

Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U. S. East Coast (Phase 2)

NTHMP Semi-Annual Report

May 15, 2014

Project Progress Report

Award Number: **NA13NWS4670014**

National Weather Service Program Office

Project Dates: September 1, 2013 – August 31, 2014

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BACKGROUND

In contrast to the long history of tsunami hazard assessment on the US West coast and Hawaii, tsunami hazard assessment along the eastern US coastline 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 trench (PRT) or near Leeward Islands, or a flank collapse of the Cumbre Vieja Volcano (CVV) in the Canary Islands). Moreover, considerable geologic 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.

In FY10-12, we have begun the process of hazard analysis and inundation map development for the U. S. East Coast. Simulating tsunami sources from the PRT, CVV and Azores-Gibraltar convergence zone, together with a number of relevant near-field SMF, we have concentrated on developing tsunami inundation maps for a nearly continuous coastal region located north of Ocean City, MD to Cape Cod, MA, plus Myrtle Beach, SC, including Long Island Sound but excluding major bays or estuaries such as Chesapeake Bay, Delaware Bay, the Hudson River and Narragansett Bay). FY13 work centers on continuing to develop inundation maps for the southern coastal areas along the US east coast, following

the same methodology. While we were initially supposed to only model areas as far south as Georgia, after discussions with the NTHMP U.S. Gulf Coast group, we have extended the geographic range of our region of responsibility to also include the Atlantic coast of Florida, thus effectively placing the state of Florida in two different NTHMP regions. This extension sets the context for one of the proposed tasks discussed next.

Our proposed new tasks in FY13 were:

1. Inundation studies for Virginia Beach/Norfolk VA, Savannah GA and Jacksonville, FL using existing source information
2. Inundation studies for Miami Beach, FL, Palm Beach, FL and neighboring communities, using new sources developed for the West Bahama Banks.

Similar to our earlier work during FY 10-12, modeling in this project will be carried out using a set of models developed at the University of Delaware, including FUNWAVE-TVD (a Boussinesq model for tsunami propagation and inundation simulations, in Cartesian or spherical coordinates, and NHWAVE, a RANS three-dimensional, sigma-coordinate model for simulating fully non-hydrostatic short wave response to large scale ground motion.

FUNWAVE and NHWAVE are open source, publically available programs, which have been benchmarked according to NTHMP standards for use in NTHMP-sponsored work. Both codes are efficiently parallelized using MPI and use a one-way coupling methodology, allowing for large scale computations of tsunami propagation and coastal impact in a series of nested grids of increasingly fine resolution. Both models deal with breaking dissipation via a TVD algorithm and also implement bottom friction. As in the FY10-12 work, we will use NHWAVE only to compute the initial tsunami waves generated from SMF sources (both translational slides and rotational slumps), and once the tsunamigenic part of the SMF is complete, we will continue simulating tsunami propagation in FUNWAVE. In addition to results needed to construct inundation maps, we are collecting information on flow fields and velocities in affected navigable inlets and harbor facilities that will be useful in future navigation hazard analysis.

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	<i>Perform inundation studies for Virginia Beach, VA, Savannah, GA and Jacksonville, FL</i>	<i>Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts</i>	<i>MMS</i>	<p><i>Source and propagation modeling have been conducted in order to provide boundary data for regional grids indicated by the red boxes in Figure 1, using sources developed for FY10-12 work.</i></p> <p><i>Nesting for the regional grids down to local resolution (10 or 30m) is being developed. Local inundation mapping to be conducted during summer 2014 with some time overrun.</i></p>
2	<i>Perform inundation studies for Miami Beach and Palm Beach, FL:</i>	<i>Prioritize inundation map development</i>	<i>MMS</i>	<p><i>SMF source has been developed in conjunction with the University of Miami, and UM has conducted initial regional modeling.</i></p> <p><i>Results from other sources have been collected for the boundary of the southernmost red box in Figure 1, for use in Florida coastal inundation studies.</i></p> <p><i>After obtaining a DEM from NGDC for Miami, FL, we will conduct inundation studies for the region from Miami Beach to West Palm Beach.</i></p>

PROBLEMS ENCOUNTERED

The DEM for the Miami Beach, FL area is still under development by NGDC. We will be able to begin detailed local work on that area when the DEM becomes available. It has also been difficult to obtain detailed DEM's from FEMA work for the same areas, and for this reason we have shifted our focus from the Jacksonville FL region to the Outer Banks region of North Carolina, for which an NGDC DEM exists.

