# TSUNAMI INUNDATION MAPPING FOR OCEAN CITY, MD NGDC DEM

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## Abstract

This document reports the development of tsunami inundation maps for the region covered by the NGDC tsunami DEM for Ocean City, MD. Section 1 describes NTHMP requirements and guidelines for this work. The location of the study and the bathymetry data utilized are described. Tsunami sources that potentially threaten the upper East Coast of the United States are briefly discussed. Modeling inputs are described in the Section 3, including model specifications and simulation methods such as nesting approaches used in generating inundation maps. The process of generating inundation maps from tsunami simulation results is described in Section 4, along with other results such as arrival time of the tsunami. GIS data sets and organization, including inundation maps, maximum velocity maps, maximum momentum flux maps, are described in Appendix A. Modeling inputs for simulation are provided in Appendix B for interested modelers. In Appendix C, NTHMP guidelines for inundation mapping are provided.

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# 1 Introduction

The US National Tsunami Hazard Mitigation Program (NTHMP) supports the development of inundation maps for all US coastal areas through numerical modeling of tsunami inundation. This includes high-resolution modeling and mapping of at-risk and highly populated areas as well as the development of inundation estimates for non-modeled and low hazard areas. This report describes the development of inundation maps for a region covered by the Ocean City NGDC tsunami DEM (Grothe et al, 2010).

In section 2, background information about the mapped area is provided. Possible tsunami sources that threaten the upper United States East Coast (USEC), and are considered in this analysis, are described. Modeling inputs are described in section 3. Section 4 presents simulation results and the development of mapping products. The process of obtaining the tsunami inundation line, which is the most significant result of this work, is explained in this section. Three appendices provide information about GIS data storage and content (Appendix A), modeling inputs (Appendix B), and NTHMP inundation mapping guidelines (Appendix C).

# 2 Background Information about Map Area

## 2.1 Location of coverage, and communities covered

The National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (NGDC) have generated digital elevation models (DEM) as input for studies focusing on hazard assessment of catastrophes like tsunamis and hurricanes at a number of U. S. coastal areas. The Ocean City NGDC DEM covers a portion of the mid-Atlantic coastline including Delaware, Maryland, and the northern half of the Delmarva portion of Virginia (Grothe et al., 2010). The DEM covers several populated coastal communities including Lewes, DE, Rehoboth Beach, DE, Bethany Beach, DE, Ocean City, MD and Chincoteague, VA. Figure 1 shows the coverage area of the DEM. NGDC DEM's are provided in latitude/longitude coordinates with 1/3 arc-second resolution. The DEM vertical datum is mean high water (MHW), and vertical elevations are in meters. More information about the bathymetry data is given in Section 3.2.

## 2.2 Tsunami sources

The Ocean City region has rarely experienced tsunami inundation. A general overview of historic and potential tsunamigenic events in the North Atlantic Ocean is provided by Atlantic and Gulf of Mexico Tsunami Hazard Assessment Group (2008). In this project, tsunami sources that threaten the upper US East Coast (USEC) were categorized into three main categories, and have been studied separately due to their differences in physics and location. First, two seismically active sources in the Atlantic Ocean were used; a subduction zone earthquake in the Puerto Rico trench, and a simulation of the historic Azores Convergence Zone earthquake of 1755. A far field subaerial landslide due to a volcanic collapse in Canary Islands is also modeled. Finally, near-field Submarine Mass Failures (SMFs) close to the edge of USEC continental shelf are used here as well. A brief introduction and references to detailed studies of the sources are provided in this section.

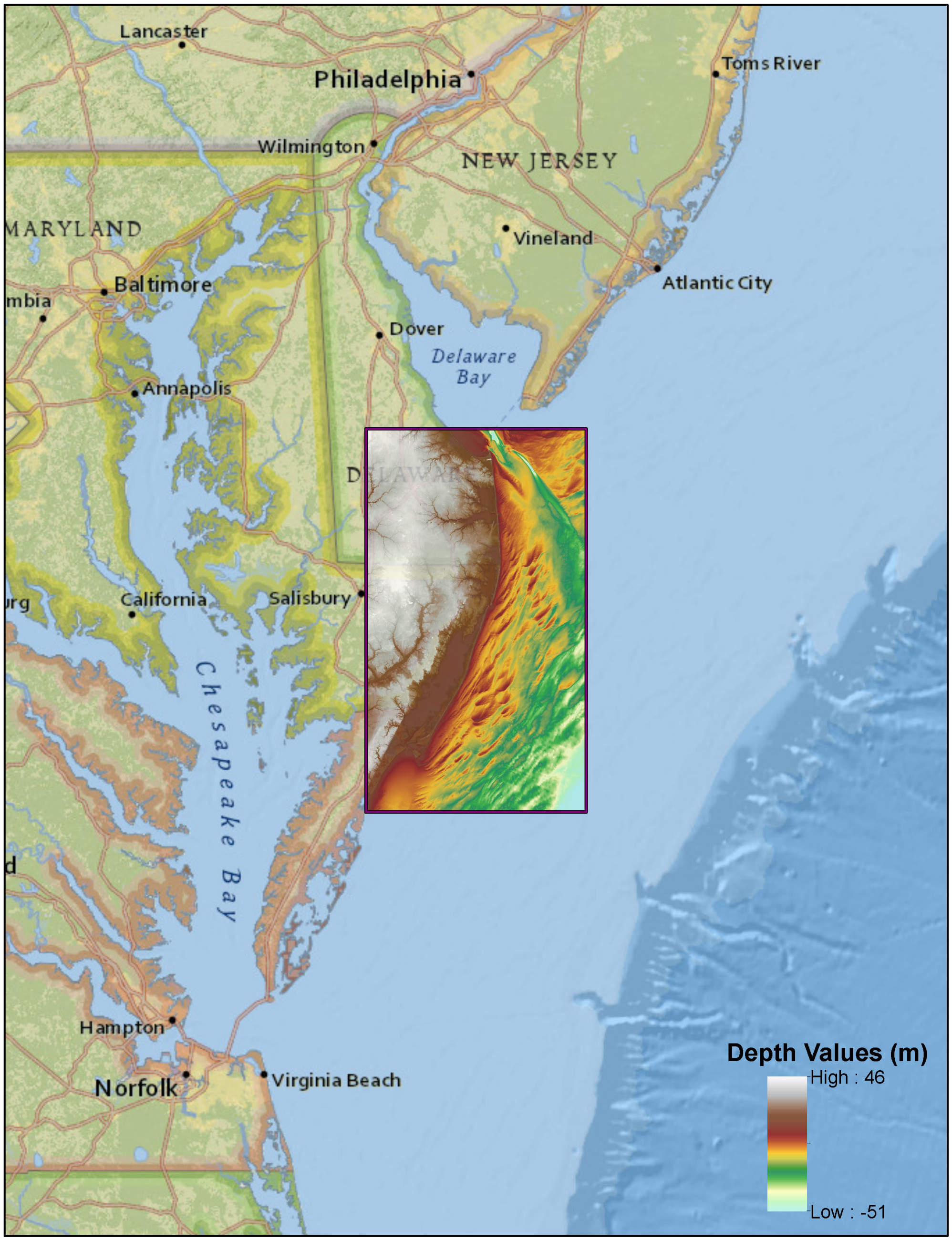



Figure 1: Location of the NGDC Ocean City DEM (Grothe et al, 2010). Color bar shows depth values in meters for areas inside of the DEM boundary.

### 2.2.1 Coseismic sources

**2.2.1.1 Puerto Rico Trench:** Previous research has confirmed the possibility of large earthquakes in the Puerto Rico Trench (PRT) in the Caribbean Subduction Zone (CSZ) (e.g. Grilli et al., 2010). These studies implied that an extreme event with return period of 200 to 300 years could be powerful enough ($M_w = 9.0$) to rupture the entire PRT and initiate a tsunami that will influence the USEC. Grilli and Grilli (2013a) have carried out detailed computations for that event for use as initial conditions for tsunami inundation modeling on the USEC.

**2.2.1.2 Azores Convergence Zone:** The other coseismic source used here is located on the Azores Gibraltar plate boundary, known as the source of the biggest historical tsunami event in the North Atlantic Basin (Gonzalez et al., 2007). The 1755 Lisbon earthquake ($M_w = 8.6 - 9.0$) generated tsunami waves with heights between 5 to 15 meters, impacting the coasts of Morocco, Portugal, Newfoundland, Antilles, and Brazil. The procedure for obtaining the initial condition for tsunami propagation is quite similar to the PRT rupture and is discussed in Grilli and Grilli (2013b).

### 2.2.2 Volcanic cone collapse

In recent years, a potential cone collapse of the volcanic cone Cumbre Vieja (CVV) in the Canary Islands has received attention as a possibly catastrophic source threatening the USEC. In this project, a multi-fluid 3D Navier-Stokes solver (THETIS) was used to compute the volcanic collapse tsunami source (Abadie et al., 2012; Harris et al., 2012). Detailed description of the CVV modeling for use in this project is described in Grilli and

Grilli (2013c). Two different slide magnitudes were studied for this work; an 80 km$^3$ slide, representing a plausible event in a return period window on the order of 10,000 years, and a 450 km$^3$ source, consistent with estimates of the maximum event for the geological feature. The magnitude of the latter event is significantly larger than all of the other cases studied in this project. Thus, it was decided to exclude the 450 km$^3$ source from inundation line calculations, and illustrate its results separately as a representation of the worst case scenario condition. This is due to the fact that this source return period is expected to be much more than 10,000 years.

### 2.2.3 Submarine mass failure

The US East Coast is fronted by a wide continental shelf, which contributes to the dissipation of far-field tsunami sources, and diminishes the damage caused by simulated waves from these sources on the coastline. On the other hand, it has been noted in literature (e.g. Grilli et al. 2014) that there is a potential of a Submarine Mass Failure (SMF) on or near the continental shelf break, causing tsunamis that affect adjacent coastal areas. Considering the fact that the only tsunami event that has caused fatalities on the US East Coast was an SMF tsunami (Grand Banks, 1929), it is necessary to study possible impacts and consequences of such catastrophes with respect to heavily populated coastal communities on the USEC. In this project, four different locations are chosen as the most probable to experience a submarine mass failure tsunami. The process of obtaining the initial condition for near-shore propagation and inundation modeling for all of these sources are comprehensively documented in Grilli et al. (2013). The landslide movement is simulated with the NHWAVE model (Ma et al., 2012; Tehranirad et al., 2012) and the results shown here are interpolated into 500 meter grids for propagation and inundation modeling 800 seconds after slump movement is initiated (Grilli et al., 2013).

# 3 Modeling Inputs

## 3.1 Numerical model

Tsunami propagation and inundation in this study is simulated using the fully nonlinear Boussinesq model FUNWAVE-TVD (Shi et al, 2012a). FUNWAVE-TVD is a public domain open-source code that has been used for modeling tsunami propagation in ocean basins, nearshore tsunami propagation and inland inundation problems. The code solves the Boussinesq equations of Chen (2006) in Cartesian coordinates, or of Kirby et al. (2013) in spherical coordinates. A users manual for each version is provided by Shi et al (2011). FUNWAVE-TVD has been successfully validated for modeling tsunami wave characteristics such as shoaling, breaking and runup by Tehranirad et al. (2011) following NTHMP requirements (see Appendix C). Additional description of modeling specifications and input files is provided in Appendix B.

One key specification in the model is the choice of friction coefficient defined for tsunami simulation. Geist et al. (2009) have performed a study on sensitivity of tsunami elevation with respect to a range of bottom friction coefficients and demonstrated that large coefficients will unrealistically damp tsunami wave height. A review of the existing literature suggests that a value of $C_d = 0.0025$ represents a reasonable friction coefficient for tsunami simulations, as suggested by several researchers (e.g. Grilli et al., 2013), and this value is used here.

## 3.2 Bathymetric Input Data

### 3.2.1 Ocean City NGDC DEM

In this project, an integrated bathymetric-topographic digital elevation model (DEM) that generated by National Geophysical Data Center (NGDC) is used for high-resolution inundation mapping for the area around Ocean City, MD (Grothe et al., 2010). This DEM covers most of the Delmarva Peninsula from the southern part of Delaware Bay down to Metompkin Bay in Virginia (Figure 1). The horizontal datum is set to be World Geodetic System of 1984 (WGS 84), and the vertical datum is mean high water (MHW). The resolution of the Ocean City DEM is 1/3 arc-second, which, with respect to the study location, means that the North-South resolution is 10.27 meters, and East-West direction grids are 8.10 meters (computed using the latitude in the middle of the domain). All of the runs in this domain have been performed in Cartesian coordinates. Considering the coverage area of this grid, the difference between Cartesian grid and spherical grid (Simply comparing the total length of domain in Cartesian grid and spherical grid) is about 1.5 meters for the whole domain. This means that the average offset for each point is of O($10^{-6}$) meters. Therefore, because of the negligible differences between Cartesian and spherical grids, this grid was used as Cartesian grid directly to capture fully nonlinear effects of the tsunamis nearshore. Further information about this grid is also given in Table 1.

