Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U. S. East Coast

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BACKGROUND

Tsunami hazard assessment along the US East Coast (USEC) is still in its infancy, in part due to the lack of historical tsunami records and the uncertainty regarding the magnitude and return periods of potential large-scale events (e.g., transoceanic tsunamis caused by a large Lisbon 1755 type earthquake in the Azores-Gibraltar convergence zone, a large earthquake in the Caribbean subduction zone in the Puerto Rico (PRT) trench or near Leeward Islands, or a flank collapse of the Cumbre Vieja Volcano (CVV) in the Canary Islands) (Fig. 1). Moreover, considerable geologic (e.g., Chaytor et al., 2009; Twichell et al., 2009) and some historical evidence (e.g., the 1929 Grand Bank landslide tsunami, and the Currituck slide site off North Carolina and Virginia) suggests that the most significant tsunami hazard in this region may arise from Submarine Mass Failures (SMF) triggered on the continental slope by moderate seismic activity (as low as $M_w = 6$

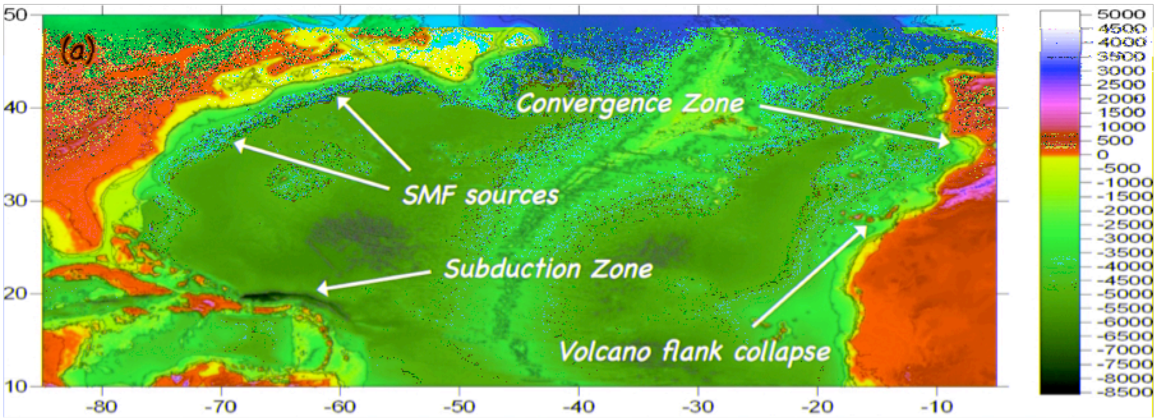


Fig. 1: Potential tsunami sources for U.S. East coast in the North Atlantic Ocean basin (ETOPO2's two second arc length ocean bathymetry is shown in the background).

Both Cartesian (Shi et al., 2012) and curvilinear grids (Kirby et al., 2009, 2012; note this implementation is only mildly nonlinear) are used, in a variety of nested computational domains at various grid scales (from the Atlantic Ocean basin scale (4' to 2') to regional (1' to 1/3') and local grid scales (3" to 1/3")). These nested domains are used to model the propagation of the various selected tsunami sources, from their initial location to that of the region of interest along the US eats coast, where impact from a particular source is deemed to be significant. The last and final nested grid where detailed inundation is computed typically corresponds to the size of a local Digital Elevation Map (DEM), for which we have bathymetric and topographic information at a very fine scale (e.g., 1/3" arc or about 10 m).

Whether frequency dispersion matters (e.g., for the SMF and other slide sources) or not (e.g., for the large co-seismic sources), our FNBM modeling framework contains all the relevant physics without need to modify the model or its equations, whether one type of tsunami source or another is used. The same goes for linear versus nonlinear effects in generated tsunami wave trains, as well as for dissipation by bottom friction or bathymetrically induced breaking (which are modeled through adequate semi-empirical terms). Finally, the spherical coordinate implementation of FUNWAVE-TVD includes Coriolis effects (Kirby et al., 2009, 2012), together with a very efficient parallel MPI and nested-domain implementation, which make FNBM transoceanic simulations possible, with typically on the order of 10h CPU time on a multi-core desktop computer or on the cluster computing environment available at the University of Delaware (UD), Center for Applied Coastal Research.

Large co-seismic sources (e.g., PRT trench or Lisbon 1755 sources) are modeled as initial instantaneous ocean surface deformations, based on estimates of event size, magnitude and geological parameters, using Okada's (1985) method. For reference, we recently successfully conducted case studies of the 2004 Indian Ocean tsunami using FUNWAVE and of a hypothetical Puerto Rico tsunami, following this methodology (Grilli et al., 2007, 2010;

Ioualalen et al., 2007; Karlsson et al., 2009). Co-seismic source parameters are obtained from both our past work (e.g., Grilli et al., 2008, 2010) and other recent work reported in the literature (e.g., MG special issue, 2009).

Both historical (e.g., 1929 Grand Bank) and other local SMF sources are modeled according to the methodology reported in Watts et al. (2003, 2005) and Grilli et al. (2005), and validated for a number of historical case studies (e.g., Day et al., 2005; Tappin et al., 2008). In this method, relevant SMF sources are semi-empirically generated from geomechanical, geological, and geometrical parameters, and specified as initial conditions (wave elevation and velocities) in the FNBM propagation model. Such (experimentally validated) sources were derived, based on a large number of 3D simulations of slide kinematics using a model solving fully nonlinear (inviscid) 3D Euler equations with a free surface. Since our earlier modeling and scaling analyses showed that the key parameter in SMF tsunami generation is initial acceleration, and typical SMF deformation rates do no significantly affect key tsunami features (Grilli and Watts, 2005), the methodology assumes rigid (translational or rotational) slides. But this is not a limitation and if known from sediment rheological properties, slide deformation effects can be included in the tsunami source. A more recently developed approach is also used for modeling SMF tsunamis, in which tsunami generation is first simulated using NHWAVE, a non-hydrostatic model solving Euler equations in Sigma coordinates (Ma et al., 2012), on the basis of similar laws of motion and methods for rigid slides and slumps as discussed above. The initial tsunami is then used in FUNWAVE-TVD to compute further propagation and coastal impact.

Location and parameters for local SMF sources (other than historical) are first identified by performing a first-order (i.e., screening) probabilistic analysis of SMF hazard along the east coast. Such work was conducted by Grilli et al. (2009) for coastal areas from New Jersey to Maine and is being extended to the entire USEC. Results of this analysis are presented in terms of 100 and 500 year runup from seismically induced tsunamigenic SMFs. An extensive Monte Carlo (MC) model was developed and employed to this effect, in which distributions of relevant parameters (seismicity, sediment properties, type and location of slide, volume and dimensions of slide, water depth, etc.) were used to perform large numbers of stochastic stability analyses of submerged slopes (along actual transects across the shelf), based on conventional pseudo-static limit equilibrium methods for both translational and rotational failures. The distribution of predicted slope failures along the upper US East Coast was found to match published data quite well (Booth et al., 1985, 1993; Chaytor et al., 2007, 2009). Estimates of tsunami runup associated with SMF hazard were found to be low at most locations except, for the 500-yr tsunami, for two regions off Long Island, NY (up to 3-m) and off the New Jersey coast (up to 4-m). However, detailed deterministic tsunami generation, propagation and inundation modeling is required, in order to accurately estimate the inundation (and runup) hazard at these sites. This is being done in this project. To estimate relevant SMF sources from the Florida border to New Jersey, a similar MC analysis is being done for this East coast region, and observed slope failure distributions are again being used to ground truth the MC model predictions.

Recent field measurements, slope stability analyses, and 3D-Navier-Stokes multi-fluid (material) modeling work (Abadie, et al., 2009, 2010) were reviewed and used to define and simulate realistic scenarios for a CVV flank collapse source. These are being used to develop a defensible approach for estimating tsunami hazard from this hypothetical event, in which tsunami hazard is simulated from the few selected CVV flank collapse scenarios.

The relative degree of hazards for East Coast communities is assessed by combining ocean scale simulations of transoceanic tsunami sources, such as Lisbon 1755 like or Puerto Rico Trench co-seismic events, and CVV collapse, with regional scale simulations of these events, along with the regional scale SMF events. Detailed inundation studies are being conducted for highest-risk East Coast communities, and results of these studies will be used to construct a first-generation of tsunami inundation maps for the chosen communities.

ACCOMPLISHMENTS

The following section summarizes the status of accomplishments for each Objective and related Tasks funded under this grant award. Summary descriptions are organized according to the overall objectives of the NTHMP that reflects the Sub-Committee structure. The work is divided between the two participating institutions, with the University of Rhode Island working on source identification and tsunami generation and large scale/regional propagation modeling, and the University of Delaware working on tsunami nearshore propagation and inundation modeling and on developing the final inundation maps.

Objective. Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U. S. East Coast

Mapping and Modeling Sub-Committee:

Task #	Project	Strategic Plan Metric	Subcom.	Accomplishment
1.1	*Literature Review on East Coast tsunami sources*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*Literature review completed and posted on web site given above. See Grilli et al., 2011, Research Report CACR-11-08, University of Delaware. (on web site)*

1.2	*Monte Carlo modeling of East Coast SMF sources*	*Prioritize inundation map development*	*MMS*	*Bathymetry and geologic data for east coast continental margin has been collected. MC analysis has been completed. Results presented in Krause (2011) and Baxter et al (2011) (on web site). Methodology is still under development, pending further results from ongoing West Coast project on methodologies for probabilistic tsunami hazard assessment (PTHA).*

1.3	*Reanalysis of previous Cumbre Vieja simulations.* *Simulation of event using 3-D Multi-fluid VOF model.*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*CVV flank collapse scenarios were selected based on slope stability analyses. These were modeled using the 3D-NS THETIS code to define tsunami sources. FUNWAVE simulations using the latter were performed in regional grid (to estimate impact on other Canary Island and provide 2D source) and are being performed in ocean scale basin grids. This work is presented in Abadie et al. (2011, 2012) and Harris et al. (2012), all posted on website. Results are now being used as one component of local inundation results.*

1.4	*Establish method for determining sources for inundation models based on MC simulation*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*This work is underway, based on results of Eggeling (2012) and a new collaboration with the USGS Woods Hole group (who has done extensive field work on underwater landslides for the East Coast); at present, historical data is being used instead of the MC simulation results. Methodology for probabilistic analysis of sources is under continuing development, in parallel to West Coast effort by UW and California/URS.*

1.5	*DEM, GIS databases for East Coast inundation studies*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*East Coast tsunami DEM's collected. DEM's being used are developed either from NGDC tsunami DEM's or FEMA Region II or III DEM's developed for hurricane/storm surge flooding analysis. Inundation results based on NGDC DEM's are being developed for Myrtle Beach, SC, Ocean City, MD, Atlantic City, NJ, Eastern Long Island (Montauk), NY and Nantucket/Martha's Vinyard/Cape Cod, MA. FEMA DEM's are used to fill in gaps between the coverage provided by NGDC DEM's, giving continuous coverage from Ocean City, MD to Cape Cod, MA (see Figure 19).* *Input for inundation studies include seismic sources (Puerto Rico, Azores), volcanic cone collapse (CVV) and landslide sources (now based on Currituck slide-like events moved to reasonable candidate locations along the Eastern Seaboard, pending more conclusive development of PTHA methodology based on ongoing studies. Figure 20 shows an indication of the local 10m horizontal resolution being utilized in inundation studies.* *A study is ongoing to establish whether East Coast mapping should extend into coastal plane estuaries: preliminary results were presented by Tehranirad et al. (2012a).*

PROBLEMS ENCOUNTERED

Uncertainty about the procedure to be adopted for choosing Submarine Mass Failure (SMF) sources for the East Coast study sites, along with a delay in participating in a joint effort with USGS to determine the validity and relevance of sources chosen to date in the probabilistic analysis and a more recent result of Eggeling (2012) showing the limited applicability of the MC analysis so far, have led to a delay in the start of mapping efforts for the initial Mid-Atlantic sites. For this reason, we have separately indicated our desire to shift our initial mapping effort to the Myrtle Beach area of South Carolina, which we judge to primarily be at risk from transoceanic sources.

Analysis of higher-resolution nearshore results, particularly for the Cumbre Vieja Volcano (CVV) source showed an unusually large decrease in the maximum wave height over wide continental shelves due to intense and prolonged breaking. Concerns on whether the magnitude of the dissipation in breaking bores that form from the tsunami is sufficiently accurate has resulted in a parallel effort to characterize the accuracy of different breaking models (Grilli et al., 2012).

RELATED EFFORTS

Office of Naval Research funding has been used to develop a modernized version of the Boussinesq model code FUNWAVE being used to predict tsunami propagation and inundation in the present study. This code greatly improves the treatment of shoreline inundation and thus is particularly useful in the context of the NTHMP project. The code is described in Shi et al. (2012). Tsunami benchmarking of the code for all the PMEL mandatory benchmarks is described in Tehranirad et al. (2011). Both manuscripts are posted on the project web site. This effort is also reported in the summary report for the NTHMP-sponsored Model Benchmark Workshop organized in March 2011 at Texas A&M University in Galveston.

