DEVELOPMENT OF A TSUNAMI FORECAST MODEL FOR FAJARDO, PUERTO RICO

Aurelio Mercado

October 30, 2008
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Development of the Tsunami Forecast Model for Fajardo, Puerto Rico

Aurelio Mercado
October 30, 2008
Abstract

This report describes the development of a Standby Inundation Model (SIM) for Fajardo, Puerto Rico, as a component of the National Oceanic and Atmospheric Administration (NOAA) Short-term Inundation Forecasting for Tsunamis (SIFT) system. The optimized MOST model can obtain accurate amplitude of first waves and reasonable inundation limit within 10 minutes for the study area upon receiving the information of the earthquake source determined from real-time data assimilation and inversion. The model is validated using numerical results from a high-resolution MOST reference model since there are no historical tsunami instrumental records for the island. The developed SIM is tested against different scenarios of large virtual tsunamis numerically generated from the Muertos Trough, the Puerto Rico Trench and the South Caribbean Marginal Fault subduction zones.

1.0 Background and Objectives

The National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami Research (NCTR) at NOAA Pacific Marine Environmental Laboratory (PMEL) is developing a tsunami forecasting tool known as Short-term Inundation Forecasting for Tsunamis (SIFT) for NOAA Tsunami Warning Centers (TWC) (Titov et al., 2005). The primary goal of the system is to provide NOAA TWCs with operational tools that combine real-time deep-ocean Bottom Pressure Recorder (BPR) recordings from the DART tsunameter network (González et al., 2005) and seismic data with a suite of numerical codes, Method of Splitting Tsunami (MOST) (Titov and Synolakis, 1998; Titov and González, 1997), to produce efficient forecasts of tsunami arrival time, heights and inundation. To achieve accurate and detailed information on the likely impact of incoming tsunami on specific coastal communities within certain time limits and to reduce false alarms, Standby Inundation Models (SIMs) are being developed and integrated as crucial components of SIFT for a limited number of 75 US coastal cities and territories that are potentially at most risk.

The primary objective of the present study is to develop and test a SIM for real-time forecast of tsunami waves and inundation for the city of Fajardo on the island of Puerto Rico. Figure 1 shows the Caribbean Sea and the island of Puerto Rico. Also shown is the approximate location of the city of San Juan metropolitan area on the north coast of Puerto Rico.

2. Forecast Methodology

2.1 Tsunami model and methodology for the NOAA SIFT system

MOST (Titov and Synolakis, 1998; Titov and González, 1997) is a 2D finite-differences numerical model based on the nonlinear long-wave approximation. It uses a splitting scheme to separate the original two-dimensional problem into two sequential one-dimensional problems.

The MOST model accommodates a base level grid (0), for wave transoceanic propagation and three levels of telescoping grids (A, B, and C) with increasing spatial and temporal resolution for simulation of wave inundation onto dry land. The linear solution is evaluated at the base level while the nonlinear are calculated at the next three. Grid 0 is not dynamically couple with the other three, which is more efficient since it can provide multiple sets of boundary conditions for subsequent detailed calculations at different locations.
The numerical solution is obtained by an explicit finite-differences scheme with a second-order approximation in space and first order in time. The MOST model uses a Neumann-type technique to determine the waterline position through the computed flow velocity.

The PMEL real-time tsunami forecasting scheme is a process that comprises of two steps, (1) data assimilation and inversion, and (2) forecasting by Standby Inundation Models (SIMs). Each one of these two steps is explained next.

### 2.1.1 Data Assimilation and Inversion

Besides seismic and coastal tide gauges, real-time deep ocean bottom pressure data from the DART tsunameter network, is used as a primary data source since it can provide rapid tsunami observation without harbor and instrument responses. The linearity of wave dynamics of tsunami propagation in the deep ocean allows for applications of inversion schemes to construct a tsunami scenario based on the best fit to given tsunameter data. Details of the inversion method can be found in Titov et al. (2003) and Wei et al. (2003).

PMEL has developed a linear propagation model database for unit sources in the Atlantic and Caribbean Sea, with each unit source a typical \( M_w = 7.5 \) subduction zone earthquake. Based on a sensitivity study of far-field tsunami characteristics (Titov et al., 1999), the parameters of the unit sources are: length = 100 km, width = 50 km, dip = 15°, rake = 90°, depth = 5 km, slip = 1 m. The strike of each source is aligned with the local orientation of the subduction zone. Details of the fault parameters for each subduction zone will be published by NCTR (Gica et al., 2008). The model simulation results for each unit solution, including amplitudes and velocities, are stored in a database. The database also provides the offshore forecast of tsunami amplitudes and all other wave parameters around the Caribbean Sea and North Atlantic Ocean immediately once the data assimilation is complete. The inversion algorithm, which combines real-time tsunami-meter data of offshore amplitude with the propagation database, provides an accurate offshore tsunami scenario without additional time-consuming model runs.