In the USA the period to determine MHW spans 19 years and is referred to as the National Tidal Datum Epoch. For this project, inundation mapping processes have been performed with MHW datum maps following NTHMP requirements (see Appendix C). There are different approaches to relate MHW to NAVD88 values in the literature, and also, one can use existing datum conversion models to investigate the difference (e.g. Vdatum generated by NOAA, Park et al., 2003). However, it should be noted that the difference between these values is not constant for the whole domain. For Ocean City, MD, MHW is at NAVD88+26.3 cm. For Lewes, DE, MHW is at NAVD+79.25.

### 3.2.2 NGDC Coastal Relief Model (CRM)

Bathymetry data for shelf regions lying outside the NGDC Ocean City DEM are obtained from the INGDC's 3 arc-second U.S. Coastal Relief Model (CRM) (Divins and Metzger, 2003). This data delivers a complete view of the U.S. coastal areas, combining offshore bathymetry with land topography into a unified representation of the coast. However, the deeper part of the Ocean beyond the shelf break is not covered in this data.

### 3.2.3 ETOPO 1

Bathymetry data for deeper parts of the ocean beyond the shelf break is taken from the ETOPO1 DEM (Amante and Eakins, 2009). ETOPO1 is a 1 arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry. It was built from numerous global and regional data sets, and is available in ”Ice Surface” (top of Antarctic and Greenland ice sheets) and ”Bedrock” (base of the ice sheets) versions. Here, we use the Bedrock version in areas where the CRM data is not available.

## 3.3 Model Grids

Although the Ocean City DEM satisfies the bathymetry data requirements for nearshore simulations, proper offshore bathymetry data is required to model the tsunamis far from the shoreline. Accordingly, Grids A and B (Figure 2) are generated for low resolution modeling over the ocean basin and continental shelf. The input data for the tsunami sources is divided into two categories. The first category consists of Cosiesmic and CVV sources, which were simulated in larger scale ocean-scale model runs, with results recorded on the boundaries of Grid A. The ocean-basin simulations in which this data were recorded was performed with a 16 arc second spherical grid. Grid A was generated in order to keep the nesting scale 4 or less (see section 3.4), and continue the simulation with a 4 arc second grid. The grid sizes of the Grid A are 503.2 m in the north-south direction and 535.0 m in east-west direction (Table 1). On the other hand, the SMF sources fall within the modeled region and are initially modeled with a Cartesian grid using NHWAVE (Ma et al., 2012) with 500 m resolution. The input data was in the form of initial conditions, in contrast to the first category where the data is in form of boundary conditions. Therefore, it was required to generate another grid larger than Grid A to allow space for model sponge layers (or damping regions) on the boundaries. Also, in order to directly use input data as generated by NHWAVE, the grid sizes for Grid B were chosen to be 500 m.

Depth values for these grids were obtained from the 1 arc-minute ETOPO-1 database, while nearshore bathymetry and topography were obtained from the CRM. The horizontal datum and vertical datum are set to be WGS84 and MHW, similar to Ocean City NGDC DEM. These grids are mapped from spherical coordinates into a Cartesian grid. This means that there are some mapping errors considering the magnitude of these grids. For example, for Grid A, the total difference between two different coordinate systems is 132 m comparing the arc length (spherical) with the straight line (Cartesian). The average offset difference for each grid point between two coordinates is 12 cm, which is negligible considering a grid size of about 500 m. To minimize the error around the mapping area, the grid is lined up close to the Ocean City DEM. The total difference between spherical and Cartesian coordinates for Grid B is 465 meters. The average offset difference between two coordinates is 31 cm for each point of this gird. To make the error as small as possible for the western part of the domain (close to Ocean City, MD), this grid is also lined up with the mapping area. Therefore, larger error values shows up in the eastern and southern parts of the domain, which is not of concern because they fall within the sponge layer region.

Figure 2 shows the location of these grids, as well as the location of the SMF sources simulated in this project. Further information about these grids are provided in Table 1. Figure 3 shows the initial surface elevation of each SMF source mapped onto Grid B. The results of the simulations using Grids A and B were recorded on the Ocean City DEM boundaries in order to perform higher resolution modeling in nearshore regions. This process is described in the next section of this document.

### 3.4 Nesting approach

In order to save computational time, an appropriate nesting approach is required to decrease the grid sizes from coarser grids offshore to finer grids nearshore. Accurate nesting should insure that there would not be a loss of data on any of the boundaries on which coupling is performed. The nesting scale represents the change in the grid size between two levels of simulation. For example, if the 500 m grid results are used to perform a 125 m simulation, the nesting scale is 4. Although the coupling capabilities of FUNWAVE-TVD are such that large nesting scales could be used, a largest nesting scale of 4 has been used in this study in order to avoid any loss of data. As described in previous sections of this

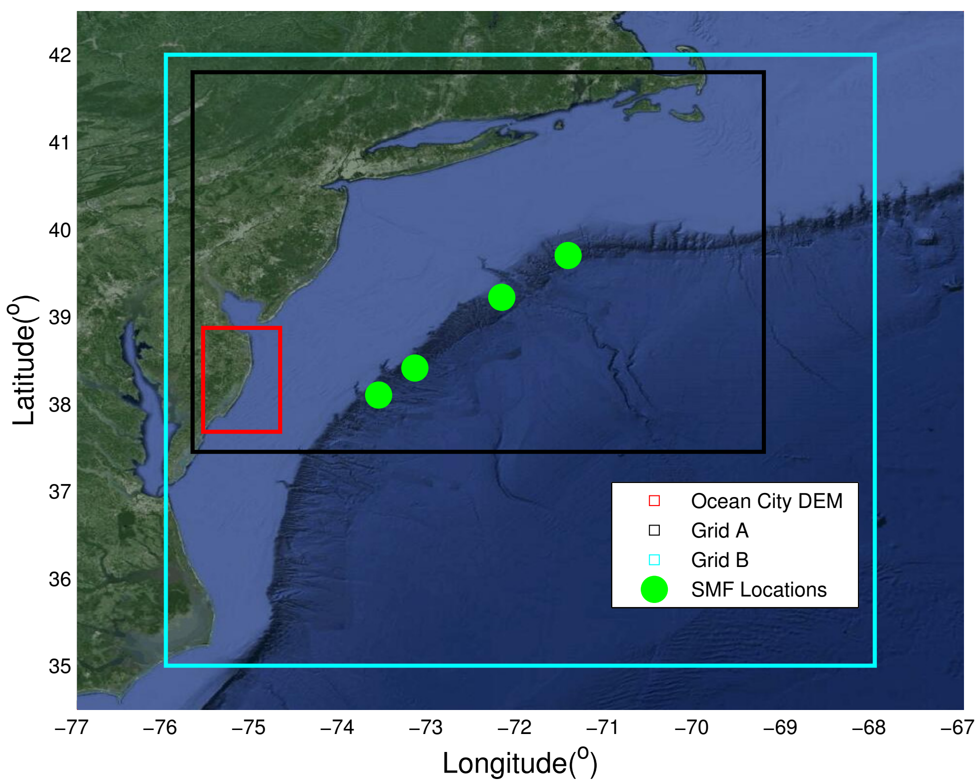



Figure 2: Locations of the Grids used in this project and also the center of SMF sources simulated here.

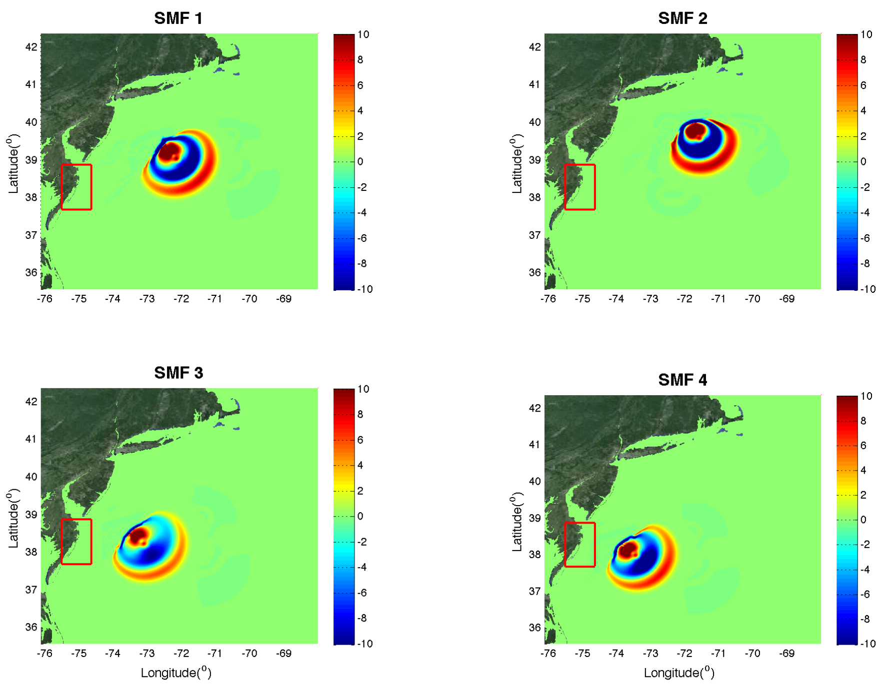



Figure 3: Location of Grid B and Ocean City DEM used in this project, and also the initial stage of SMF sources.

report, Grids A and B are used to generate data on Ocean City DEM boundaries. Both of these grids have grid sizes of roughly 500 meters and larger. Next, using the recorded data on the boundaries of Ocean City NGDC DEM, simulations with grid sizes of roughly 125.0 meters (about 4 arc-sec) are implemented on this grid to record proper data around four DEMs with resolution of 1 arc-sec (extracted from 1/3 arc-sec Ocean City DEM) in the main region to resolve tsunami inundation inland (and near-shore) with 30 meter (about one arc-sec) grid size. Finally, tsunami propagations over several locations were modeled with 1/3 arc-second resolution (about 8-10 meters) which is the highest resolution utilized in this project. Grilli et al. (2014) have used the similar nesting approach and confirmed the values chosen here. Figure 5 depicts the diagram for the nesting approach performed in this project. In addition, characteristics of each grid are defined in Table 1.

Due to computational considerations, 1/3 arc second runs were only performed for several areas to be covered by high resolution inundation maps, until it was determined that runs at 1 arc second resolution were generally adequate for the present DEM's, where the built environment and other land use features are not specifically resolved. Also, only the 80 $km^3$ and 450 $km^3$ CVV, and the SMF4 sources were modeled, which were shown to be the worst cases based on low resolution initial simulations. All of the runs in this document were performed in Cartesian coordinates.