ONR funding has also led to the development of a non-hydrostatic wave model NHWAVE, which has been benchmarked for landslide and inundation simulation and is used for generating SMF tsunami sources in our currently adopted methodology. The basic model as well as the benchmark test is described in Ma et al. (2012), posted on the website.

NSF funding is being used to develop a nesting methodology for FUNWAVE simulations, using various resolution grids (e.g., basin scale, regional, and local).

ANTICIPATED OUTCOMES

This project is aimed at providing a comprehensive analysis, simulation and first generation mapping effort for at-risk coastal communities on the U. S. East Coast. An extensive review of the literature on potential tsunami sources with possible effects on East Coast states has been conducted (Grilli et al., 2011, posted on the website). A probabilistic analysis of the potential hazards associated with submarine mass failure (SMF) events on the East Coast continental margin has been conducted (Grilli et al., 2009; see Kraus, 2011, posted on the website). Reanalysis and simulation of Cumbre Vieja volcanic cone failure and a variety of co-seismic events has been conducted in order to assess the relative importance of a range of ocean scale events (Abadie et al., 2011, 2012; posted on the website). Methodology for performing simulations from source to final inundation at prioritized East Coast sites is being established (Harris et al., 2012; posted on the website).

This work will lead to an identification of events representing worst-case scenarios and an indication of the magnitude and spatial distribution of the coastal impact of such events along the US East Coast. These results will be used to establish priorities for performing detailed inundation studies for chosen East Coast communities. It is anticipated that up to four such sites will be included in the scope of the present project. Presently, work is ongoing for the Myrtle Beach, Ocean City, and Atlantic City DEMs, as well as the Long Island region. The detailed local studies will lead to first-generation inundation maps for the chosen sites, which will be based on established NTHMP guidelines for map development.

TSUNAMI SOURCE SELECTION

Co-seismic sources

Following the standard procedure in tsunami hazard assessment, the large co-seismic sources (i.e., PR trench or Lisbon 1755 sources) are modeled as initial instantaneous ocean surface deformations, based on estimates of each event's size, magnitude, and geological parameters, using Okada's (1985) method. [For reference, we recently successfully conducted case studies of the 2004 Indian Ocean tsunami and of a hypothetical Puerto Rico tsunami, using FUNWAVE, following this methodology (Grilli et al., 2007, 2010; Ioualalen et al., 2007; Karlsson et al., 2009).] Co-seismic source parameters were obtained from both our past work (Grilli et al., 2010) and other recent work reported in the literature (e.g., Gica et al., 2008; MG special issue, 2009).

More specifically, Fig. 2 shows the locations of 16 sources used to model tsunami hazard for the Azores-Gibraltar Convergence Zone (AGCZ). Each source is run separately in the propagation model, and has the estimated magnitude and size of the M 8.5 Lisbon 1755 event and is specified at a different location based on a geological analysis (Barkan et al., 2009). The AGCZ is quite complex and only rarely produces large earthquakes, so a more precise understanding of a worst-case tsunami generated is not possible at this time. Recent work performed for the European tsunami warning centers has also studied this area, as reported by Gailler et al. (2012). To study near-field hazard from the AGCZ, they considered hundreds of potential sources. However, for our purpose, which is the far-field effects on the US East Coast, it is sufficient to consider a more limited number of sources. Hence, similar to Barkan et al. (who studied the potential source parameters of the 1755 tsunami), we consider the 16 source locations shown in Fig. 2, as well as many different strike angles for one of the sources in order to determine the most devastating potential fault for the USEC.

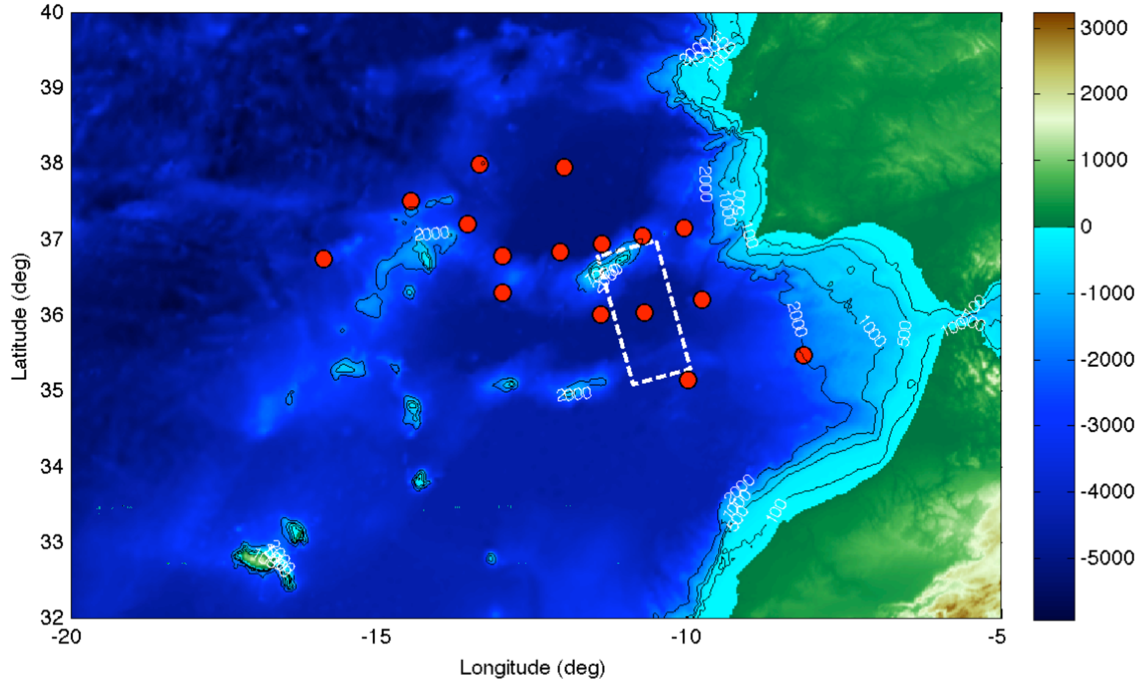


Fig. 2: Choice of potential AGCZ sources, identical to that of Barkan et al. (2009). Red dots refer to source centers; white rectangle refers to the size of the sources. These are M 8.5 sources, assuming a shear modulus of 4.2 10^{10} kg/m s^2, a slip of 13.1 m and a source area 200 km by 80 km.

Fig. 3 similarly shows the location and size of 28 sources selected for tsunami propagation modeling in the Caribbean Subduction Zone (CSZ). These are from NOAA's SIFT database (Short-term Inundation Forecast for Tsunamis; Gica et al., 2008). The largest hazard from the CSZ would in fact be an earthquake that would rupture the entire Puerto Rico Trench (PRT).

This extreme case, with an estimated M 9.0 magnitude and a 200-300 year return period, was considered in Grilli et al.'s (2010) preliminary analysis of USEC tsunami hazard. In the present work, we simulated the same M 9.0 PRT single source as in Grilli et al. (2010), but we also considered a M 8.8 source made of 12 individual sources (Table 1), as shown in Fig. 3. This composite source encompasses the entire Puerto Rico segment. Since the subduction zone is curved in the area of Puerto Rico, using these multiple Okada sources (i.e., each with constant 10 m slip) is more descriptive than using a single one, at least for such large ruptures. Fig. 4 shows the initial condition of this source.

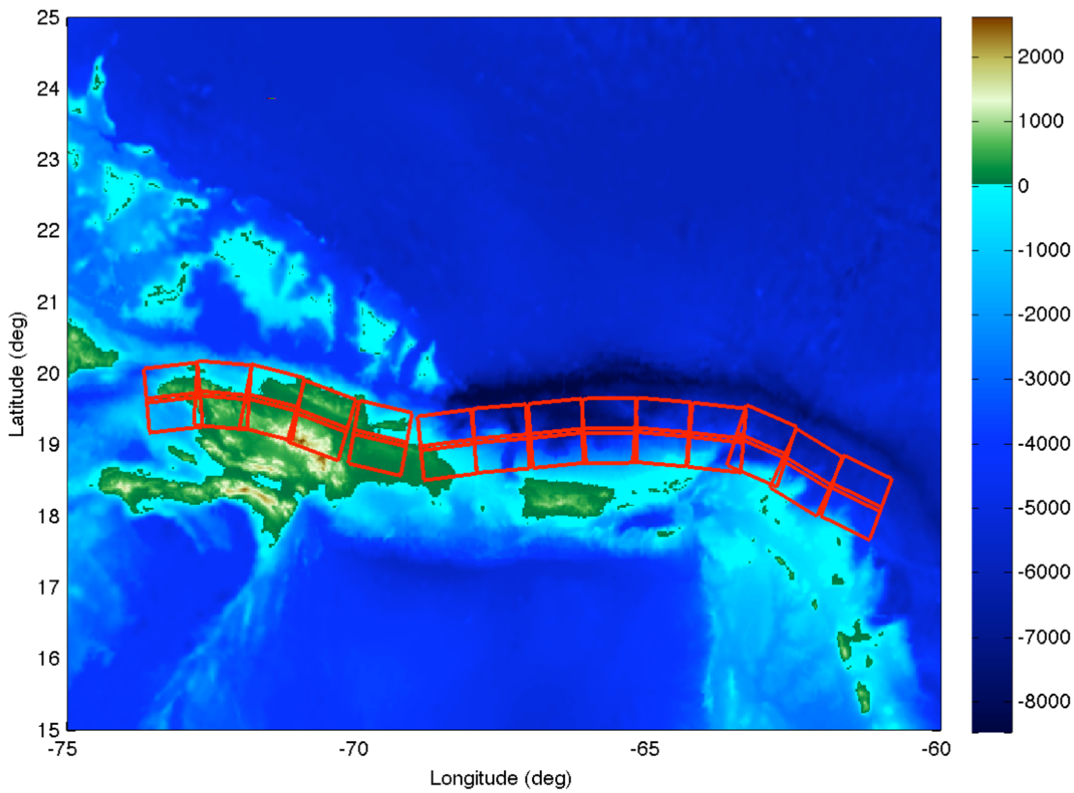


Fig. 3: SIFT sources (Gica et al. 2008) of interest in the CSZ. The 10 (5x2) sources on the left correspond roughly to the Hispaniola trench, the middle 12 (6x2) correspond to the Puerto Rico Trench (PRT), and the right 6 (3x2) sources correspond to a segment of the Lesser Antilles trench.

Table 1 – Parameters of the Individual Subfaults of the PRT Co-seismic Source. Source depth refers to the depth at the top of the fault plane.

Latitude	Longitude	Length	Width	Slip	Rake	Dip	Strike	Depth
18.8870°	63.8800°W	100 km	50 km	10 m	90°	20°	95.37°	21.1 km
19.3072°	63.8382°W	100 km	50 km	10 m	90°	20°	95.37°	5.0 km
18.9650°	64.8153°W	100 km	50 km	10 m	90°	20°	94.34°	21.1 km
19.3859°	64.7814°W	100 km	50 km	10 m	90°	20°	94.34°	5.0 km
18.9848°	65.6921°W	100 km	50 km	10 m	90°	20°	89.59°	21.1 km
19.4069°	65.6953°W	100 km	50 km	10 m	90°	20°	89.59°	5.0 km
18.9484°	66.5742°W	100 km	50 km	10 m	90°	20°	84.98°	21.1 km
19.3688°	66.6133°W	100 km	50 km	10 m	90°	20°	84.98°	5.0 km
18.8738°	67.5412°W	100 km	50 km	10 m	90°	20°	85.87°	21.1 km
19.2948°	67.5734°W	100 km	50 km	10 m	90°	20°	85.87°	5.0 km

18.7853°	68.4547°W	100 km	50 km	10 m	90°	20°	83.64°	21.1 km
19.2048°	68.5042°W	100 km	50 km	10 m	90°	20°	83.64°	5.0 km

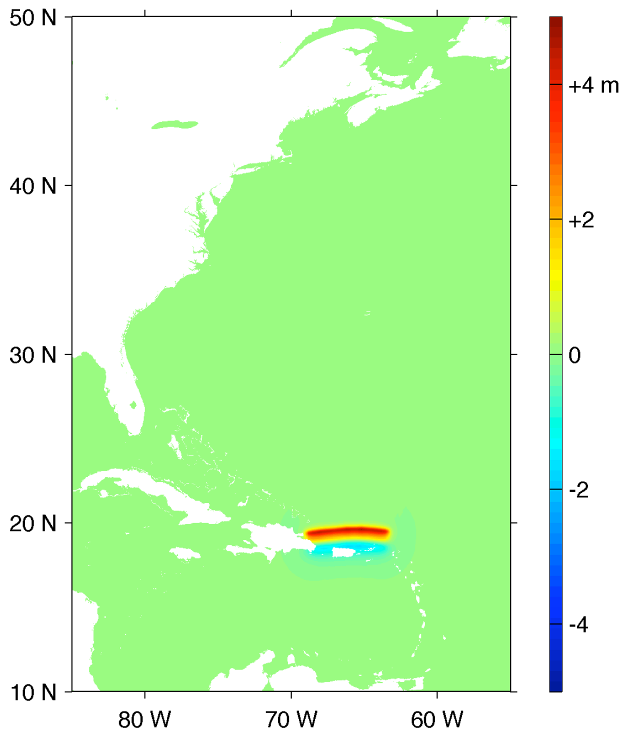


Fig. 4: Initial condition for PRT test case in 2' grid, consisting of 12 (6x2) Okada sources.