The locations of the unit sources for the Caribbean region are shown in Fig. 2. Table 2 presents the combination of unit sources from the forecast model database used for the optimization process in this report. At each subduction zone, two lines of sources (A – top; B – bottom) are placed next to each other. The unit sources corresponding to segments AB 47-53 (\( M_w = 9.0 \), along the Puerto Rico Trench), AB 87-92 (\( M_w = 8.9 \), Muertos Trough), AB22-29 (\( M_w = 9.0 \), North of South America and A,B 38-49 (\( M_w = 9.1 \), Eastern Caribbean Subduction Zone) were used. These correspond to earthquakes with maximum estimated magnitudes considered likely for these seismic zones.
<table>
<thead>
<tr>
<th>Source Location</th>
<th>Unit Sources</th>
<th>Slip for each unit source (m)</th>
<th>L (km)</th>
<th>Mw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puerto Rico Trench</td>
<td>47,48,49,50,51,52,53 Rows A, B</td>
<td>11</td>
<td>700</td>
<td>9.0</td>
</tr>
<tr>
<td>Muertos Trough</td>
<td>87,88, 89, 90, 91, 92 Rows A, B</td>
<td>11</td>
<td>600</td>
<td>8.9</td>
</tr>
<tr>
<td>North of South America</td>
<td>22,23,24,25,26,27, 28,29, Rows A, B</td>
<td>11</td>
<td>800</td>
<td>9.0</td>
</tr>
<tr>
<td>Eastern Caribbean Subduction Zone</td>
<td>38,39,40,41,42,43, 44,45,46,47,48,49 Rows A,B</td>
<td>11</td>
<td>1200</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Table 1 Caribbean Sources used for testing the Fajardo SIM.

![Figure 1 Location of the four source areas used to test the Fajardo grids.](image)

2.1.2 Standby Inundation Model (SIM) Forecasting

A SIM applies the non-linear components of the MOST model using three nested grids (A, B, and C), with increasing resolution to telescope into the inundation forecasting area. The inundation area (grid C) includes the high concentration of population in the coastal communities, and the National Weather Service warning points (WP).

To provide site-specific forecasting for rapid, critical decision-making in emergency management, SIMs are implemented and optimized for both speed and accuracy. First, a SIM utilizes the pre-computed time series of offshore wave height and depth-averaged velocity from the database as the boundary and initial conditions once the offshore scenario is defined. Second, by reducing the calculation areas and grid resolutions, the optimized setup can provide forecasting results within 10 minutes (for a minimum of 4 hours of simulation time), which allows larger time steps without
violations of the CFL conditions. Finally, to insure forecasting accuracy, results from the optimized runs are validated with historical tsunami tide gauge records (if available) as well as a reference model run made with higher resolutions and larger calculation domains.

3. Site Context

Figure 2 Google Earth - Fajardo, Puerto Rico metropolitan area.

Fajardo was founded in 1760 by Bravo de Rivera, a Spanish governor. It was originally named Santiago de Fajardo. It is a small but popular city in Puerto Rico located in the east region of the island, bordering the Atlantic Ocean, north of Ceiba and east of Luquillo. Fajardo is spread over 7 wards and Fajardo Pueblo (The downtown area and the administrative center of the city). It is both a principal city of the Fajardo Metropolitan Statistical Area and the San Juan-Caguas-Fajardo Combined Statistical Area.

Fajardo is the hub of the majority of recreational boating in Puerto Rico and a popular launching port to Culebra, Vieques, and the American and British Virgin Islands. It is also the home to the largest Marina in the Caribbean, called Puerto del Rey. The town contains various hotels; the El Conquistador Resort is one of its most famous hotels. Fajardo is popular among tourists, especially local tourists, because of its seafood, hotels, closeness to the small islands of Palomino, Icaco and Palominito, and the many daily trips that were are available to Vieques and Culebra, both by boat and by the four airlines that served Fajardo Airport recently closed. Off shore near Fajardo few islets can be found: Icacos, Palominos, Palominitos and Diablo, uninhabited coral islands.

3.1 Bathymetry and Topography

For this study the NOAA’s National Geophysical Data Center (NGDC) provided high-resolution gridded data based on recent shallow water LIDAR topographic and
bathymetric surveys and multi-beam surveys for deeper waters. A 1 arc second grid was supplied that covered the entire island of Puerto Rico, as shown in Figure 3. A detailed report accompanied the NGDC data (Taylor et al., 2006), and should be consulted for details regarding data processing. NGDC additionally supplied a higher resolution grid for the Fajardo metropolitan areas. Figure 6-8 show the 1/3 arc second shaded relief for the Fajardo area. The parameters for grids are shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>1 second</th>
<th>1/3 arc second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat</td>
<td>16.9995-</td>
<td>18.000-</td>
</tr>
<tr>
<td></td>
<td>19.000</td>
<td>18.0500</td>
</tr>
<tr>
<td>Long</td>
<td>68.000-</td>
<td>65.3500</td>
</tr>
<tr>
<td></td>
<td>64.9995</td>
<td>65.0000</td>
</tr>
<tr>
<td>ncols</td>
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<td>2401</td>
<td>5941</td>
</tr>
<tr>
<td>Cellsize (arc sec)</td>
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<td>1/3</td>
</tr>
<tr>
<td>X Grid spacing (degree)</td>
<td>.000833</td>
<td>9.26098X10^{-5}</td>
</tr>
<tr>
<td>Y Grid spacing (degree)</td>
<td>.000833</td>
<td>9.26098X10^{-5}</td>
</tr>
<tr>
<td>Zmin (m)</td>
<td>-6620.873</td>
<td>-2816.29</td>
</tr>
<tr>
<td>Zmax (m)</td>
<td>1315.26</td>
<td>304.34</td>
</tr>
</tbody>
</table>

Table 2 1 and 1/3 second parameters of the NGDC grids developed for Puerto Rico and Fajardo

