MODELING OF TSUNAMI GENERATION, PROPAGATION AND REGIONAL IMPACT ALONG THE UPPER U.S. EAST COAST FROM THE PUERTO RICO TRENCH

BY

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Background

Earlier work indicates the possibility that a large earthquake in the Puerto Rico Trench (PRT), which marks the Caribbean Subduction Zone (CSZ), would generate a large coseismic tsunami that would potentially severely impact the entire upper US East Coast (USEC), in addition to Puerto Rico and many of the Caribbean islands (e.g., Grilli et al., 2010). This work further indicates that such an extreme PRT event could reach a M_w 9.0 moment magnitude by rupturing the entire PRT and would have an estimated return period of 200 to 300 years (Grilli et al., 2010).

As part of the NTHMP tsunami inundation mapping activity along the upper USEC (north of Virginia), here, we simulate tsunami generation and transoceanic propagation to the USEC for an extreme M_w 9.0 coseismic source in the PRT, defined by combining a number of NOAA's unit (i.e., M_w 7.5) SIFT sources (Short-term Inundation Forecast for Tsunamis; Gica et al., 2008).

Tsunami generation and propagation for a M_w 9.0 seismic event made of a single rectangular source was previously simulated using FUNWAVE (Wei et al., 1995) in a Cartesian grid (corrected for in distance for spherical effects; Grilli et al., 2010). As part of this NTHMP work, a M_w 8.9 coseismic tsunami was initially simulated based on the combination of 12 individual M_w 7.5 SIFT sources, still on a Cartesian grid (Kirby and Grilli, 2012). This event's moment magnitude was chosen as the worst case scenario for coseismic tsunami generation in the PRT, as suggested by ten Brick et al. (2007, 2008). Note, ten Brick et al. also questioned the possibility of a megathrust event occurring in the PRT because of the similarity between the geometry and the dynamic of the plates in the Puerto Rico and Sumatra – Andaman Trenches (both are curved and the rate of convergence between the subducting North American plate and the overlying Caribbean plate is increasingly more oblique in the West). Similarly, they discussed the dissimilarities between both trenches and concluded that a Mw 8.85 event in the PRT would represent a worst case scenario, while admitting that further analysis is necessary.

In the present work, we consider a slightly larger M_w 9.0 PRT seismic event, with a moment magnitude similar to that used in Grilli et al. (2010) for their worst case scenario. The present simulations, however, differ in: (1) the source definition, with the current source being formed of 12 sub-sources, based on the NOAA's SIFT database, which allows recreating the arc-shaped geometry of the PRT; and (2) simulations are performed on a spherical grid using the latest version of FUNWAVE (Kirby et al., 2013; see also details in Shi et al., 2012), in a 1 arc-minute resolution grid (finer than the 2' grids used earlier), over a wide section of the Atlantic Ocean basin. We elected to return to the earlier and larger M_w 9.0 worst case scenario, as a conservative upper limit, by considering two additional factors: (1) the occurrence in the last decade of extreme devastating events in large subduction zones, of unexpected, unpredicted, or previously thought unlikely magnitude, leading to human disasters, such as the Sumatra-Andaman/Indian Ocean M_w 9.2 event in 2004, which triggered the December 26 Tsunami (Grilli et al., 2007; Ioualalen et al., 2007) and the 2011 Japan Trench s M_w 9.0 seismic event, associated with the Tohoku tsunami disaster (Grilli et al., 2013); (2) the magnitude of extreme events should be stochastically assessed and not deterministically; no current quantitative statistical analysis is available which would provide a narrow enough confidence interval for such rare extreme events of long return period. However, despite the absence of such studies, it is widely accepted that there is a large statistical uncertainty associated with return periods of large seismic events.

Tsunami sources and propagation simulation

Tsunami model grids

The free surface elevation/a.k.a. coseismic tsunami source caused by the M_w 9.0 PRT extreme seismic event is generated as an initial condition (without initial flow velocity) in a local Cartesian grid with 1 km mesh (referred to as Grid 1), based on Okada's (1985) method. Once generated, the source tsunami surface elevation and horizontal velocity fields are interpolated on a larger, 1 arc-minute mesh ocean basin scale spherical grid (about 1.8 km; referred to as Grid 2), in which far-field tsunami propagation is computed using FUNWAVE-TVD. On the basis of these results, the UoD team performed additional nearshore and coastal inundation simulations in a series of finer nested grids near the USEC (reported separately for each regional DEM under consideration). To this effect, the boundary of the larger regional grid near the USEC (referred to as Grid 3; from Maryland to Southern Connecticut covering the coasts of Delaware, New Jersey, New York and Connecticut) is defined within the Grid 2 domain. The limits and discretization (mesh size) of the three grids are listed in Table 1 and grid boundaries are shown in Figure 1. In all grids, bathymetric data is obtained from the ETOPO-1 data base (see Figure 8).

Stations (i.e., numerical wave gages) are defined at each grid node along the boundary of Grid 3 which surrounds the far-field potential impact coastal area, on the East Coast of the United States.