CVV flank collapse sources

The Cumbre Vieja Volcano (CVV) flank collapse (Fig. 5) has been identified as an extreme subaerial landslide tsunami source in the Atlantic Ocean basin, of unknown but likely very long return period, with the potential to generate very high and steep near-field and significant far-field waves along the USEC. Due to the complexity of both the source mechanism and the flow in near field waves, a 3D multi-material Navier-Stokes solver (THETIS) is used to generate the initial conditions in a fine local grid (Fig. 5). This initial source is then propagated towards the USEC in FUNWAVE-TVD in a series of nested grid, as done for the co-seismic sources. Four different scenarios were considered in the THETIS simulations, with slide volumes of 20, 40, 80, and 450 km^3. Initial sources can be seen in Fig. 6 and details can be found in Abadie et al. (2009, 2010, 2011, 2012). Initial near-field impact and far-field propagation and coastal impact calculated for the USEAC in 30" arc nested grid can be found in Abadie et al. (2011, 2012) and Harris et al. (2012).

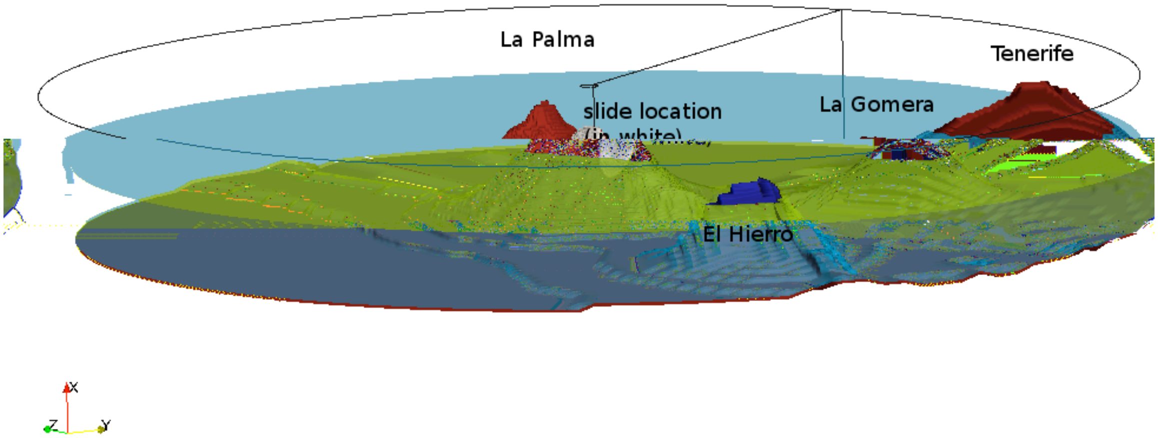


Fig. 5: Sketch of cylindrical computational domain in THETIS model, for CVV flank collapse simulations, assuming a 80 km^3 subaerial slide case, with view of bottom bathymetry, neighboring islands, and slide location (marked in white) (Abadie et al., 2011, 2012).

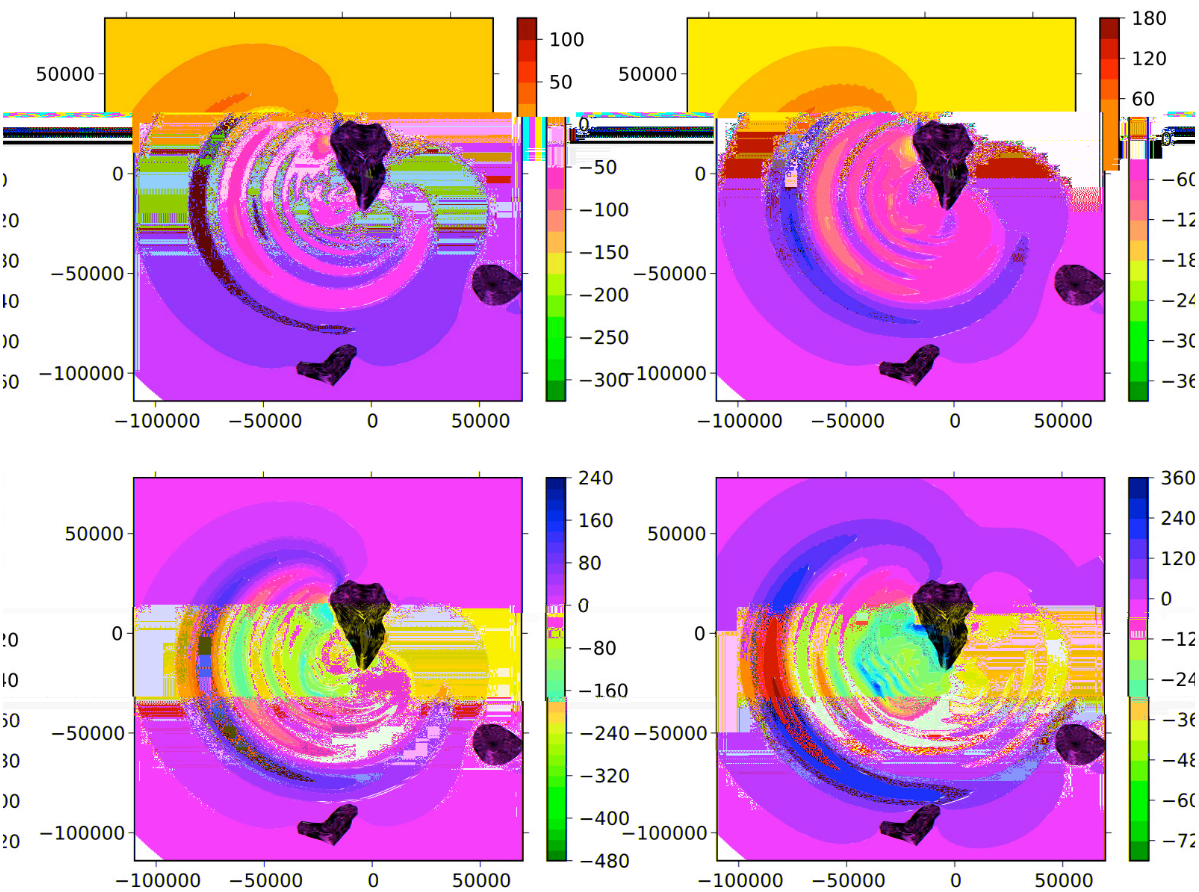
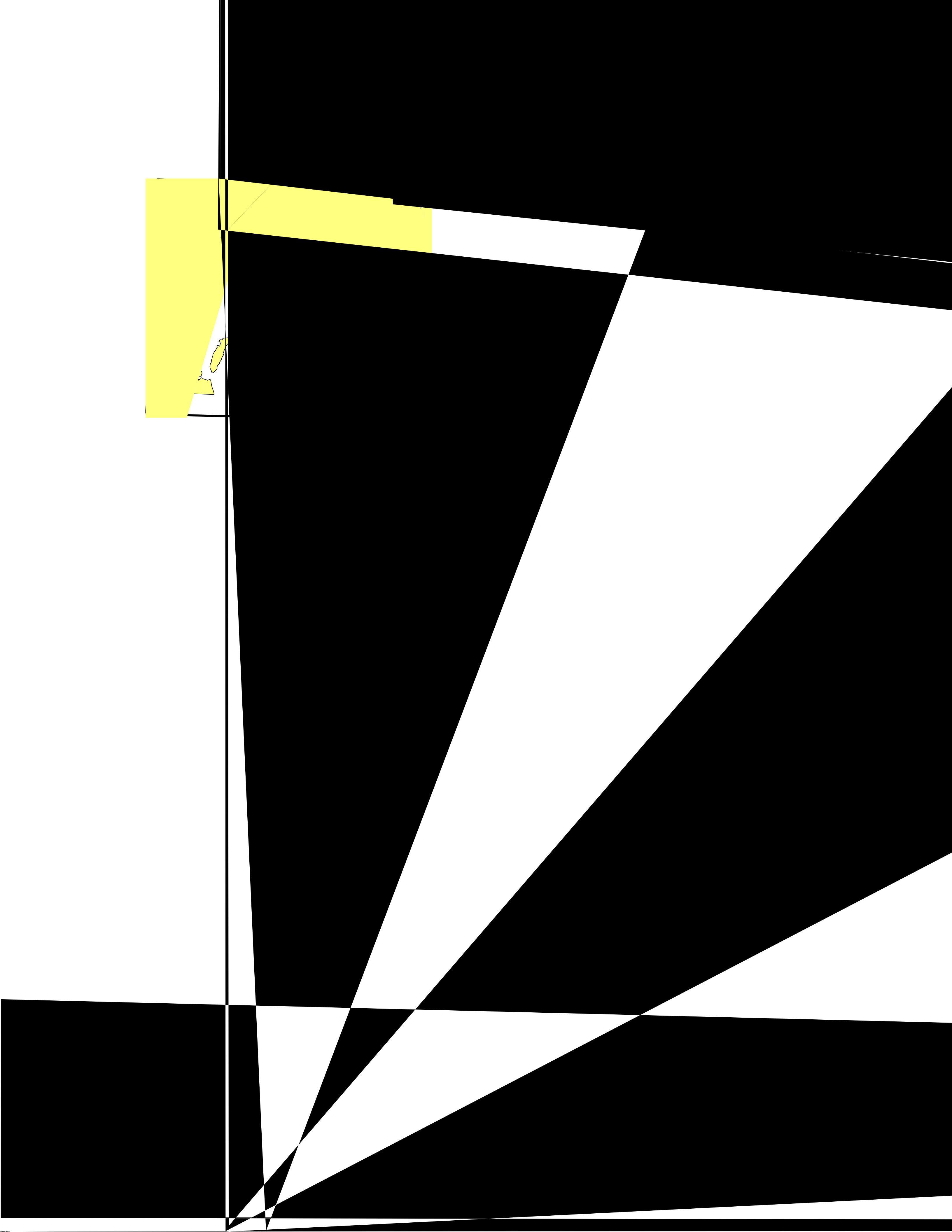


Fig. 6: THETIS computations in geometry shown in Fig. 5. Computed free surface elevation at t = 450 s, for initial slide volume of: a) 20 km^3, b) 40 km^3 , c) 80 km^3 , d) 450 km^3. [Note the different color scales.]

SMF tsunami sources

When large Submarine Mass Failures (SMFs) occur on or near the continental shelf break, they may cause significant near-field tsunamis. Although only a few historical landslide tsunamis have been clearly identified in the region, simulation work performed at URI for NTHMP indicates that SMFs may govern the tsunami hazard along much of the U.S. East Coast.

The locations and parameters of SMF sources (other than historical) have previously been selected by performing a probabilistic Monte Carlo (MC) screening analysis of SMF tsunami hazard along the USEC continental slope (Baxter et al., 2011; Krauss, 2011). The distribution of predicted slope failures along the upper US East Coast was found to match published data quite well (Booth et al., 1985, 1993; Chaytor et al., 2007, 2009). This work followed and extended the methodology developed by Grilli et al. (2009), for coastal areas from New Jersey to Maine. More recent, improved, stability analyses (Eggeling, 2012), however, have shown that this method needs to be supplemented by additional work, as three-dimensional effects such as the stability of canyon walls may be critical to producing realistic SMF sources. Since
MC stochastic results were deemed insufficiently reliable, for the time being, we elected instead



and some geometrical and material properties, and the maximum distance the SMF travels can be related to the length of the continental slope. While this represents a crude approximation, earlier work showed that the motion of a rigid SMF constitutes a worst-case scenario, and the approximate SMF shape and deformation only have second-order effects on the wave shape.

Thus, the solid block rotational slide parameterization of Grilli and Watts (2005) is used to specify the seabed motion, which is modeled in the non-hydrostatic multi-layer model NHWAVE (Ma et al., 2012) for the duration of the SMF motion. The resulting wave elevation and water velocity fields are then reinterpolated and used as an initial condition in FUNWAVE-TVD, similar to the other two sources. Specifically, the SMF vertical elevation below the slope is modeled as (Enet and Grilli, 2007):

$$
\begin{aligned}
\zeta(\xi,\chi) &= \frac{T}{1-\varepsilon}\max\left[0,\ \operatorname{sech}(k_b\xi)\operatorname{sech}(k_w\chi)-\varepsilon\right] \\
k_b &= \frac{2}{b}\operatorname{acosh}\frac{1}{\varepsilon} \\
k_w &= \frac{2}{w}\operatorname{acosh}\frac{1}{\varepsilon}
\end{aligned}
$$

where the local coordinate system is rotated to be aligned with the SMF center and location (see Fig. 8):

$$
\begin{aligned}
\xi &= (x-x_0)\cos\theta-(y-y_0)\sin\theta-s(t) \\
\chi &= (x-x_0)\sin\theta+(y-y_0)\cos\theta
\end{aligned}
$$

The SMF slump law of motion is parameterized by a characteristic time of motion and distance of motion:

$$
s(t)=\begin{cases} 0 & t<t_i \\ s_0\left(1-\cos\left\{\dfrac{t-t_i}{t_0}\right\}\right) & t_i\le t<t_i+\pi t_0 \\ 2s_0 & t_i+\pi t_0\le t \end{cases}
$$

where *s(t)* denotes the slump center of mass motion. This brings the SMF to rest at distance s_f and time t_f similar to that predicted by Locat et al. (2009) for the Currituck landslide. With the above definitions, the instantaneous seafloor depth above the SMF is given by:

$$h(x,y,t) = h_0(x,y) + \zeta\{\xi(x,y),\chi(x,y),t\} - \zeta\{\xi(x,y),\chi(x,y),t_i\}$$

where the SMF height is subtracted from the local instantaneous depth.