ANTICIPATED OUTCOMES

Results for the additional mapping efforts described here will be presented in the form of technical reports for each NGDC DEM or similarly sized coastal region, and in the form of draft inundation maps for coastal communities within the DEM regions. The technical reports describe the model nesting procedure for each region, the hierarchy of model input files and stored output, the and the structure of GIS data sets available for map development and analysis. Figure 3 shows a sample draft map for Ocean City, MD (FY10-12) work, which is our present prototype for our map products. Project results are displayed at the project website <http://chinacat.coastal.udel.edu/nthmp.html> and will be displayed at the NTHMP website ws.weather.gov/nthmp/index.html as they are finalized.

PUBLICATIONS AND PRESENTATIONS REFERENCING FY13 WORK

- Grilli, A. and Grilli, S. T., 2013. Far-field tsunami impact on the US East Coast from an extreme flank collapse of the Cumbre Vieja volcano (Canary Islands). Research Report No. CACR-13-03, Center for Applied Coastal Research, University of Delaware.
- Grilli, A and Grilli, S. T., 2013. Modeling of tsunami generation, propagation and regional impact along the upper US East Coast from the Puerto Rico Trench. Research Report No. CACR-13-02, Center for Applied Coastal Research, University of Delaware.
- Grilli, A. and Grilli, S. T. 2013c. Modeling of tsunami generation, propagation and regional impact along the upper US East Coast from the Azores convergence zone. Research Report No. CACR-13-04, Center for Applied Coastal Research, University of Delaware.
- Grilli, S. T., O'Reilly, C. and Tajalli Baksh, T., 2013. Modeling of SMF tsunami generation and regional impact along the upper US East Coast. Research Report No. CACR-13-05, Center for Applied Coastal Research, University of Delaware.
- Grilli, S. T., O'Reilly, C., Harris, J. C., Tajalli Bakhsh, T., Tehranirad, B., Banhashemi, S., Kirby, J. T., Baxter, C. D. P., Eggeling, T., Ma, G. and Shi, F., 2014 "Modeling of SMF tsunami hazard along the upper U. S. East Coast: Detailed impact around Ocean City, MD", submitted to *Nat. Hazards*, February.
- Harris, J. C., Tehranirad, B., Grilli, A. R., Grilli, S. T., Abadie, S., Kirby, J. T. and Shi, F., 2014, "Far-field tsunami hazard on the western European and US east coast from a large scale flank collapse of the Cumbre Vieja volcano, La Palma", submitted to *Pure and Applied Geophysics*, April.

Schnyder, J. S. D., Kirby, J. T., Shi, F., Tehranirad, B., Eberli, G. P., Mulder, T., Ducassou, E. and Principaud, M., 2013, "Potential for tsunami generation by submarine slope failures along the western Great Bahama Bank", *6th Int. Symp. on Submarine Mass Movements and their Consequences*, GEOMAR, Kiel, September 23-25.

Schnyder, J. S. D., Kirby, J. T., Shi, F., Tehranirad, B., Eberli, G. P., Mulder, T. and Ducassou, E., 2013, "Potential for tsunami generation along the western Great Bahama Bank by submarine slope failures", Abstract NH41A-1689, *AGU Fall Meeting*, San Francisco, December.

