing the forecast model.
2. Creation of new events to represent customized synthetic scenarios used by the researcher(s) in developing the forecast model, if any.
3. Submission of test model runs with the forecast system, and export of the results from A, B, and C grids, along with time series.
4. Recording applicable metadata, including the specific version of the forecast system used for testing.
5. Examination of forecast model results from the forecast system for instabilities in both time series and plot results.
6. Comparison of forecast model results obtained through the forecast system with those obtained during the forecast model development.
7. Summarization of results with specific mention of quality, consistency, and time efficiency.
8. Reporting of issues identified to modeler and forecast software development team.
9. Retesting the forecast models in the forecast system when reported issues have been addressed or explained.

Synthetic model runs were tested on a DELL PowerEdge R510 computer equipped with two Xeon E5670 processors at 2.93 Ghz, each with 12 MBytes of cache and 32GB memory. The processors are hex core and support hyperthreading, resulting in the computer performing as a 24 processor core machine. Additionally, the testing computer supports 10 Gigabit Ethernet for fast network connections. This computer configuration is similar or the same as the configurations of the computers installed at the Tsunami Warning Centers so the compute times should only vary slightly.

Results

The Ocean City forecast model was tested with NOAA's tsunami forecast system version 3.2.

The Ocean City, Maryland forecast model was tested with three synthetic scenarios. Test results from the forecast system and comparisons with the results obtained during the forecast model development are shown numerically in Table 2 and graphically in Figures 1 to 3. The results show that the forecast model is stable and robust, with consistent and high quality results across geographically distributed tsunami sources and mega-event tsunami magnitudes. The model run time (wall clock time) was under 30 minutes for 8 hours of simulation time, and under 15 minutes for 4 hours. This run time is over the 10 minute run time for 4 hours of simulation time that satisfies time efficiency requirements. This is because coverage of the A grid needs to be extended further offshore of the continental shelf to better adapt the model boundary conditions from the propagation database. As the shallow continental shelf slows down the tsunami propagation and allows more time for warning and forecast, it is understandable that forecast models in the east coast, such as Ocean City, take more time to finish.

Three synthetic events were run on the Ocean City forecast model. The modeled scenarios were stable for all cases tested, with no instabilities or ringing. Results show that the largest modeled height was 126.87 cm and originated in the Caribbean (ATSZ 48-57) source. Amplitudes greater than 100 cm were recorded for the one of three test sources. The smallest signal of 25.58 cm was recorded for the far field South Sandwich Islands (SSSZ 1-10) source. Direct comparisons, of output from the forecast tool with results from available development synthetic events, demonstrated that the wave pattern is similar in shape, pattern and amplitude but does not match by eye. These discrepancies are mainly caused by different propagation databases used to provide the boundary conditions for model runs. Developed in 2010, the forecast model report shows the Ocean City model results based on an old tsunami propagation database, while the SIFT testing results in Appendix C reflect the tsunami propagation database that was updated in December of 2011. Table 1 shows the computed maximum and minimum wave amplitude by SIFT and by model based on old tsunami propagation database. It is known that the new propagation database will lead to improvement of the model results.

Source Zone	Tsunami Source	α [m]	SIFT Max (cm)	Development Max (cm)	SIFT Min (cm)	Development Min (cm)
ATSZ	A38-A47, B38-B47	25	58.945	56.4	-34.556	-45.58
ATSZ	A48-A57, B48-B57	25	126.869	139.2	-58.821	-62.44
SSSZ	A1-A10, B1-B10	25	25.581	28.36	-13.811	-31.41

Table 1. Table of maximum and minimum amplitudes (cm) at the Ocean City, Maryland warning point for synthetic and historical events tested using SIFT 3.2 and obtained during development.