# 4 Results

This section describes the data recorded for each inundation simulation and its organization as ArcGIS rasters for subsequent map development. The tsunami arrival time is an

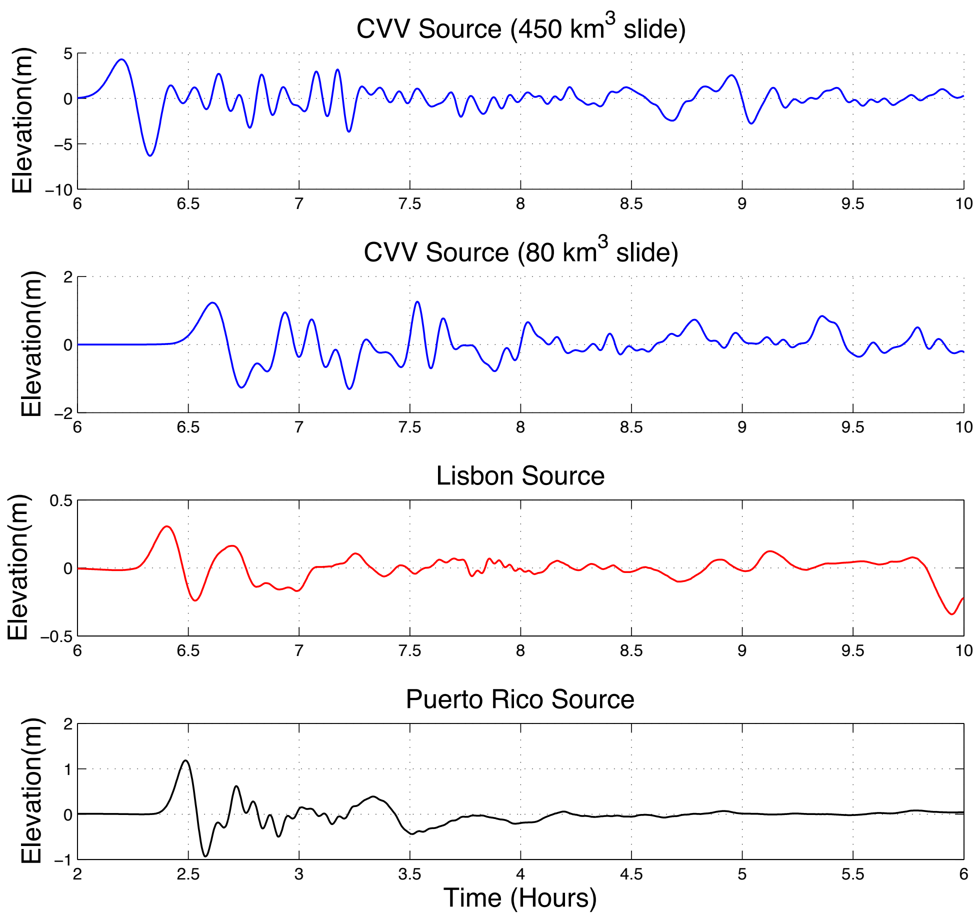



Figure 4: Gauge data at the southeastern edge of Grid A for coseismic and volcanic collapse sources

| Grid Name | Grid Numbers | | Grid Size (m) | | Boundary Coordinates | | | |
|---|---|---|---|---|---|---|---|---|
| | $mx$ | $ny$ | $dx$ | $dy$ | $E$ | $W$ | $S$ | $N$ |
| Grid A | 1100 | 900 | 503.20 | 535.50 | -69.25 | -75.70 | 37.45 | 41.80 |
| Grid B | 1500 | 1500 | 500.00 | 500.00 | -67.50 | -76.00 | 35.00 | 42.00 |
| OC_4arc (Same bondaries with Ocean City DEM) | 627 | 1072 | 97.20 | 123.24 | -74.71 | -75.58 | 37.68 | 38.87 |
| OC_1arc_1 | 1000 | 1000 | 24.30 | 30.81 | -75.02 | -75.30 | 38.54 | 38.83 |
| OC_1arc_2 | 1000 | 1200 | 24.30 | 30.81 | -75.02 | -75.30 | 38.24 | 38.57 |
| OC_1arc_3 | 1200 | 1000 | 24.30 | 30.81 | -75.12 | -75.45 | 37.98 | 38.26 |
| OC_1arc_4 | 1200 | 1000 | 24.30 | 30.81 | -75.22 | -75.56 | 37.73 | 38.01 |
| Lewes and Rehoboth Beach (1/3 arc-sec)(OC_10m_1) | 675 | 1200 | 8.10 | 10.27 | -75.06 | -75.12 | 38.70 | 38.81 |
| Dewey (1/3 arc-sec)(OC_10m_2) | 900 | 900 | 8.10 | 10.27 | -75.05 | -75.14 | 38.62 | 38.71 |
| Bethany Beach (1/3 arc-sec)(OC_10m_3) | 900 | 900 | 8.10 | 10.27 | -75.04 | -75.12 | 38.48 | 38.57 |
| Ocean City 1 (1/3 arc-sec) (OC_10m_4) | 540 | 1500 | 8.10 | 10.27 | -75.04 | -75.09 | 38.35 | 38.50 |
| Ocean City 2 (1/3 arc-sec) (OC_10m_5) | 900 | 900 | 8.10 | 10.27 | -75.06 | -75.14 | 38.29 | 38.37 |
| Chincoteague (1/3 arc-sec) (OC_10m_6) | 900 | 1200 | 8.10 | 10.27 | -75.31 | -75.40 | 37.85 | 37.96 |

Table 1: Grid specification for all of the grids used in this project

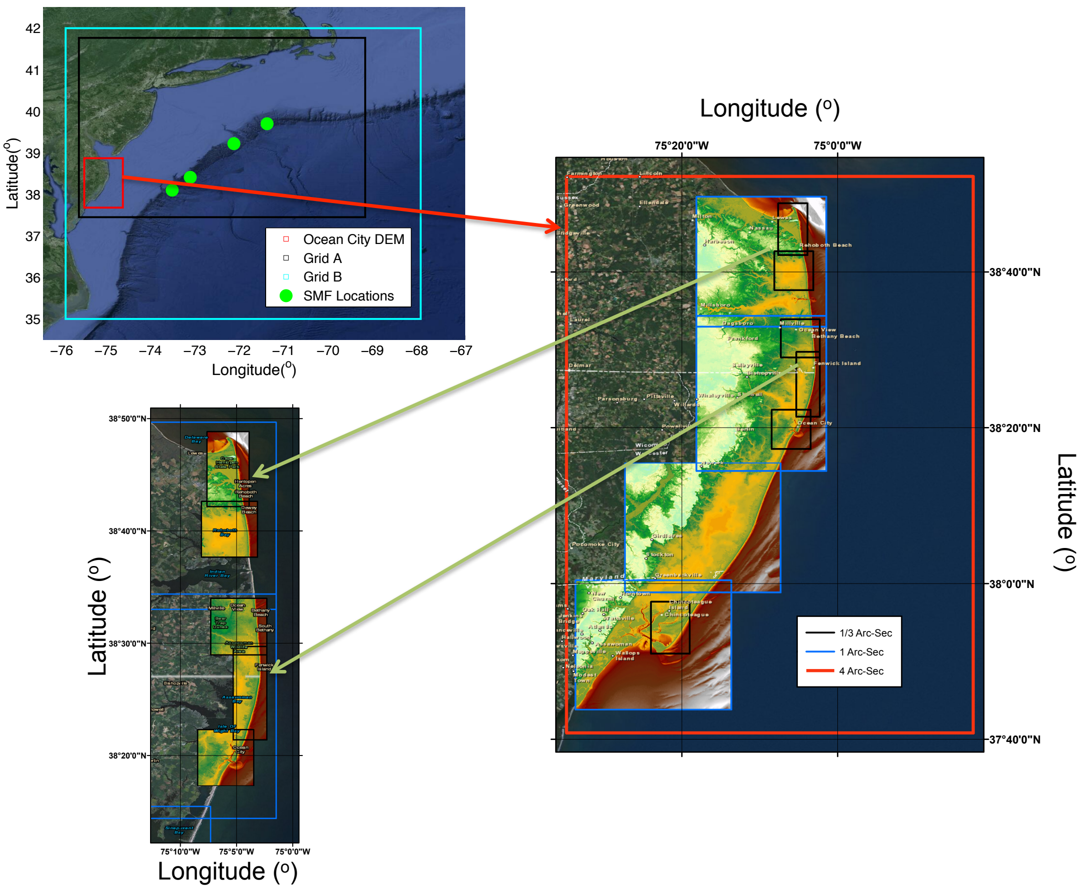



Figure 5: The sequence of grid nesting. The figure on the top left depicts the Grid A and B as well as the location of the Ocean City DEM. The figure on the right show the 1 arc-sec grids described in Table 1. Also, in the bottom left figure the 1/3 arc-sec domains are shown (Also described in Table 1).

essential piece of information for evacuation planners. The results are categorized into onshore and offshore results. The onshore results depict the characteristics of the tsunami on the land during inundation. Onshore tsunami effects are mainly demonstrated through three parameters,

1. Maximum inundation depth

2. Maximum velocity

3. Maximum momentum flux

Yeh (2007) reported different forces created by a tsunami on structures and concluded that, having the three mentioned quantities, one can calculate good estimates of forces on onshore structures resulting from tsunamis. Moreover, tsunamis can affect ship navigation; therefore, in order to cover maritime planning and navigational issues during a tsunami, three other parameters are recorded and depicted offshore in this project. These three offshore parameters include,

1. Maximum vorticity

2. Maximum velocity

3. Maximum recorded water surface elevation

All six variables are recorded for each of the modeling domains introduced in Table 1 for all of the tsunami sources discussed in previous sections. Appropriate rasters are generated which are compatible with ArcGIS and other GIS software for mapping purposes. Finally, the inundation line, which is calculated from the envelope of tsunami inundation extent for each source, will be presented.

## 4.1 Arrival time

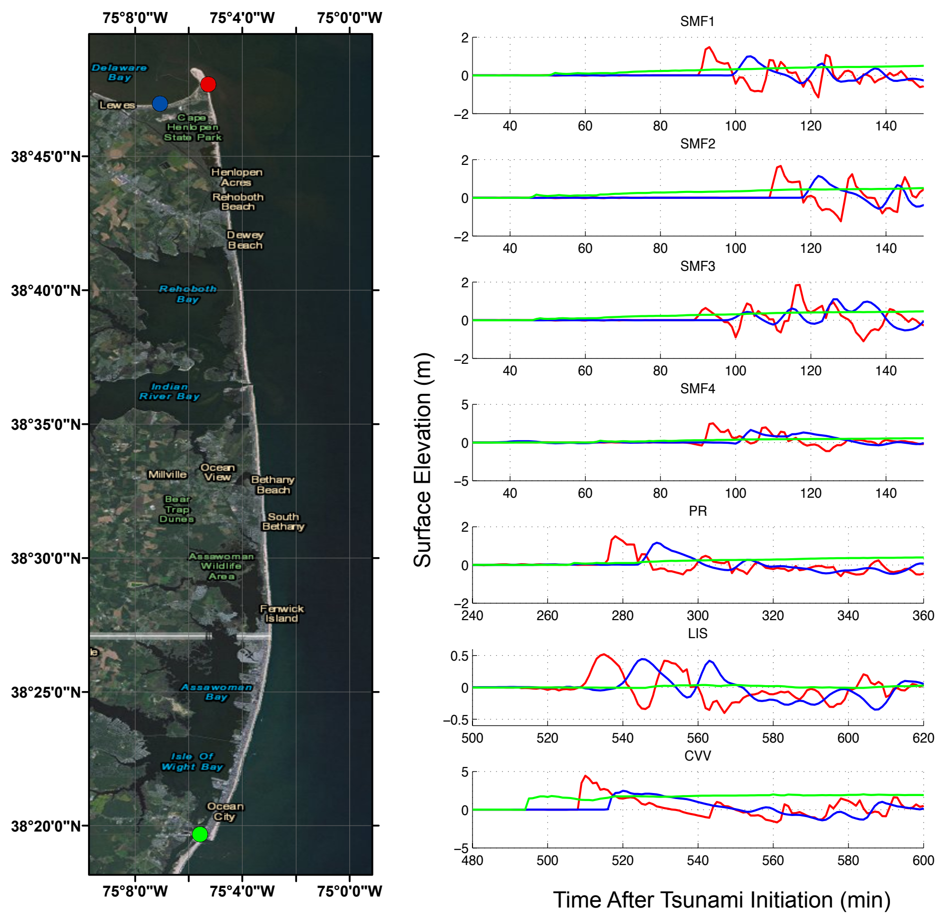



Figure 6: Recorded surface elevation for NOAA gauges which are located in Ocean City DEM, Ocean City (Green), Cape Henlopen (Red), and Lewes (Blue)

Tsunami arrival time plays an important role in evacuation planning during the occurrence of an event. It is vital to report the arrival time of each tsunami relative to the time of initial detection of an event. Here, the arrival time of the tsunami is based on the time that the first tsunami bore passes the shoreline. Table 2 reports tsunami arrival times for several places located in Ocean City NGDC DEM. For each location, arrival times of all different tsunami sources have been reported. The arrival time for each city in Table 2 is a value for that particular location (for example, averaged along Ocean City, MD shoreline) with about a 5 minute error margin. Since tsunami propagation in the ocean is constrained by bathymetry, the propagation of tsunamis toward the Ocean City area is quite similar for all of the different sources. The southern part of the domain (e.g. Ocean City, MD) is the first spot that would face the tsunami. However, within 10 to 15 minutes difference, the northern part of the domain that is facing Atlantic Ocean (e.g. Rehoboth Beach) will be affected by the tsunami as well. Finally, within 30 to 40 minutes lag in comparison with the southern parts of the domain, tsunami would reach parts of the domain inside Delaware Bay (e.g. Lewes). Figure 6 demonstrates the location of NOAA gauges and their recorded surface elevation for all of the sources. The tsunami impact differences between the areas behind the barriers and areas facing the ocean directly is clear in the figure. The Cape Henlopen, DE gauge that is located in the ocean experience much stronger signal in comparison to Ocean City, MD, where the guage is located behind the barrier. Basically the protected areas behind barrier islands experience tsunami effects more like a storm surge but with a much smaller time scale. Also, the Lewes, DE gauge data is similar to Cape Henlopen with about 10 to 15 minutes lag. SMF sources are clearly the closest source to the location of study, and will reach the entire domain within 1 to 2 hours. The tsunami induced by Puerto Rico Trench (PRT) will affect the Ocean City greater area between 4 to 5 hours after the earthquake. The Lisbon historic event and the Cumbre Vieja Volcanic collapse (CVV) sources have similar transoceanic travel time, and will influence the domain

8 to 9 hours after the incident.

| Location | SMF1 | SMF2 | SMF3 | SMF4 | PR | LIS | $CVV^1$ | $CVV^2$ |
|---|---|---|---|---|---|---|---|---|
| Ocean City, MD | 75 | 90 | 70 | 70 | 260 | 515 | 510 | 495 |
| Bethany Beach, DE | 80 | 100 | 80 | 80 | 265 | 520 | 515 | 500 |
| Rehoboth Beach, DE | 90 | 110 | 90 | 90 | 275 | 530 | 525 | 510 |
| Lewes, DE | 100 | 120 | 100 | 100 | 285 | 540 | 535 | 520 |

Table 2: Arrival time in minutes after tsunami initiation for different locations and sources in Ocean City DEM based on the location of NOAA gauges. $CVV^1$ and $CVV^2$ refer to 80 $km^3$ and 450 $km^3$ slide volumes respectively.