	Grid 1 Source grid	Grid 2 Transatlantic grid	Grid 3 Coastal grid
Minimum Longitude	-71	- 75.70	-79.20
Maximum Longitude	-61	- 55.00	-78.40
Minimum Latitude	16	37.45	33.25
Maximum Latitude	23	41.80	33.95
Discretization in Longitude/latitude	1 km [= ~35 arc-second]	1 arc-minute = 0.0167 deg.	
Discretization in Latitude	1 km [= ~33 arc –second]	1 arc-minute = 0.0167 deg.	

Table 1: Grids Limits and spatial discretization cells size (see Figure 1).

Source generation

The extreme PRT seismic event is defined as the combination of 12 NOAA SIFT sources (Gica et al., 2008), whose locations seismic parameters values used in the present simulations are given inTable 2. The standard SIFT unit sources are defined in terms of

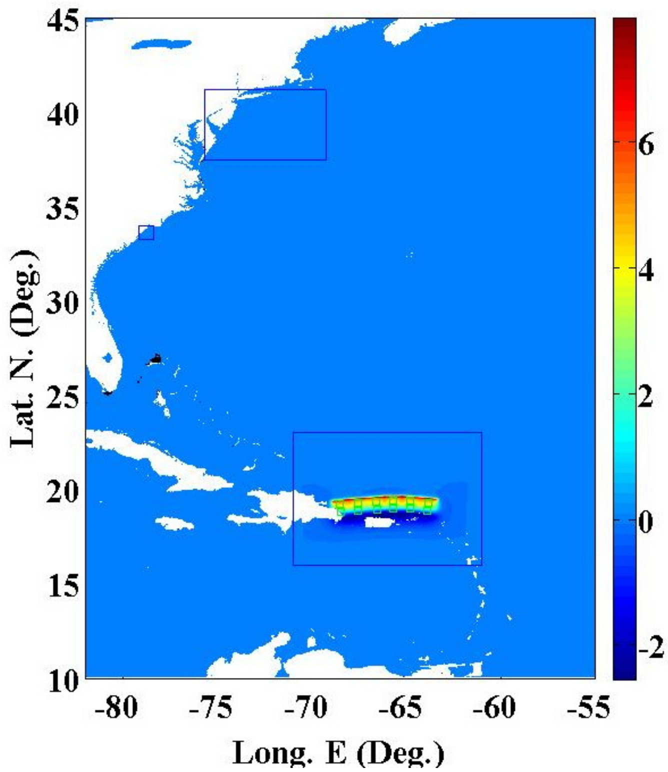


Figure 1: Areas of grids used in FUNWAVE-TVD tsunami simulations: Grid 1, black box around the PRT tsunami source; Grid 2 is the larger grid (figure size) for far-field simulations; and Grid 3 is the first nested regional grid at the coast. Color scale (in meter) indicates the composite Mw 9 PRT coseismic tsunami source elevation (shown within Grid 1, north of Puerto Rico; see details in Figure 3).

Latitude (Deg.)	Longitude (Deg)	Depth (km)	Strike (Deg.)	Dip (Deg.)	Length (km)	Width (km)	Rake (Deg.)	Slip (m) Mw=8.8	Slip (m) Mw=8.9	Slip(m) Mw=9.0
18.887	63.88	21.1	95.37	20	100	50	90	7.4	10.5	14.8
19.3072	63.8382	5	95.37	20	100	50	90	7.4	10.5	14.8
18.965	64.8153	21.1	94.34	20	100	50	90	7.4	10.5	14.8
19.3859	64.7814	5	94.34	20	100	50	90	7.4	10.5	14.8
18.9848	65.6921	21.1	89.59	20	100	50	90	7.4	10.5	14.8
19.4069	65.6953	5	89.59	20	100	50	90	7.4	10.5	14.8
18.9484	66.5742	21.1	84.98	20	100	50	90	7.4	10.5	14.8
19.3688	66.6133	5	84.98	20	100	50	90	7.4	10.5	14.8
18.8738	67.5412	21.1	85.87	20	100	50	90	7.4	10.5	14.8
19.2948	67.5734	5	85.87	20	100	50	90	7.4	10.5	14.8
18.7853	68.4547	21.1	83.64	20	100	50	90	7.4	10.5	14.8
19.2048	68.5042	5	83.64	20	100	50	90	7.4	10.5	14.8

Table 2: Location and parameters of the 12 individual sources used in combination to define potential Puerto Rico Trench seismic events of moment magnitude 8.8, 8.9 and 9.0. Sources are based on NOAA SIFT unit sources with slip parameter scaled to provide selected magnitude (see Figure 1).

fault parameters, required in the Okada (1985) method of tsunami source generation, whose values correspond to an hypothetical seismic moment magnitude of M_w 7.5 and a unit slip of 1 meter. The fault parameters are: source depth, subfault width, and length (in km), and characteristic angles of the fault plane, strike, rake and dip (in degree). The fault slip (m) is defined by simple linear scaling of the seismic energy, based on the NOAA unit source (see next section). Slip values for each unit source are listed in Table 2, for three total seismic moment magnitudes of, M_w 8.8, M_w 8.9 and M_w 9.0, with M_w 9.0, representing the maximum extreme event simulated in the present analysis. The other two slip distributions are provided for comparison.

