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 (PR) 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 $M_w = 6$ to the maximum expected in the region $M_w = 7.5$); such tsunamigenic landslides can potentially cause concentrated coastal damage affecting specific communities (Fig. 1).

In this project, we assess tsunami hazard from the above and other relevant tsunami sources recently studied in the literature (ten Brink et al., 2007, 2008; MG special issue, 2009), and model the corresponding tsunami inundation in affected USEC communities. Based on our past experience with a variety of tsunami sources and case studies, we model tsunami propagation, inundation, and runup using the robust and well-validated Fully Nonlinear Boussinesq Model (FNBM) FUNWAVE (Wei et al., 1995; Kennedy et al., 2000; Chen et al., 2000) in its most recent TVD and parallelized (MPI) implementation (i.e., FUNWAVE-TVD; Shi et al., 2012).

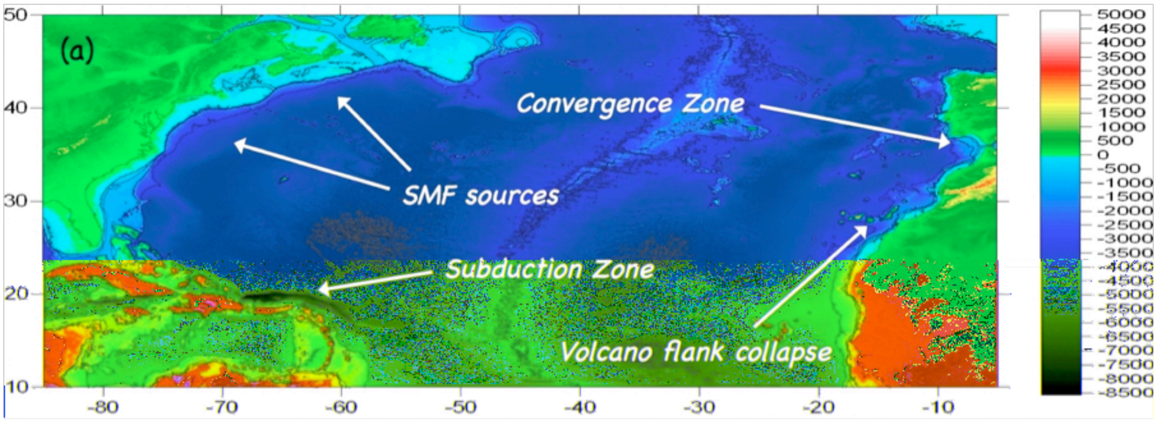


Fig. 1: Potential tsunami sources for U.S. East coast in the North Atlantic Ocean basin (ETOPO2's two second arc length ocean bathymetry is shown in the background).

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 1h 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., PR 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 eqs. 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. A more thorough document describing progress in the University of Rhode Island portion of the project is posted on the project web site. University of Delaware progress will be posted once inundation studies for initial sites are underway.

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)*

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), both posted on website.*

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 both MC results and on results of a new collaboration with the USGS Woods Hole group (who has done extensive field work on underwater landslide for the East Coast).*

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. Local GIS and mapping people are learning NTHMP guidelines, familiarizing themselves with previous efforts on West Coast and other Pacific regions. Inundation mapping for Ocean City, MD and Atlantic City, New Jersey will begin after analysis of MC landslide simulations. A study is ongoing to establish whether East Coast mapping should extend into coastal plane estuaries: preliminary results will be presented by Tehranirad et al (2012).*

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, 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.

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. 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., 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).

Fig. 3 similarly shows the location and size of 28 M 7.5 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).

