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 $M_w = 6$ 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), 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).

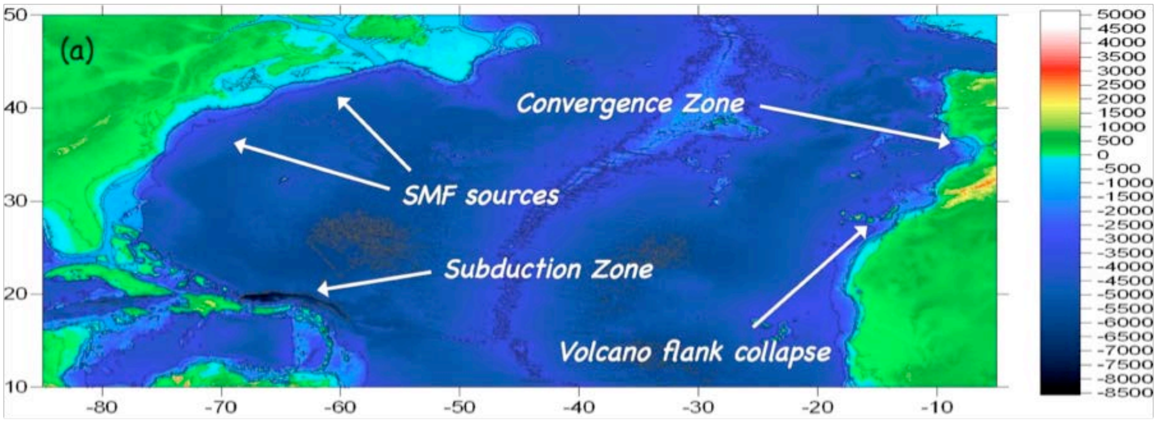

Fig. 1: Potential tsunami sources for U.S. East coast in the North Atlantic Ocean basin (ETOPO2's two second arc length ocean bathymetry is shown in the background).

Both Cartesian (Shi et al., 2012) and curvilinear grids (Kirby et al., 2013) 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. During this initial mapping effort for the East Coast, the last and final nested grid where detailed inundation is computed typically corresponds to 1" arc or about 30 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., 2013), 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 community cluster mills.hpc.udel.edu available at the University of Delaware (UD).

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., 2010) and other recent work reported in the literature.

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.

In the absence of an accepted methodology for performing probabilistic analysis of SMF hazards, we have adopted a strategy of using candidate slides corresponding in size to large historical events, but located at regions of the shelf which are judged to have an adequate sediment supply to support the occurrence of a large event.

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). In liu of a full probabilistic analysis, candidate events corresponding to probable maximum events are studies at regions of the shelf having large suspected deposits of material which could be mobilized by seismic activity.*

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*	*In the absence of an as-yet generally approved procedure for performing the probabilistic slide analysis, this work has been replaced by a deterministic approach involving a set of plausible events (tied to adequate local sediment supply) modeled on the historic Currituck event.*

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 5 shows an indication of the local 10m horizontal resolution being utilized in inundation studies.* *Draft inundation maps are now being prepared for the modeled regions. Maps are based primarily on the California map style as a template. (Figure 6).* *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 change in the procedure for performing landslide hazard analysis. The study is now based on a suite of four Currituck-like events positioned along the continental margin in locations with significant sediment storage.

More recently, an evaluation of the choice of East Coast sources (by the MMS subcommittee inAugust 2014) has led to a reduction in size of the Cumbre Vieja slide volume used for mapping purposes, from 450 km^3 to 80 km^3. This change affects all our draft reports and map products, and revisions to these documents are still underway.

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. The model has since been extended to cover the modeling of deformable landslides (Ma et al., 2013), which could serve as the basis for future NTHMP work. Benchmark testing for NHWAVE is described in Tehranirad 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).