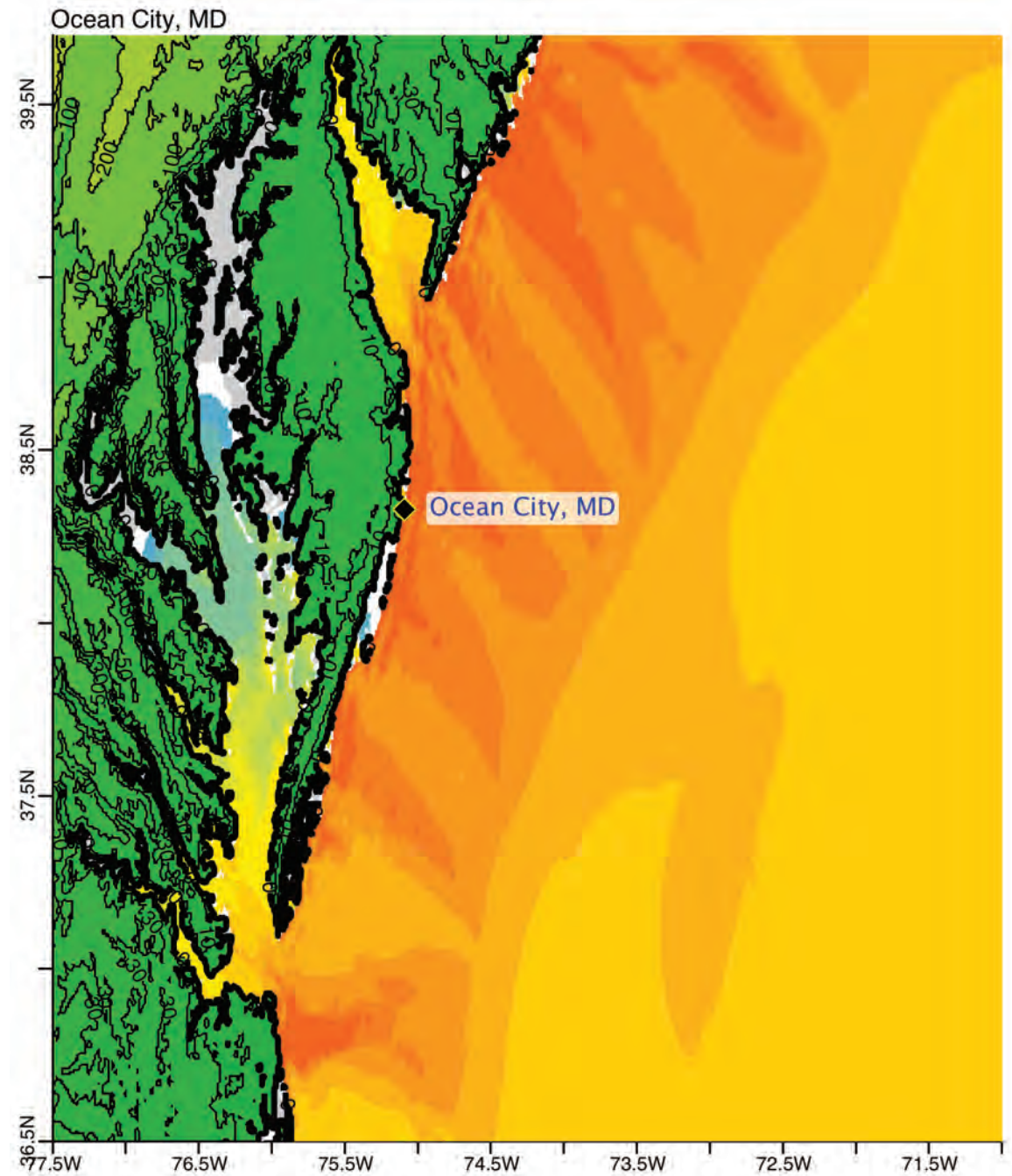


Figure 1. Max computed wave amplitude of A grid, Ocean City, Maryland, for synthetic event ATSZ 38-47.

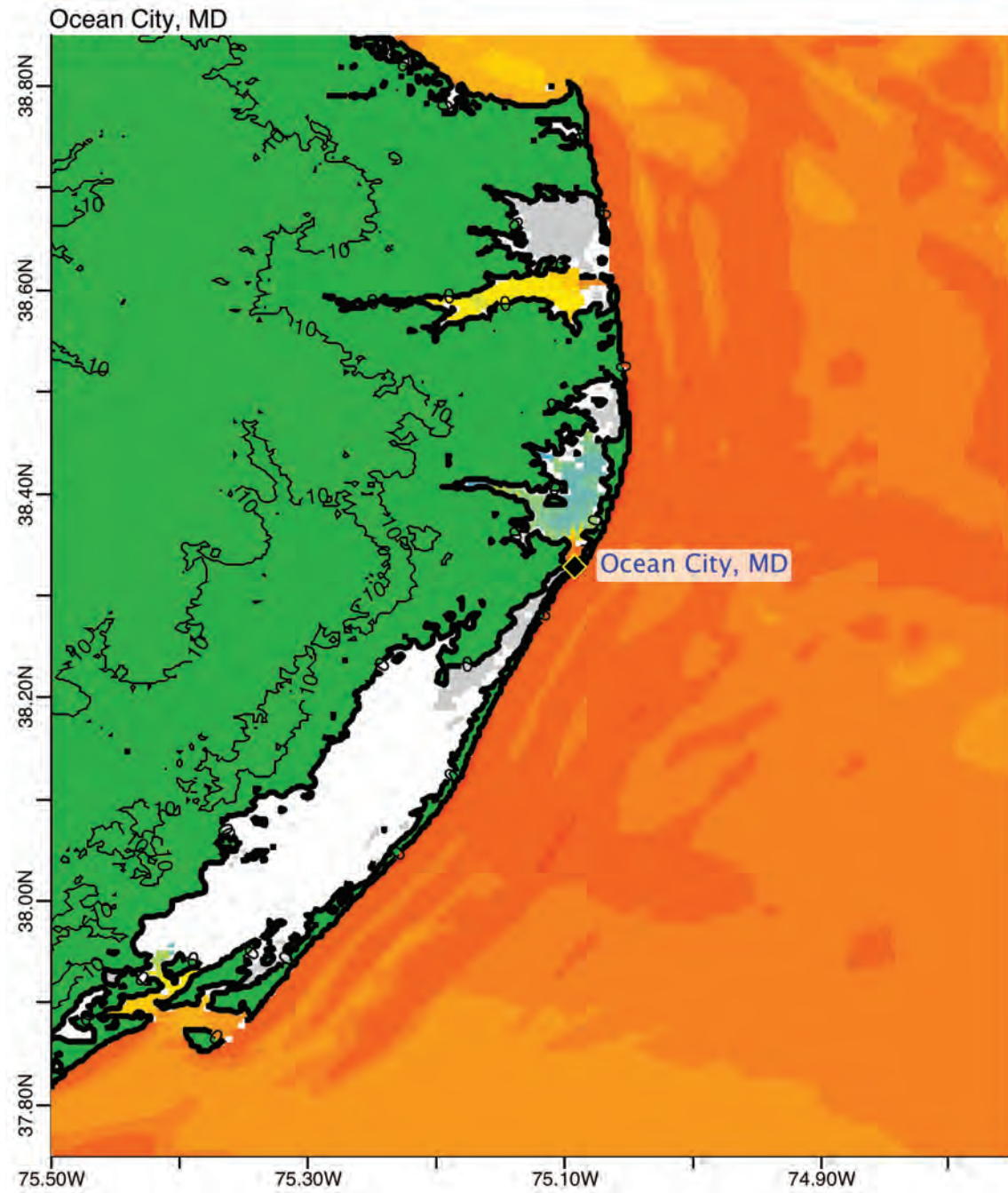


Figure 2. Max computed wave amplitude of B grid, Ocean City, Maryland, for synthetic event ATSZ 38-47.