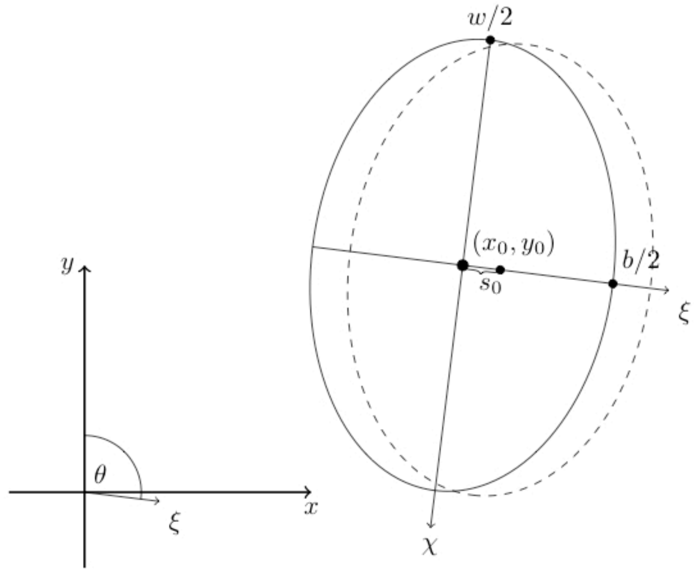


Fig. 8: Geometric parameterization of SMFs moving in transect direction x, with an azimuth angle θ from North.

Once their location selected along the USEC continental slope, the motion of each SMF source is modeled according to the methodology reported in Watts et al. (2003, 2005) and Grilli and Watts (2005), which was validated for a number of historical case studies (e.g., Day et al., 2005; Tappin et al., 2008). In this method, the kinematics of SMF sources is semi-empirically generated from geomechanical, geological, and geometrical parameters. However, unlike in earlier simulations (e.g., Day et al., 2005; Tappin et al., 2008), in the present work the initial tsunami wave elevations and velocities caused by each SMF are first computed in NHWAVE; this model was validated for SMF tsunami generation based on Enet and Grilli's (2007) experiments (Tehranirad et al, 2012b). Once the majority of tsunami generation has occurred, the SMF source is then propagated in nested grids in the FUNWAVE propagation model, as discussed before.

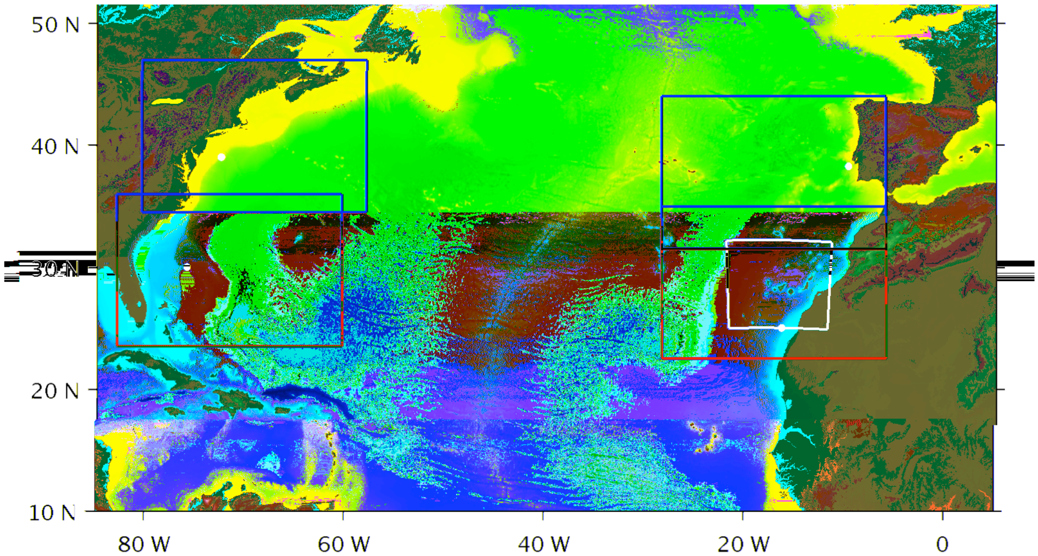


Fig. 9: Multi-model, nested grid simulations: (1) CVV: Thetis (3D) 500 m grid, to FUNWAVE (Cart. 2D) 1000 m grid (white box), to FUNWAVE 2’, 30”, 7.5” (Spherical 2D) and 30 m (Cart. 2D) grids; (2) AGCZ and PRT: FUNWAVE 2’, 30”, 7.5” (Spherical 2D) and 30 m (Cart. 2D) grids

TSUNAMI PROPAGATION AND LOW RESOLUTION COASTAL INUNDATION MODELING

Simulations of tsunami propagation for the CVV and co-seismic tsunami sources discussed above were performed using FUNWAVE-TVD, in a series of nested grids, down to regional and nearshore scales along the USEC. For the CVV case, THETIS is first used to compute the subaerial landslide source in a 3D grid with a 500x500 m horizontal footprint (Figs., 5 and 6). Results are then reinterpolated into FUNWAVE, first in a 1000 m Cartesian grid and then in 2’, 30”, 7.5” spherical nested grids, to end with a 30 m Cartesian grid off of the coastal area of interest for inundation mapping (Fig. 9). For the PRT and AGCZ co-seismic cases, 2’, 30”, 7.5” nested spherical FUNWAVE grids are used for propagation from the source to, similarly, end with a 30 m nested Cartesian grid off of the coastal area of interest for inundation mapping (Fig. 9).

Similar simulations are currently being performed for the selected representative SMFs parameterized to reproduce the historical Currituck slide. In this case, the initial simulations use NHWAVE, in a 1000x1000 m, and then a 7.5” Cartesian FUNWAVE grid.

CVV simulations. Table 2 shows the size, location, sponge layer widths, and simulation time for each grid and Figs. 10a-c shows instantaneous surface elevations computed for a series of times. Note, while the 30” grid encompasses all of the upper East Coast, from the Carolinas, this particular 7.5” grid focuses on New Jersey, which includes Atlantic City, one of the locations of detailed tsunami inundation performed in this project, for which we have an accurate DEM. The initial surface elevation and velocity for the 2 arc-minute grid are obtained from THETIS' 3D results for a 450 km^3 volcano collapse, 20 min. after the flank collapse is triggered. Subsequent surface elevations and velocities are obtained by interpolating results from the preceding coarser resolution grid.

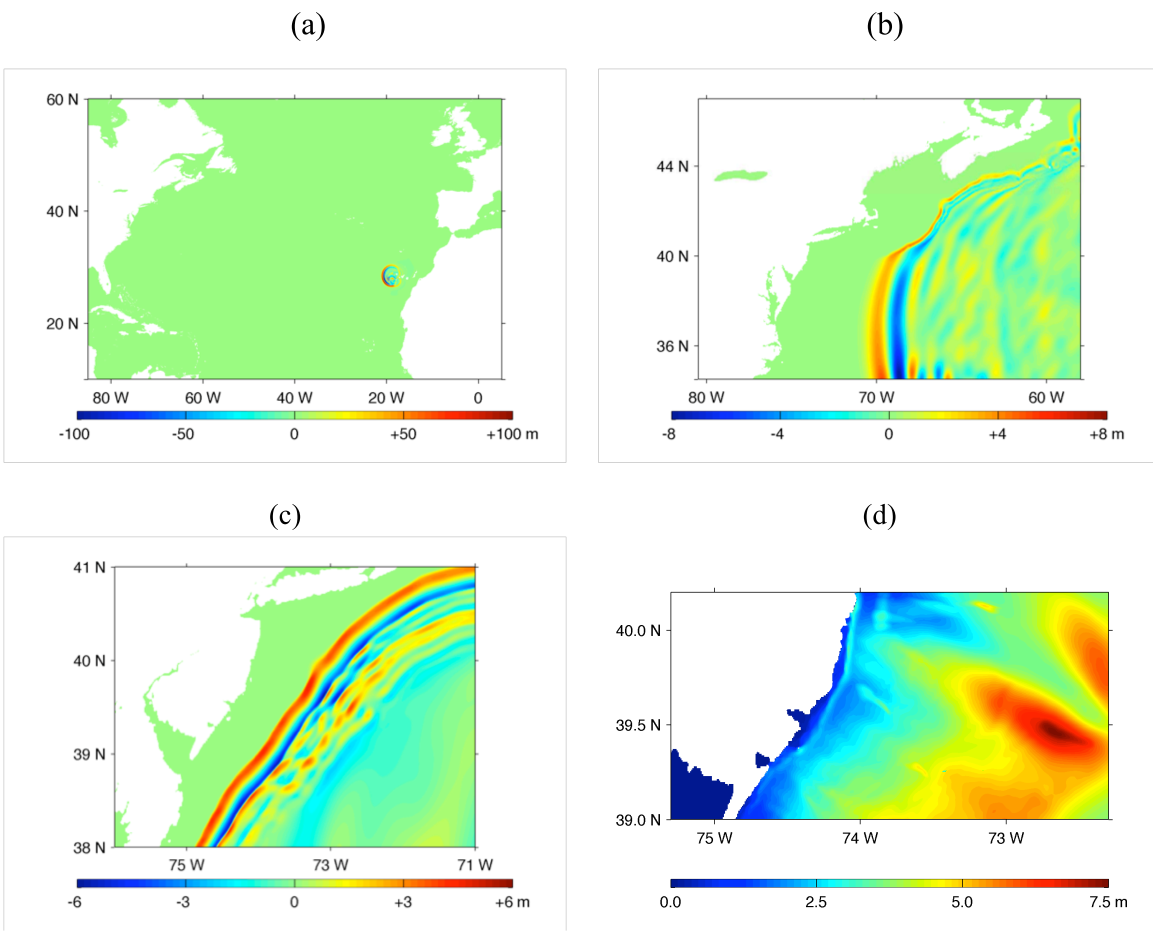


Fig. 10. (a) Initial wave elevation from Abadie et al. (2012) for a 450 km^3 CVV landslide, 20 min. after the flank collapse is initiated; (b) Initial wave elevation on 30" grid (from interpolated 2' ocean basin grid results), 6 hours and 40 min. after the flank collapse is initiated; (c) Initial wave elevation on 7.5" grid (from interpolated 30" grid results), 8 hours after the flank collapse is initiated; (d) Maximum wave elevation (of all grids) at 7.5" resolution (or about 220 m).

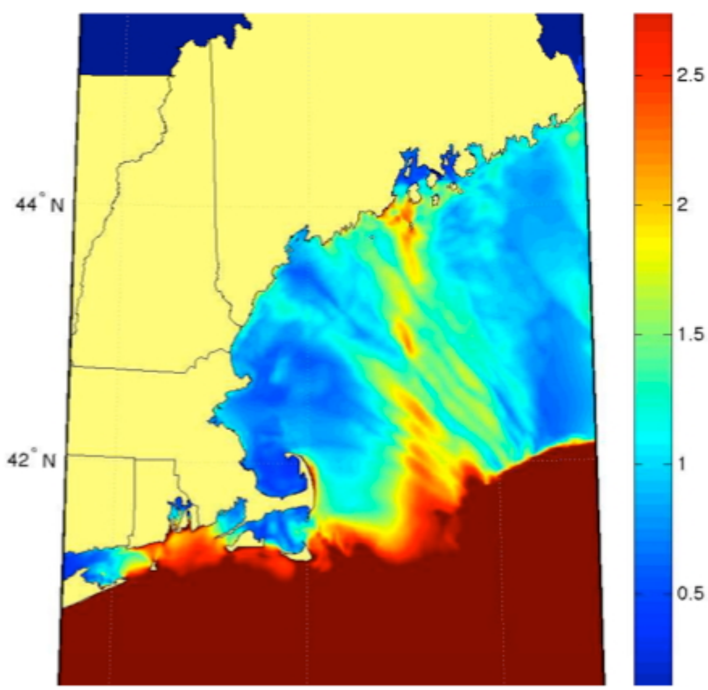
It is remarkable that while the maximum wave elevation in the finest grid offshore is around 7 m (Fig. 10d), indicating a wave height nearly double, near the shoreline the maximum elevation computed in the last but still fairly coarse resolution grid (about 220 m) is only about 1 m. While this large predicted decay/dissipation of incident tsunami waves may be affected by grid resolution, the 7.5" grid should certainly be fine enough to resolve such incident long wave trains propagating over the continental shelf. Other results of simulations in 30" grids, shown in Fig. 11, confirm these observations of intense dissipation of incident waves in our numerical simulations, whenever a wide shelf is present.