Figure 2 gives definitions of the relevant fault parameters used in each unit SIFT source (Aki and Richards, 1980; University of Southern California, www.opensha.org).

NOAA SIFT Source scaling

The seismic moment, M_o (N.m), is defined as,

$$M_o = \mu \; L \; W \; S \qquad (1)$$

with μ a material constant estimated at 4 10^{10} N/m^2 (4 10^{11} dynes/cm^2), L and W the length and width of the fault (km), respectively, and S the fault slip (m). The moment magnitude, M_w (dimensionless), is related to the seismic moment by the following relationship,

$$M_w = \tfrac{2}{3} \log_{10}(M_o) - 6 \qquad (2)$$

Assuming that we want to estimate the slip of a source for a given moment magnitude, say M_{w2}, we find the energy scaling factor SF, between the corresponding seismic moment M_{o2} to the unit source seismic moment M_{o1} and moment magnitude M_{w1} = 7.5, as,

$$SF = \frac{M_{o2}}{M_{o1}} = \frac{10^{\left(\frac{3}{2}M_{w2}+6\right)}}{10^{\left(\frac{3}{2}7.5+6\right)}} = 10^{\left(\frac{3}{2}(M_{w2}-7.5)\right)} \qquad (3)$$

and, we define the “corresponding slip”, S_2, as,

$$S_2 = S_1 \; SF \qquad (4)$$

with S_1, the slip of the unit source, equal to 1 m.

In the case of a source divided in multiple identical segments (n segments), Eq. (10 Implies that the slip of each segment, S_i, is the total slip S_2 divided by the number of segments,

$$S_i = S_2/n \qquad (5)$$

Definitions *(Aki and Richards , 1980)*
http://www.opensha.org/glossary-strikeDipRake

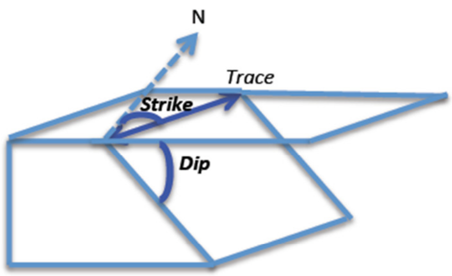
Strike *Fault strike is the direction of a line created by the intersection of a fault plane and a horizontal surface, 0° to 360°, relative to North. Strike is always defined such that a fault dips to the right side of the trace when moving along the trace in the strike direction.*

Dip *Fault dip is the angle between the fault and a horizontal plane, 0° to 90°.*

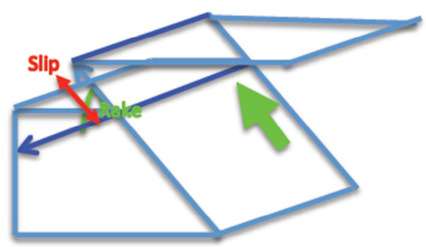
Rake *Rake is the direction a hanging wall block moves during rupture, as measured on the plane of the fault. It is measured relative to fault strike, ±180°. For an observer standing on a fault and looking in the strike direction, a rake of 0° means the hanging wall, or the right side of a vertical fault, moved away from the observer in the*
Strike *direction (left lateral motion). A rake of ±180° means the hanging wall moved toward the observer (right lateral motion). For any rake>0, the hanging wall moved up, indicating thrust or reverse motion on the fault; for any rake<0° the hanging wall moved down, indicating normal motion on the fault.*

Slip *Slip is the relative displacement of formerly adjacent points on opposite sides of a fault, measured on the fault surface.*

Strike and Dip angles



Slip and Rake
Rake=90° → Reverse fault ;dip<20° →Thrust fault



Schematic NOAA SIFT PRT unit sources (Not at scale !)

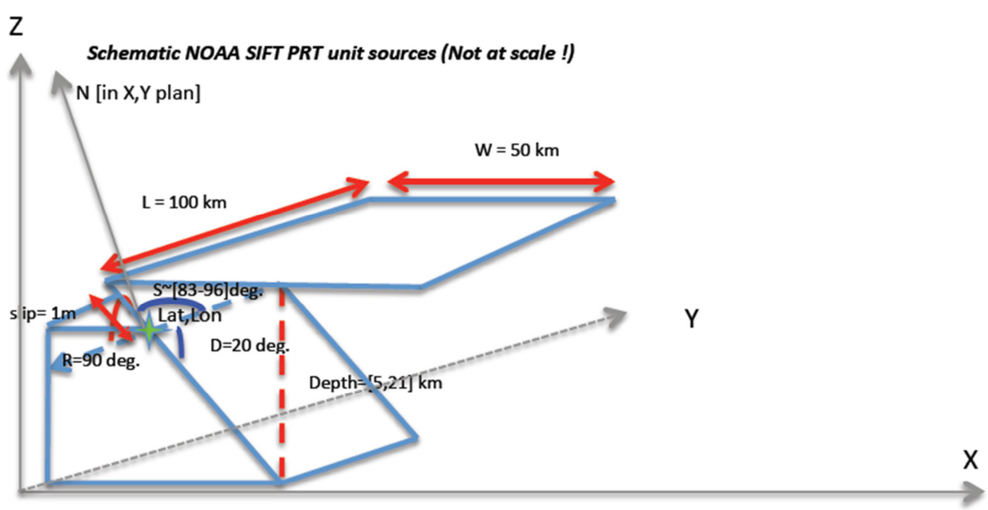


Figure 2: Schematic view of NOAA's SIFT unit source definitions and parameters, such as used in the PRT Mw 9 composite source (Figure 3).