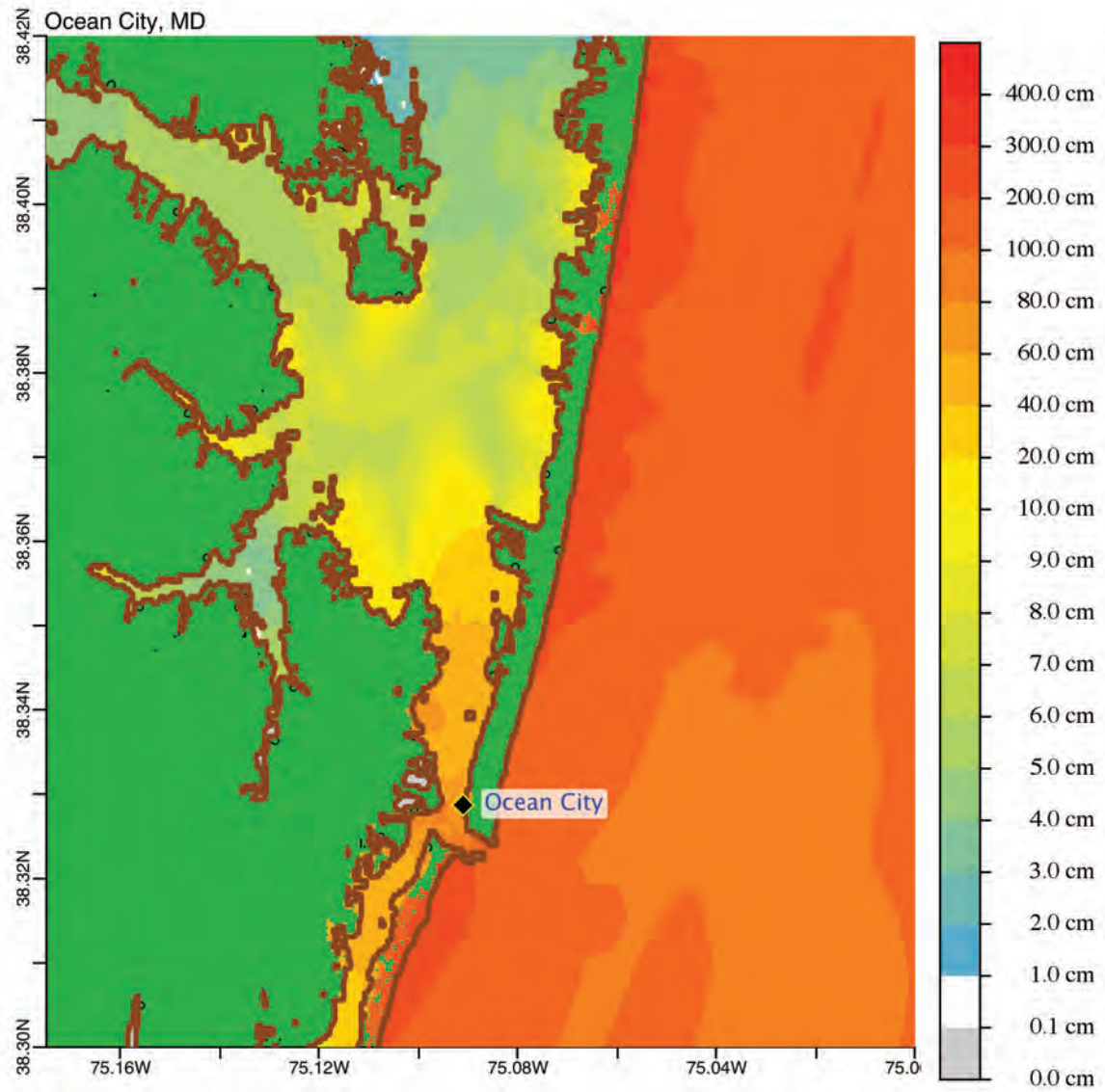
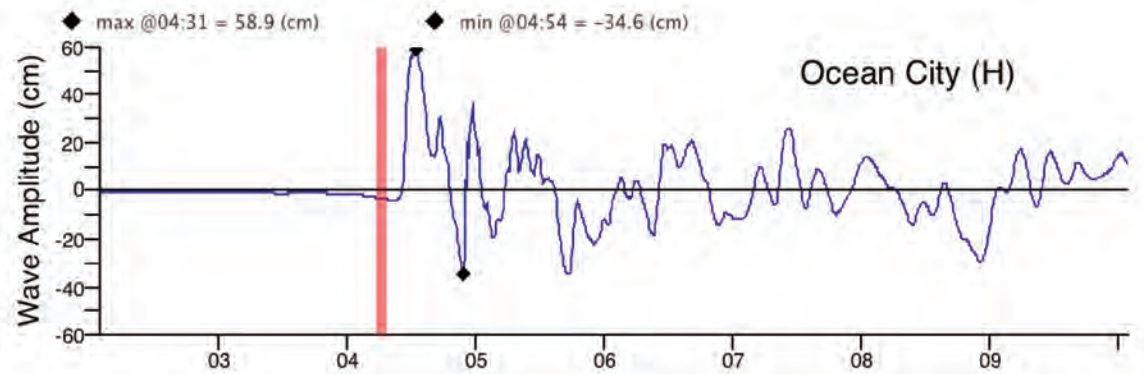


Figure 3. Max computed wave amplitude of C grid, Ocean City, Maryland, for synthetic event ATSZ 38-47.

(a)



(b)

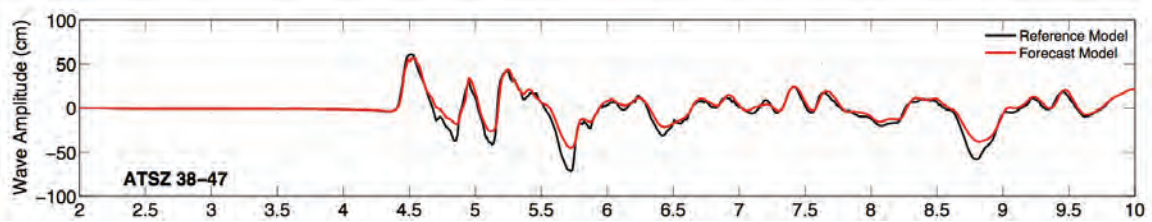


Figure 4. Computed time series at Ocean City tide gage, for synthetic event ATSZ 38-47: (a) time series computed in the forecast system; (b) time series shown in the forecast model report.