Hence, without further analysis, these results would suggest that coastlines such as the upper part of the USEC, with wide, shallow continental shelves are well-protected against the somewhat shorter wavelength long waves that are characteristics of landslide tsunamis, because of the intense breaking dissipation that occurs over the wide shelf. However, we know from observations of recent tsunamis that long incident waves also develop into undular bores made of much shorter waves during their propagation over the shelf and shorter waves in these bores will break and dissipate significantly before reaching the shoreline, but still pose a significant coastal hazard. Hence, the model grid (and equations for the dissipation) should accurately resolve these phenomena to properly model coastal tsunami impact, which may not be true in the 7.5" grid.

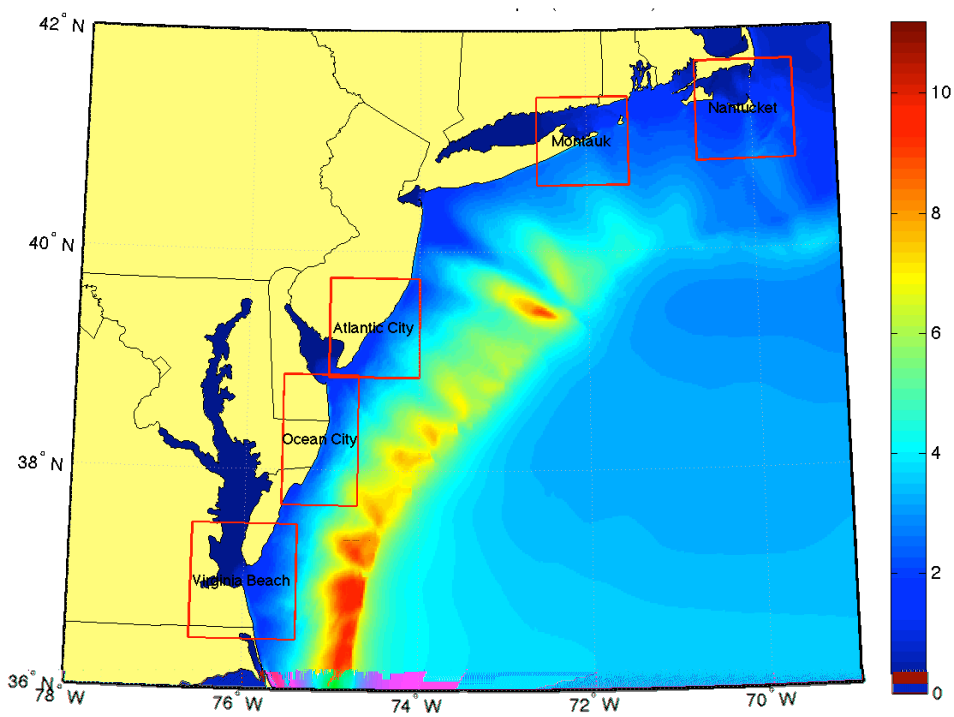
Table 2. Grid parameters for the CVV source.

Res.	Latitude	Longitude	Sponge (N/E/S/W)	Sim. time
2.0'	10.0° N – 60.0° N	85.0° W – 5.0° E	200 / 200 / 200 / 200 km	6h20m
30"	34.5° N – 47.0° N	80.5° W – 58.0° W	10 / 150 / 150 / 10 km	1h20m
7.5"	38.0° N – 41.0° N	76.0° W – 71.0° W	100 / 100 / 100 / 100 km	3h00m

(a)



(b)



(c)

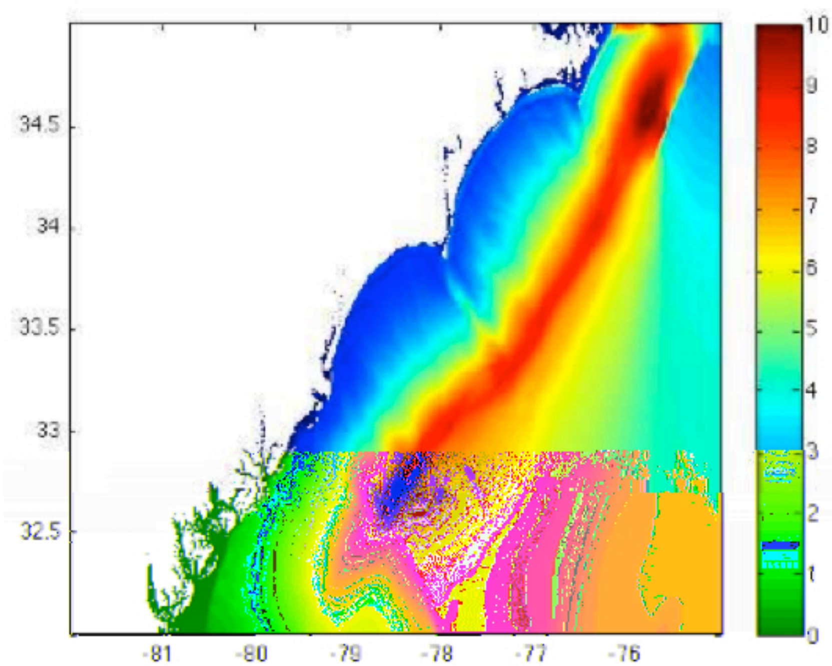
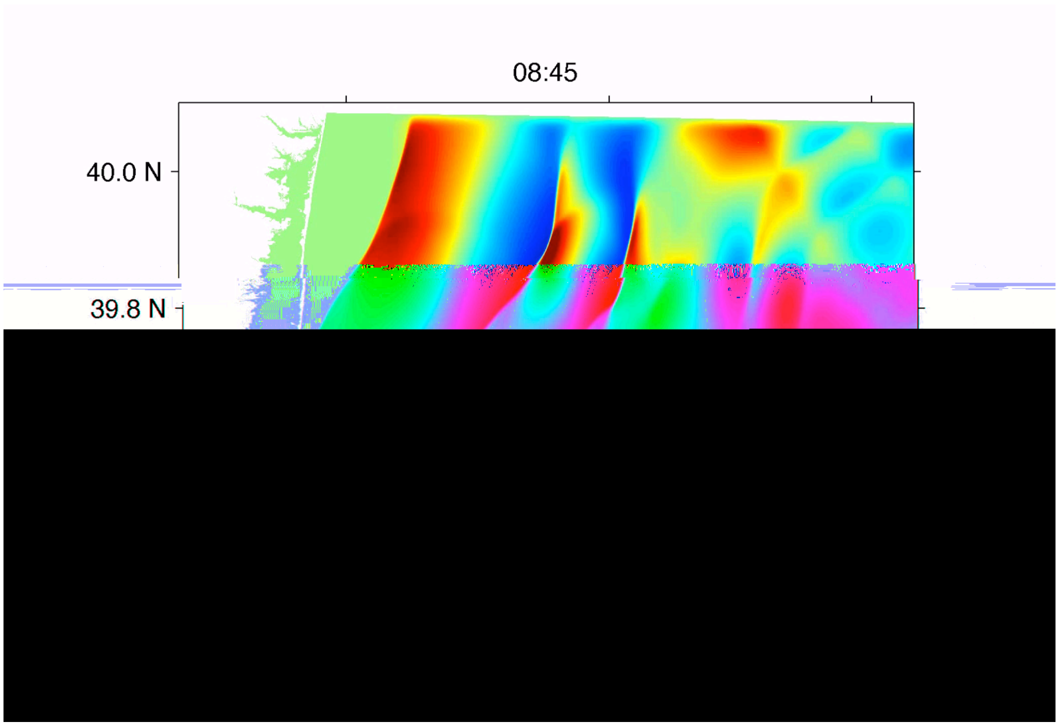


Fig. 11. Maximum envelope of wave elevation computed for a 450 km^3 CVV landslide, off of: (a) Maine, Massachusetts, and Rhode Island in 30" grid resolutions (or about 900 m); (b) Long Island (NY), New Jersey, Delaware and Virginia in 1' grid resolution; (c) North and South Carolina in 30" grid resolution.

(a)



(b)

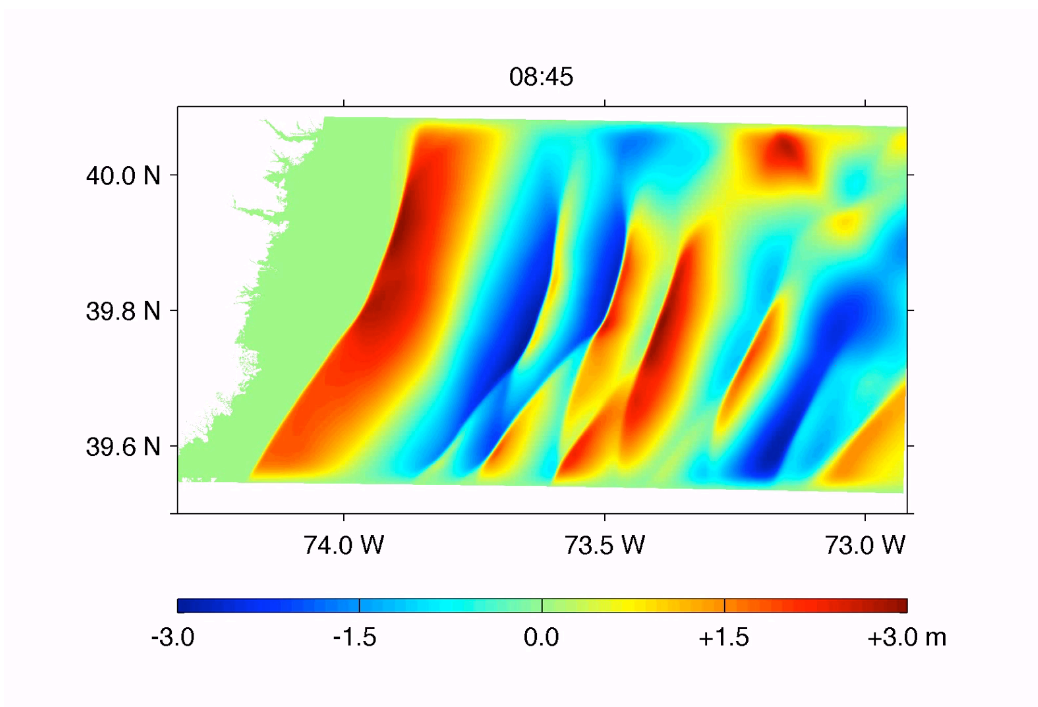
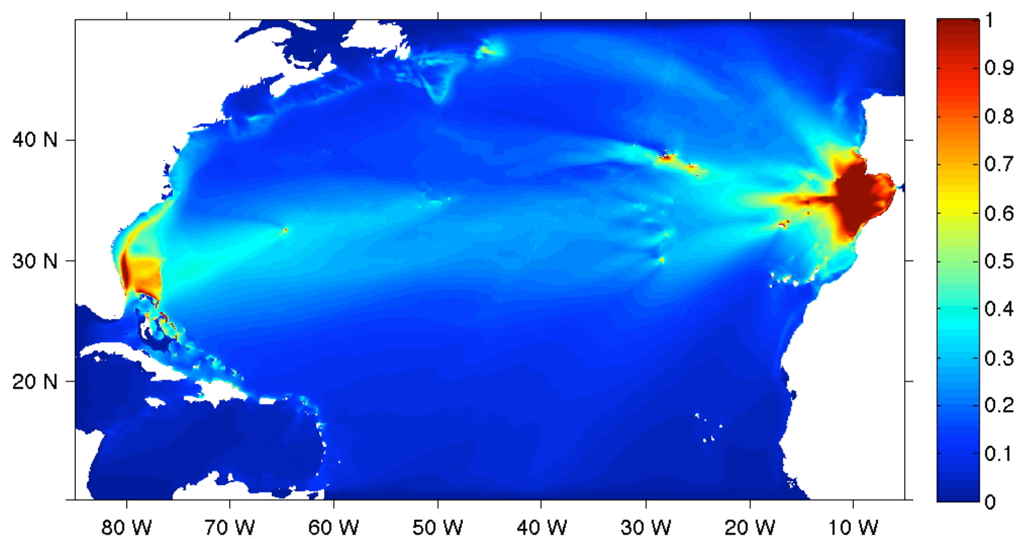


Fig. 12. Animation of computations for a 450 km^3 CVV landslide, in 30 m grid off of Atlantic City, NJ: (a) in the presence of a barrier island; (b) with the barrier leveled at 1 m above MWL to simulate erosion and breaching.

Therefore, because of the intense dissipation of incident waves seen here and since the exact dissipation rate of breaking bores may not be modeled accurately enough at the finest resolutions used here, we are presently performing sensitivity analyses of model results to grid size and other parameters before deciding whether the coastal hazard from an extreme CVV event is negligible (also see Grilli et al., 2012).