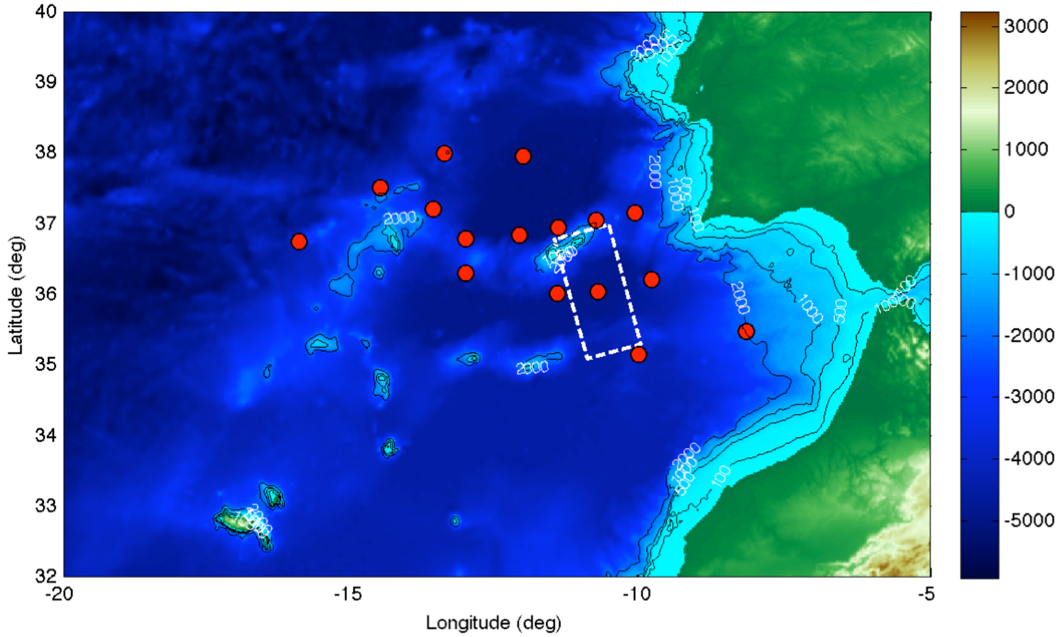


Fig. 2: Choice of potential AGCZ sources, identical to that of Barkan et al. (2009). Red dots refer to source centers; white rectangle refers to the size of the sources. These are M 8.5 sources, assuming a shear modulus of 4.2 10^{10} kg/m s^2, a slip of 13.1 m and a source area 200 km by 80 km

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 source made of three composite sources, for a total of 28 individual sources, as shown in Fig. 3. This composite source encompasses the entire Puerto Rico, Hispaniola, and Lesser Antilles segments. 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. In the model, these 28 sources are assumed to each have a M 8 magnitude (for a total M 9 magnitude) and are simultaneously run in the propagation model, to simulate the extreme tsunami hazard on the USEC from a M 9 source in the PRT.

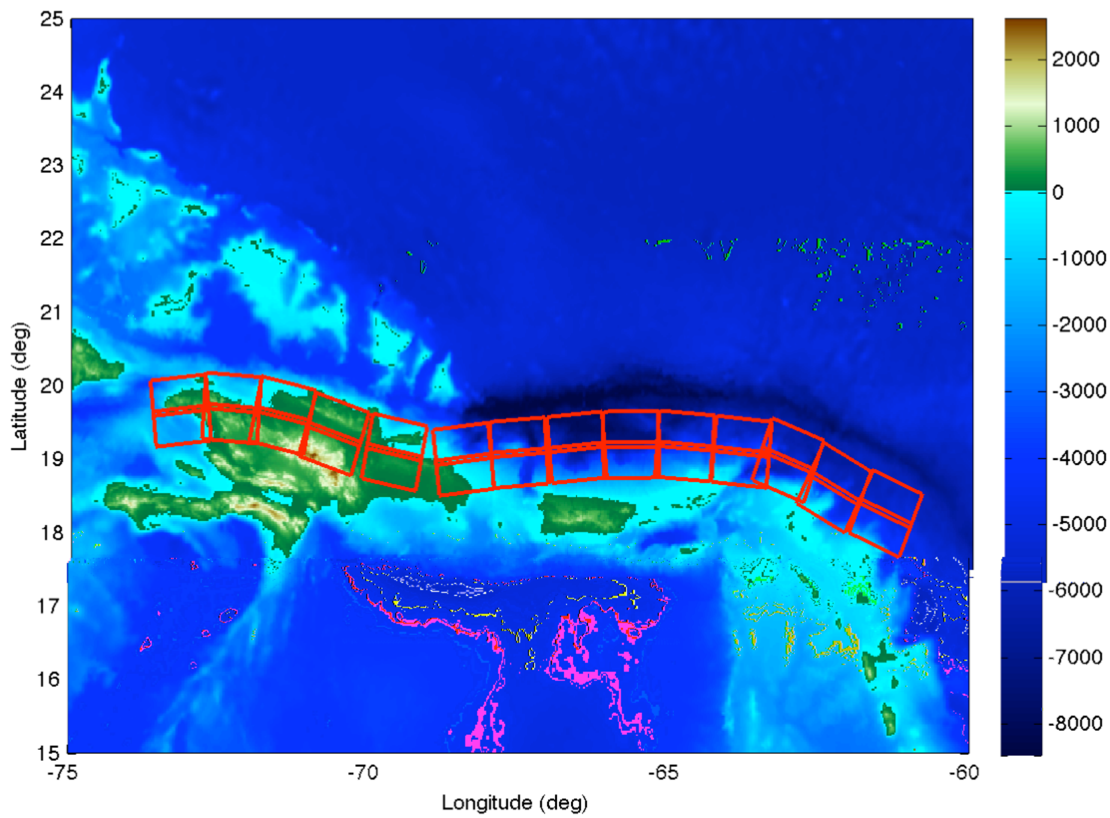


Fig. 3: SIFT sources (Gica et al. 2008) of interest in the CSZ. The 10 (5x2) sources on the left correspond roughly to the Hispaniola trench, the middle 12 (6x2) correspond to the Puerto Rico Trench (PRT), and the right 6 (3x2) sources correspond to a segment of the Lesser Antilles trench.

CVV flank collapse sources

The Cumbre Vieja Volcano (CVV) flank collapse (Fig. 4) 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. 4). 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. 5 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).