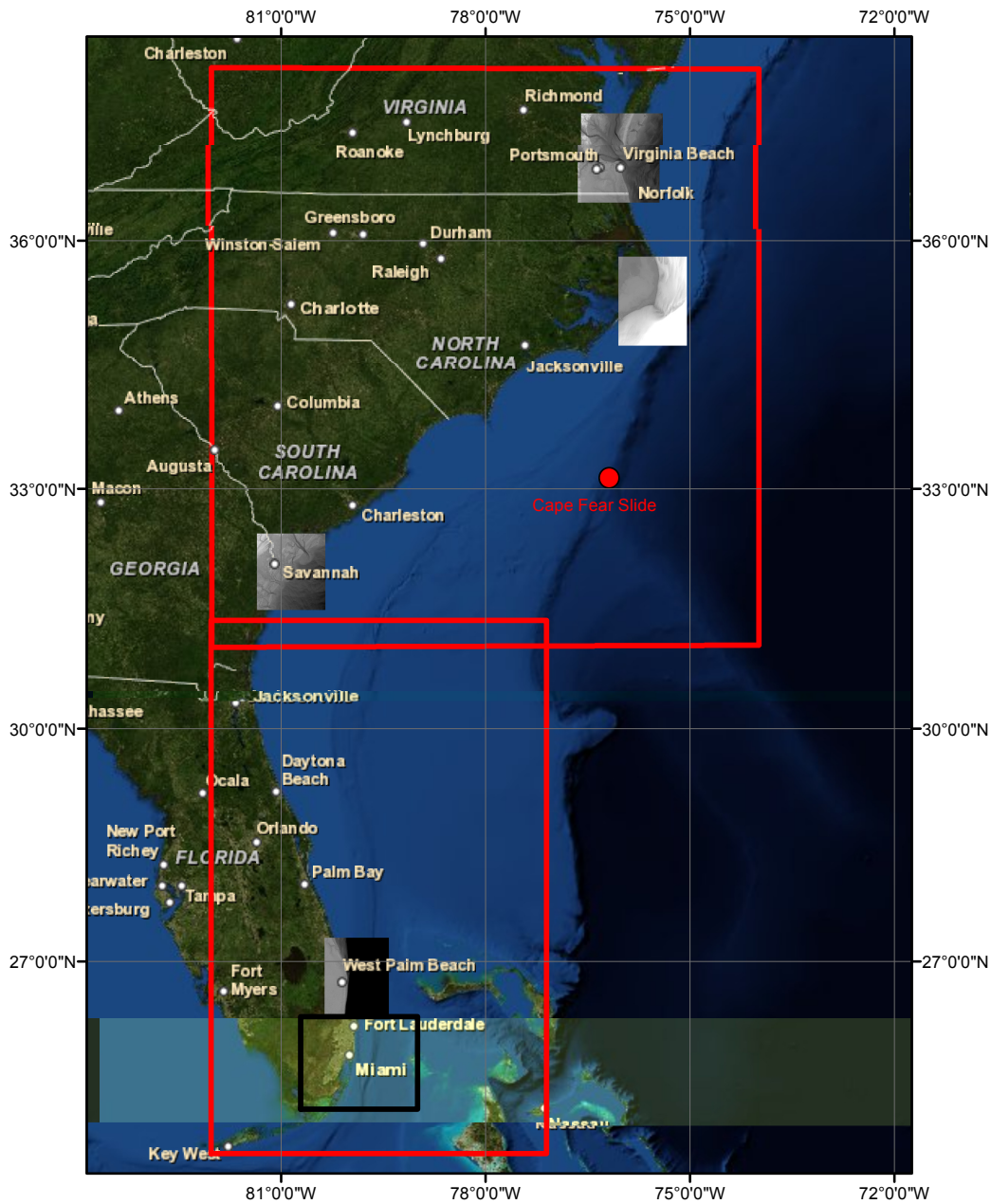


Figure 1: Sequence of DEM's being used for high resolution modeling in S.E. US., including an approximate outline for the anticipated DEM for Miami Beach, FL. Red boxes indicate regions gridded at 500m resolution which represent the transfer of data from URI ocean scale or landslide modeling to UD regional scale propagation and inundation modeling.