(a)



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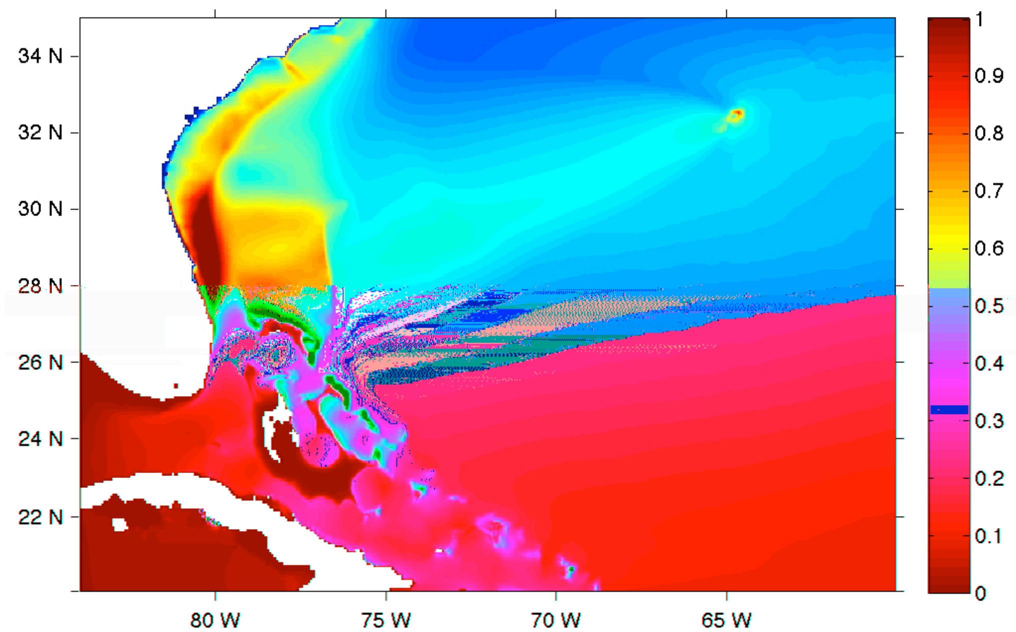


(c)

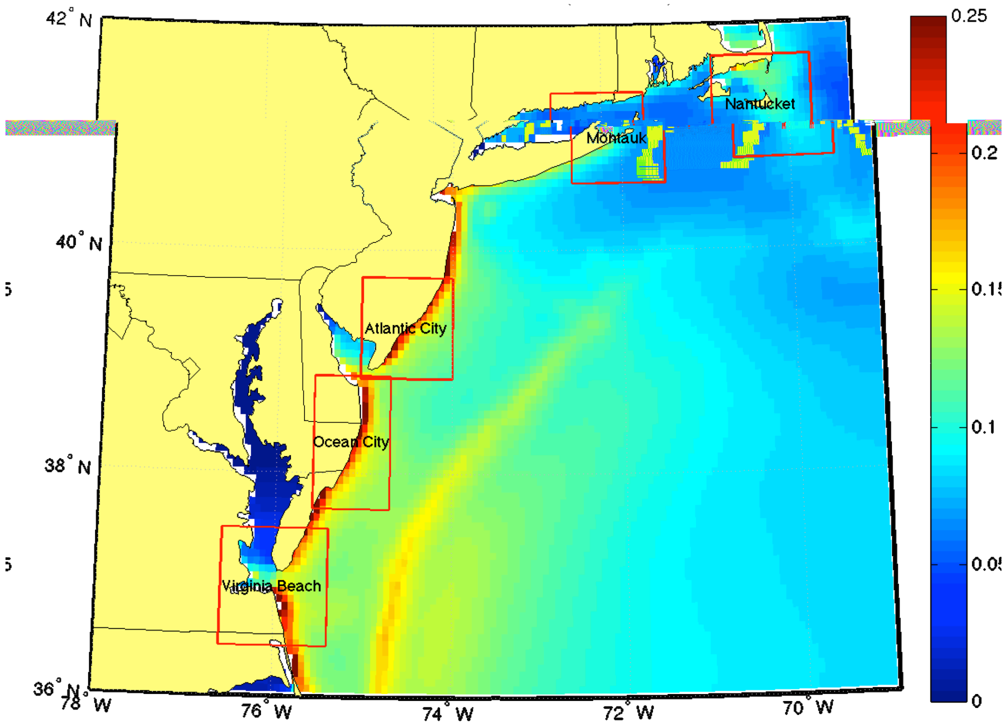


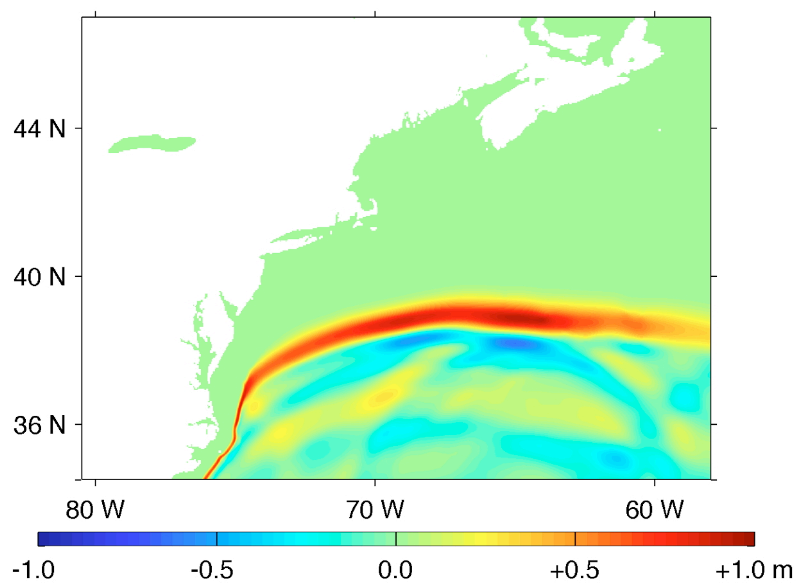
Fig. 13: Envelope of maximum surface elevation (in m) for AGCZ sources (see Fig. 2): (a) 35.144N and -10.055W source (lower source in Fig. 2) in 4' grid; (b) same source in 2' grid; (c) for all the AGCZ sources, in 2' grid.

This is illustrated in Fig. 12a, which shows further results of the CVV simulation computed in a 30 m grid centered near Atlantic City, in the form of an animation of model results. In addition to the large dissipation of incident waves over the shelf, the barrier island is seen to offer almost total protection of the nearshore lagoon against tsunami waves. As the barrier would be likely to be severely eroded and breached at multiple locations by the first few large tsunami waves, the same simulation is shown in Fig. 12b, with the barrier leveled at 1 m above mean water level. Clearly, tsunami impact is significantly increased in the latter case.

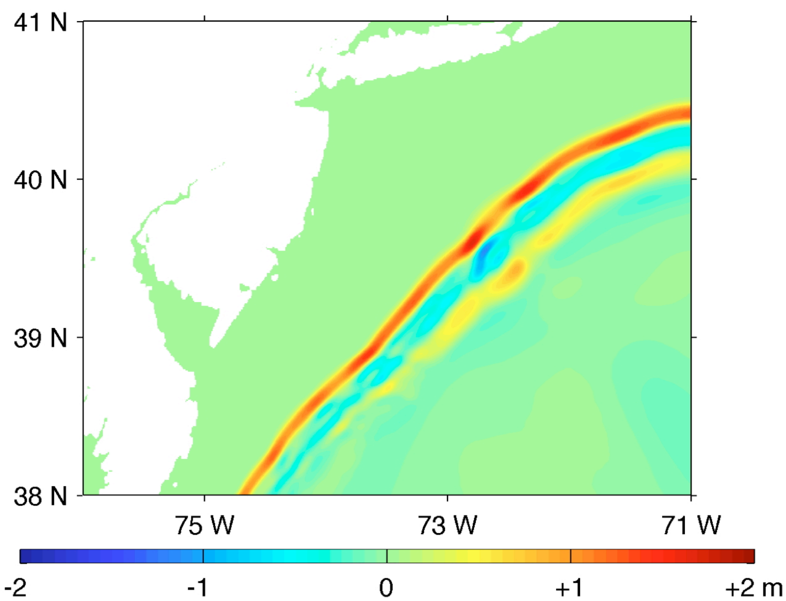
AGCZ simulations. Figs. 13a and 13b show envelopes of computed maximum surface elevations both in the Atlantic Ocean (4' grid) and along the USEC (2' grid), for an AGCZ source located at 35.144N and -10.055W (i.e., the lower red dot in Fig. 2), with a 270 deg. strike. The latter parameter influences source directivity and has been varied in simulations to maximize impact on various parts of the USEC. Here, we see a maximum impact on Florida and the Caribbean Islands, with over 1 m elevation waves offshore, while the upper USEC is much less impacted. While this is true in general, for all the AGCZ sources we tried (see Fig. 2), Fig. 13c shows the maximum impact obtained from all AGCZ sources along the upper USEC, yielding up to 0.25 m elevations offshore.

PRT simulations. Figs. 14a-c show instantaneous initial surface elevations specified in a series of nested grids, with 30", 7.5", and 30 m resolution (details about grid parameters are given in Table 3), based on the sources listed in Table 1 (Fig. 3) and 2' grid computations shown in Figs. 4. Note, while the 30" grid encompasses all of the upper East Coast, from the Carolinas, this particular selected 7.5" grid focuses on New Jersey, which includes Atlantic City, and the 30 m grid, is centered north of Atlantic City. As for CVV, the barrier island at this location has ben eroded down to 1m above sea level, to maximize tsunami impact. We see (Fig. 14c), in this case, that over 2 m elevation waves are predicted at 25-35 km offshore of the coast, in the 30 m grid.

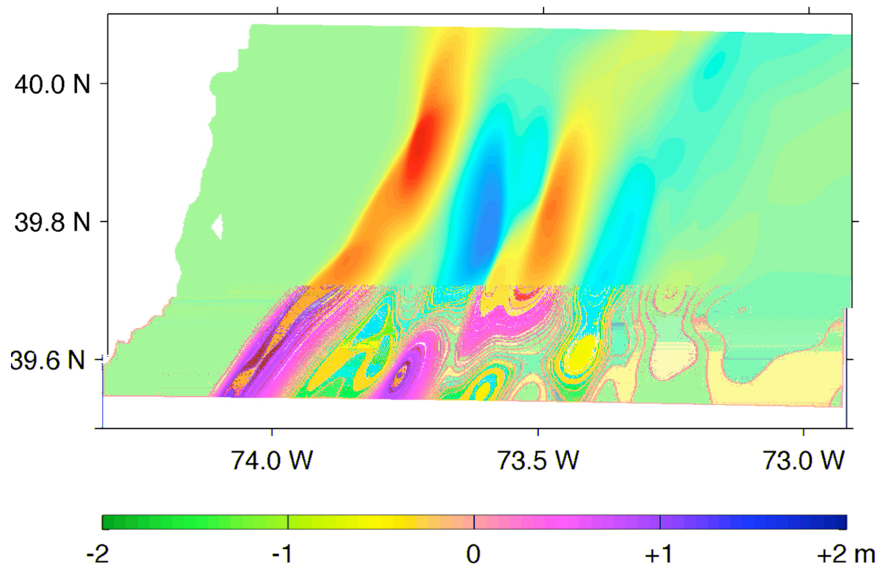
(a)



(b)



(c)



(d)

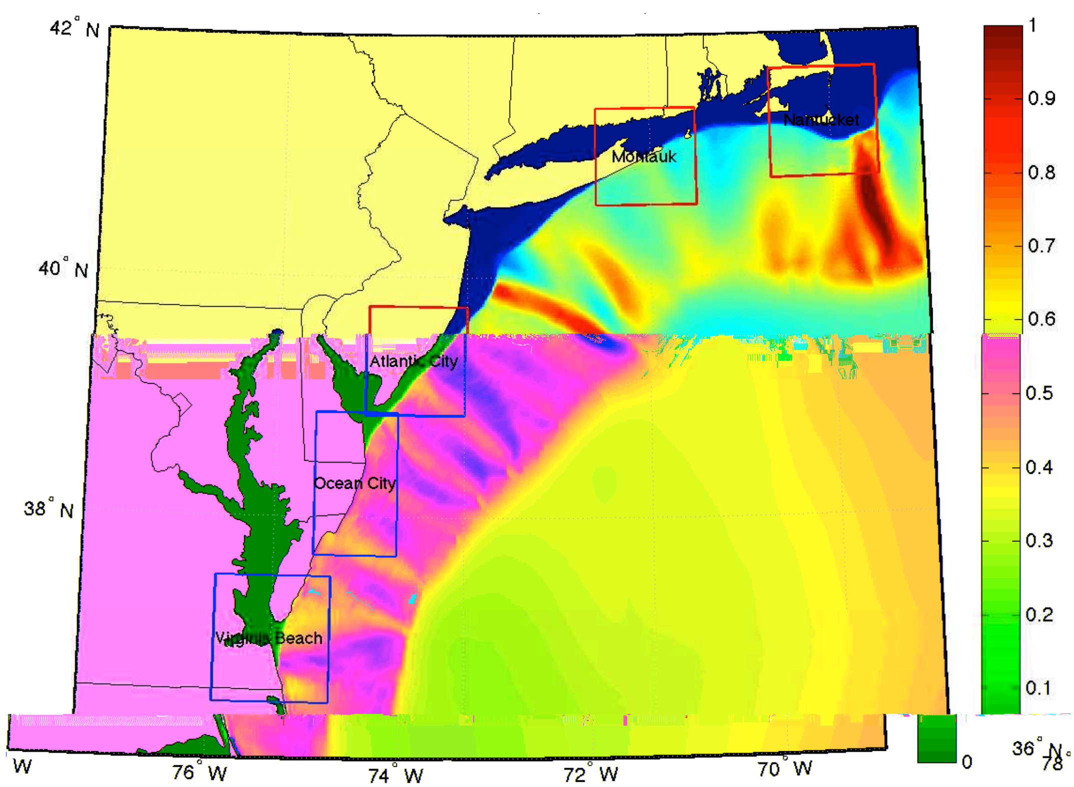


Fig. 14: Simulation results for the PRT sources of Figs. 3,4 and Table 1, in a series of nested grids: (a) Initial surface elevation in 30" grid (from interpolated 2' ocean basin grid results); (b) Initial surface elevation in 7.5" grid (from interpolated 30" grid results); and (c) Initial surface elevation in 30 m grid, North of Atlantic City – eroded barrier island (from interpolated 7.5" grid results); (d) Maximum surface elevation in 30" grid.