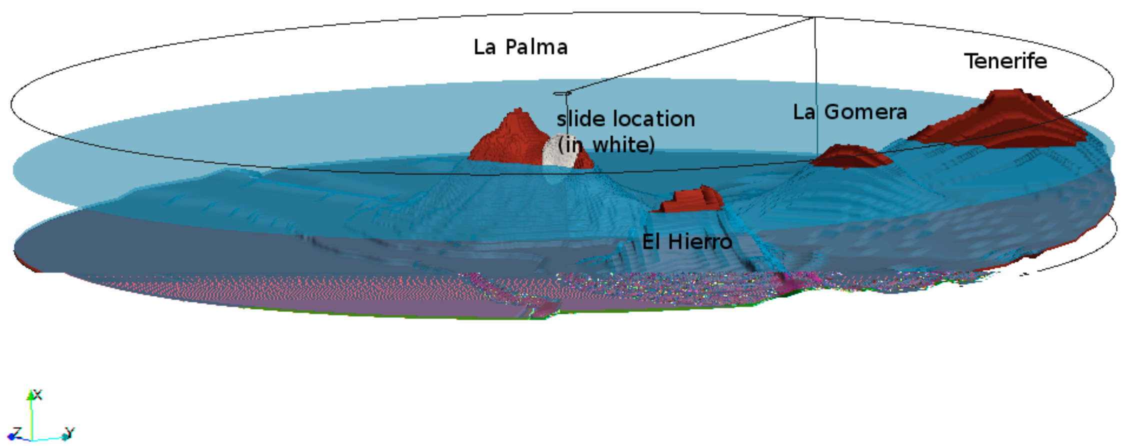


Fig. 4 : Sketch of cylindrical computational domain in THETIS model, for CVV flank collapse simulations, assuming a 80 km^3 subaerial slide case, with view of bottom bathymetry, neighboring islands, and slide location (marked in white) (Abadie et al., 2011, 2012).

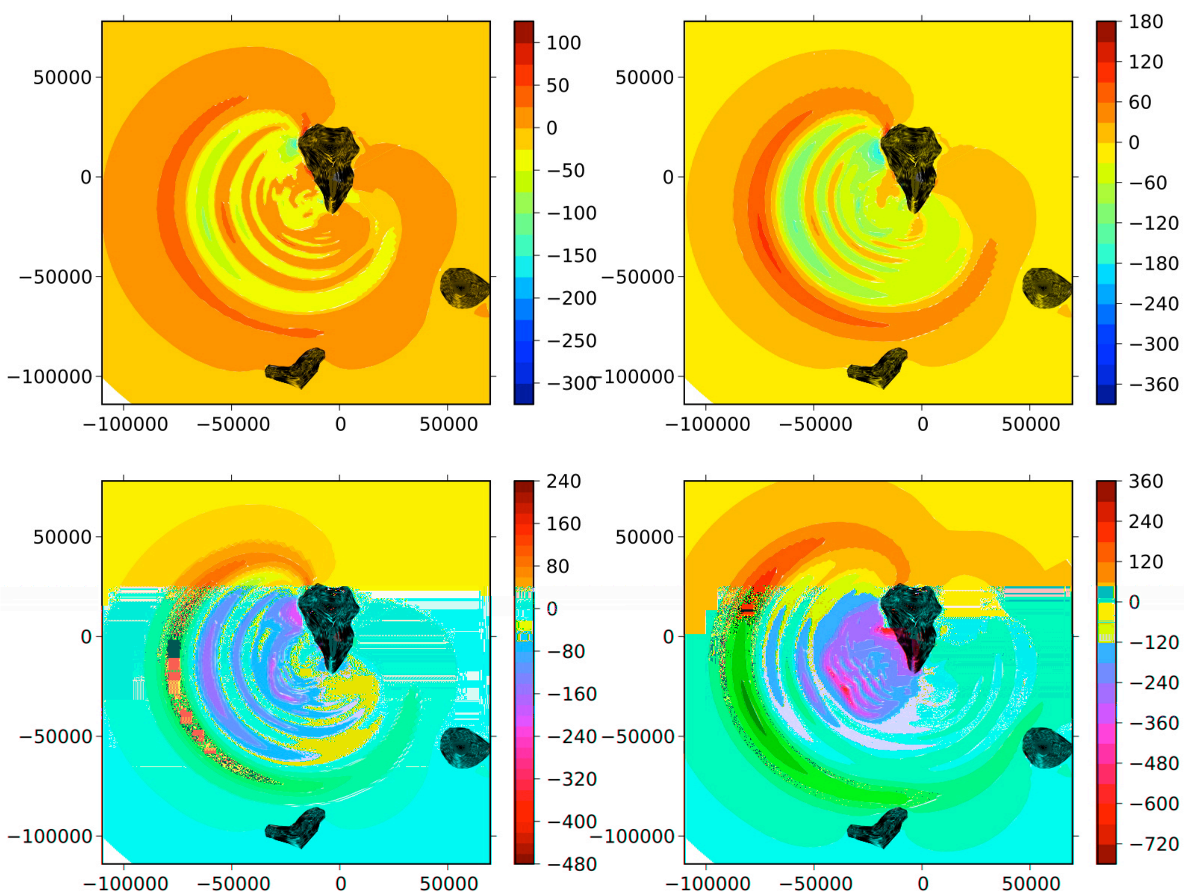


Fig. 5 : THETIS computations in geometry shown in Fig. 4. Computed free surface elevation at t = 450 s, for initial slide volume of: a) 20 km^3, b) 40 km^3, c) 80 km^3, d) 450 km^3. [Note the different color scales.]