Tsunami source generation

In this work, coseismic tsunami sources are generated according to the standard Okada (1985) method, in which the seafloor deformation computed in a homogeneous half-space with a planar dislocation is specified on the free surface as an initial condition without any flow velocity. The method uses a boundary integral representation of the half-space solution, over a Cartesian grid, which is computed here using a Matlab-based code developed at the "Institut de Physique du Globe de Paris" by Beauducel (2012). The combination of the 12 unit sources listed in Table 2 yields a slightly arced larger source, with approximate horizontal dimensions of 600 by 100 km (similar to the size of the single source used by Grilli et al., 2010), along the strike directions defined in the unit sources. Such a source, according to Okada's method, would create an initial wave reaching 6 to 10 meters above the calm sea surface (Figure 1 and Figure 3).

As indicated, based on an initialization from Grid 1 results, FUNWAVE-TVD is run in spherical coordinates in Grid 2, which has a 1 arc-minute resolution [1920 X 2100 cells], using an efficient parallelized MPI implementation. One hundred km wide sponge layers are specified along the open boundaries of Grid 2 to prevent reflection. The minimum depth parameter in the code is set to 0.1 m to limit the bottom friction near the coasts of Islands (e.g., Bermuda). The friction coefficient is set to C_d = 0.0025 (corresponding to medium sand).

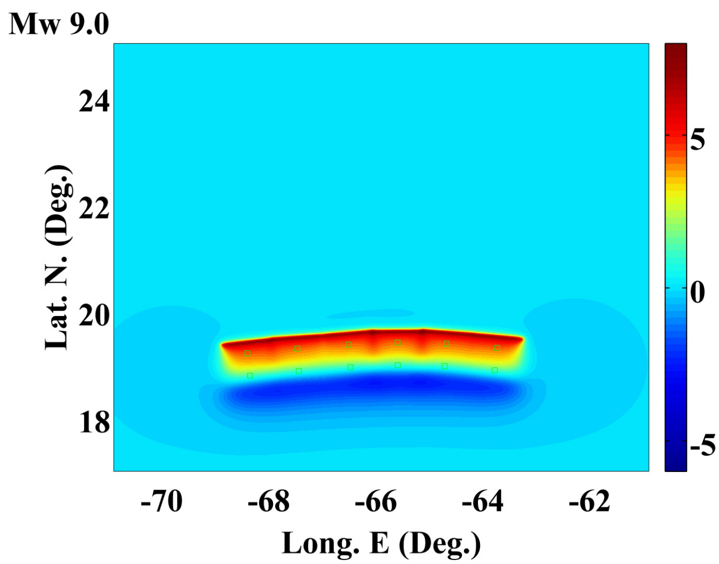


Figure 3: Initial surface elevation in Grid 1 (color scale in meters) for a Mw 9.0 composite coseismic tsunami source in the Puerto Rico Trench (PRT), made of 12 NOAA scaled SIFT unit sources (Table 2). The source is computed based on Okada's (1985) method.

Simulation results

Figure 4, Figure 5, and Figure 6 show three snapshots of instantaneous surface elevation, of the "worst case scenario" M_w 9.0 tsunami source computed in Grid 2 (Figure 1) using FUNWAVE-TVD, after 30 minutes, 102 minutes (time when reaching Bermuda), and 200 minutes (time when reaching the continental shelf along the US East Coast), respectively. We see an initial strong northward directionality of the highest tsunami waves, towards the USEC. Once waves reach the shallower continental shelf, however, due to refraction, they start wrapping up around the bathymetric contours (Figure 6).

Figure 7 shows the maximum surface elevation computed in Grid 2, at any time during the tsunami propagation. We see that waves on the order of at least 2 m elevation reach the continental shelf break.

The potential impact along the New England Coast is assessed in more detail by selecting a series of stations/numerical wave gages along a South–North transect between an offshore station 1 (at 4300 m depth) and a shallow station 5 (at 55 m depth). Stations are listed in Table 3 and shown in Figure 8. The four intermediate stations were selected between 2000 and 100 m depth.