Figure 3 shows a filled contour plot of the full-resolution data. The resolution of the DEM was decreased to 1.35 sec and a surface plot is shown in Figure 4. Figure 5 shows a shaded relief version of the same data. Figures 6-8 show different representations of the 1/3 arc second grid of the Fajardo area. Figure 9 is a Google Earth image of the Fajardo 1/3 arc second extents.
Figure 3 Puerto Rico 1 arc sec DEM at full resolution. Depths are shown in meters.
Figure 4 Puerto Rico 1.35 arc sec DEM looking from the east. Depths are shown in meters.
Figure 5 Puerto Rico 1.35 arc sec DEM. MHW line is shown in red.
Figure 6 Fajardo 1/3 arc sec DEM at full resolution. Depths are shown in meters. The red cross denotes the location of the Warning Point (WP).
Figure 7  Fajardo 1/3 arc sec DEM surface plot, looking from the East. Depths are shown meters. The red cross shows location of the WP. Notice the string of small islands and shoals named La Cordillera, which offers a natural protection for waves coming from north. Also notice the very sharp depth transition both north and south.
Figure 8 Fajardo 1/3 arc sec DEM shaded relief plot. Black cross shows the location of the WP. Notice the string of small islands and shoals named La Cordillera, which offers a natural protection for waves coming from north. Also notice the very sharp depth transition both north and south.
Figure 9 Google Earth photo of the area covered by the Fajardo 1/3 s DEM. Red symbol shows the location of the WP.
3.2 Tide Gauges
The Fajardo tide gauge was established in 1964 and upgraded to its present installation in 2007. The GPS location of the tide gauge is 18 20.1’N and 65 37.8’W. The tide gauge location replaces the warning point used for the development of the forecast model. SIM testing using the new warning point is located in Appendix C.

3.3 Model Setup

3.3 Reference Grids

Though run up estimates were made along the west coast for the 1918 Puerto Rico tsunami, there is no historical tide gauge data, therefore it is important to maximize the accuracy of the reference grids.

Figure 10 shows the location of the Reference Grids A, B, and C inside the 1 s DEM for the whole island. The first version was attempted for Reference Grid A was of 3 s resolution. That of Grid B was 2 s resolution, and that of Grid C was 1 s resolution. Since there are no historical tsunami signals to compare with, it is felt that the reference runs should be made with as high resolution, and extensive geographical coverage, as possible, even if the runs may take several days.

![Figure 10 Location of reference grids A, B, and C.](image)

Grid_A_ref_3s_v1.dat was obtained from the 1 s DEM (pr_1s.asc), which using regrid_ngdc.m was regridded to 3 s. Then, using Surfer Extract command, it was
cropped to the area shown in Figure 9. It was passed through BATHCORR.F, with wave height = 0.5, and steepness parameter (SP) equal to 1. It should be stated that in all uses of BATHCORR.F the bathymetry was processed up to the 0 m contour. Only 7 points were changed, and only 1 pass was necessary. The CFL-based maximum time step came out to $\Delta t_A = 0.418$ s.

Reference Grid B was obtained from pr_1s.asc using regrid_ngdc.m. The Fajardo 1/3 s DEM was not used since we required Reference Grid B to cover bathymetry northward of the Fajardo DEM. The grid was passed through BATHCORR.F with wave height = 0.5, and SP = 1, and it changed only 6 points, thus only one pass was necessary. This was named Grid_B_ref_2s_v1.dat, and the CFL-based maximum time step came out to $\Delta t_B = 0.2787$ s.

Reference Grid C was obtained from the Fajardo 1/3 s DEM by means of regrid_ngdc.m. The output was passed through Surfer Extract command to crop it to the location and size shown in Figure 10. It was passed through BATHCORR.F with wave height = 0.5, and SP = 1, and only 4 points were changed. It was named Grid_C_ref_1s_v1.dat, and the CFL-based maximum time step was $\Delta t_C = 0.969$. Notice that for these three grids the CFL time step is controlled by Grid B due to the influence of the 4000 m-plus depth at its southeast corner.

As mentioned above, four sources were used to test the grids. And the earthquakes used were very large, so we should not be surprised if we get very large runups. It is not obvious where to draw the line between a very large runup due to a very large, close earthquake, and an unreal runup due to a very large, close earthquake. All four sources were tested with these v1 grids, which have not been smoothed since all of them were passed through BATHCORR.F with SP = 1.0. And the condition imposed on the grids was no obvious blowup for 10 hours of wall clock time. The only source that gave no problem at all was the one labeled Eastern Caribbean Subduction Zone (ECSZ). For all other sources MOST blew up at the very steep shelf slope south of the western end of the island of Vieques (the island to the southeast of Puerto Rico). And consistently, it was in Grid B, all of the time after 4 hours of simulation.

So it was decided to pass all three grids again through BATHCORR.F with wave height = 2, and SP = 0.5. For Grid_A_ref_3s_v1.dat it changed 64 points for the first pass, 9 for the second, and 2 for the third. $\Delta t_A$ came out to 0.418 s, the same as before. The output was named Grid_A_ref_3s_v2.dat. For Grid_B_ref_2s_v1.dat, 18 points were changed during the first pass, and only 1 during the second. The output was named Grid_B_ref_2s_v2.dat. $\Delta t_B$ came out to 0.2787 s, the same as before. Finally, for Grid_C_ref_1s_v1.dat, only 11 points were changed during the only pass through BATHCORR.F required. $\Delta t_C = 0.969$ s, the same as before, and this new version of Grid C was named Grid_C_ref_1s_v2.dat.