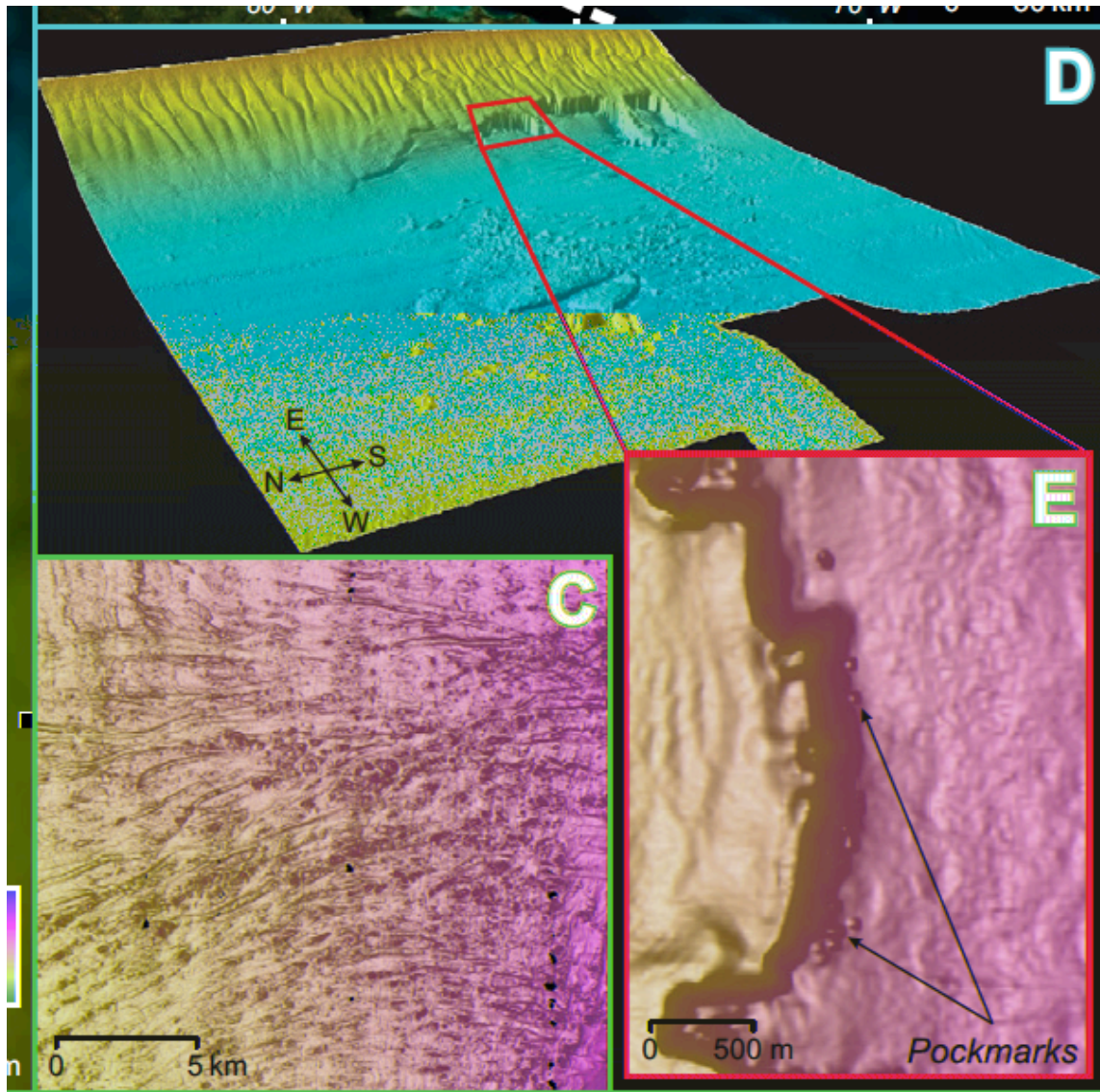
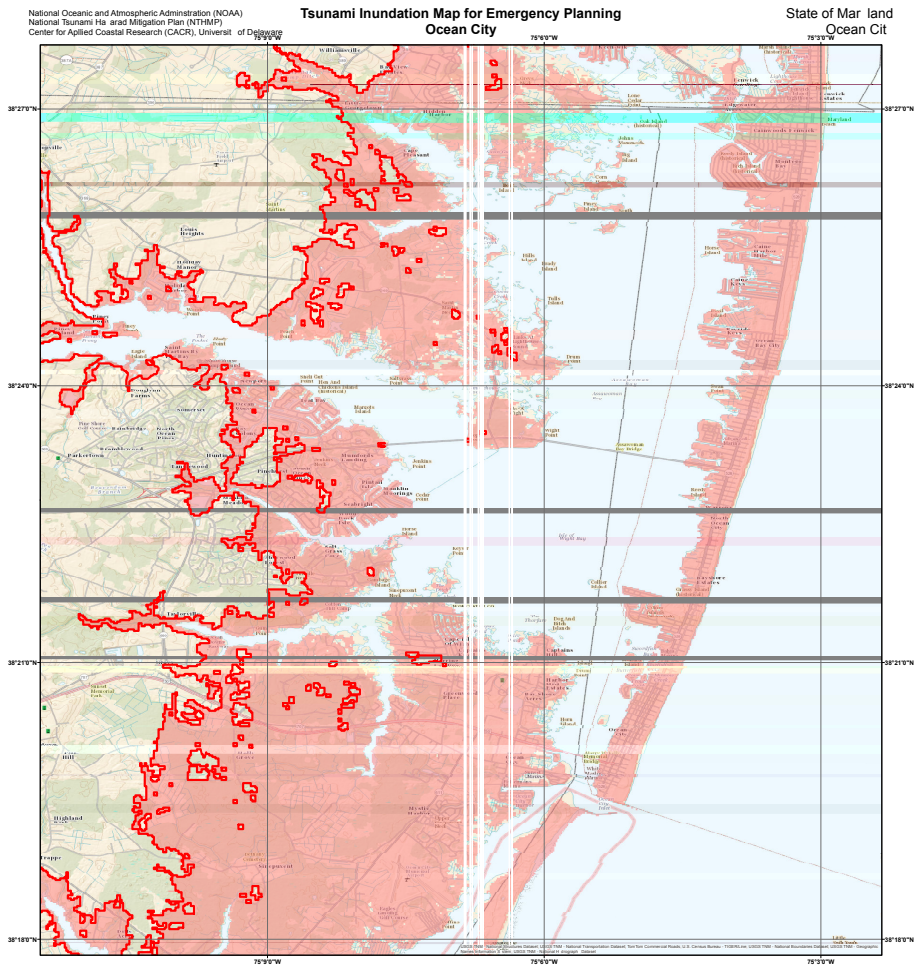