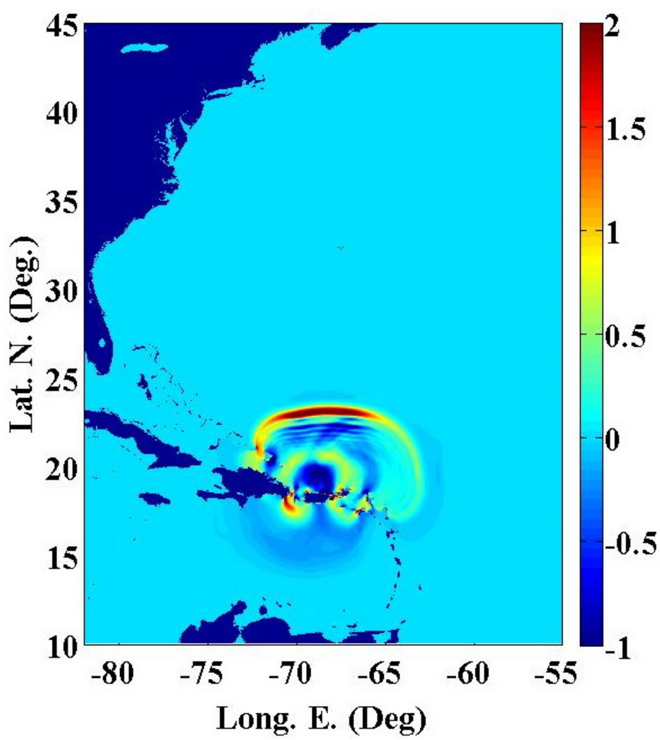


Figure 4: Surface elevation (color scale in meters) after 30 minutes for extreme Mw 9 PRT seismic event.

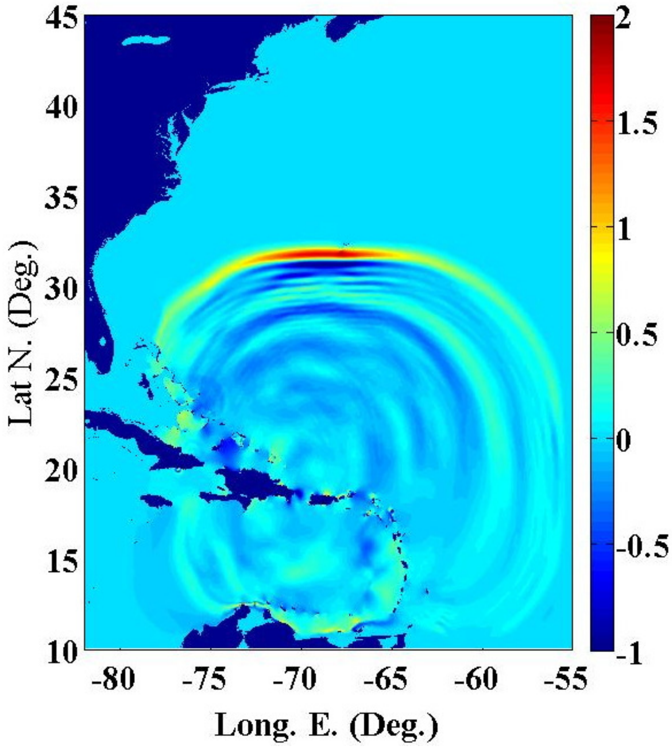


Figure 5: Surface elevation (color scale in meters) after 102 minutes (reaching Bermuda) for extreme Mw 9 PRT seismic event.

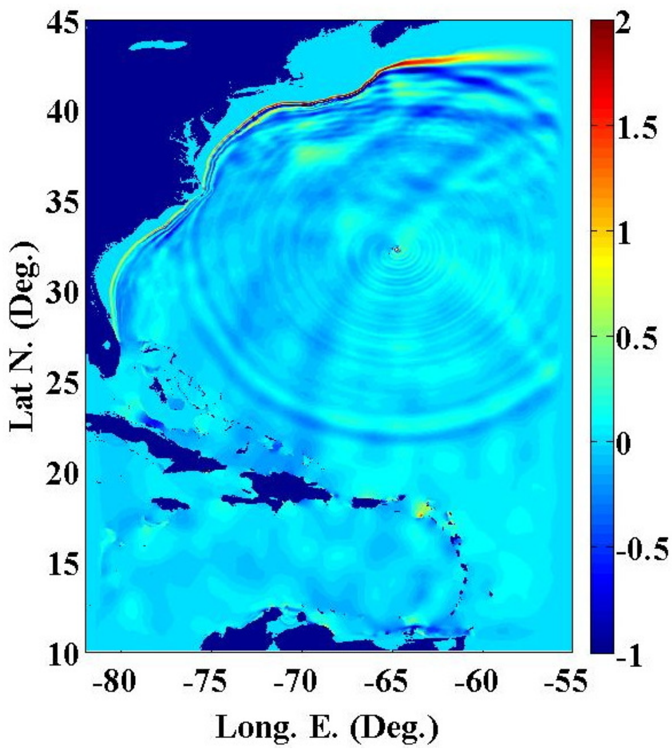


Figure 6: Surface elevation (color scale in meters) after 200 minutes for extreme Mw 9 PRT seismic event.