SMF tsunami sources

Once selected along the USEC continental slope, the SMF tsunami sources are modeled according to the methodology reported in Watts et al. (2003, 2005), Grilli and Watts (2005), and 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. Unlike in earlier simulations (e.g., Day et al., 2005; Tappin et al., 2008), however, in the present work the initial tsunami wave elevations and velocities caused by each SMF are first computed in the non-hydrostatic multi-layer model NHWAVE (Ma et al., 2012); this model was validated for SMF tsunami generation based on Enet and Grilli's (2007) experiments. Once the majority of tsunami generation has occurred, the SMF source is then propagated in nested grids in the FNBM propagation model, as discussed before.

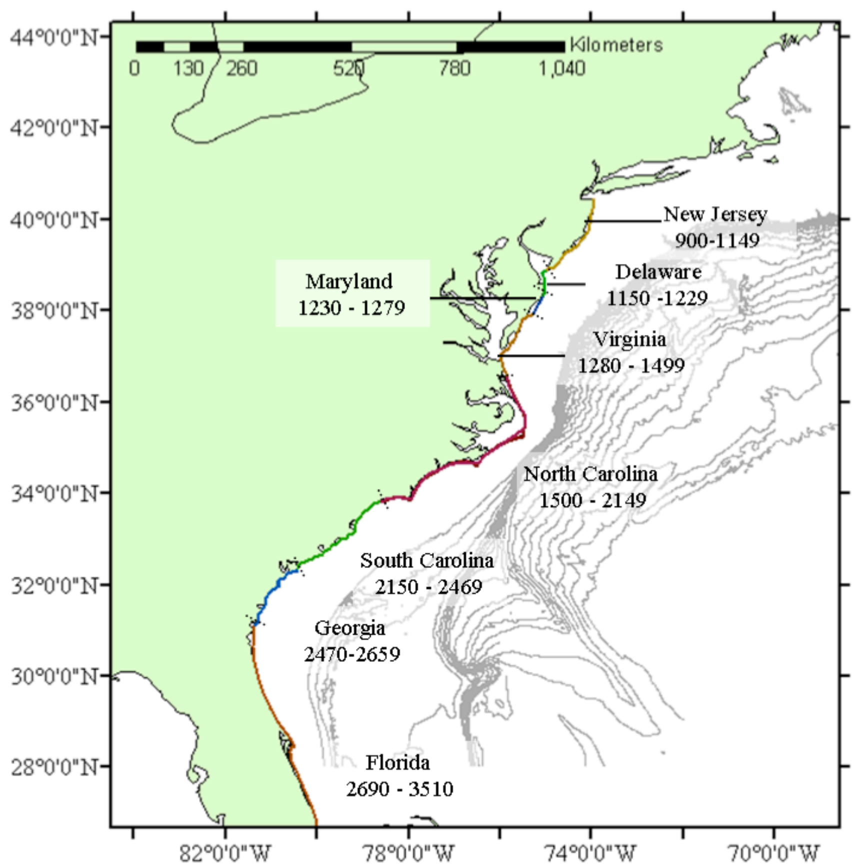


Fig. 6 : Simplified coastline with names of corresponding coastal states, ranges of indices of studied coastal points, numbered N-S (Baxter et al., 2011; Krauss, 2011). Note, coastal points 1-899 correspond to the upper East Coast already studied in Grilli et al. (2009).