Figure 2: SMF landslide source being developed for inundation modeling for eastern Florida. The SMF is based on failure in carbonate deposits on the western Grand Bahama Banks. C: Detail of erosive furrows, D: Three dimensional view of mass transport complex, E: Detail of small pockmarks at top of northern scar. (from Figure 1 in Mulder et al. 2012)



METHOD OF PREPARATION

Tsunami source modeling was performed by the University of Rhode Island (URI) funded by the National Tsunami Hazard Mitigation Program. First, a large earthquake in the Puerto Rico Trench (PRT) in the well-known Caribbean Subduction Zone (SZ) was modeled (Griff and Goff, 2013a). The other tectonic source that was modeled here is located on Ascension plate boundary (Griff and Goff, 2013b). Both of these sources are generated according to the standard Okada method. Cumbre Vieja volcanic (CVV) collapse located in Canary Islands is also considered to be another significant tsunami source which threatens the location of study. A multi-fluid 3D Navier-Stokes solver (M3D2S) was used to compute the volcanic collapse tsunami source (Griff and Goff, 2013c). Also, in this project four different locations are chosen on the US East coast shall break as the most probable sites appearance a submarine mass failure (SMF) (Griff et al., 2015). The landslide movement is simulated with M3D2S model.

For bathymetry data, the integrated bathymetric-topographic digital elevation model (DEM) generated by National Geospatial-Intelligence Center (NGIC) is used for high-resolution inundation mapping. The ocean-bathymetry data were obtained from the 1 arc-minute ETOPO-5 database, while nearshore bathymetry and morphology were obtained from NOAA Coastal Relief Models, which are typically provided on a 1/3 arc-second grid.

Tsunami runup propagation and onshore inundation were performed by University of Delaware based on the National Tsunami Hazard Mitigation Program. Here, we used FUNWAVE-TD code to obtain the tsunami inundation line. FUNWAVE-TD (Shi et al., 2012) is a public domain open-source code that has been used for modeling tsunami propagation inside ocean basin, nearshore tsunami propagation and inland inundation problems. We used the recorded data on the boundaries of Ocean City (MOC DEM) to perform our nesting approach to achieve high resolution results close to the shoreline. Simulations with grid sizes of roughly 125.0 meters (about 4 arc-sec) are implemented on this grid to meet proper along-shore four (DOA) with resolution of 1/3 arc-sec (obtained from 1/3 arc-sec Ocean City DEM) inside the main region. Using this data, 1 and 1/3 arc-sec grids were used to generate the inundation line (Griff and Goff, 2015).