Work on SMF modeling using NHWAVE has led to model extensions including a treatment of the slide as a multiphase suspended sediment load (Ma et al., 2013) and, more recently, treatment of the slide as a discrete, depth-integrated layer moving below a clear water layer (Ma et al, 2014). NHWAVE played a fundamental role in the analysis of potential landslide effects during the 2011 Tohoku-oki tsunami event (Tappin et al, 2014)

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. At present, inundation lines have been constructed at 30m resolution for the entire coastline from Chincoteague, VA to Cape Cod, MA, with more highly-populated regions having modeling done at 10m resolution. 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. Reports describing source simulations have been posted on the NTHMP website. Reports describing inundation results and associated map products are under development and will be posted publically after local stakeholders are allowed a preview period.

TSUNAMI SOURCE SELECTION, TSUNAMI PROPAGATION AND LOW RESOLUTION COASTAL INUNDATION MODELING

Tsunami source selection and low resolution simulation for East Coast inundation mapping are now described in a series of reports (Grilli et al, 2013; Grilli and Grilli 2013a,b,c) which are available on the project web site http://chinacat.coastal.udel.edu/nthmp.html.

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 to 30 m. 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 2). 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 3).

Modeling inundation down to high coastal resolution requires a choice of 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 is 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 is performed to get down to the desired final resolution, as illustrated in Figure 4. Typically, five levels of nesting are being used to get from the 250 km grid down to 10 m resolution at the shoreline. The nested grids are oriented in E-N directions rather than coast-following directions in order to avoid problems of rotational mappings during the nesting process.

INUNDATION MAPPING INPUT

Work is underway to construct inundation hazard maps for a set of sites within the extent of coastline ranging from the MD/VA border to Cape Cod, including Ocean City, MD, Atlantic City, NJ 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 2 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.

INUNDATION LINE DEVELOPMENT

Inundation calculations are underway based on CVV, Puerto Rico and Azores events, together with landslide events based on the Currituck slide but displaced to appropriate alternate locations along the continental shelf boundary. A sample of inundation lines for a portion of Ocean City, MD are shown in Figure 5. Information on model inputs and configuration as well as a guide to ArcGIS-based inundation line layers will be provided for each of the DEM regions indicated in Figure 3. Draft inundation maps (based primarily on the California map layout as a template) are under development for modeled areas. The draft map for Ocean City, MD, with an inundation line based entirely on the CVV volcanic cone collapse with a volume of failed material of 450 km^3, is included as Figure 6. Map products and inundation reports are presently being revised to reflect a change in the estimate of the CVV slide volume to 80 km^3.