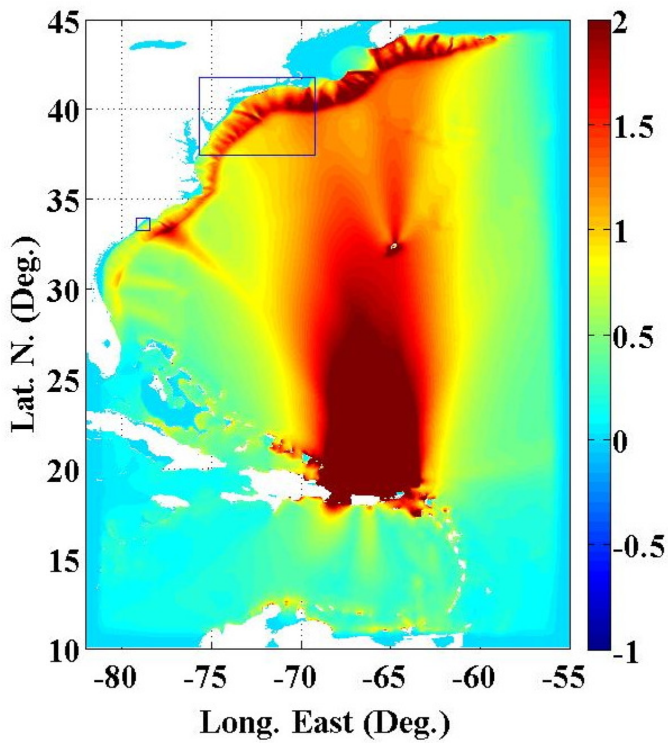


Figure 7: Maximum surface elevation (color scale in meters) computed with FUNWAVE-TVD for the worst case scenario, Mw. 9.0 PRT coseismic source (made of 12 unit sources; Table 2), in Grid 2 (Figure 2).

Time series computed at the 5 stations are shown in Figure 9 and Figure 10. These show that the tsunami would reach the deeper water station 1 after 2 h 30 min., with a leading wave elevation of 1.2 m; this wave would grow when propagating into shallower waters to reach about 2.2 m at station 4.

We show on Figure 11 that this growth in surface elevation closely follows the expected theoretical Greens law. In Figure 10, we further show a relative decrease of the leading wave amplitude while traveling closer to shore, likely due to effects of bottom friction, with model simulations predicting a leading wave of the order of magnitude of 1.2 m. Further computations in finer nested grids were performed by the UoD team that refined model predictions in coastal areas, and are reported separately for each coastal region being studied.

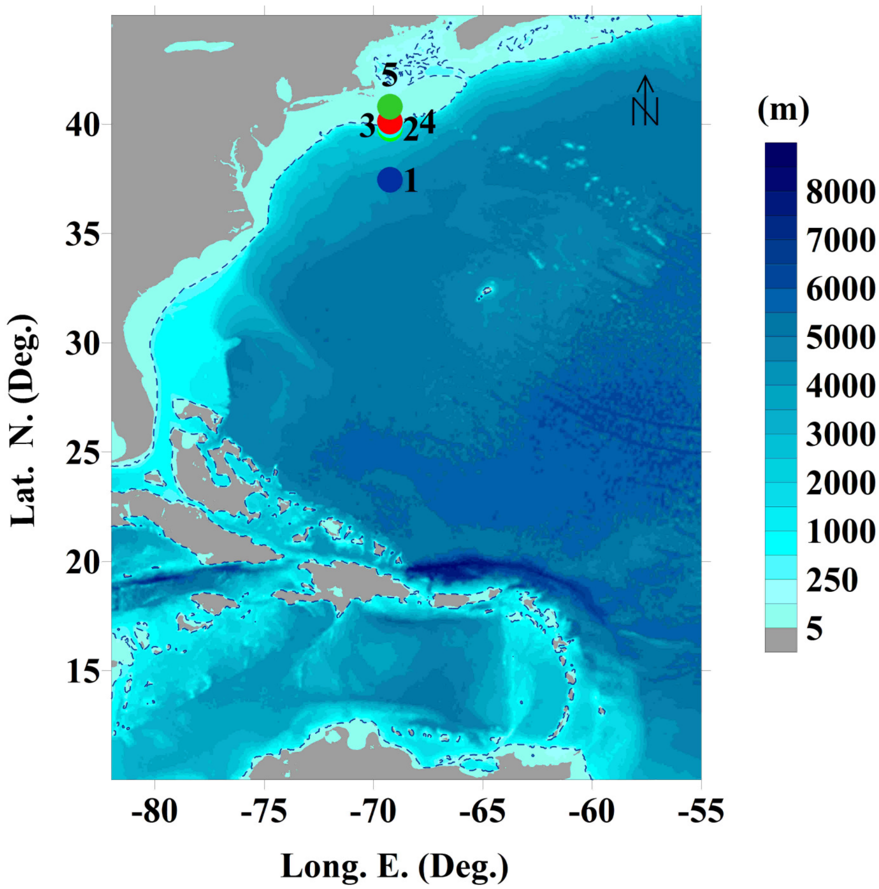


Figure 8: Bathymetry (color scale) and Location of 5 stations used to compute time series of surface elevation, to assess the maximum tsunami impact offshore of New England. Station locations and depth are listed in Table 3. The dash line marks the 200 m isobath.