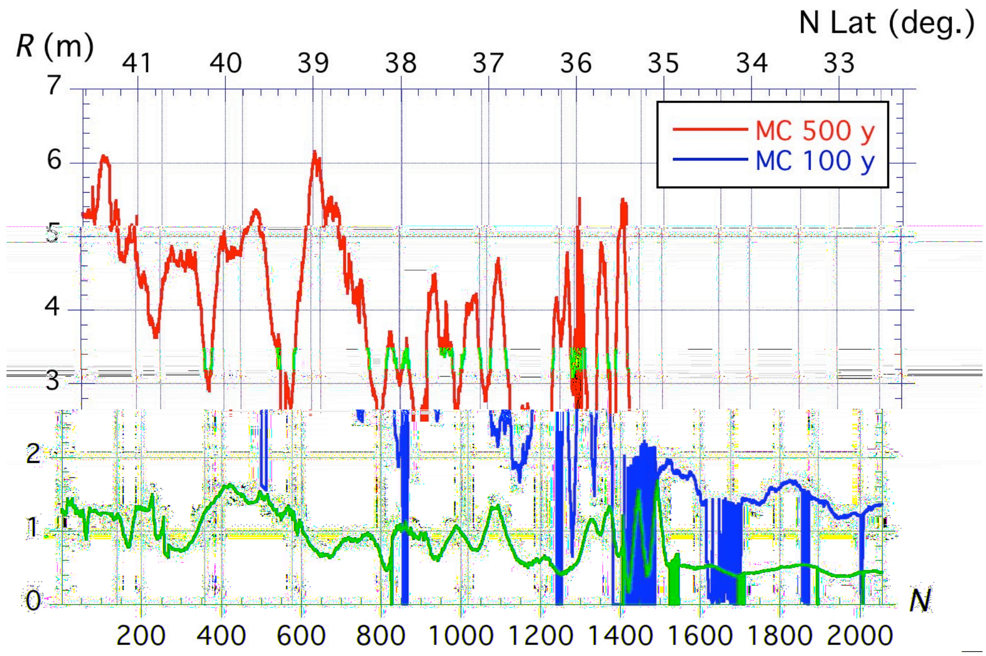


Fig. 7: Runup predicted by MC simulations of SMF tsunamis, for the USEC, for 100-yr. and 500-yr. runup events (Baxter et al., 2011; Krauss, 2011). The bottom x-axis is the index of studied coastal points, numbered N-S and the upper x-axis denotes the latitude (Fig. 6).

The locations and parameters of SMF sources (other than historical) were 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). This work followed and extended the methodology developed by Grilli et al. (2009), for coastal areas from New Jersey to Maine. Results of this analysis were presented in terms of 100 and 500 year runup from seismically induced tsunamigenic SMFs. In the MC model, 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).

In the MC analysis, the USEC is simplified and defined by 3510 "coastal points" (Fig. 6) where runups caused by SMFs are calculated. Fig. 7, for instance shows results of the MC analysis done in the present work for the USEC from Massachusetts down to North Carolina. As also found in Grilli et al. (2009), the 500 year runup shows an elevated hazard off of Nantucket, eastern Long Island, western Long Island (Hudson River canyon) and Atlantic City. We also see elevated hazard off of Virginia and in northern North Carolina. South of the NC Outer Banks SMF tsunami hazard appears to rapidly drop.

It should be stressed that runup values in this MC screening analysis (Fig. 7) should not be taken in absolute value, as these are based on many hypotheses. Only detailed tsunami simulations can provide accurate inundation and runup values for the regions identified to have an elevated risk. To do so, based on results of the MC 500 year runup analysis, parameters of representative SMFs are being selected in areas of the USEC deemed to have elevated SMF tsunami hazard. Fig. 8 shows an example of 500 year runup SMFs selected along some transects off of areas deemed at elevated risk.

For each identified SMF (such as in Fig. 8), detailed deterministic tsunami generation, propagation, and inundation modeling is being performed using NHWAVE and FUNWAVE-TVD, as discussed above; Fig. 12 shows an example of such simulations.

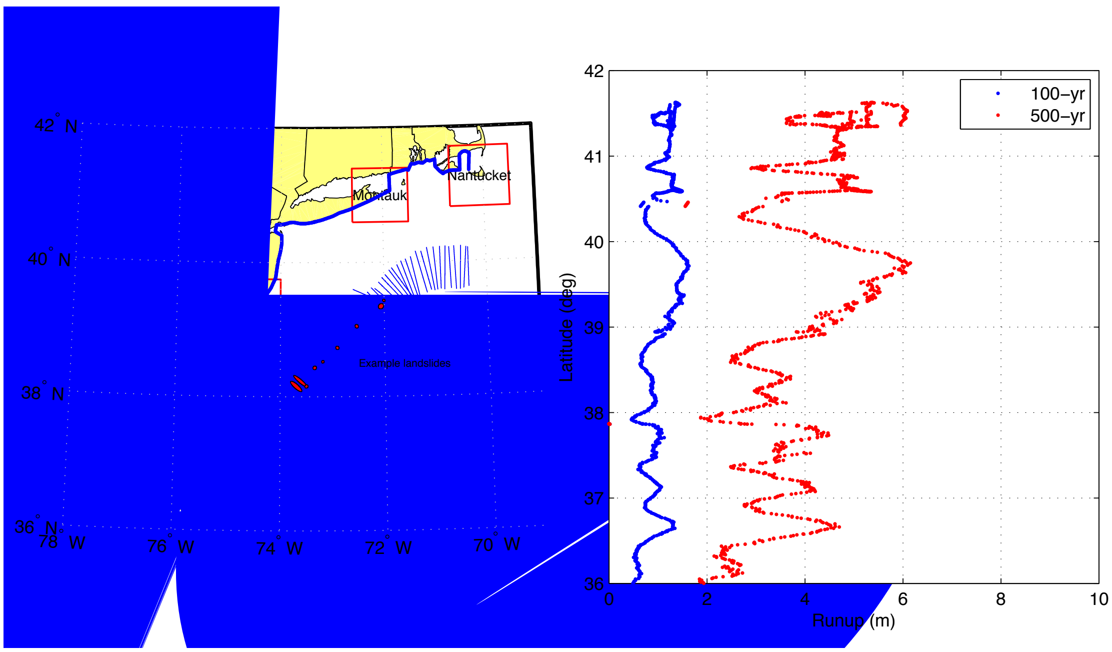


Fig. 8: Right panel: Northern part of runups shown in Fig. 7. Left panel: SMF transects (blue lines) used in MC analysis and location and size of underwater landslides causing 500 year runup (red ellipses). The solid blue line indicates the simplified coastline used in MC simulations and the red boxes mark the size and locations of DEMs currently available form NOAA-NGDC.