## 4.2 Raster Data

One of the most important results of this work is the inundation map corresponding to each tsunami source. In order to facilitate the GIS work, appropriate rasters which are compatible with any GIS software such as ArcGIS are created for all of the grids mentioned in Table 1. As an example, Figure 7 depicts the inundation depth for the SMF4 for the Ocean City DEM grid with 4 arc-second resolution. In this figure the domains in which 1 Arc-second resolution runs have been performed are displayed as well.

Figures 8-11 show the maximum inundation depth for the 1 Arc-second domains shown in Figure 7. These figures provide a comparison for different sources studied in this project. This includes the envelope inundation map for SMF and coseismic sources as well as both CVV sources. The inundation depth for SMF sources are similar to each other, however, the inundation depth values for SMF4 is larger for the most part in comparison to the other SMF sources. This is probably because of the fact that the SMF4 is the closest SMF source to the location of study. Also, the PRT event is the dominant coseismic source by far, and its inundation pattern is similar to SMF sources with some differences especially behind the barriers. Since coseismic sources have larger wavelengths, they are able to penetrate behind the barriers with less attenuation in comparison to SMF sources. Figures 8-11 show that the CVV 450 $km^3$ source is clearly the dominant source for the area studied here, and represents worst case scenario by far in comparison to other sources. However, because its return period is estimated to be beyond 10000 years, it is excluded from inundation line calculations at this point. The 80 $km^3$ slide CVV has a similar inundation pattern to Puerto Rico source and SMF4. Except for some few locations it is the dominant source among all other sources, excluding the CVV 450 $km^3$ slide source.

The other important criteria required to be reported for inundated area, is the maximum momentum flux. Figure 12 is an example of the maximum momentum flux which is extracted from Bethany Beach 1/3 Arc-sec domain for the SMF4 tsunami. Maximum-recorded velocity is another essential quantity required to be reported for inundated area. Maximum velocity is also an important factor for navigational issues during a tsunami. Therefore, for better realizations of maximum velocity maps, two different maps are acquired for maximum velocity on land (basically inundated area) and maximum velocity offshore, which are shown in Figure 13. Finally, the other important variable for navigational problems during a tsunami, which is the maximum vorticity is also reported with the similar method as the other gridded values. Figure 14 depicts the maximum vorticity in Ocean City inlet during SMF4 tsunami. All of the rasters in this project have the Mean High Water (MHW) datum and have ASCII format. In each raster file, the grid size (number of row and columns), the latitude and longitude coordinates corresponding to the southern and western boundaries of the domain, and cell size that defines the resolution of the simulation are included. Also, no data value for each raster is defined as well to limit

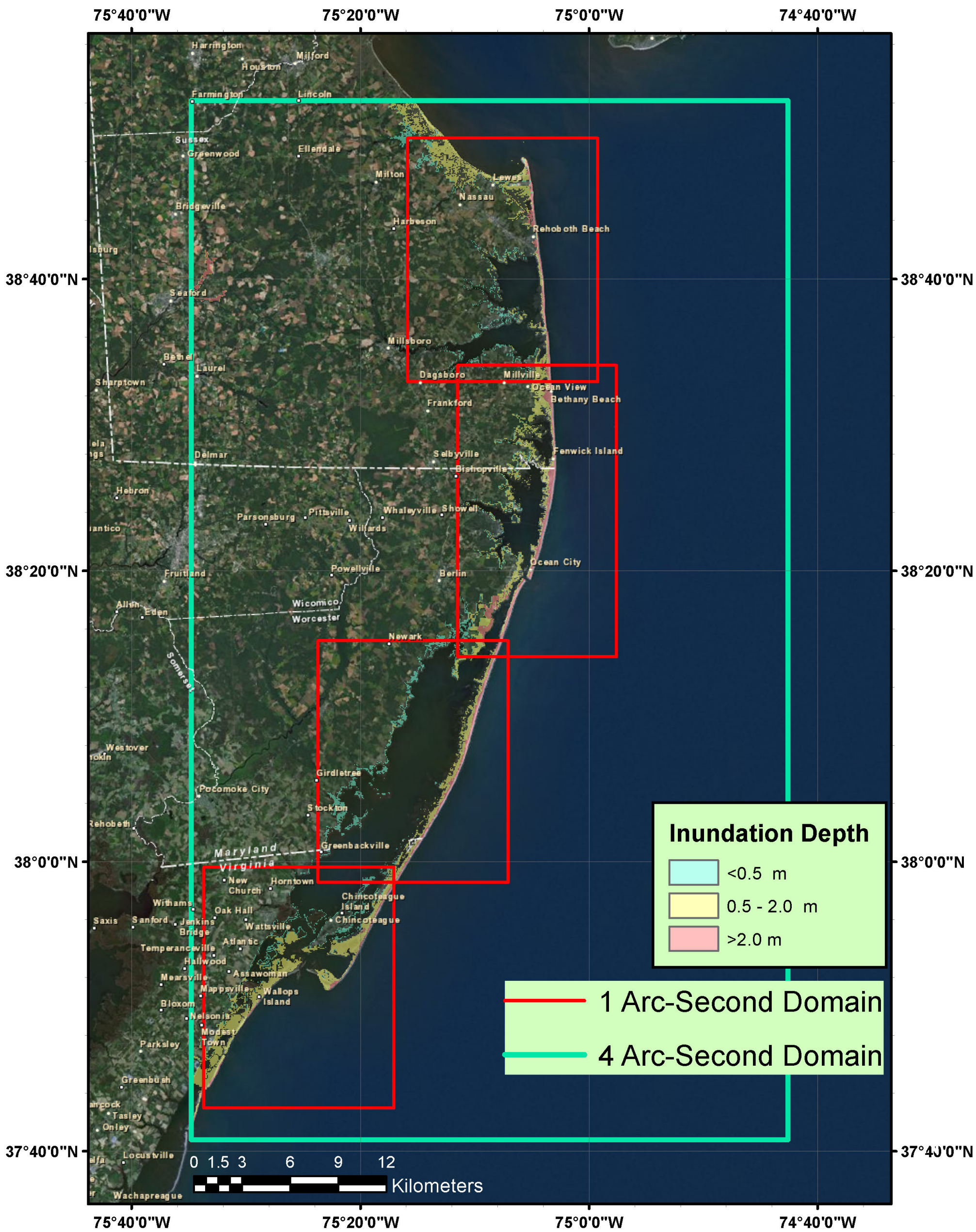



Figure 7: SMF4 Inundation Map for the Ocean City DEM with 4 arc-second resolution. Red squares depicts the 1 arc-second resolution domains

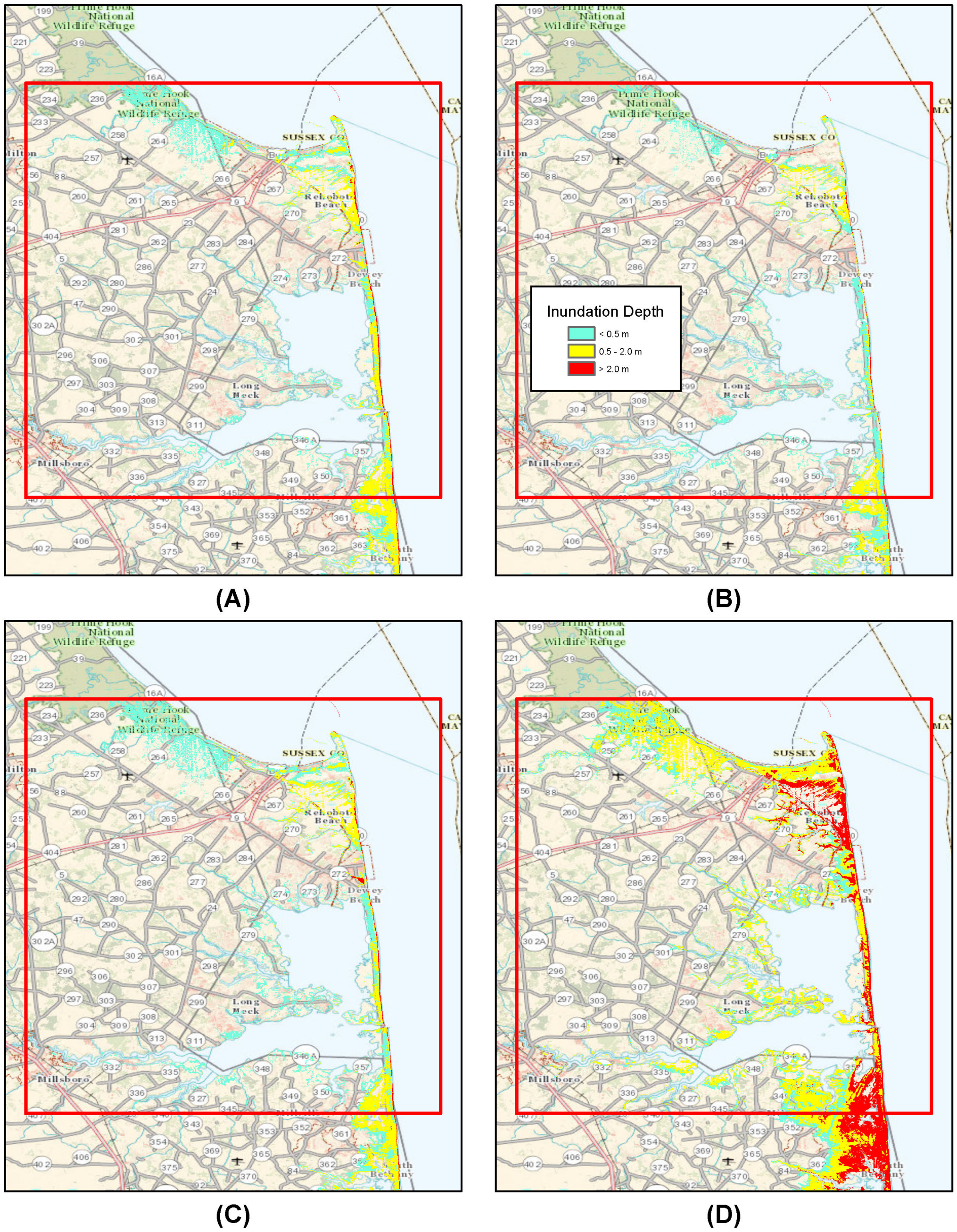



Figure 8: Inundation depth for OC_1arc_1 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 km$^3$ slide, and D) CVV 450 km$^3$ slide. Red box depicts OC_1arc_1 domain boundaries.