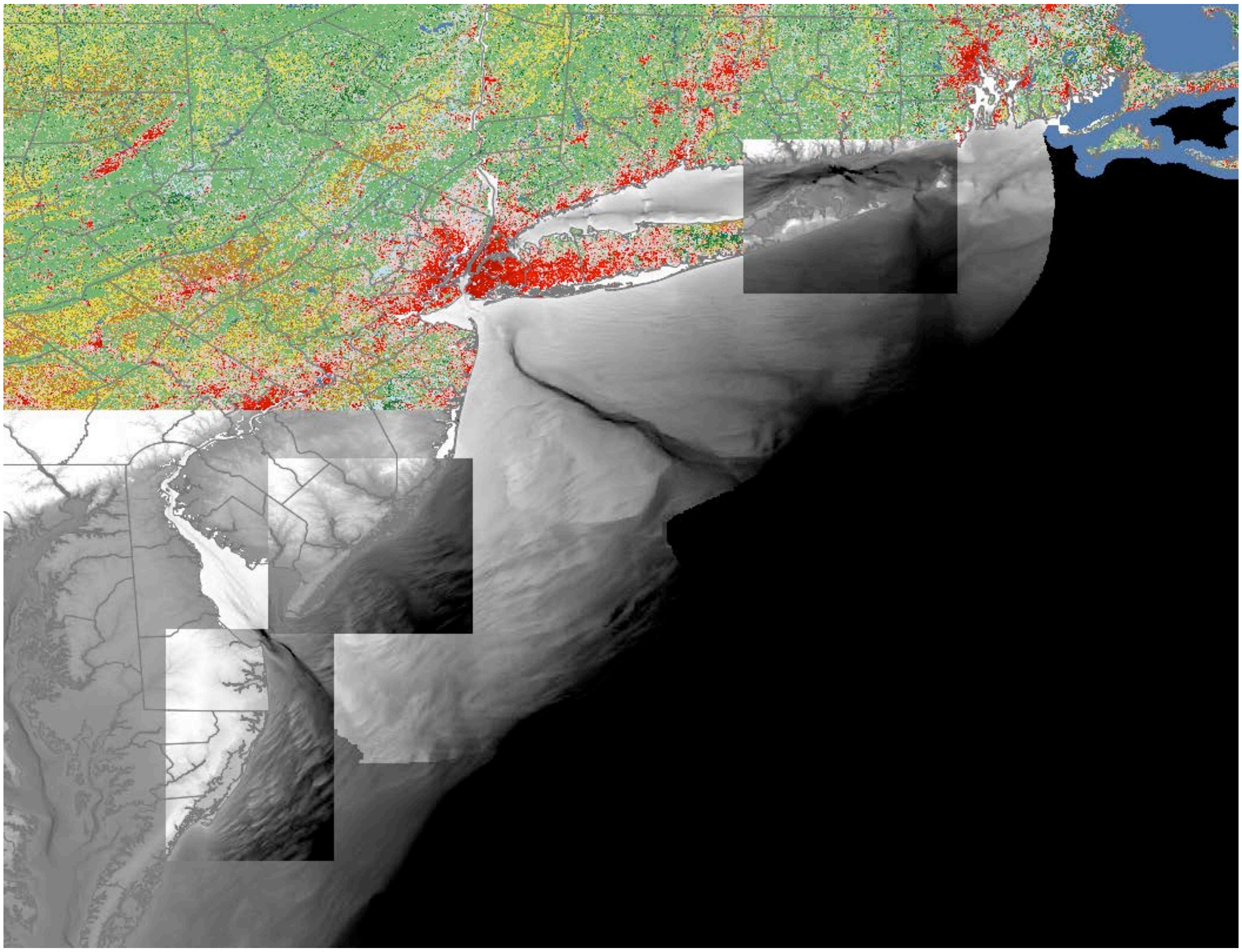

Figure 2: Mosaic of DEM and land use information based on NGDC tsunami DEM’s, FEMA DEM’s for Region 2 and Region 3 hurricane studies, and National Land Cover Data. Work covered by this project will provide maps for the Ocean City, Atlantic City and Montauk DEM’s (smallest highlighted areas) and Myrtle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

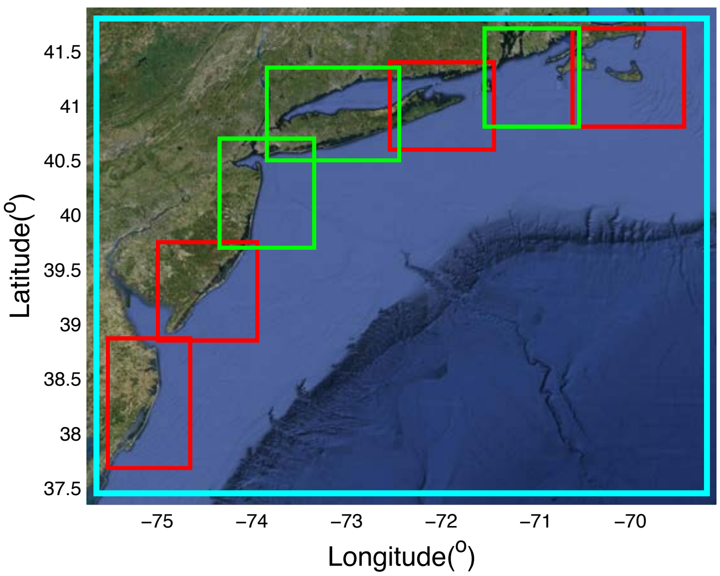

Figure 3: Sequence of DEM's being used for high resolution modeling in N.E. US. Red boxes indicate NGDC tsunami DEM's, including Ocean City, MD, Atlantic City, NJ, Montauk, NY and Martha's Vinyard, MA. Green boxes are similarly sized DEM's developed using FEMA DEM's, providing coverage of Northern New Jersey, New York and Narragansett Bay, Rhode Island.