Another attempt was made for the 3 sources for which the unsmoothed grids (specifically, Grid B) gave problem. And, again, Grid B consistently blew up at the same location. So it was decided to locally smooth Grid B using Surfer’s smoothing option with 5 passes of a Gaussian Low-Pass filter (see Table 3) inside the rectangular area shown in Figure 11, and 2 passes of the same filter in the buffer rectangular area shown in the figure. This buffer area allows for a smoother transition between the stronger smoothed area and the non-smoothed area. This rectangular area covers the entire, very steep, shelf slope on the southern part of Reference Grid B. Although only south of the west end of Vieques did the grid have problems, it was felt that the whole of the very sharp shelf break should be smoothed in order to avoid future problems with other sources. Figure 12 shows the difference between the original and smoothed grids (original – smoothed; results are shown only inside the rectangular area which was smoothed, since outside this area the difference is zero). It can be seen that it is right south of the western end of Vieques that the largest amount of smoothing happened. Although the figure shows that smoothing also occurred all along the shelf...
break of Grid B. The smoothed Grid B was again passed through BATCORR.F with wave height = 2, and SP = 0.5, and no changes were made. The new, (Surfer) locally smoothed, Reference Grid B was named Grid_B_ref_2s_v3.dat, and its time step remained as before.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>1</th>
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<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3 Low-pass Gaussian Weights

After the final smoothing of Grid B all of the reference runs, with all of the sources, did execute with no problem. So the finally adopted reference grids were:

- Grid_A_ref_3s_v2.dat, $\Delta t_A = 0.418$ s
- Grid_B_ref_2s_v3.dat, $\Delta t_B = 0.2787$ s
- Grid_C_ref_1s_v2.dat, $\Delta t_C = 0.969$ s

Figure 11 Very steep area of the reference Grid B that was smoothed by a Gaussian filter whose weights are given in Table 4. Inside red rectangle 5 passes were made, while 2 were made between the red and blue rectangles (buffer area).
Figure 12 Difference between the original and smoothed grids (original – smoothed; only inside the rectangular area smoothed, since outside this area the difference is zero). It can be seen that it is right south of the western end of Vieques that the largest amount of smoothing happened.

4.0 Results
The follow section details the results of the testing the Reference Inundation model for Fajardo.

4.1 Puerto Rico Trench Source
Tables 4 and 5 show the *.in and *.lis files for 10-hours simulation for the Puerto Rico Trench source reference runs. It should be stated that for some reason the output *.lis file is incomplete. Ten hours of simulation are used to verify that there is no blowup after the first 4 hours.
0.001 Minimum amplitude of input offshore wave (m): FAJARDO

REFERENCE
0 Input minimum depth for offshore (m)
0.1 Input "dry land" depth for inundation (m)
0.0009 Input friction coefficient (n**2)
1 let a and b run up
50.0 max eta before blow up (m)
0.23 Input time step (sec)
156522 Input amount of steps (4 hrs)
1 Compute "A" arrays every n-th time step, n=
1 Compute "B" arrays every n-th time step, n=
520 Input number of steps between snapshots (120 s)
0 ... Starting from
2 ... Saving grid every n-th node, n=

Table 4 *.in Input File for 10-hours simulation for Puerto Rico Trench Reference Runs

Site: Fajardo
Minimum amplitude of input offshore wave (m): 1.0000000000000000E-003
Input minimum depth for offshore (m): 0.0000000000000000
Input "dry land" depth for inundation (m): 0.1000000000000000
Input friction coefficient (n**2): 9.0000000000000000E-004
Input runup switch (0 - runup only in gridC, 1 - runup in all grids): 1
Max allowed eta (m): 50.000000
Input time step (sec): 0.23000000
Input amount of steps: 156522
Compute "A" arrays every n-th time step, n= 1
Compute "B" arrays every n-th time step, n= 1
Input number of steps between snapshots (should be a multiple of A,B and C time steps):

Table 5 *.lis Output File for 10-hours simulation for Puerto Rico Trench Reference Runs

Figures 13 to 15 show plots of the resulting maximum elevations for Reference Grids A, B, and C, respectively. Figure 16 shows the sea surface elevation time series at the warning point for Reference Grid C.
Figure 13 Maximum elevations for Reference Grid A after 10 hours of simulation for Puerto Rico Trench source.
Figure 14 Maximum elevations for Reference Grid B after 10 hours of simulation for Puerto Rico Trench source.
Figure 15 Maximum elevations for Reference Grid C after 10 hours of simulation for Puerto Rico Trench source.

Figure 16 Sea surface elevation time series at the warning point for Reference Grid C after 10 hours of simulation for Puerto Rico Trench source.

### 4.2 Muertos Trough Source

Tables 6 and 7 show the *.in and *.lis files for 10-hours simulation for the Muertos Trough source reference runs.
Table 6 *.in Input File for 10-hours simulation for Puerto Rico Trench Reference Runs

Minimum amplitude of input offshore wave (m): 1.0000000000000000E-003
Input minimum depth for offshore (m): 0.0000000000000000
Input "dry land" depth for inundation (m): 0.1000000000000000
Input friction coefficient (n**2): 9.0000000000000000E-004
Input runup switch (0 - runup only in gridC, 1 - runup in all grids): 1
Max allowed eta (m): 50.00000
Input time step (sec): 0.2300000000000000
Input amount of steps: 156522
Compute "A" arrays every n-th time step, n= 1
Compute "B" arrays every n-th time step, n= 1
Input number of steps between snapshots (should be a multiple of A,B and C time steps) : 520

Table 7 *.lis Output File for 10-hours simulation for Puerto Rico Trench Reference Runs

Figures 17 to 19 show plots of the resulting maximum elevations for Reference Grids A, B, and C, respectively. Figure 20 shows the sea surface elevation time series at the warning point for Reference Grid C.
Figure 17 Maximum elevations for Reference Grid A after 10 hours of simulation for Muertos Trough source.