Finally Fig. 14 d shows the envelope of computed maximum tsunami elevation for the PRT source, in the 30” regional grid. These results indicate that tsunami impact from a M9 PRT source would be significant along the upper USEC wherever incident waves are large and/or bathymetric focusing due to refraction occurs. We see, this is the case off of Nantucket, MA, western Long Island, NY, northern NJ, the Atlantic City area etc…

Table 3 : Grid parameters for the PRT composite source of Figs. 3,4 and Table 1 (Fig. 14).

Resolution	Latitude	Longitude	Sponge (N)	Sponge (E)	Sponge (S)	Sponge (W)	Sim. Time
2’	10°N–50°N	85°W–55°E	100km	100km	100km	100km	2h40m
30”	34.5°N–47°N	80.5°W–58°W	200km	200km	200km	10km	0h40m
7.5”	38°N–41°N	76°W–71°W	100km	100km	100km	100km	1h05m
30m	39.5°N-40.1°N	74.32°W-72.92°W	5km	0km	0km	5km	2h00m

Table 4 : Grid parameters for “Currituck-like” SMF source located off of NJ. First grid is NHWAVE grid and next two grids are FUNWAVE grids.

Resolution	Latitude	Longitude	Sponge (N)	Sponge (E)	Sponge (S)	Sponge (W)	Sim. Time
500m	36.96°N–40.65°N	76.18°W–70.28°W	0km	0km	0km	0km	0h21m40s
7.5”	38°N–41°N	76°W–71°W	100km	100km	100km	100km	1h25
30m	39.5°N-40.1°N	74.32°W-72.92°W	5km	0km	0km	5km	2h00

SMF simulations. Although this part of the work is still ongoing, preliminary results are shown here, first for the actual Currituck simulation (Fig. 15), i.e., using both parameters and locations of the actual event. Then we show results obtained for a similar SMF (i.e., “Currituck-like”) located off of NJ (Fig. 16), in a series of nested grids at 500m, 7.5”, and 30 m resolution (with parameters detailed in Table 4). Note, the final 30 m grid is selected at the same location as the same resolution grids used for the CVV, and PRT co-seismic sources above, as this is one of the locations of detailed tsunami inundation performed in this project, for which we have an accurate DEM.

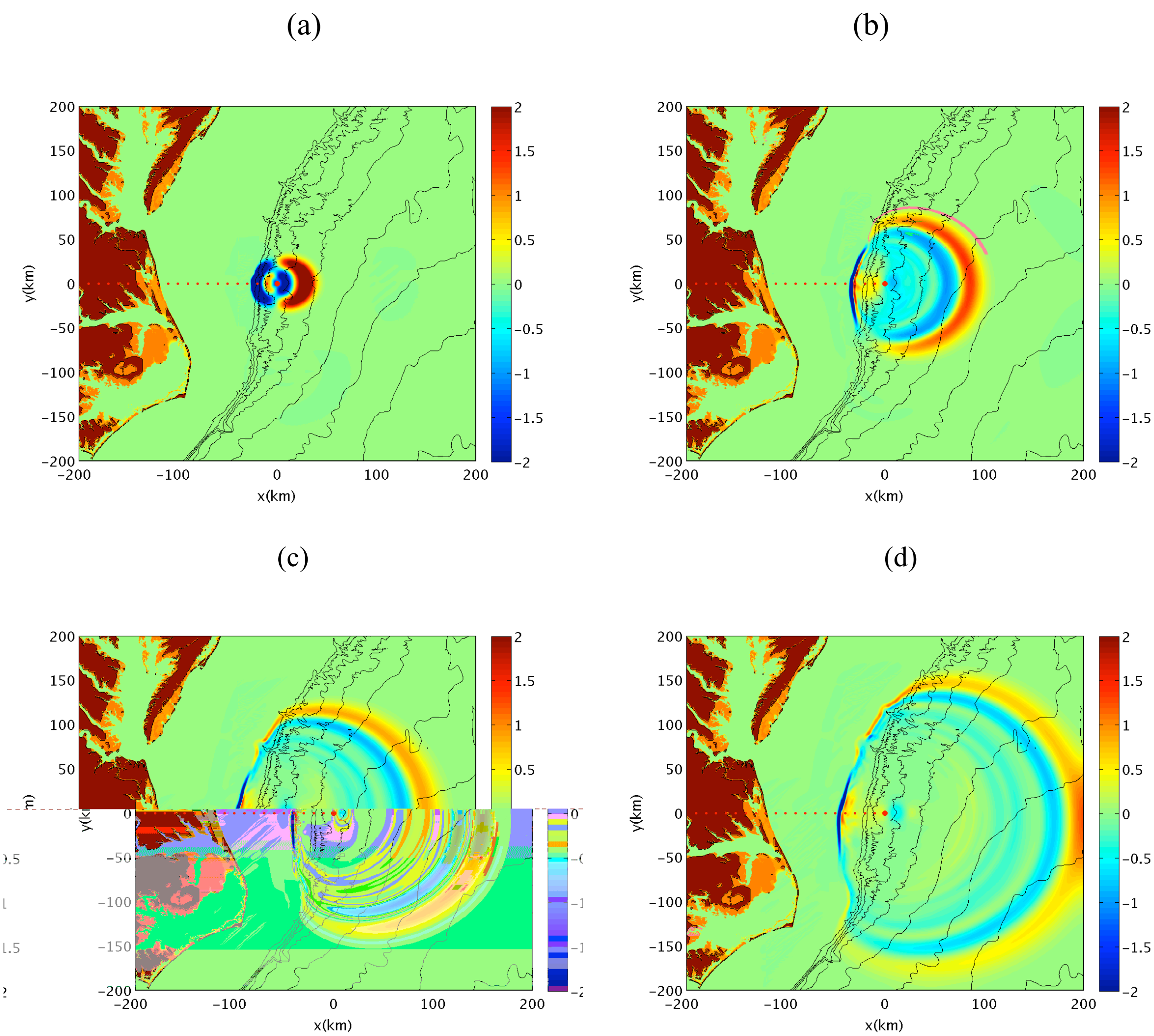
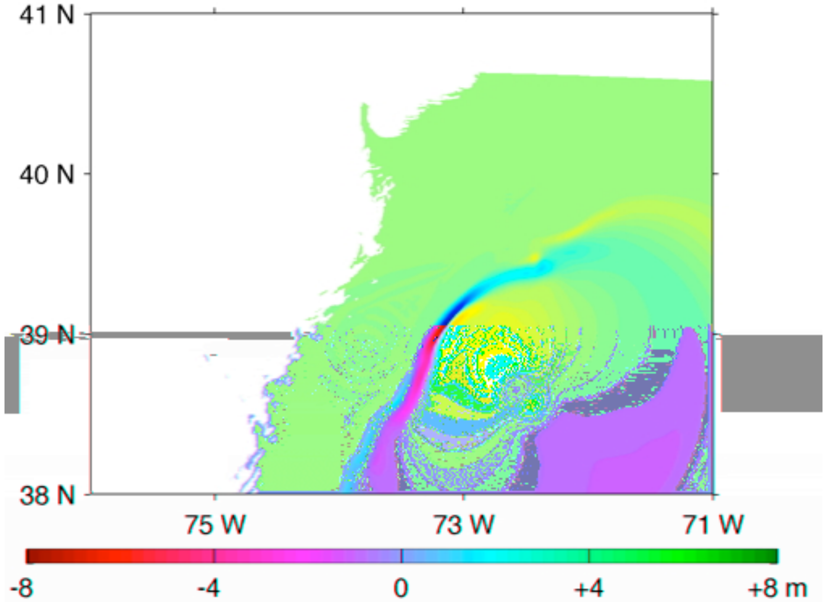


Fig. 15: Currituck SMF tsunami simulation in a 500 m NHWAVE grid. Surface elevation (meters) computed by at (a) 180s; (b) 540s; (c) 900s; (d) 1150s. The dashed red line indicates the location of a 1D transect used for subsequent high-resolution modeling in FUNWAVE-TVD (not shown here; see details in Grilli et al., 2012).

Fig. 15 shows that, as expected, the actual Currituck SMF source generates a typical highly dispersive (i.e, made of multiple and rather short long waves; hence justifying using a non-hydrostatic model such as NHWAVE for the generation part and the dispersive propagation model FUNWAVE later on for the coastal impact) and mostly bi-directional landslide tsunami, with narrow directional spreading and one wave train propagating towards a focused area of the coastline, and a far-field tsunami wave train propagating offshore in the opposite direction. While the far-field tsunami is expected to quickly decay in elevation, the onshore moving tsunami wave train will gradually develop in a series of undular bores with a number of large leading waves intensely breaking over a large part of the shelf and thus causing large dissipation (see Grilli et al., 2012 for details).

(a)



(b)

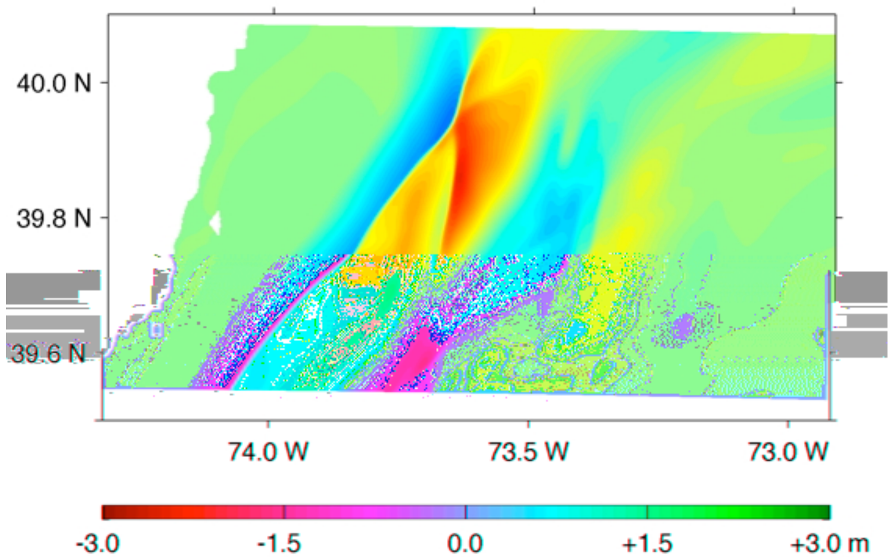


Fig. 16: Simulation of a SMF similar to Currituck, located off of New Jersey, in a series of nested grids (se Table 4): (a) Initial surface elevation specified in 7.5" grid (from NHWAVE 500 m interpolated grid results; note coastal topography is not accurately represented here); (b) Initial surface elevation in 30 m grid (from interpolated 7.5" grid results).

Here, we see in Fig. 16b that incident tsunami waves about 25 km off of the selected coastal area would reach over 3 m positive or negative elevation. Large amounts of dissipation, however, occur in this grid, which very much reduce tsunami hazard and impact. This is currently the object of more work and simulations using even finer grids (10 and 5 m).

TRANSITION TO HIGH RESOLUTION INUNDATION MODELING FOR MAPPING PURPOSES

The inundation efforts discussed above are designed to identify possible hot spots for detailed modeling. In the final stage of modeling for each site under consideration, simulations will be carried out down to a resolution of 10 m, equivalent to the resolution in NGDC tsunami DEMs. The DEMs for these modeling efforts are constructed from a combination of NGDC DEMs (where available) combined with previously tested and utilized DEMs developed for FEMA flooding and storm surge studies (also where available) together with high resolution DEMs developed by individual stakeholder agencies (state or county) (Figure 17). At present, we are utilizing DEMs which provide coverage for Myrtle Beach, SC, and for the continuous coastline from Ocean City, MD to Cape Cod, MA (Figure 18).

Modeling inundation down to a 10 m resolution requires a choice on where to shift the modeling effort from the spherical coordinate ocean scale propagation modeling to a local Cartesian coordinate system. This shift is needed because we wish to utilize the fully nonlinear framework of the Cartesian FUNWAVE model to handle the final stages of breaking and inundation. This choice of coordinates also fits better with the process of generating SMF sources using the NHWAVE model, which is only implemented in a Cartesian grid. Based on estimates of where this transition would be made in a manner that minimizes the transfer of nesting data from the ocean scale modeling (handled mainly by the URI group) to the local scale modeling (handled by the UD group), it has been decided to pass the data at a grid size with a scale of about 250 km in extend and at a spatial resolution of 125 m to 250 m. For a trans-oceanic co-seismic event, this transfer consists of time series of model variables at the locations of the nested grid boundary. The nested model would be driven by this boundary data in a one-way sense. For SMF sources, NHWAVE would be run for the nested grid region (assuming the source to be located in the same 250 km region as the target inundation area) in order to establish the initial flow field, and this would then be transferred to FUNWAVE as a hot-start on the 250 km grid. A further set of nestings would be performed to get down to the desired 10 m resolution, as illustrated in Figure 19. Typically, five levels of nesting are being used to get from the 250 km grid down to 10 m resolution at the shoreline. The 10 m grids will be oriented in E-N directions rather than coast-following directions in order to avoid problems of rotational mappings during the nesting process. This will require us to run several overlapping 10 m simulations within the region of each 250 km grid, and final inundation data will be taken from the central region of each 10 m grid segment.