TSUNAMI PROPAGATION AND LOW RESOLUTION COASTAL INUNDATION MODELING

Simulations of tsunami propagations for the co-seismic and CVV sources discussed above were performed using FUNWAVE-TVD in a series of nested grids down to regional scale, along the USEC (1’ grid cells or so). Similar simulations are currently being performed for the selected representative 500 year runup SMFs.

Envelopes of computed maximum surface elevations near the USEC are shown in Fig. 9 for the ACZ sources, in Fig. 10 for the M 9 Puerto Rico Trench source, and in Fig. 11 for the 80 km^3 CVV source. Fig. 12 shows results of tsunami simulations for the first SMF source shown in Fig. 8 (bottom). In this simulation, the NHWAVE domain was 140 km^2, with a 10 km wide sponge layer on the south and east sides, and was run for 15 min. The FUNWAVE-TVD domain was 240 km^2, in order to include the shoreline, with the same sponge layer, and was run for an additional 2.5 hours. FUNWAVE was initialized with NHWAVE results after 15 mins and both domains had a 500 by 500 m horizontal grids. The instantaneous wave elevation shown in Fig. 12a was computer 75 min. after the slump started moving.

Once all the SMF sources will have been simulated, results of maximum surface elevations for all the source types affecting the USEC will be combined, in order to establish the relative degree of tsunami hazard for East Coast communities. Detailed inundation studies will then be conducted for the 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. As part of this project, 4 such detailed inundation simulation and mapping studies were budgeted (2 in FY11 and 2 in FY12). Based on preliminary hazard assessments and DEM availability, the following locations/DEMS (see Figs. 9-12) were selected: (i) Montauk, Long Island, NY; (ii) Atlantic City, NJ; (iii) Ocean City, MD; and (iv) Charleston, SC (which includes Myrtle beach).

Regarding these and other areas possibly having elevated tsunami hazard, the following observations can be drawn from Figs 7-11:

1. Nantucket, MA is mostly impacted by the PRT source and local landslide. There is a DEM for it, but it is not part of our list of currently funded areas.
2. Eastern Long Island (Montauk) is impacted by the PRT source and local landslides. There is a DEM for it, but it is not part of our list of currently funded areas.
3. Western Long Island is similarly impacted as 2., but we do not have a DEM for it and it is not on our list of currently funded areas.
4. Northern NJ from Stafford to Sandy Hook is similarly impacted as 2., but we do not have a DEM for it it is not on our list of funded areas.
5. Southern NJ from Stafford to Cape May is mostly impacted by local landslides. We have a DEM (Atlantic City) for it and it is part of our list of funded areas.
6. Eastern DELMARVA peninsula, down to Virginia beach is mostly impacted by CVV and local landslides. We have a DEM centered on Ocean City, which is part of our list of funded areas.
7. North Carolina is impacted by ACZ and CVV sources, and local landslides.
8. Further south, down to the Charleston, SC area, whose DEM includes Myrtle Beach and the northern part of Horry and Georgetown, the landslide risk goes down and risk is driven mostly by the CVV source. We will be doing the Charleston DEM as part of our funded work, but there will be parts not covered south and north of it where there is elevated tsunami risk as well.