Figure 18 Elevations for Reference Grid B after 10 hours of simulation for Muertos Trough source.
Figure 19: Maximum elevations for Reference Grid C after 10 hours of simulation for Muertos Trough source.

Figure 20: Sea surface elevation time series at the warning point for Reference Grid C after 10 hours of simulation for Muertos Trough source.
4.3 Source north of South America

Tables 8 and 9 show the *.in and *.lis files for 10-hours simulation for the source north of South America. Figures 21 to 23 show plots of the resulting maximum elevations for Reference Grids A, B, and C, respectively. Figure 24 shows the sea surface elevation time series at the warning point for Reference Grid C.

| 0 Input minimum depth for offshore (m) |
| 0.1 Input "dry land" depth for inundation (m) |
| 0.0009 Input friction coefficient (n**2) |
| 1 let a and b run up |
| 50.0 max eta before blow up (m) |
| 0.23 Input time step (sec) |
| 156522 Input amount of steps (4 hrs) |
| 1 Compute "A" arrays every n-th time step, n= |
| 1 Compute "B" arrays every n-th time step, n= |
| 520 Input number of steps between snapshots (120 s) |
| 0 ...Starting from |
| 2 ...Saving grid every n-th node, n= |

Table 8 *.in Input File for 10-hours simulation for North of South America Reference Runs

Site: Fajardo
Input prefix: 32118
Input Directory: /home2/amercado/DATA/PR/Fajardo/MOST_runs_2/
Read Computational parameters:
/home2/amercado/DATA/PR/Fajardo/MOST_runs_2/most3_facts_nc.in
Minimum amplitude of input offshore wave (m): 1.0000000000000000E-003
Input minimum depth for offshore (m): 0.0000000000000000
Input "dry land" depth for inundation (m): 0.1000000000000000
Input friction coefficient (n**2): 9.0000000000000000E-004
Input runup switch (0 - runup only in gridC, 1 - runup in all grids): 1
Max allowed eta (m): 50.00000
Input time step (sec): 0.2300000000000000
Input amount of steps: 156522
Compute "A" arrays every n-th time step, n= 1
Compute "B" arrays every n-th time step, n= 1
Input number of steps between snapshots (should be a multiple of A,B and C time steps) : 520

Table 9 *.lis Output File for 10-hours simulation for North of South America Reference Runs
Figure 21 Maximum elevations for Reference Grid A after 10 hours of simulation for source north of South America.

Figure 22 Maximum elevations for Reference Grid B after 10 hours of simulation for source north of South America.
4.4 Eastern Caribbean Subduction Zone Source

Tables 10 and 11 show the *.in and *.lis files for 10-hours simulation for the source at the Eastern Caribbean Subduction Zone.
Table 10 *.in Input File for 10-hours simulation for North of Eastern Caribbean Subduction Zone Reference Runs

Minimum amplitude of input offshore wave (m): 1.0000000000000000E-003
Input minimum depth for offshore (m): 0.0000000000000000
Input "dry land" depth for inundation (m): 0.1000000000000000
Input friction coefficient (n**2): 9.0000000000000000E-004
Input runup switch (0 - runup only in gridC, 1 - runup in all grids): 1
Max allowed eta (m): 30.00000
Input time step (sec): 0.2300000000000000
Input amount of steps: 156522
Compute "A" arrays every n-th time step, n= 1
Compute "B" arrays every n-th time step, n= 1
Input number of steps between snapshots (should be a multiple of A,B and C time steps) : 520
...Starting from: 0
...Saving grid every n-th node, n= 2

Table 11 *.lis Output File for 10-hours simulation for Eastern Caribbean Subduction Zone Reference Runs

Figures 25 to 27 show plots of the resulting maximum elevations for Reference Grids A, B, and C, respectively. Figure 28 shows the sea surface elevation time series at the warning point for Reference Grid C.
Figure 25 Maximum elevations for Reference Grid A after 10 hours of simulation for Eastern Caribbean Subduction Zone source.
Figure 26 Maximum elevations for Reference Grid B after 10 hours of simulation for Eastern Caribbean Subduction Zone source.
Figure 27 Maximum elevations for Reference Grid C after 10 hours of simulation for Eastern Caribbean Subduction Zone source.

Figure 28 Sea surface elevation time series at the warning point for Reference Grid C after 10 hours of simulation for Eastern Caribbean Subduction Zone source.
4.1 Optimized Grids

Figure 29 shows outlines of the finally adopted optimized grids. These were

- Grid_A_opt_24s_v2.dat, $\Delta t_A = 3.349$ s
- Grid_B_opt_8s_v5.dat, $\Delta t_B = 2.148$ s
- Grid_C_opt_3s_v3.dat, $\Delta t_C = 3.341$ s

The optimized Grid A was obtained from the reference Grid A by re-gridding to 24 s using Surfer → Extract reading every 8 points, and passed through BATHCORR.F with wave height = 2, SP = 0.5, which modified 501 points for the first pass, 105 points for the second pass, 17 points for the third pass, 7 points for the fourth pass, 4 points for the fifth pass, 2 points for the sixth pass, 2 points for the seventh pass, and 2 points for the eighth pass. Its geographical coverage remained identical as the reference grid. Attempts were made to reduce its coverage, but they resulted in a too degraded elevation time series at the warning point of the optimized Grid C.