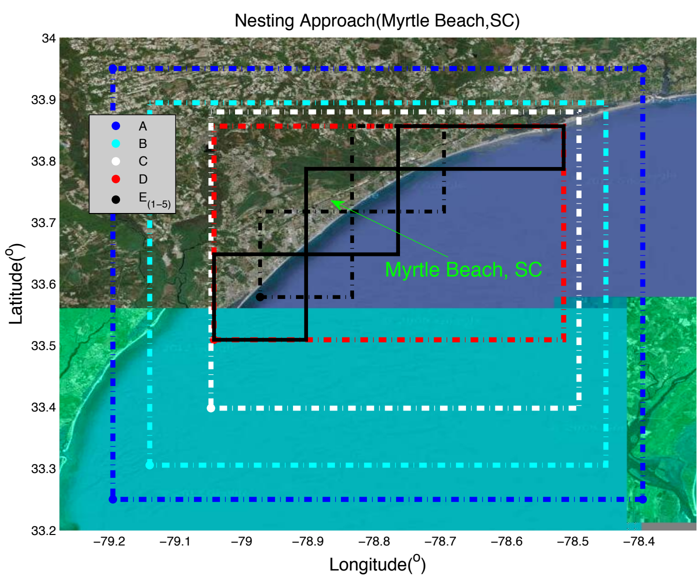

Figure 4: Sequence of nested grids within tsunami DEM's used to get final 10m resolution at inundated shoreline. Myrtle Beach, SC NGDC DEM.

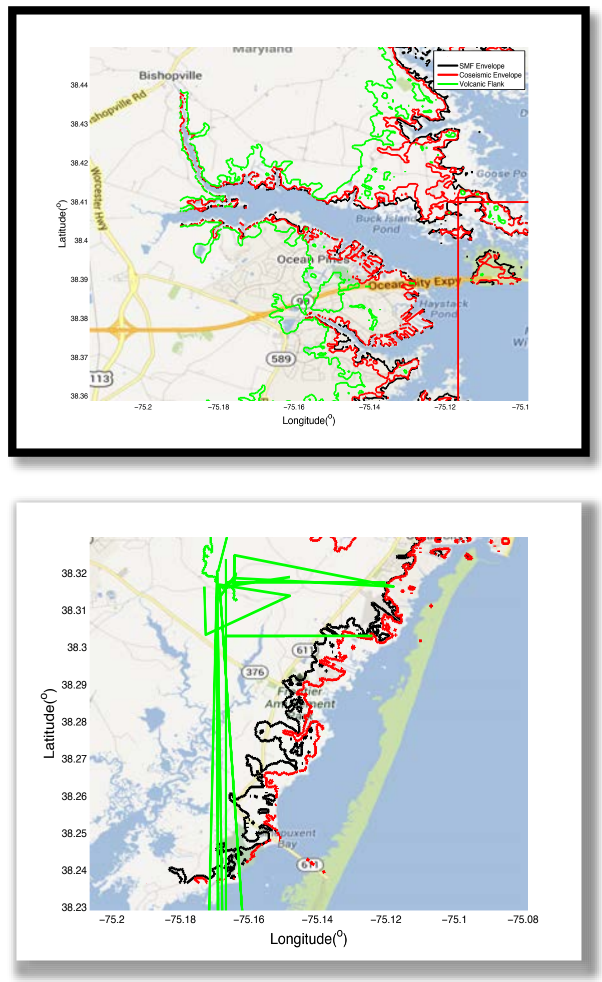

Figure 5. Sample inundation lines constructed based on CVV results alone (green lines), a composit based on all co-seismic events (black line) and a composite of all SMF events (red line) for Ocean City, MD and two subregions illustrating lines constructed at 30m horizontal resolution.