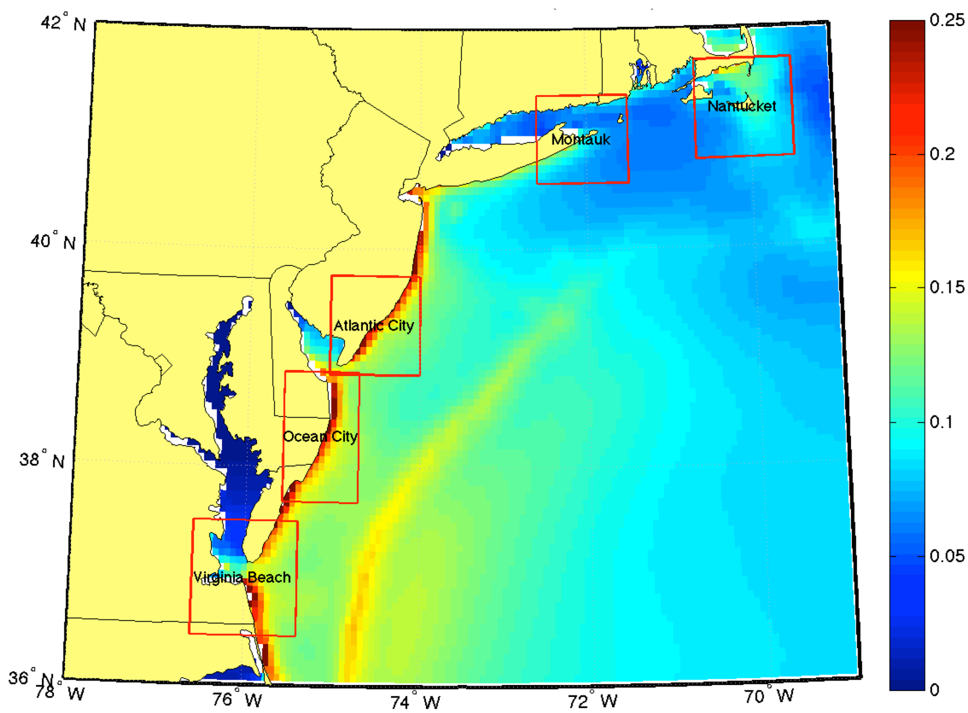


Fig. 9 : Maximum tsunami elevation in a 4' ocean grid, computed for the ACZ sources of Fig. 2.

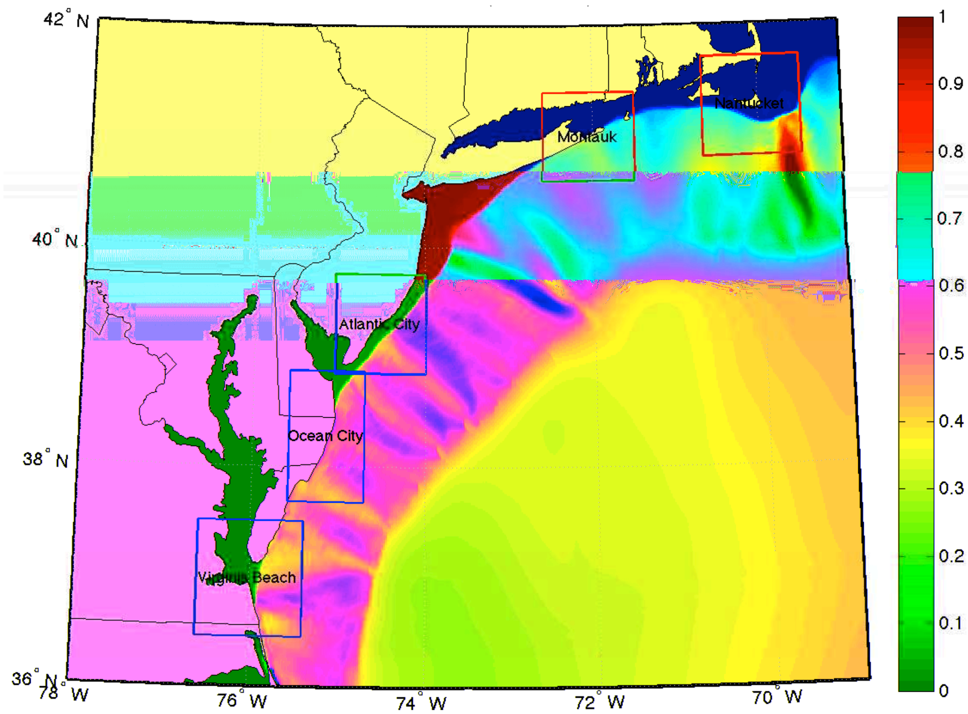


Fig. 10 : Maximum tsunami elevation in a 1’ regional grid, for the M 9.0 Puerto Rico Trench source.