INUNDATION MAPPING INPUT

Work is underway to construct inundation hazard maps for a set of sites including Ocean City, MD, Atlantic City, NJ, Myrtle Beach, SC and Long Island, NY (based on NGDC DEMs) and Northern New Jersey, New York Harbor and Western Long Island, and Rhode Island (based on FEMA DEM's). Figure 17 displays a mosaic of data for the northern part of this region, with inputs as described below.

1. NGDC tsunami DEM's at 1/3 arc second ((~10 meter) have been obtained and processed for Atlantic City, NJ, Ocean, City, MD, Montauk, NY, and Myrtle Beach, SC. These contain both gridded bathymetry and land topography data. Maps for Myrtle Beach, Atlantic City and Ocean City will be based mainly on these DEM's.

2. DEM data from FEMA R3, developed as part of their storm surge study, were obtained for the entire Region 3 study region. These are 1/3 arc-second (~10 meter) and contain both gridded bathymetry and land topography data.

3. DEM data from FEMA R2 were obtained (via Dewberry) for a large portion of the R2 region, from the southern coast of Delaware to the southern coast of Massachusetts. These are 10 meter resolution and contain primary gridded bathymetry data.

4. High resolution bare-earth land topography data, from recent lidar, were obtained (via Dewberry) for the coastlines of New Jersey and New York, including western Long Island. These have various resolutions at approximately 6 ft and 10 ft. These may need to be examined in light of post Sandy coastal damage as mapping efforts go forward.

5. High resolution bare-earth land topography data, from recent lidar, were obtained for the coastlines of Delaware and Maryland at approximately 2-3 meter resolution.

6. Additional high resolution (1-3 meter) bare-earth land topography data, from recent lidar, was obtained for coastal areas in New Jersey. Obtained from NJ Office of GIS.

7. We are in the process of obtaining high resolution bare-earth land topography data for Myrtle Beach, SC to augment and check the NGDC DEM.

A range of land use data has been obtained to assist in interpreting bare earth DEM's and to select friction coefficients for inundation studies.

1. Data were obtained from the National Land Cover Data (NLCD) for 2006. This data is consistent throughout the US and is gridded at 30 meter resolution.

2. High resolution landcover/landuse data (vector based) were obtained for the coastal areas of New Jersey, Delaware, and Maryland.

3. We are in the process of obtaining high resolution landcover/landuse data (vector based) for Myrtle Beach, SC and Montauk, NY.

Initial inundation calculations are now underway based on CVV and Puerto Rico events, together with landslide events based on the Currituck slide but displaced to appropriate alternate locations along the continental shelf boundary.

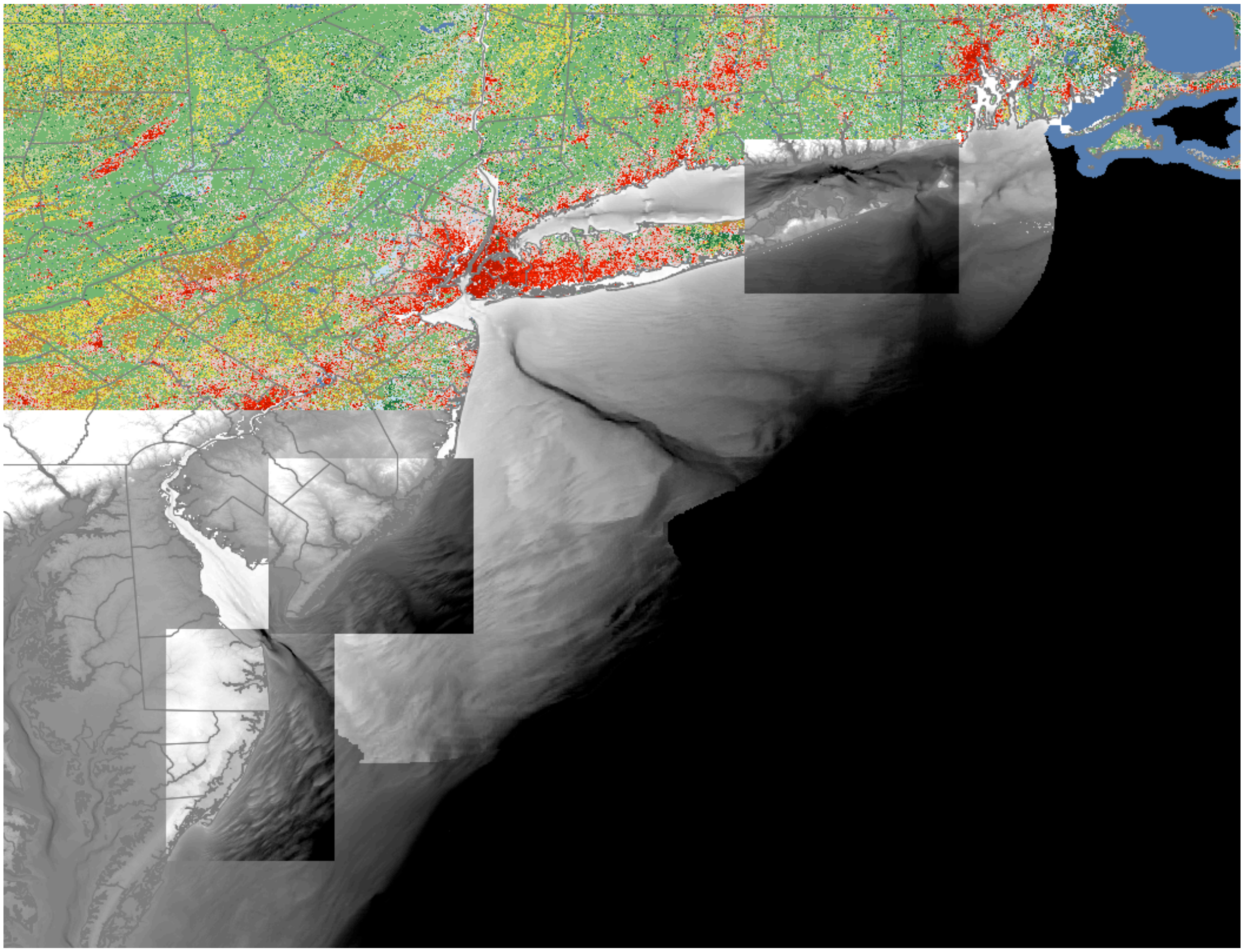


Figure 17: Mosaic of DEM and land use information based on NGDC tsunami DEM's, FEMA DEM's for Region 2 and Region 3 hurricane studies, and National Land Cover Data. Work covered by this project will provide maps for the Ocean City, Atlantic City and Montauk DEM's (smallest highlighted areas) and Myrtle Beach, SC using NGDC DEM's, and the remainder of the western half of Long Island using FEMA DEM's.

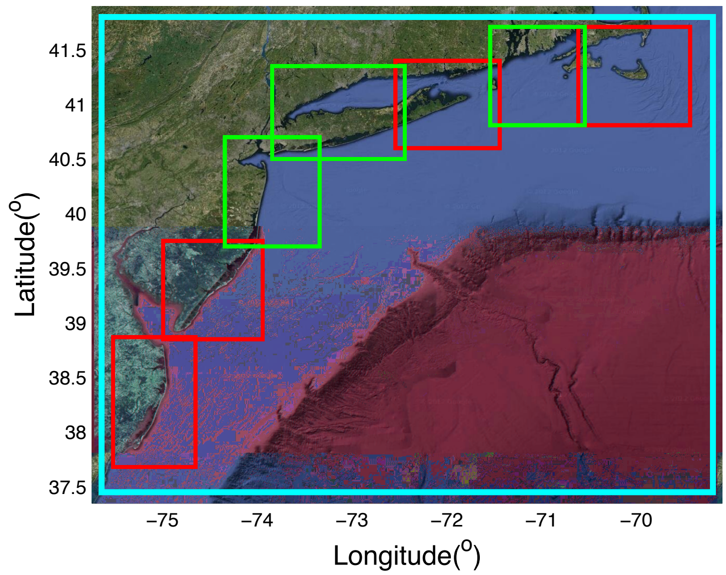


Figure 18: Sequence of DEM's being used for high resolution modeling in N.E. US. Red boxes indicate NGDC tsunami DEM's, including Ocean City, MD, Atlantic City, NJ, Montauk, NY and Martha's Vinyard, MA. Green boxes are similarly sized DEM's developed using FEMA DEM's, providing coverage of Northern New Jersey, New York and Narragansett Bay, Rhode Island.

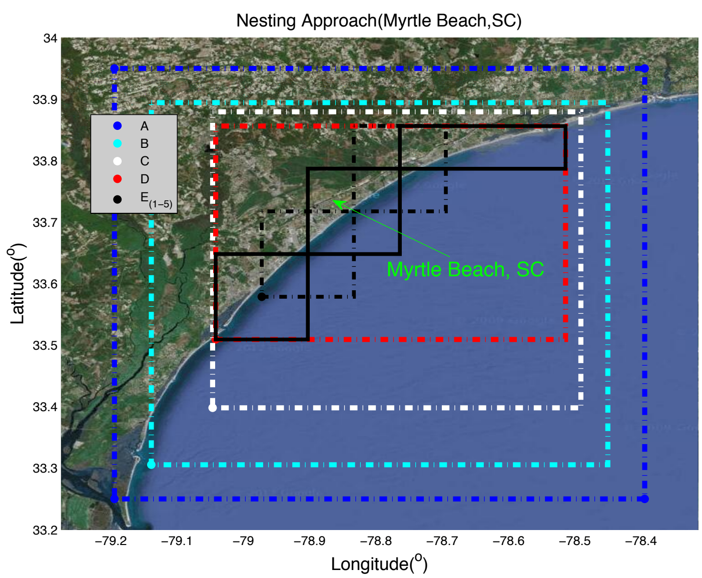


Figure 19: Sequence of nested grids within tsunami DEM's used to get final 10m resolution at inundated shoreline. Myrtle Beach, SC NGDC DEM.

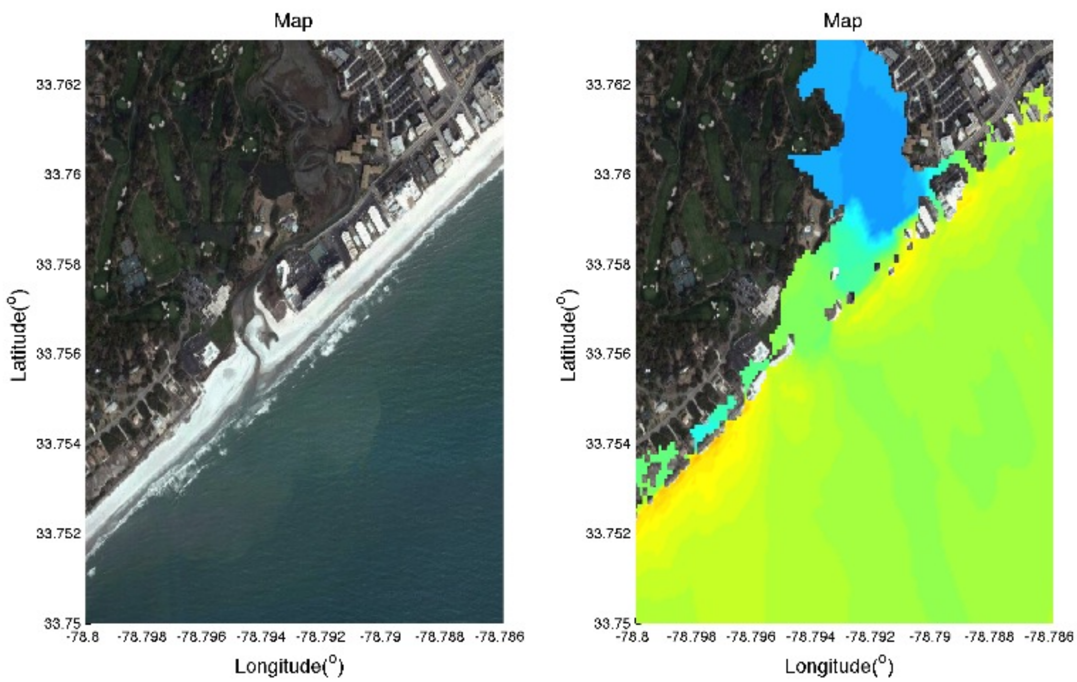


Figure 20: Google Earth view (left) and extent and maximum runup height of inundation (right) for a segment of Myrtle Beach, SC. (Event is for illustration and does not represent input to final tsunami inundation map).

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