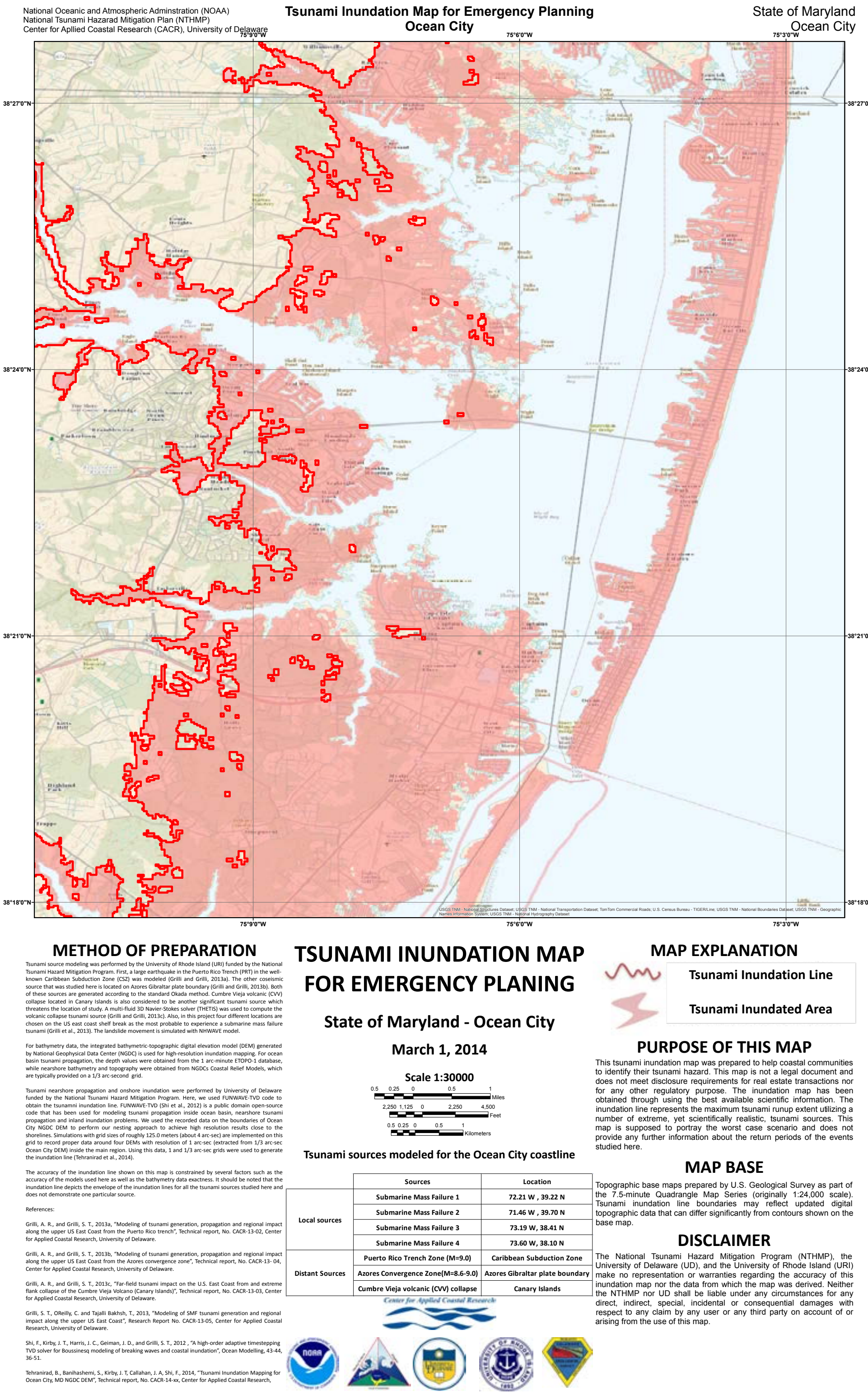

Figure 6. Draft inundation map for Ocean City, MD. Maximum inundation extent here results entirely from the large (450 km^3) CVV event, and indicates a complete overtopping of the hevily developed barrier island and extensive flooding of low lying marshy areas behind it. Maps are presently being revised to account for a reduction in size of the CVV event to 80 km^3.

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