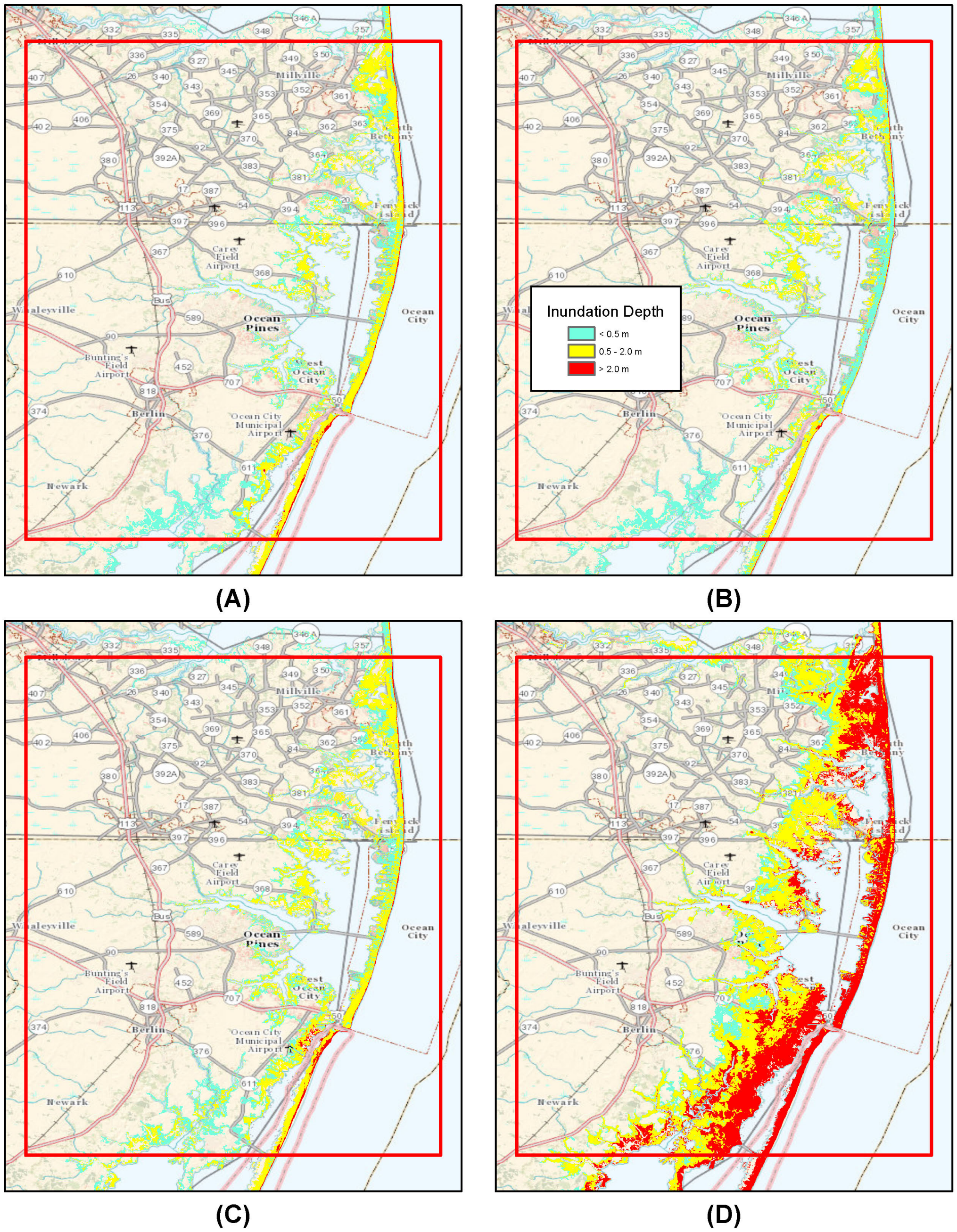



Figure 9: Inundation depth for OC_1arc_2 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 km$^3$ slide, and D) CVV 450 km$^3$ slide. Red box depicts OC_1arc_2 domain boundaries.

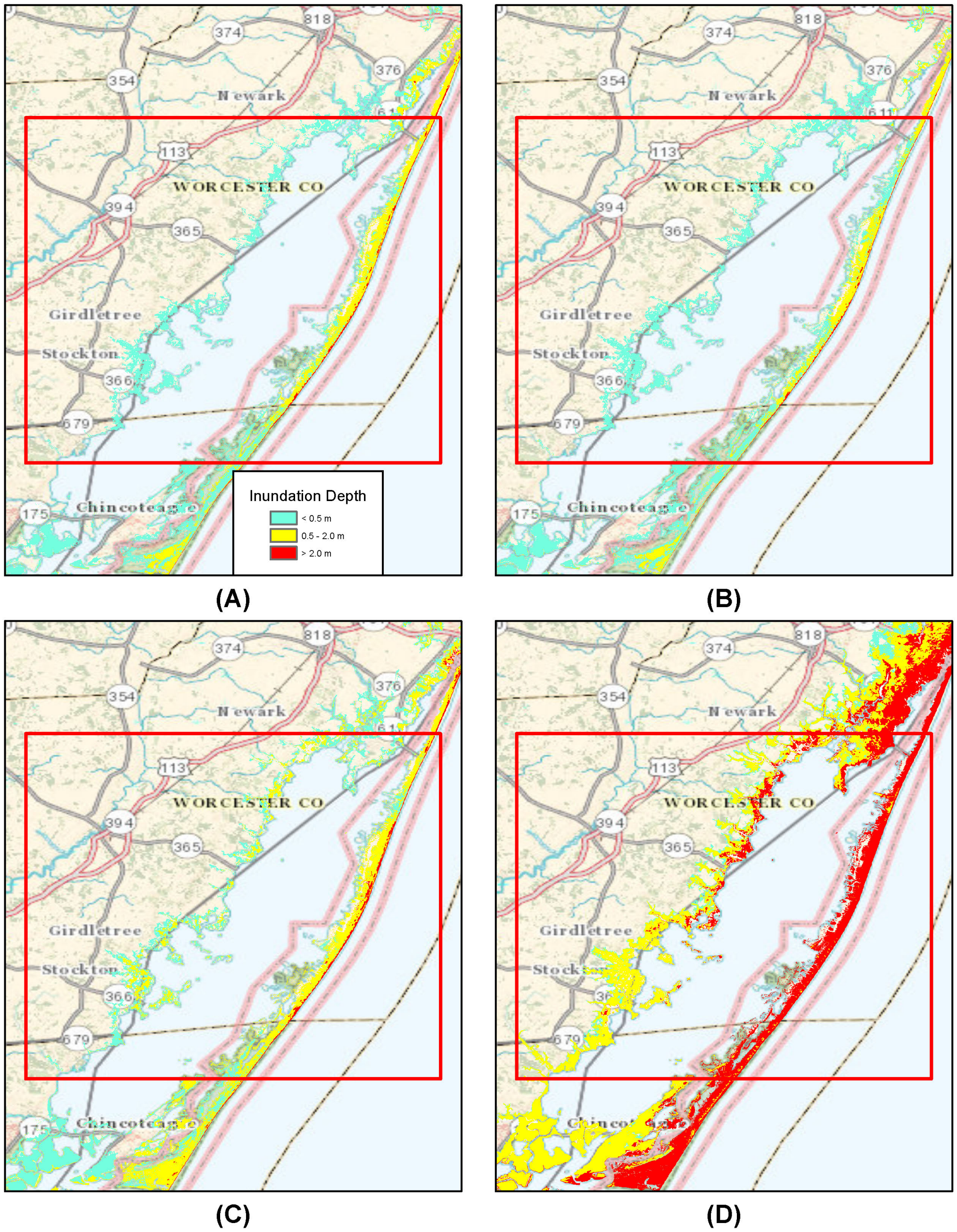



Figure 10: Inundation depth for OC_1arc_3 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 $km^3$ slide, and D) CVV 450 $km^3$ slide. Red box depicts OC_1arc_3 domain boundaries.

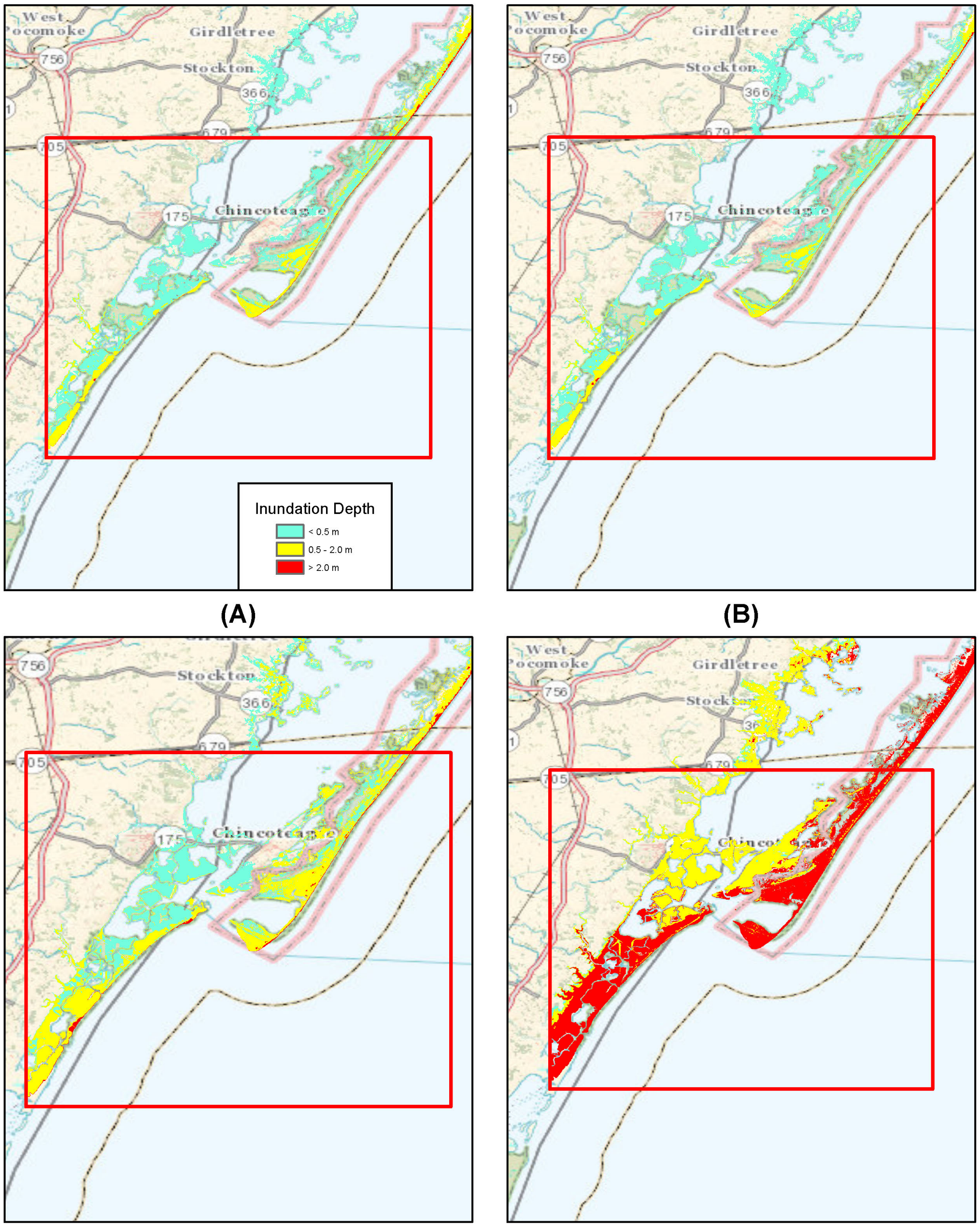



Figure 11: Inundation depth for OC_1arc_4 domain, A) SMF Envelope, B) Coseismic Envelope, C) CVV 80 $km^3$ slide, and D) CVV 450 $km^3$ slide. Red box depicts OC_1arc_4 domain boundaries.

the information to the inundated areas or other areas of interest. More information about the raster data is provided in Appendix A.