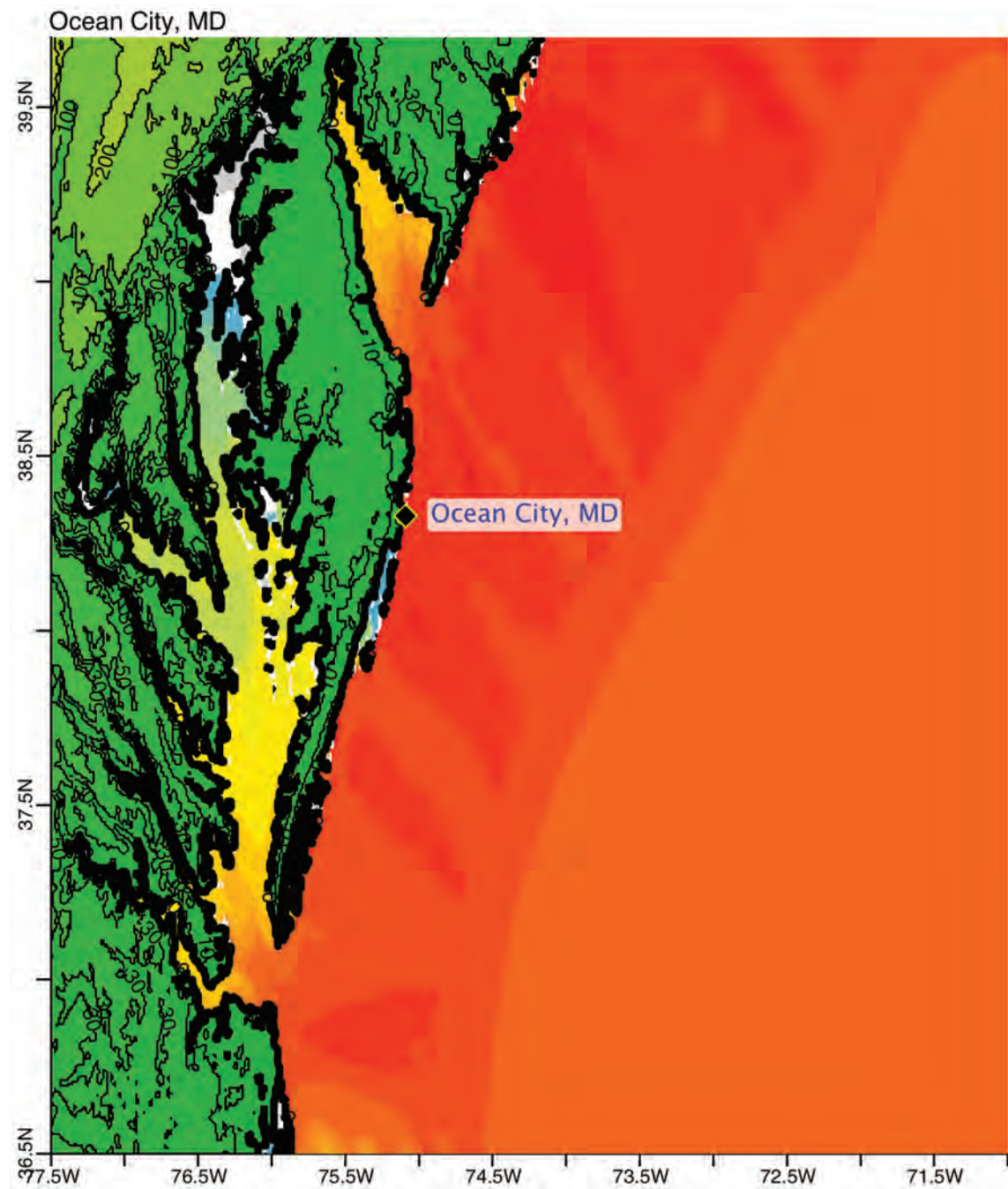


Figure 5. Max computed wave amplitude of A grid, Ocean City, Maryland, for synthetic event ATSZ 48-57.