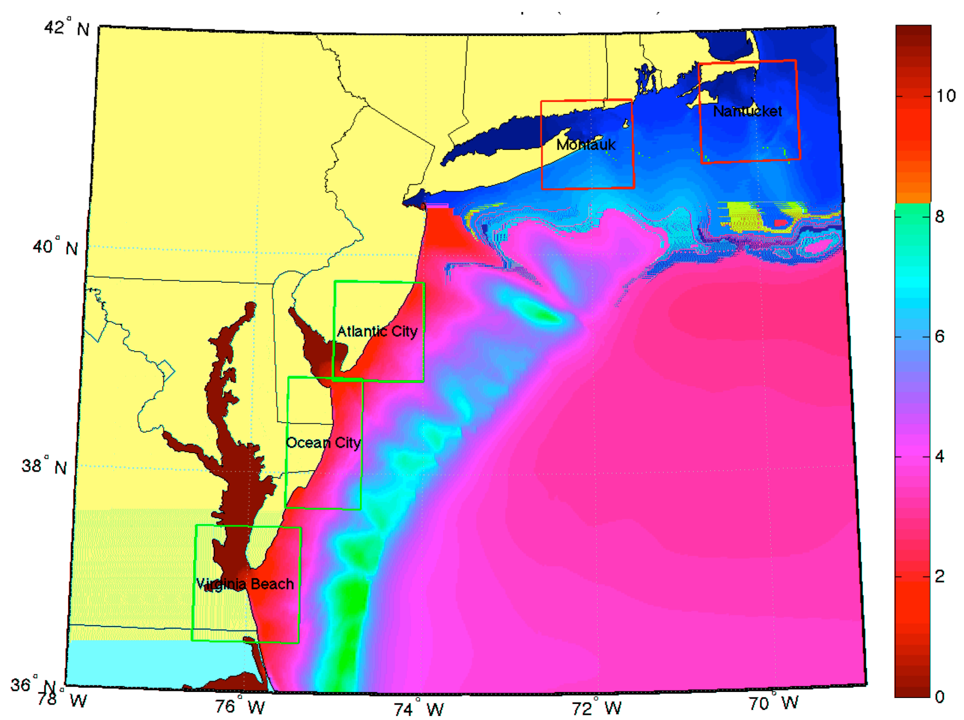
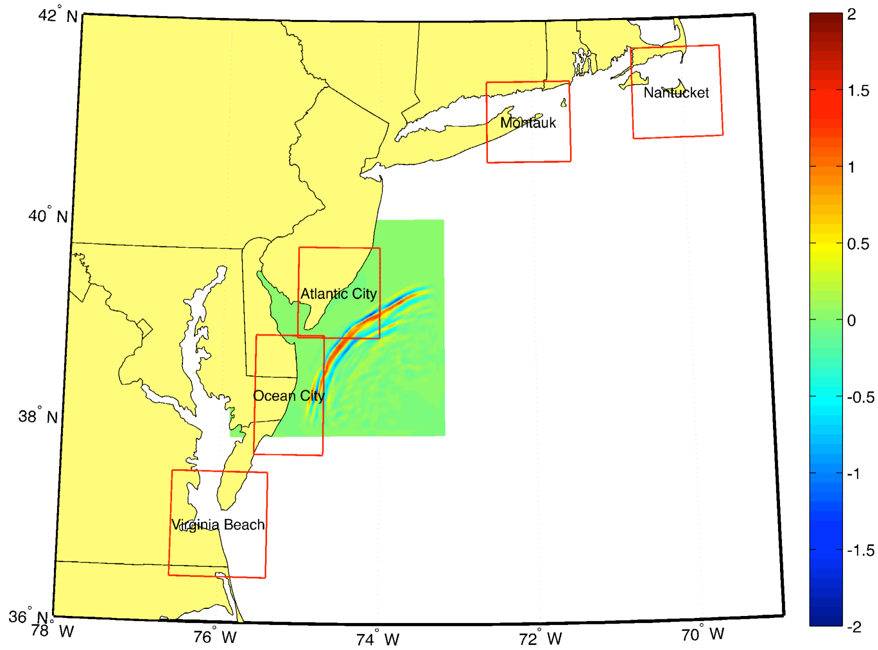


Fig. 11: Maximum tsunami elevation in a 1’ regional grid, for the CVV (80 km^3) source of Fig. 5c

(a)



(b)

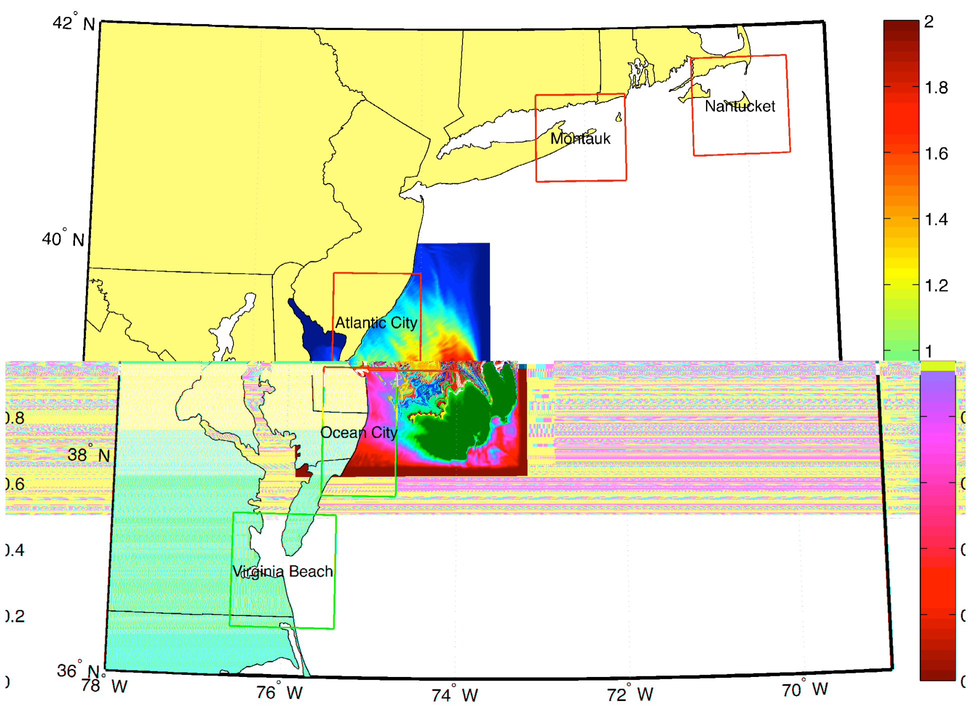


Fig. 12: Tsunami elevation computed with NHwave (up to 15 mins.) and FUNWAVE-TVD, in a 500 m regional grid, for the first SMF source shown in Fig. 8 (left; bottom source): (a) instantaneous elevation after 75 mins of propagation; (b) maximum envelope of elevation.

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