The optimized Grid B was obtained from the reference Grid B by re-gridding to 8 s, and passing it through BATHCORR.F with wave height = 2 m, and SP = 0.5, which corrected

The optimized Grid C was obtained from the reference Grid C by re-gridding to 3 s, and passed through BATHCORR.F with wave height = 2 m, and SP = 0.5, which corrected

Figure 29 Outline of finally adopted optimized Grids A, B, and C shown as solid line rectangles. For comparison, the finally adopted reference Grids A, B, and C are shown as dashed line rectangles. Notice that it is optimized Grid B the one which determines the maximum time step because of the deep "hole" on the southeast corner of the reference Grid B.
just 4 points, and only was pass was necessary. It was cropped several times until the 10 minutes or less CPU time condition was satisfied.

6.0 Optimized Runs Results

6.1 Puerto Rico Trench Source
Tables 12 and 13 show the *.in and *.lis files for 4-hours simulation for the Puerto Rico Trench source optimized runs.

<table>
<thead>
<tr>
<th>Table 12</th>
<th>*.in Input File for 4-hours simulation for Puerto Rico Trench Optimized Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Input minimum depth for offshore (m)</td>
<td>0.0000000000000000E-003</td>
</tr>
<tr>
<td>0.1 Input &quot;dry land&quot; depth for inundation (m)</td>
<td>0.0000000000000000</td>
</tr>
<tr>
<td>0.0009 Input friction coefficient (n**2)</td>
<td>9.0000000000000000E-004</td>
</tr>
<tr>
<td>1 let a and b run up</td>
<td>30.0 max eta before blow up (m)</td>
</tr>
<tr>
<td>2.1 Input time step (sec)</td>
<td>6862 Input amount of steps (4 hrs)</td>
</tr>
<tr>
<td>1 Compute &quot;A&quot; arrays every n-th time step, n=</td>
<td>1 Compute &quot;B&quot; arrays every n-th time step, n=</td>
</tr>
<tr>
<td>28 Input number of steps between snapshots (60.0 min)</td>
<td>0 ...Starting from</td>
</tr>
<tr>
<td>1 ...Saving grid every n-th node, n=</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 13</th>
<th>*.lis Output File for 4-hours simulation for Puerto Rico Trench Optimized Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum amplitude of input offshore wave (m): 1.0000000000000000E-003</td>
<td>Input minimum depth for offshore (m): 0.0000000000000000</td>
</tr>
<tr>
<td>Input &quot;dry land&quot; depth for inundation (m): 0.1000000000000000</td>
<td>Input friction coefficient (n**2): 9.0000000000000000E-004</td>
</tr>
<tr>
<td>Input runup switch (0 - runup only in gridC, 1 - runup in all grids): 1</td>
<td>Max allowed eta (m): 30.00000</td>
</tr>
<tr>
<td>Input time step (sec): 2.1000000000000000</td>
<td>Input amount of steps: 6862</td>
</tr>
<tr>
<td>Compute &quot;A&quot; arrays every n-th time step, n=</td>
<td>Compute &quot;B&quot; arrays every n-th time step, n=</td>
</tr>
<tr>
<td>Input number of steps between snapshots (should be a multiple of A,B and C time steps) : 28</td>
<td></td>
</tr>
</tbody>
</table>

Figures 30 to 32 show plots of the resulting maximum elevations for Optimized Grids A, B, and C, respectively. Figures 33 and 33 show the sea surface elevation time series comparison at the warning point for Optimized Grid C and Reference Grid C for 4 (RMSE = 0.507 m) and 10 (RMSE = 0.387 m) hours of simulation, respectively.
Figure 30 Maximum elevations for Optimized Grid A after 4 hours of simulation for the Puerto Rico Trench source.
Figure 31 Maximum elevations for Optimized Grid B after 4 hours of simulation for the Puerto Rico Trench source.

Figure 32 Maximum elevations for Optimized Grid C after 4 hours of simulation for the Puerto Rico Trench source.
Figure 33 Sea surface elevation time series at the warning point for Optimized Grid C after 4 hours of simulation for the Puerto Rico Trench source. (RMSE = 0.507 m)

Figure 34 Sea surface elevation time series at the warning point for Optimized Grid C after 10 hours of simulation for the Puerto Rico Trench source. (RMSE = 0.387 m)
6.2 Muertos Trough Trench Source

Tables 14 and 15 show the *.in and *.lis files for 4-hours simulation for the Muertos Trough source optimized runs.

| Minimum amplitude of input offshore wave (m): | 1.000000000000000E-003 |
| Input minimum depth for offshore (m): | 0.0000000000000000 |
| Input "dry land" depth for inundation (m): | 0.10000000000000000 |
| Input friction coefficient (n**2): | 9.000000000000000E-004 |
| Input runup switch (0 - runup only in gridC, 1 - runup in all grids): | 1 |
| Max allowed eta (m): | 30.00000 |
| Input time step (sec): | 2.1000000000000000 |
| Input amount of steps: | 6862 |
| Compute "A" arrays every n-th time step, n = | 1 |
| Compute "B" arrays every n-th time step, n = | 1 |
| Input number of steps between snapshots (should be a multiple of A,B and C time steps) : | 28 |
| ...Starting from: | 0 |
| ...Saving grid every n-th node, n = | 1 |