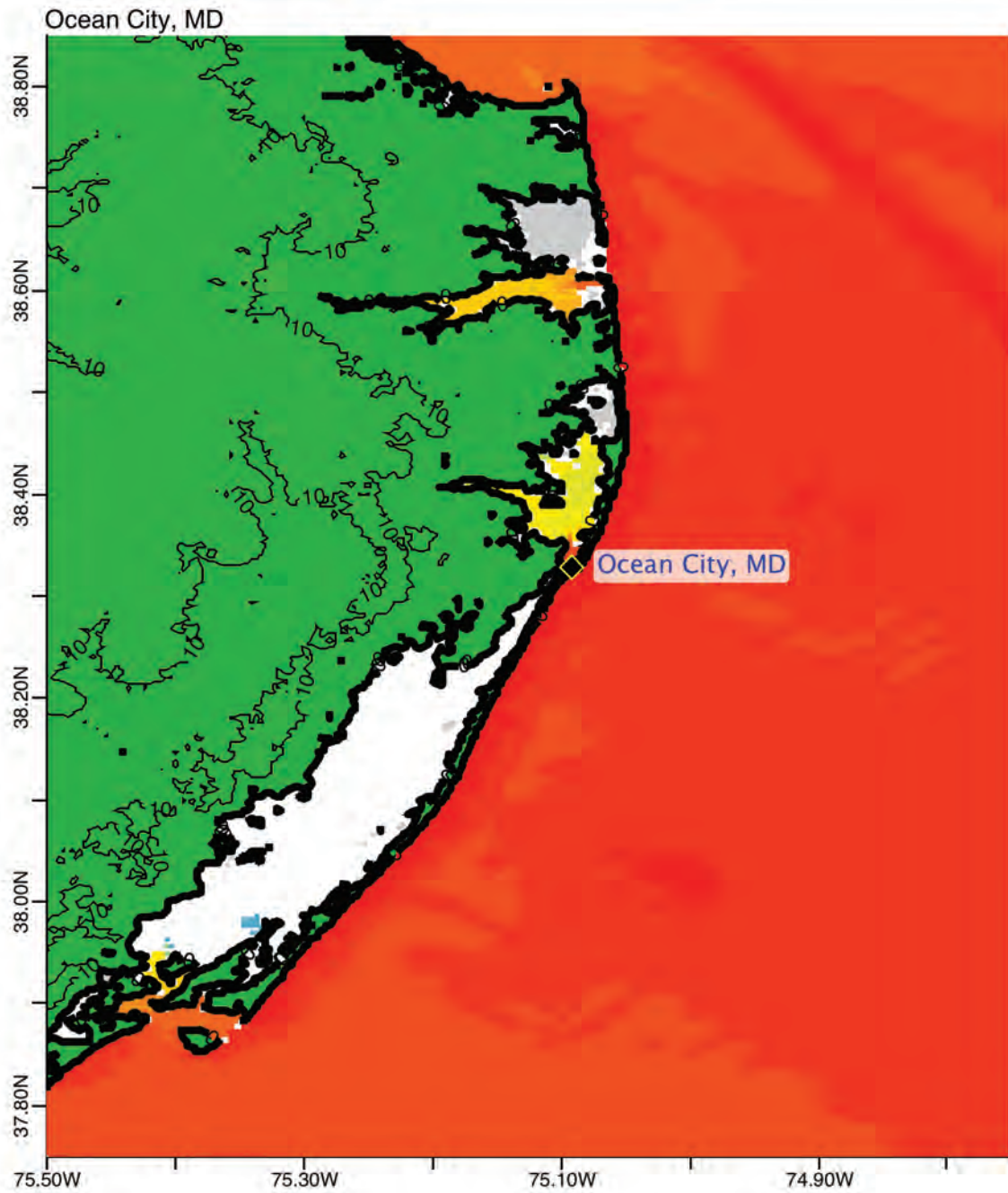


Figure 6. Max computed wave amplitude of B grid, Ocean City, Maryland, for