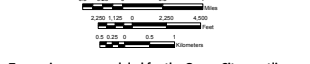
The accuracy of the inundation line shown on this map is constrained by several factors, such as the accuracy of the models used here as well as the bathymetry data accuracy. It should be noted that the inundation line depicts the envelope of the inundation line for all the tsunami sources studied here and does not demonstrate one particular source.

References:
 Griff, A. R., and Goff, S. T., 2013a, "Modeling of tsunami generation, propagation and regional impact along the upper US East Coast from the Puerto Rico trench", Technical report, No. CACR-13-05, Center for Applied Coastal Research, University of Delaware.
 Griff, A. R., and Goff, S. T., 2013b, "Modeling of tsunami generation, propagation and regional impact along the upper US East Coast from the Azores convergence zone", Technical report, No. CACR-13-04, Center for Applied Coastal Research, University of Delaware.
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 Griff, S. T., Okada, T., and Tsuji, T., 2015, "Modeling of SMF tsunami generation and regional impact along the upper US East Coast", Research Report No. CACR-15-05, Center for Applied Coastal Research, University of Delaware.
 Shi, F., Kirby, T., Hamrick, L. C., Gertmenli, D. C., and Griff, S. T., 2012, "A high-order adaptive time-stepping TD solver for Boussinesq modeling of breaking waves and coastal inundation", Ocean Modelling, 43-44: 36-53.
 Takewaki, R., Benkhaldoun, S., Kirby, T., Okada, T., A. Shi, F., 2014, "Tsunami Inundation Mapping for Ocean City, MD (MOC DEM)", Technical report, No. CACR-14-06, Center for Applied Coastal Research.

Tsunami INUNDATION MAP FOR EMERGENCY PLANNING

State of Maryland - Ocean City

March 1, 2014



Tsunami sources modeled for the Ocean City coastline

	Sources	Location
Local sources	Submarine Mass Failure 1	72.21 W, 39.22 N
	Submarine Mass Failure 2	71.46 W, 39.70 N
	Submarine Mass Failure 3	73.19 W, 38.43 N
	Submarine Mass Failure 4	73.60 W, 38.10 N
Distant Sources	Puerto Rico Trench Zone (MIR-0)	Caribbean Subduction Zone
	Azores Convergence Zone (MIR-8-9.0)	Caribbean Subduction Zone
	Cumbre Vieja volcanic (CVV) collapse	Canary Islands



MAP EXPLANATION

- Tsunami Inundation Line
- Tsunami Inundated Area

PURPOSE OF THIS MAP

This tsunami inundation map was prepared to help coastal communities to identify their tsunami hazard. This map is not a legal document and does not meet disclosure requirements for real estate transactions nor for any other regulator purpose. The inundation map has been obtained through using the best available scientific information. The inundation line represents the maximum tsunami runup extent until a number of extreme, et scientific realistic, tsunami sources. This map is supposed to portray the worst case scenario and does not provide any further information about the return periods of the events studied here.

MAP BASE

Topographic base maps prepared by U.S. Geological Survey as part of the 7.5-minute Quadrangle Map Series (original 1:24,000 scale). Tsunami inundation line boundaries may reflect updated digital topographic data that can differ significantly from contours shown on the base map.

DISCLAIMER

The National Tsunami Hazard Mitigation Program (NTHMP), the University of Delaware (UD), and the University of Rhode Island (URI) make no representation or warranties regarding the accuracy of this inundation map nor the data from which the map was derived. Neither the NTHMP nor UD shall be liable under any circumstances for any direct, indirect, special, incidental or consequential damages with respect to an claim by an user or a third party on account of or arising from the use of this map.

Figure 3. Draft inundation map for Ocean City, MD. Maximum inundation extent here results entirely from the large (450 km³) CVV event, and indicates a complete overtopping of the heavily developed barrier island and extensive flooding of low lying marshy areas behind it.