## 4.3 Inundation line

Tsunami inundation line is the main result of this project. The inundation line demonstrates the envelope of the onshore maximum inundation extent of all tsunamis studied in this work. We extracted the inundation line from inundation depth data. For each location an envelope inundation depth map was generated from all of the tsunami sources. Then, the zero contour of that map represents the inundation line, which is the extent of tsunami inundation inland. As mentioned in the previous section, the 450 $km^3$ CVV source is excluded from the inundation line calculations, and its inundation line is separately demonstrated as the low probability worst case scenario (shown in blue (Figure 15)). The main inundation line is the envelope for all of the other cases studied here (shown in red (Figure 15)). The inundation line for 4 arc-sec, 1 arc-sec, and 1/3 arc simulation domains were very close to each other for all of the sources. For most areas, the 80 $km^3$ CVV source was the dominant source controlling the inundation line; however, in a few locations the inundation line representing the SMF4 source (which is the closest SMF source to the mapping location) was the dominant tsunami source. It must be noted again that the 450 $km^3$ CVV source would have been the dominant source by far if it was not excluded from the inundation line calculations. Also, it should be noted that the inundations line in the overlapping areas between different domains were almost identical for most of the cases, which is result of a well performed nesting process. The inundation lines are saved as a shape file (.shp) in order to simplify the inundation map generation process. More

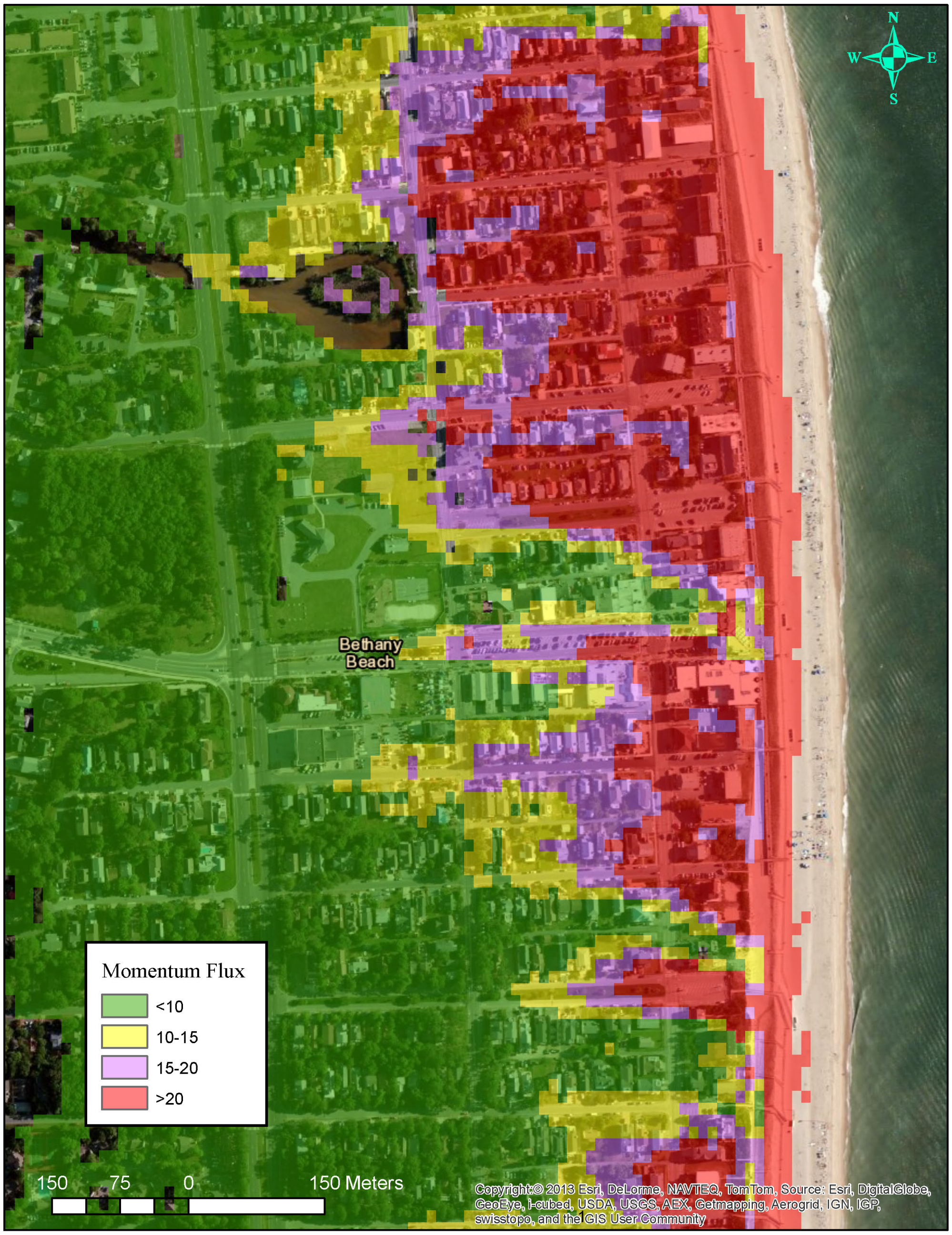
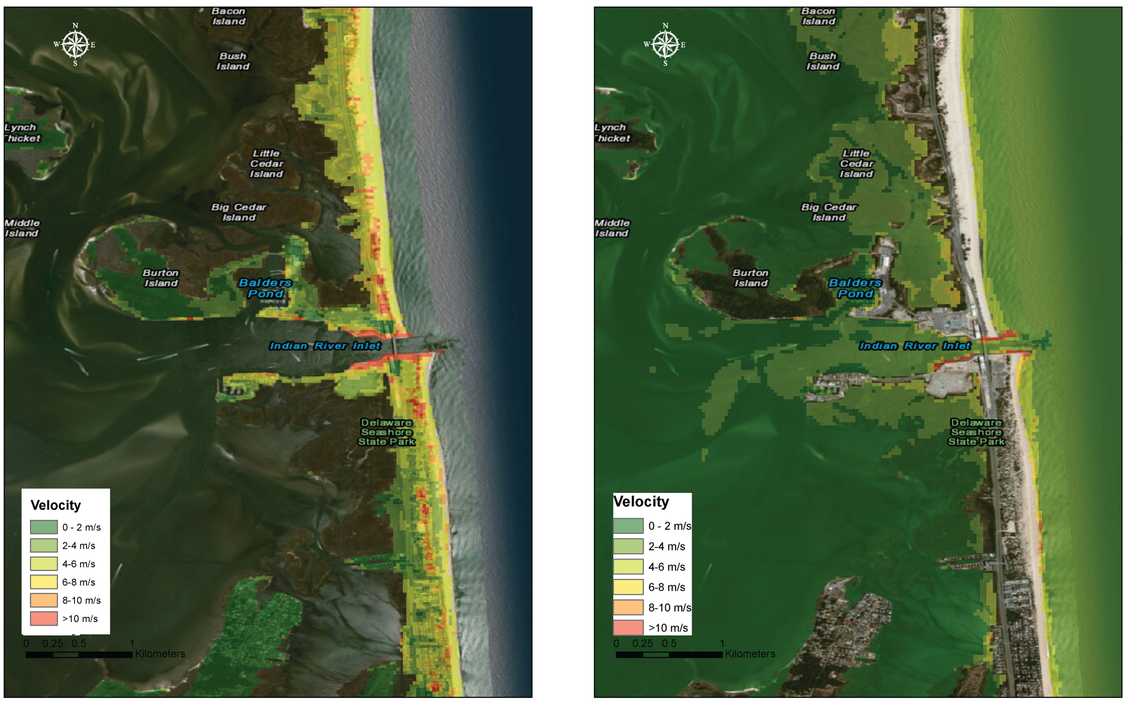



Figure 12: (Maximum Momentum Flux Map for Bethany Beach domain (1/3 Arc-sec) during SMF4 tsunami (Colorbar values are in $m^3/s^2$)




(a) (b)

Figure 13: (a) Maximum Velocity map for inundated area around Indian River Inlet (SMF4) (b) Maximum Velocity map for Indian River Inlet for offshore areas (SMF4)


Figure 14: Maximum Vorticity map for the area around Ocean City inlet

information about file formats and names is provided in Appendix A.

# 5 Map Construction

The final result of this project are inundation maps that can be used for emergency planning. The inundation line shape files (.shp) provide the main resource for constructing these maps. These shape files are mapped over USGS and ESRI topographic maps to construct the inundation map. In addition to the inundated area and the inundation line, information regarding the map construction is provided on each map. The tsunami sources used to obtain these maps are mentioned in these maps. Also, the process of map construction is briefly described on the map. Figures 16-19 show the draft inundation maps for the "Lewes, DE, and Rehoboth Beach, DE", "Bethany Beach, DE, "Ocean City, MD" communities in 1:30,000 scale, as well as an inundation map for"Chincoteague, VA" in 1:40,000 scale. The location of these maps are shown in Figure 15. The basemaps for these figures are the USGS topographic maps obtained from (http://basemap.nationalmap.gov/ArcGIS/rest/services/USGST

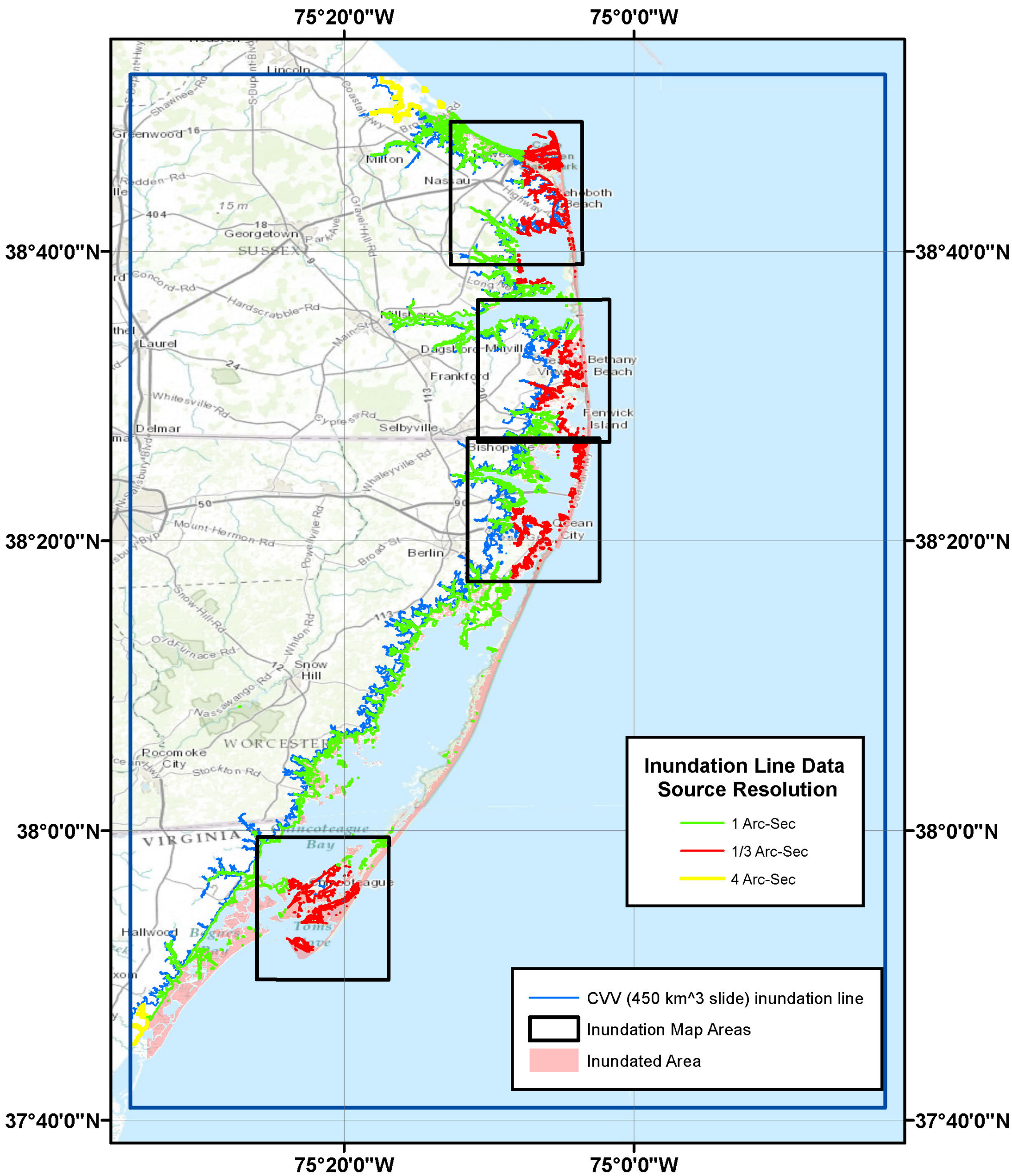



Figure 15: Tsunami inundation line for Ocean City NGDC DEM area based on tsunami sources simulated in this project. The blue boxes show the location of the inundation maps discussed in Section 5.