synthetic event ATSZ 48-57.

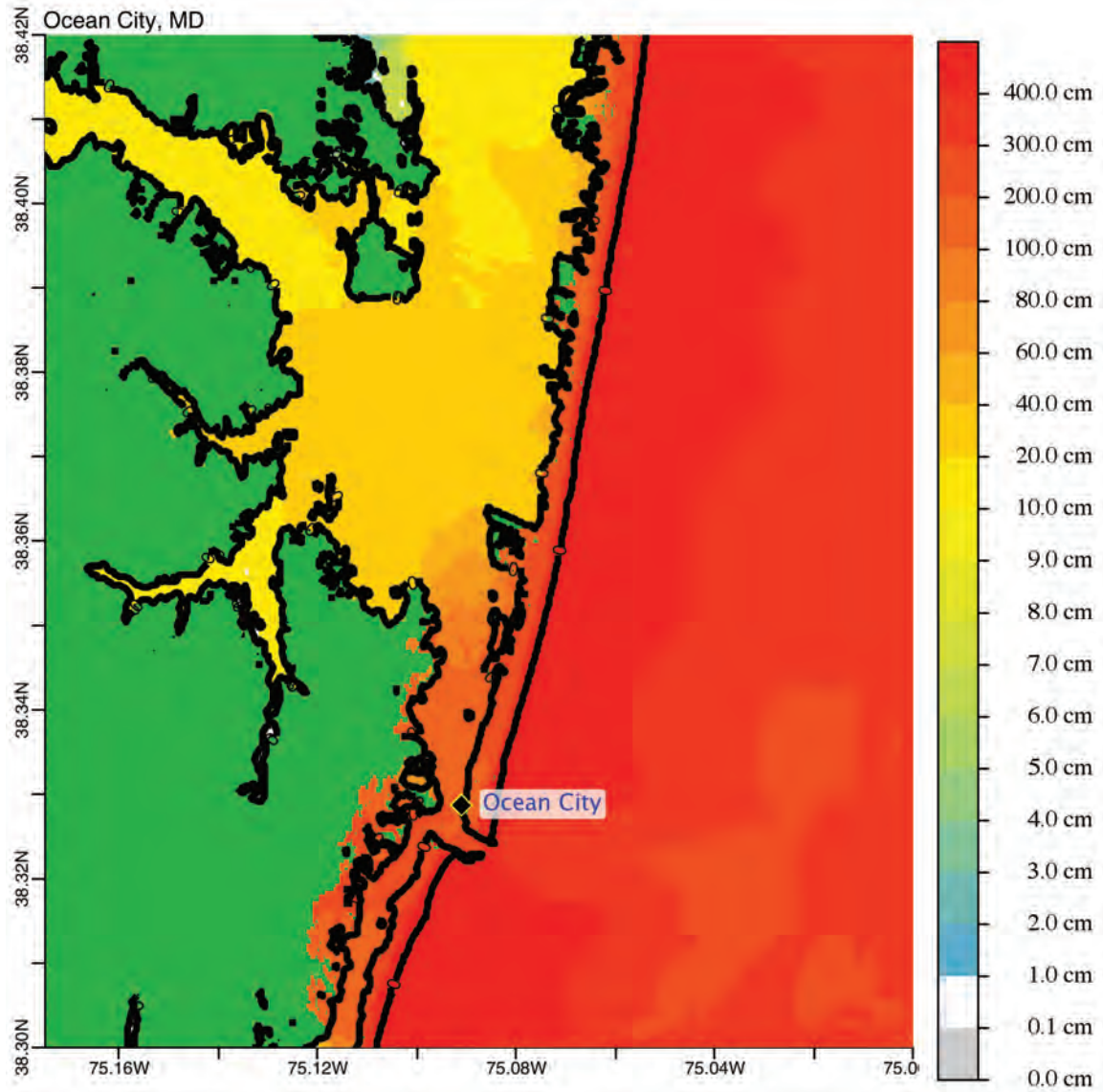
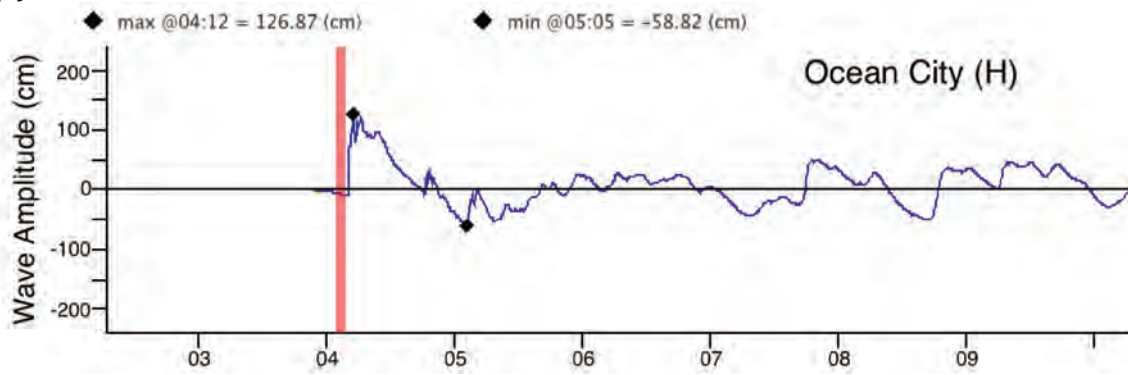