Table 14 *.in Input File for 4-hours simulation for Muertos Trough Optimized Runs

Figures 35 to 37 show plots of the resulting maximum elevations for Optimized Grids A, B, and C, respectively. Figures 38-39 show the sea surface elevation time series comparison at the warning point for Optimized Grid C and Reference Grid C for 4 (RMSE = 0.163 m) and 10 (RMSE = 0.173 m) hours of simulation, respectively.
Figure 35 Maximum elevations for Optimized Grid A after 4 hours of simulation for the Muertos Trough source.

Figure 36 Maximum elevations for Optimized Grid B after 4 hours of simulation for the Muertos Trough source.
Figure 37 Maximum elevations for Optimized Grid C after 4 hours of simulation for the Muertos Trough source.

Figure 38 Sea surface elevation time series at the warning point for Optimized Grid C after 4 hours of simulation for the Muertos Trough source. (RMSE = 0.163 m)
Figure 39 Sea surface elevation time series at the warning point for Optimized Grid C after 10 hours of simulation for the Muertos Trough source. (RMSE = 0.173 m)
### 6.3 Source North of South America

Tables 16 and 17 show the *.in and *.lis files for 4-hours simulation for the source North of South America optimized runs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum amplitude of input offshore wave (m)</td>
<td>0.001000000000000E-003</td>
</tr>
<tr>
<td>Input minimum depth for offshore (m)</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>Input &quot;dry land&quot; depth for inundation (m)</td>
<td>0.100000000000000</td>
</tr>
<tr>
<td>Input friction coefficient (n**2)</td>
<td>9.000000000000000E-004</td>
</tr>
<tr>
<td>Max allowed eta (m)</td>
<td>30.00000</td>
</tr>
<tr>
<td>Input time step (sec)</td>
<td>2.100000000000000</td>
</tr>
<tr>
<td>Input amount of steps</td>
<td>6862</td>
</tr>
<tr>
<td>Compute &quot;A&quot; arrays every n-th time step, n</td>
<td>1</td>
</tr>
<tr>
<td>Compute &quot;B&quot; arrays every n-th time step, n</td>
<td>1</td>
</tr>
<tr>
<td>Input number of steps between snapshots (should be a multiple of A,B and C time steps)</td>
<td>28</td>
</tr>
<tr>
<td>...Starting from</td>
<td>0</td>
</tr>
<tr>
<td>...Saving grid every n-th node, n</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 16 *.in Input File for 4-hours simulation for North of South America Optimized Runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum amplitude of input offshore wave (m)</td>
<td>1.000000000000000E-003</td>
</tr>
<tr>
<td>Input minimum depth for offshore (m)</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>Input &quot;dry land&quot; depth for inundation (m)</td>
<td>0.100000000000000</td>
</tr>
<tr>
<td>Input friction coefficient (n**2)</td>
<td>9.000000000000000E-004</td>
</tr>
<tr>
<td>Input runup switch (0 - runup only in gridC, 1 - runup in all grids)</td>
<td>1</td>
</tr>
<tr>
<td>Max allowed eta (m)</td>
<td>30.00000</td>
</tr>
<tr>
<td>Input time step (sec)</td>
<td>2.100000000000000</td>
</tr>
<tr>
<td>Input amount of steps</td>
<td>6862</td>
</tr>
<tr>
<td>Compute &quot;A&quot; arrays every n-th time step, n</td>
<td>1</td>
</tr>
<tr>
<td>Compute &quot;B&quot; arrays every n-th time step, n</td>
<td>1</td>
</tr>
<tr>
<td>Input number of steps between snapshots (should be a multiple of A,B and C time steps)</td>
<td>28</td>
</tr>
<tr>
<td>...Starting from</td>
<td>0</td>
</tr>
<tr>
<td>...Saving grid every n-th node, n</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 17 *.lis Output File for 4-hours simulation for North of South America Optimized Runs
Figures 40 to 42 show plots of the resulting maximum elevations for Optimized Grids A, B, and C, respectively. Figures 43-44 show the sea surface elevation time series comparison at the warning point for Optimized Grid C and Reference Grid C for 4 (RMSE = 0.086 m) and 10 (RMSE = 0.161 m) hours of simulation, respectively.

Figure 40 Maximum elevations for Optimized Grid A after 4 hours of simulation for the source north of South America.
Figure 41 Maximum elevations for Optimized Grid B after 4 hours of simulation for the source north of South America.

Figure 42 Maximum elevations for Optimized Grid C after 4 hours of simulation for the source north of South America.
Figure 43: Sea surface elevation time series at the warning point for Optimized Grid C after 4 hours of simulation for the source north of South America. (RMSE = 0.086 m)

Figure 44: Sea surface elevation time series at the warning point for Optimized Grid C after 10 hours of simulation for the source north of South America. (RMSE = 0.161 m)
### 6.4 Eastern Caribbean Subduction Zone Source

Tables 18 and 19 show the *.in and *.lis files for 4 hour simulation for the Eastern Caribbean Subduction Zone optimized runs.