Stations code on 1 arc-minute grid	Latitude N.(deg.)	Longitude E.(Deg.)	Depth(m)
[1]	37.4500	-69.25	4300
[2]	39.7846	-69.25	1800
[3]	39.9525	-69.25	400
[4]	40.1205	-69.25	100
[5]	40.7923	-69.25	55

Table 3: Location of stations located along a South-North transect, used to plot time series of Tsunami elevation offshore of Cape Cod

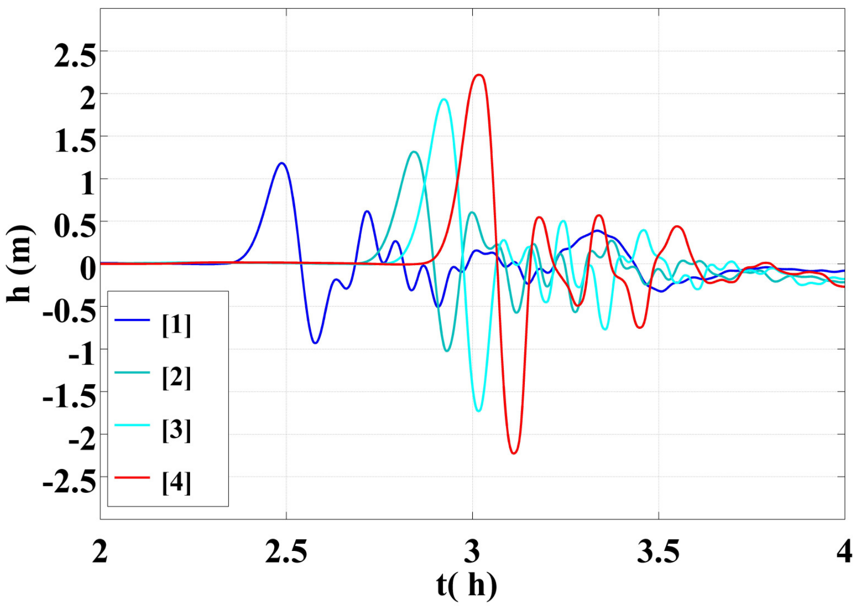


Figure 9: Time series of tsunami elevation (h) for Mw 9 PRT source, computed at stations [1], [2], [3] and [4] (Table 3, Figure 8), located at 4300, 1800, 400, and 100 m depth, respectively.

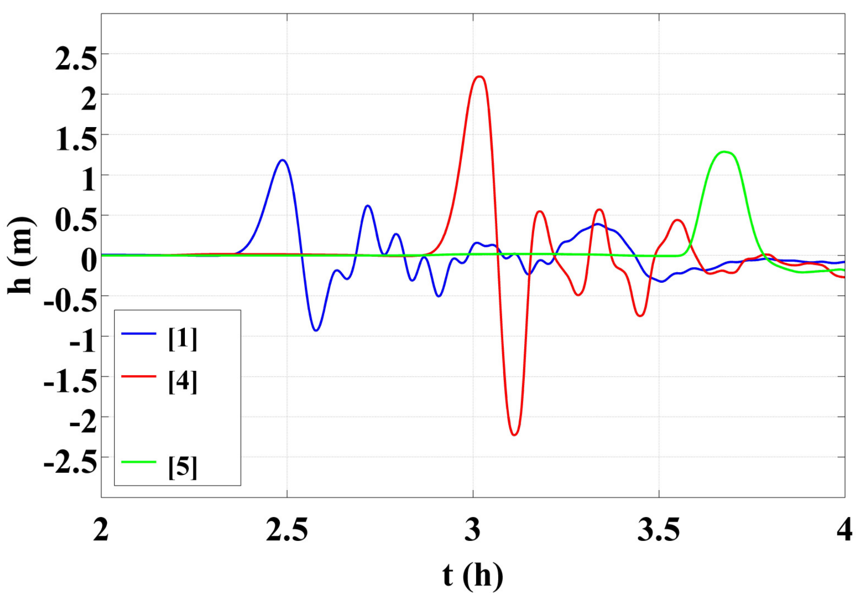


Figure 10: Time series of tsunami elevation (h) for Mw 9 PRT source, computed at stations [1], [4] and [5] (Table 3, Figure 8), located at 4300, 100 and 55 m depth, respectively.