Figure 7. Max computed wave amplitude of C grid, Ocean City, Maryland, for synthetic event ATSZ 48-57.

(a)



(b)

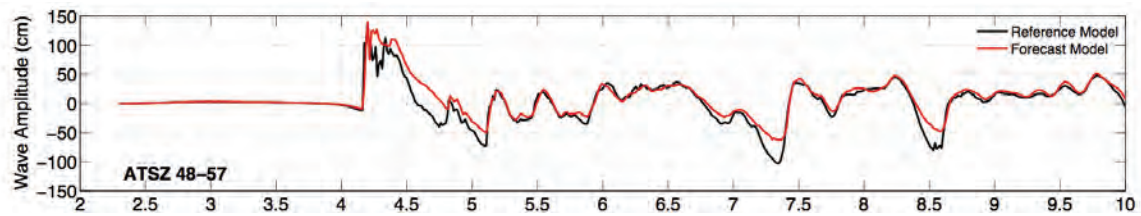


Figure 8. Computed time series at Ocean City tide gage, for synthetic event ATSZ 48-57: (a) time series computed in the forecast system; (b) time series shown in the forecast model report.

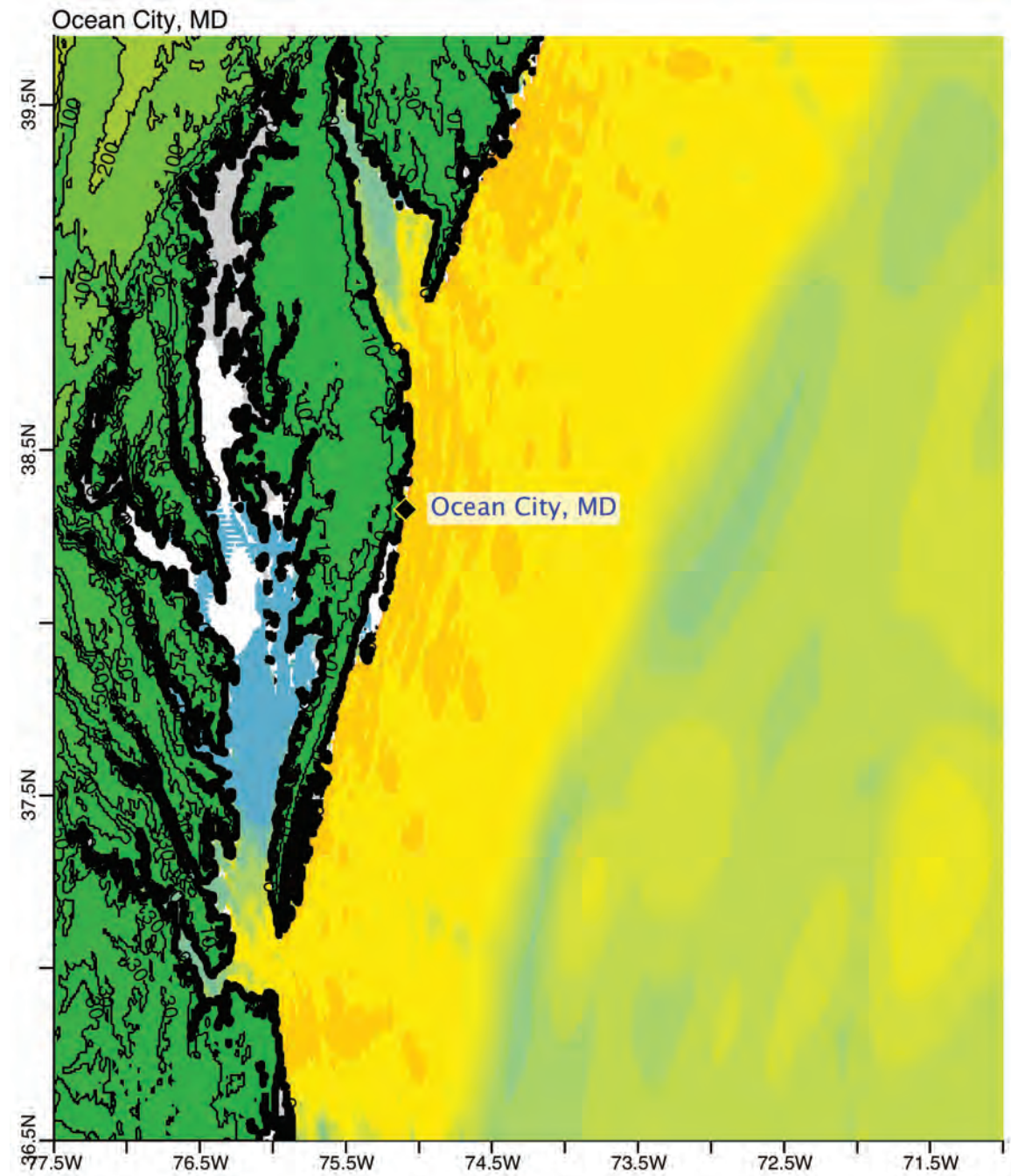


Figure 9. Max computed wave amplitude of A grid, Ocean City, Maryland, for synthetic event SSSZ 1-10.

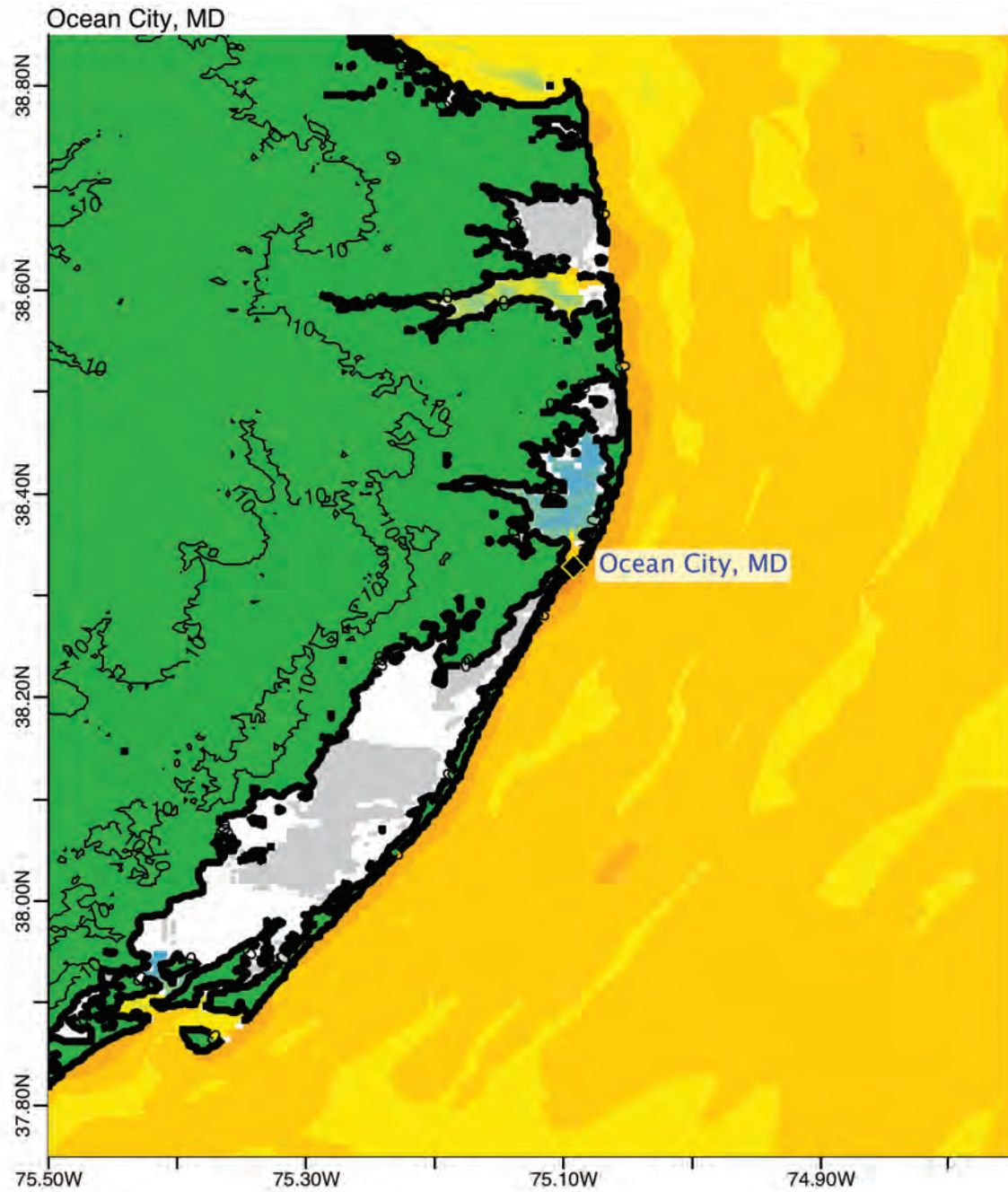


Figure 10. Max computed wave amplitude of B grid, Ocean City, Maryland, for synthetic event SSSZ 1-10.