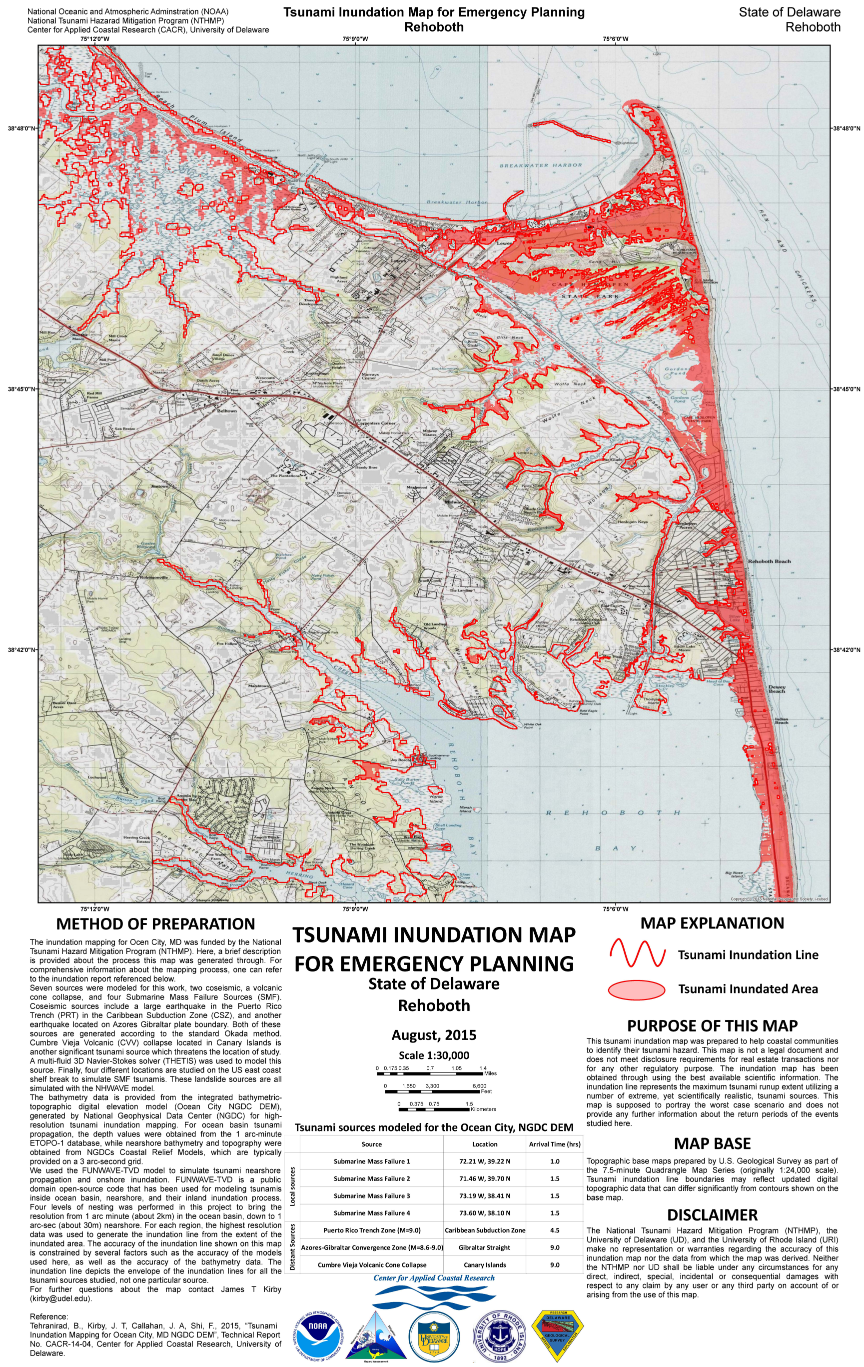



Figure 16: Inundation map for emergency planning for Lewes and Rehoboth Beach, DE in 1:30,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

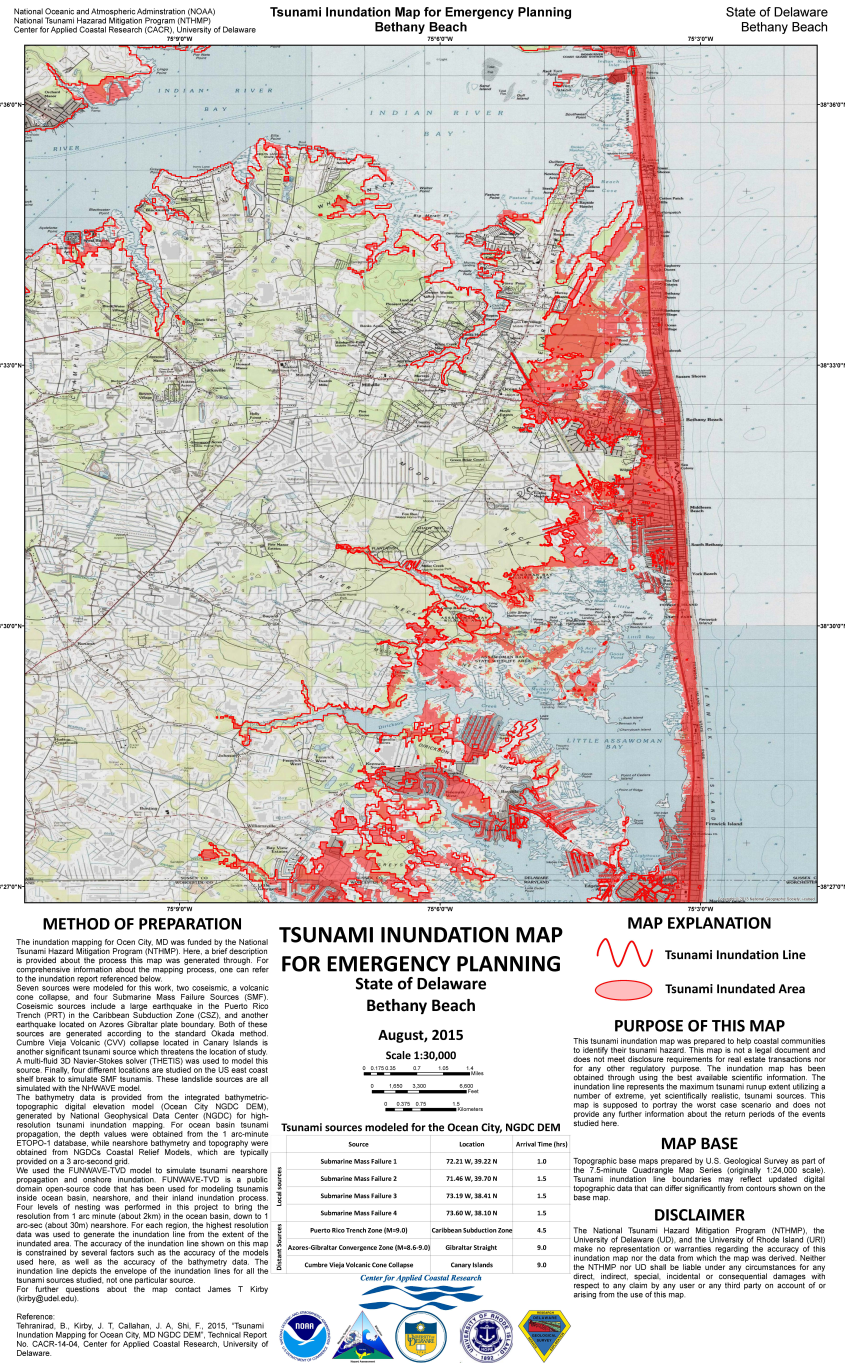



Figure 17: Inundation map for emergency planning for Bethany Beach and Fenwick Island, DE in 1:30,000 scale. The inundated area is shown in red, and the thick red line represents the inundation line for this particular area.

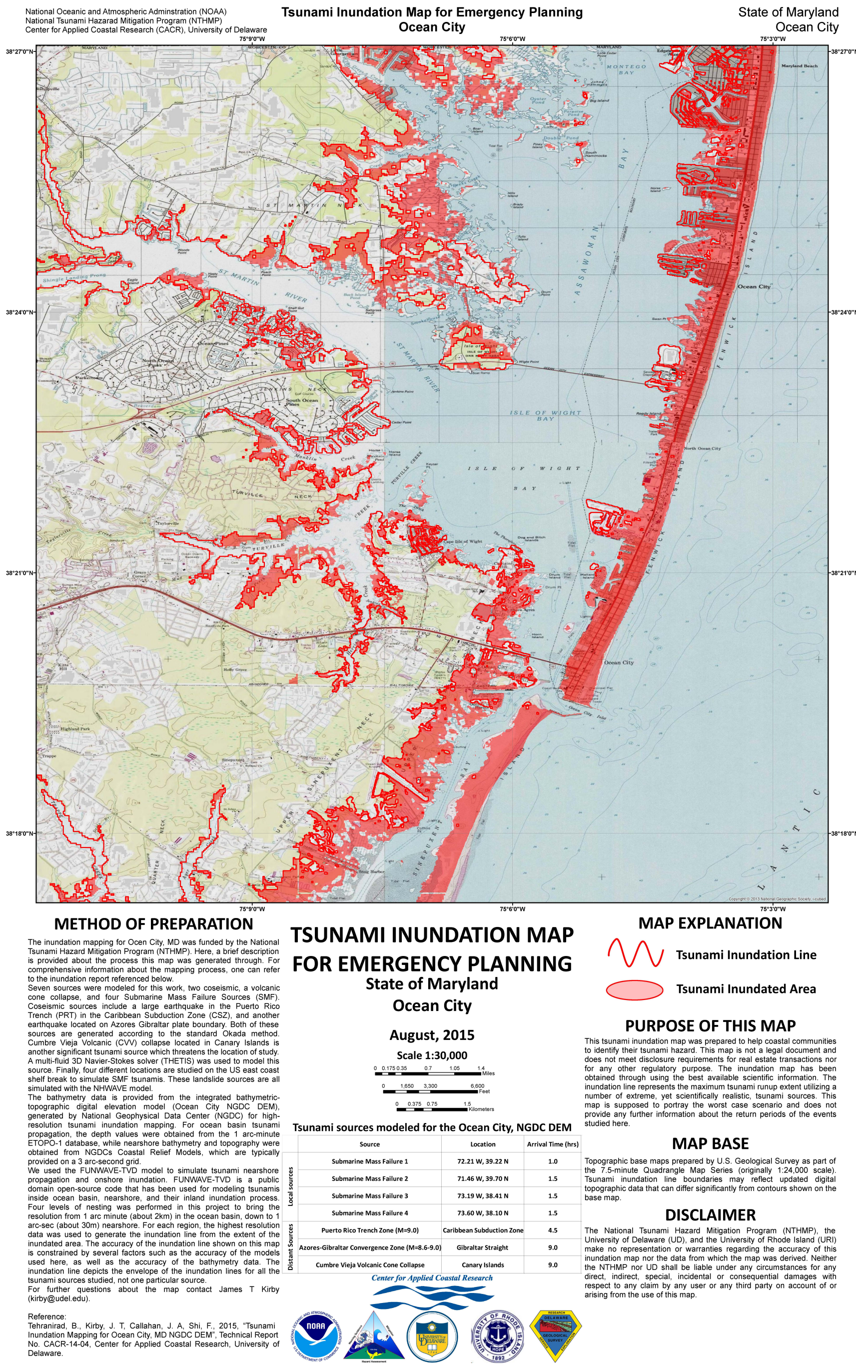



Figure 18: Inundation map for emergency planning for Ocean City, MD at 1:30,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