Table 18 *.in Input file for 4 hours simulation for Eastern Caribbean Subduction Zone Optimized Runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum amplitude of input offshore wave (m)</td>
<td>1.000000000000000E-003</td>
</tr>
<tr>
<td>Input minimum depth for offshore (m)</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>Input &quot;dry land&quot; depth for inundation (m)</td>
<td>0.100000000000000</td>
</tr>
<tr>
<td>Input friction coefficient (n**2)</td>
<td>9.000000000000000E-004</td>
</tr>
<tr>
<td>Input runup switch (0 - runup only in gridC, 1 - runup in all grids)</td>
<td>1</td>
</tr>
<tr>
<td>Max allowed eta (m)</td>
<td>30.00000</td>
</tr>
<tr>
<td>Input time step (sec)</td>
<td>2.100000000000000</td>
</tr>
<tr>
<td>Input amount of steps</td>
<td>6862</td>
</tr>
<tr>
<td>Compute &quot;A&quot; arrays every n-th time step, n=</td>
<td>1</td>
</tr>
<tr>
<td>Compute &quot;B&quot; arrays every n-th time step, n=</td>
<td>1</td>
</tr>
<tr>
<td>Input number of steps between snapshots (should be a multiple of A,B and C time steps)</td>
<td>28</td>
</tr>
<tr>
<td>...Starting from</td>
<td>0</td>
</tr>
<tr>
<td>...Saving grid every n-th node, n=</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 19 *.lis Output File for 4-hours simulation for Eastern Caribbean Subduction Zone Optimized Runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum amplitude of input offshore wave (m)</td>
<td>100.00000000000000</td>
</tr>
<tr>
<td>Input minimum depth for offshore (m)</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>Input &quot;dry land&quot; depth for inundation (m)</td>
<td>0.100000000000000</td>
</tr>
<tr>
<td>Input friction coefficient (n**2)</td>
<td>9.000000000000000E-004</td>
</tr>
<tr>
<td>Input runup switch (0 - runup only in gridC, 1 - runup in all grids)</td>
<td>1</td>
</tr>
<tr>
<td>Max allowed eta (m)</td>
<td>30.00000</td>
</tr>
<tr>
<td>Input time step (sec)</td>
<td>2.100000000000000</td>
</tr>
<tr>
<td>Input amount of steps</td>
<td>6862</td>
</tr>
<tr>
<td>Compute &quot;A&quot; arrays every n-th time step, n=</td>
<td>1</td>
</tr>
<tr>
<td>Compute &quot;B&quot; arrays every n-th time step, n=</td>
<td>1</td>
</tr>
<tr>
<td>Input number of steps between snapshots (should be a multiple of A,B and C time steps)</td>
<td>28</td>
</tr>
<tr>
<td>...Starting from</td>
<td>0</td>
</tr>
<tr>
<td>...Saving grid every n-th node, n=</td>
<td>1</td>
</tr>
</tbody>
</table>
Figures 45 to 47 show plots of the resulting maximum elevations for Optimized Grids A, B, and C, respectively. Figures 48-49 show the sea surface elevation time series comparison at the warning point for Optimized Grid C and Reference Grid C for 4 (RMSE = 0.503 m) and 10 (RMSE = 0.390 m) hours of simulation, respectively. Table 20 summarizes the results of the RIM and SIM testing for Fajardo.

Figure 45 Maximum elevations for Optimized Grid A after 4 hours of simulation for the Eastern Caribbean Subduction Zone source.
Figure 46 Maximum elevations for Optimized Grid B after 4 hours of simulation for the Eastern Caribbean Subduction Zone source.

Figure 47 Maximum elevations for Optimized Grid C after 4 hours of simulation for the Eastern Caribbean Subduction Zone source.
Figure 48: Sea surface elevation time series at the warning point for Optimized Grid C after 4 hours of simulation for the Eastern Caribbean Subduction Zone source. (RMSE = 0.503 m)
Figure 49 Sea surface elevation time series at the warning point for Optimized Grid C after 10 hours of simulation for the Eastern Caribbean Subduction Zone source. (RMSE = 0.390 m)
Table 20 Final set up for the Fajardo SIM and RIM.

5.0 Summary and Conclusions –

6.0 Acknowledgements
This research was funded by the NOAA Center for Tsunami Research (NCTR). Thanks to Frank González, Vasily Titov, Mick Spillane, Barry Eakins, Lisa Taylor, Chris Chamberlin, and Jean Newman. Special thanks to Diego Arcas, Harry Justiniano, Maritza Pagan, Nilda Aponte, and the Faculty of Arts and Sciences of the University of Puerto Rico, Mayagüez Campus.

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7.0 References


8.0 Appendix A

8.1 RIM *.in file for Fajardo, Puerto Rico

0.001 Minimum amplitude of input offshore wave (m): FAJARDO REFERENCE
0 Input minimum depth for offshore (m)
0.1 Input "dry land" depth for inundation (m)
0.0009 Input friction coefficient (n**2)
1 let a and b run up
30.0 max eta before blow up (m)
0.23 Input time step (sec)
156522 Input amount of steps (4 hrs)
1 Compute "A" arrays every n-th time step, n=
1 Compute "B" arrays every n-th time step, n=
520 Input number of steps between snapshots (2 min)
0... Starting from
2... Saving grid every n-th node, n=

Fajardo reference run (10 hrs) Eastern Caribbean Subduction Zone - Att 2