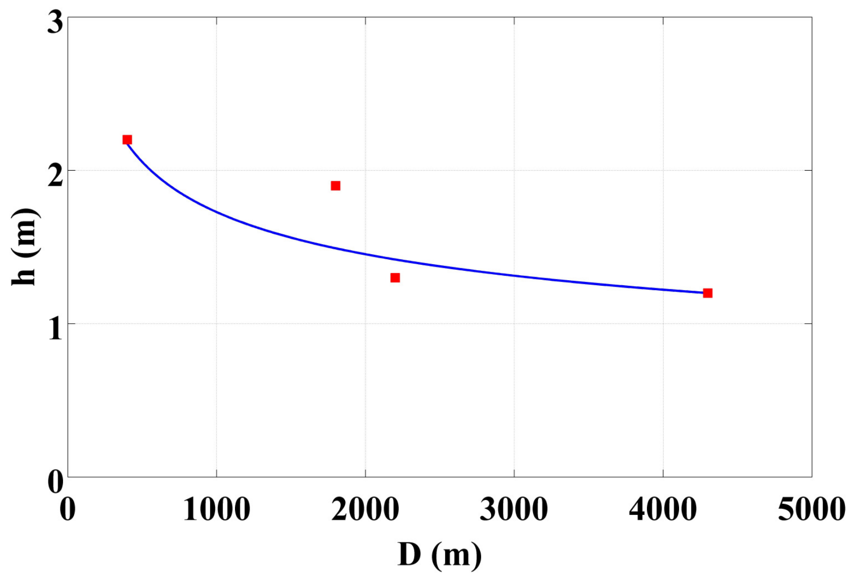


Figure 11: Comparison of surface elevation (h) as a function of depth (D) calculated for the Mw 9 PRT source at stations 1 to 4 (Table 3, Figure 8), with Green's law (D $\propto h^{-1/4}$).

References

Aki K., and P. G. Richards, Quantitative seismology, Freemann & Co, New York, 1980.

Beauducel F. (2012). Okada source software: Institut de Physique du Globe de Paris, http://www.ipgp.fr/~beaudu/matlab.html.

Gica, E., M. C. Spillane, V. V. Titov, C. D. Chamberlin, and J. C. Newman. 2008. Development of the forecast propagation database for NOAA's Short-Term Inundation Forecast for Tsunamis (SIFT). *NOAA Tech. Memo. OAR* PMEL-139.

Grilli, S.T., Ioualalen, M, Asavanant, J., Shi, F., Kirby, J. and Watts, P. 2007. Source Constraints and Model Simulation of the December 26, 2004 Indian Ocean Tsunami. *J. Waterway, Port Coastal and Ocean Engng.*, 133(6): 414-428.

Grilli, S.T., S. Dubosq, N. Pophet, Y. Pérignon, J.T. Kirby, and F. Shi. 2010. Numerical simulation and first-order hazard analysis of large co-seismic tsunamis generated in the Puerto Rico trench: near-field impact on the North shore of Puerto Rico and far-field impact on the US East Coast. *Nat. Hazards Earth Syst. Sci.*, 10: 2109–2125.

Kirby, J.T. and Grilli, S.T. 2012. Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U. S. East Coast. NTHMP semi-annual report, 34 pp.

Grilli, S.T., J.C. Harris, T. Tajalibakhsh, T.L. Masterlark, C. Kyriakopoulos, J.T. Kirby and F. Shi 2013. Numerical simulation of the 2011 Tohoku tsunami based on a new transient FEM co-seismic source: Comparison to far- and near-field observations *Pure and Applied Geophysics*, 170:1333-1359, doi:10.1007/s00024-012-0528-y.

Ioualalen, M. , Asavanant, J., Kaewbanjak, N., Grilli, S.T., Kirby, J.T. and P. Watts 2007. Modeling the 26th December 2004 Indian Ocean tsunami: Case study of impact in Thailand. *J. Geophys. Res.*, 112: C07024, doi:10.1029/2006JC003850.

Kirby, J.T., Shi, F., Tehranirad, B., Harris, J.C. and Grilli, S.T. 2013. Dispersive tsunami waves in the ocean: Model equations and sensitivity to dispersion and Coriolis effects. *Ocean Modeling*, 62: 39-55, doi:10.1016/j.ocemod.2012.11.009.

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space, *Bull. Seis. Soc. Am.,* 75(4): 1135-1154.

Shi, F., J.T. Kirby, J.C. Harris, J.D. Geiman and S.T. Grilli 2012. A High-Order Adaptive Time-Stepping TVD Solver for Boussinesq Modeling of Breaking Waves and Coastal Inundation. *Ocean Modeling*, 43-44: 36-51.

ten Brink, U. S., D. Twichell, E. Geist, J. Chaytor, J. Locat, H. Lee, B. Buczkowski, and M. Sansoucy 2007. The Current State of Knowledge Regarding Potential Tsunami Sources Affecting U.S. Atlantic and Gulf Coasts. *Report to the Nuclear Regulatory Commission. USGS.* 166 pps.

ten Brink, U., Twichell, D., Geist, E., Chaytor, J., Locat, J., Lee, H.Buczkowski, B., Barkan, R., Solow, A., Andrews, B., Parsons, T., Lynett, P., Lin, J. and Sansoucy, M., 2008, “Evaluation of tsunami sources with the potential to impact the U. S. Atlantic and Gulf coasts *Report to the Nuclear Regulatory Commission. USGS.*

Wei, G., Kirby, J. T., Grilli, S. T. and Subramanya, R., 1995. A fully nonlinear Boussinesq model for surface waves. I. Highly nonlinear, unsteady waves, *J. Fluid Mech.*, 294: 71-92.