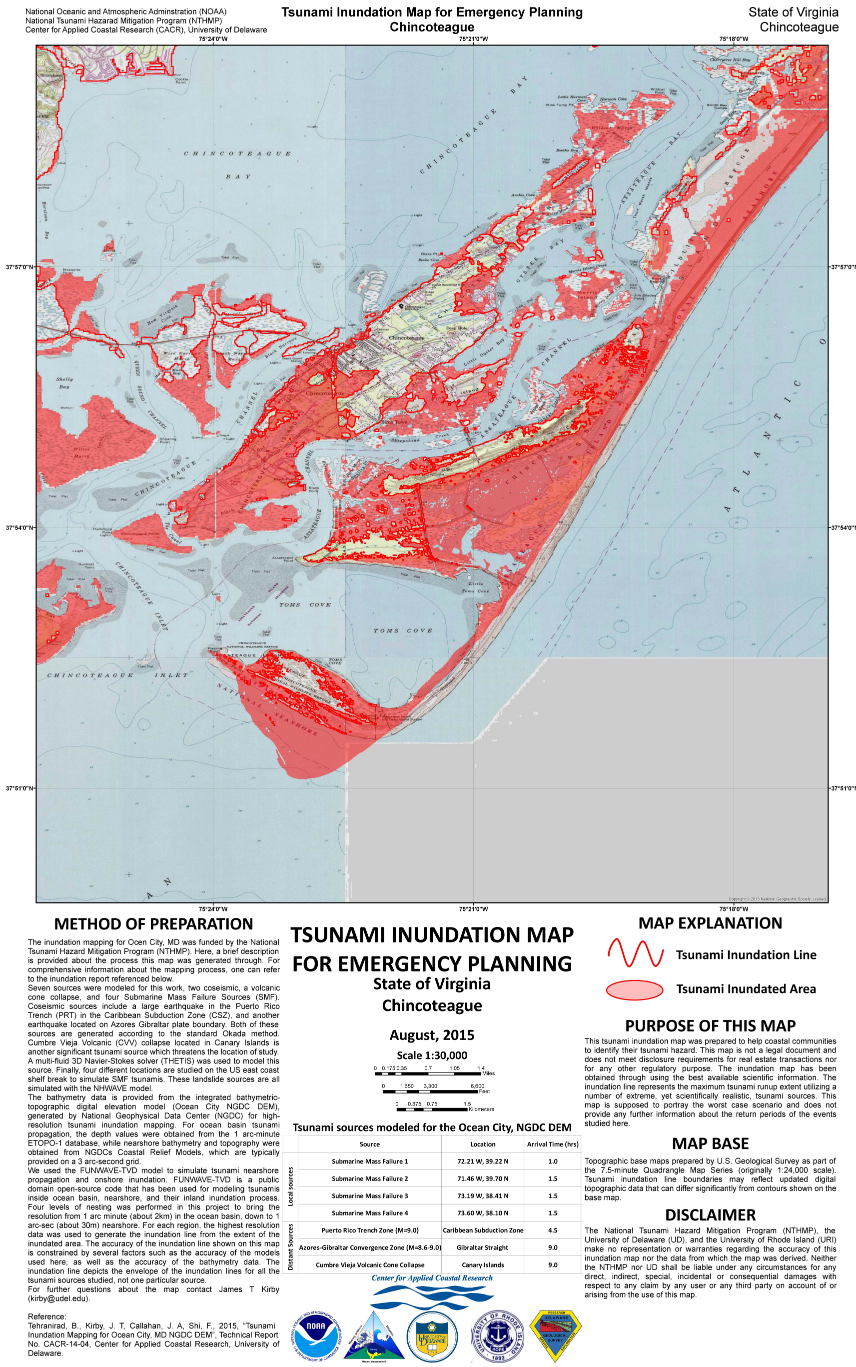



Figure 19: Inundation map for emergency planning for Chincoteague, VA at 1:40,000 scale. The inundated area is covered in red, and the thick red line represents the inundation line for this particular area.

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# Appendix A Gridded Data Information

In order to facilitate GIS work used to report tsunami inundation simulation results, the output data is saved in ESRI Arc ASCII grid format, which is compatible with GIS software such as ArcGIS. For each file, the grid spacing could have three different values (($dx, dy$)= (8.10,10.27) m, (24.30,30.81) m, and (97.20,123.24) m) depending on the domain, and the coordinate system is based on Geographic decimal degrees (Longitude and Latitude). Also, the vertical datum of all rasters is mean high water (MHW), and the horizontal datum is World Geodetic System of 1984 (WGS 84). The name of each file implies some information about the file contents as well. The first part defines the type of data and could be one of the following,

Inun . . . Onshore inundation depth

Inun_area . . . Depicts the inundated area (inundation line)

Hmax. . . Maximum recorded offshore water surface elevation

Mfmx . . . Maximum recorded onshore momentum flux

Uwet. . . Maximum recorded onshore velocity

Udry. . . Maximum recorded offshore velocity

vorm. . . Maximum recorded offshore vorticity

depth. . . depth

The rasters including inundation depth, maximum momentum flux, and maximum onshore velocity (udry) are only meaningful onshore (for initially dry points, basically inundated points), and by using the bathymetry data, nodata values have been defined for onshore points in these rasters (nodata value=-9999). The reverse is performed for maximum vorticity and maximum offshore velocity (uwet) rasters by setting the offshore values to -9999 to just consider the initially wet points in the domain. The second part of the raster name defines the tsunami source used to obtain that data. This could be seven different sources and are categorized as follows,

SMF1-4. . . Submarine Mass Failure 1-4
PR. . . Puerto Rico Trench
LIS. . . Lisbon Source
CVV. . . Cumbre Vieja Volcanic Collapse.

In each file, the grid sizes ($mx$,$ny$), the coordinates for south west corner of the domain, and the grid size are included in the file heading as well as a nodata value through the following format,

| | |
|---|---|
| ncols | 9397 |
| nrows | 12853 |
| xllcorner | -75.580046296295 |
| yllcorner | 37.679953703705 |
| cellsize | 9.2592589999999e-005 |
| NODATA_value | -9999 |

Beneath the file heading, the corresponding values to each point are written in the file with the format that starts from the southwest edge of the domain, and writes each row from western to eastern boundaries of the domain from south to north. This format is different from FUNWAVE-TVD output format, and it is flipped upside down. Therefore, the FUNWAVE-TVD outputs are flipped vertically to match with ESRI Arc ASCII grid format here. The last part of the file name represents the name of the grid that the raster is built for. The names for each grid can be found in table 1. Therefore, the raster "Inun_SMF2_oc_30_1.asc" refers to the inundation depth data for the SMF2 source for the first Ocean City grid (OC_1) with the resolution of roughly 30 m (($dx$,$dy$) = (24.30,30.81) m (corresponding to 1 arc-sec in spherical coordinates)) described in the main document (Table 1).

Finally, the inundation lines are saved as shape files (.shp) for each domain and have the same name format and projection with rasters. The combined inundation line, which depicts the inundation line for the whole domain based on the finest results available in any area, is presented as "final_inundation_line.shp" in the main folder of the results. Figure 20 shows the way the data is organized. There exists a folder for each domain (OC_1, OC_2 ) and each of them involve seven folders for each tsunami source studied here. The raster data and inundation line shape file explained above are located in these folders.

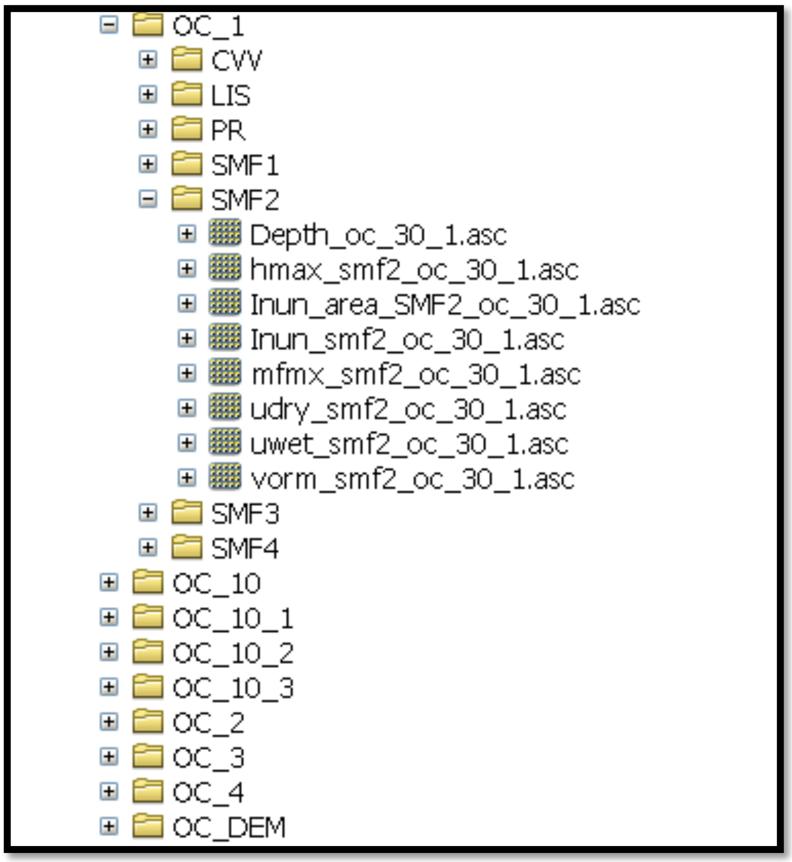


Figure 20: Screen shot of the results folder

# Appendix B Modeling inputs

A brief description of model inputs that were saved during the simulation process is provided here. These files provide sufficient data for researchers who are interested to model the tsunamis on their own. In the main results folder, there exist a folder called "input" (Figure 21). In this folder, three categories of input files exist. First, depth files for each domain are provided. The file name represents the location of the bathymetry data, and one could figure it out using Table 1. For example, if the file name is "OC_1arc_1, it is the bathymetry data for the OC_1arc_1 domain defined previously in this report (Table 1,Figure 8). Next, the coupling file for each simulation domain is provided for seven sources studied in this work. Coupling files force the boundary conditions on the domain based on recordings from coarser grids in order to simulate tsunamis with finer resolution. Similar to the bathymetry files, names of coupling files show their domain, as well as their source. For instance, the file "smf3_oc_1arc_3.txt" is the coupling file for SMF3 source for the OC_1arc_3 domain (Figure 10, Table 1). The coupling files can be easily distinguished from bathymetry files because bathymetry files do not have a tsunami source label included in their names.

General instructions for configuring input files for FUNWAVE-TVD may be found in the program's users manual (Shi et al., 2011), available at,
http://chinacat.coastal.udel.edu/papers/shi-etal-cacr-11-04-version2.1.pdf.

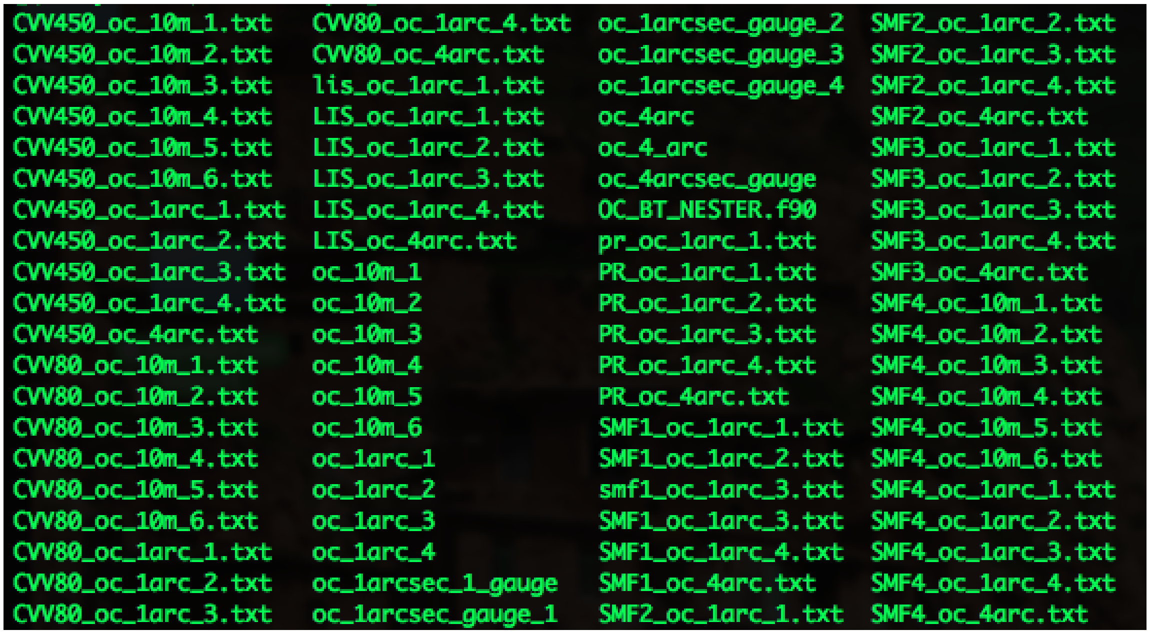


Figure 21: Screen shot of the input folder

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# Appendix C Inundation Mapping Guidelines

The development of inundation maps for tsunami hazard assessment and evacuation planning is governed by three documents and a related appendix. These include:

1. NTHMP Inundation Modeling Guidelines
   Available at: http://nws.weather.gov/nthmp/modeling_guidelines.html

2. Mapping Guidelines Appendix A
   Available at: http://nws.weather.gov/nthmp/documents/MnM_guide_appendix-final.docx

3. NTHMP Tsunami Evacuation Mapping Guidelines
   Available at:
   http://nws.weather.gov/nthmp/documents/NTHMPTsunamiEvacuationMappingGuidelines.pdf

4. NTHMP Guidelines for Establishing Tsunami Areas of Inundation for Non-Modeled or Low-Hazard Areas
   Available at:
   http://nws.weather.gov/nthmp/documents/Inundationareaguidelinesforlowhazardareas-Final092611.docx