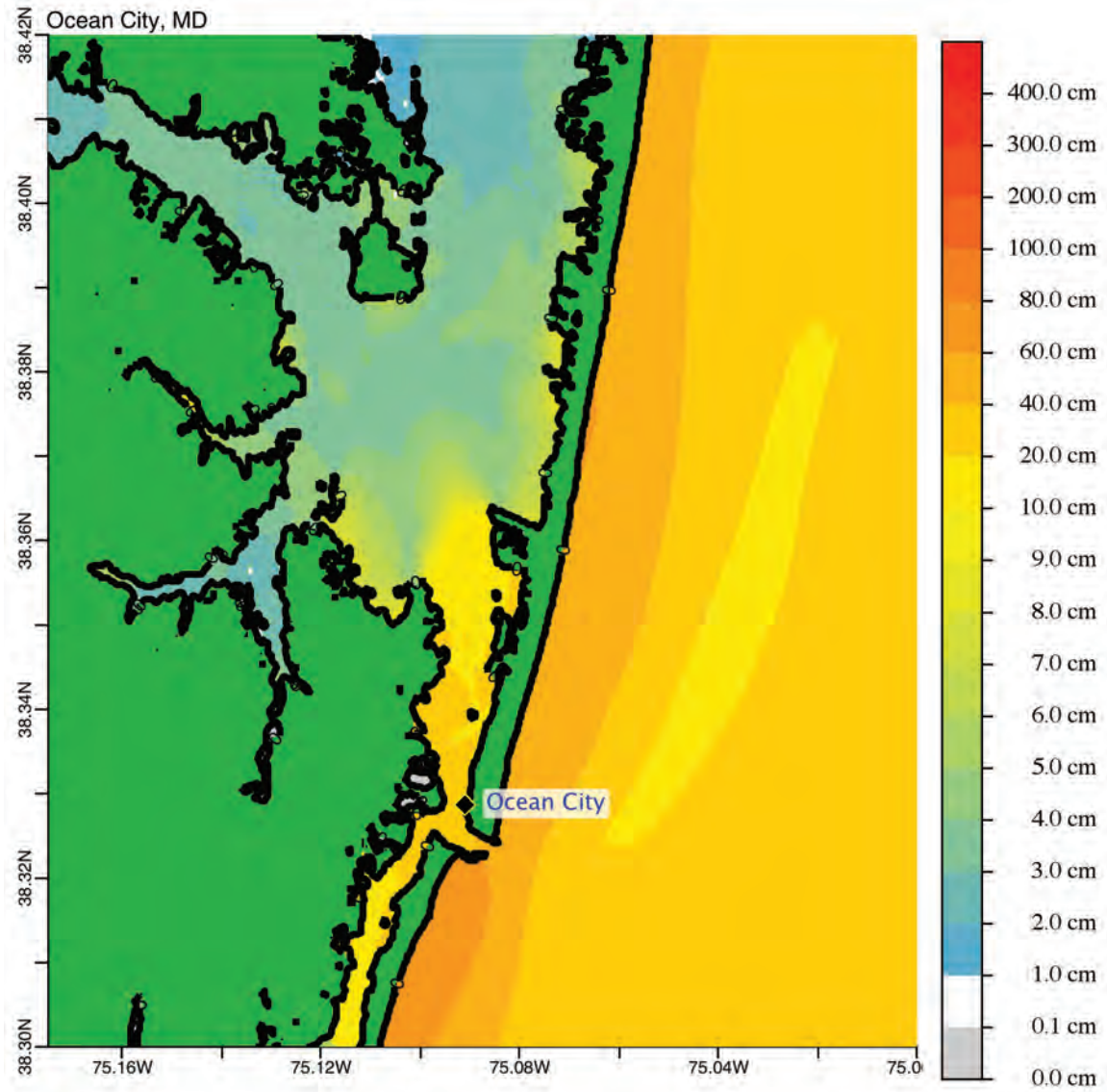


Figure 11. Max computed wave amplitude of C grid, Ocean City, Maryland, for synthetic event SSSZ 1-10.

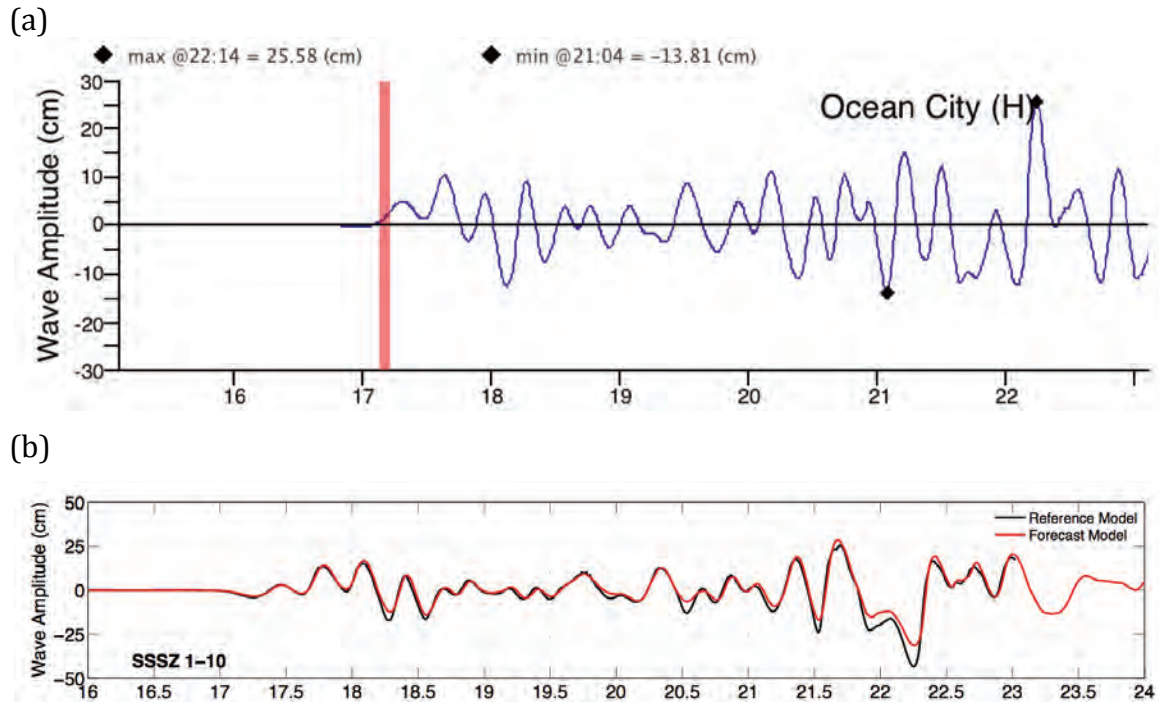


Figure 12. Computed time series at Ocean City tide gage, for synthetic event SSSZ 1-10: (a) time series computed in the forecast system; (b) time series shown in the forecast model report.