REPORT ON PUERTO RICO TSUNAMI FLOOD MAPS FOR <u>FAR-FIELD</u> EVENTS

submitted to the

Puerto Rico component of the

United States National Tsunami Mitigation Program

and the

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INTRODUCTION

This report concerns the tsunami inundation modeling carried out for far-field tsunamis.

MODEL USED

MOST, version most3_facts_nc.f. A constant Manning coefficient of 0.003 was used, a value suggested by Dr. Diego Arcas (PMEL) when I was doing SIFT maps.

BATHYMETRY/TOPOGRAPHY USED

The version of MOST used comes in two parts. The first one has to do with generation and propagation of the tsunami. Figure 1 show the propagation grid used for far-field tsunamis in the North Atlantic, which has a resolution of 120 arc seconds (approximately 3600 m at the latitude of Puerto Rico and 2366 at 50° N). This grid was prepared from the GEBCO_08 data base, that comes with 30 arc seconds resolution.

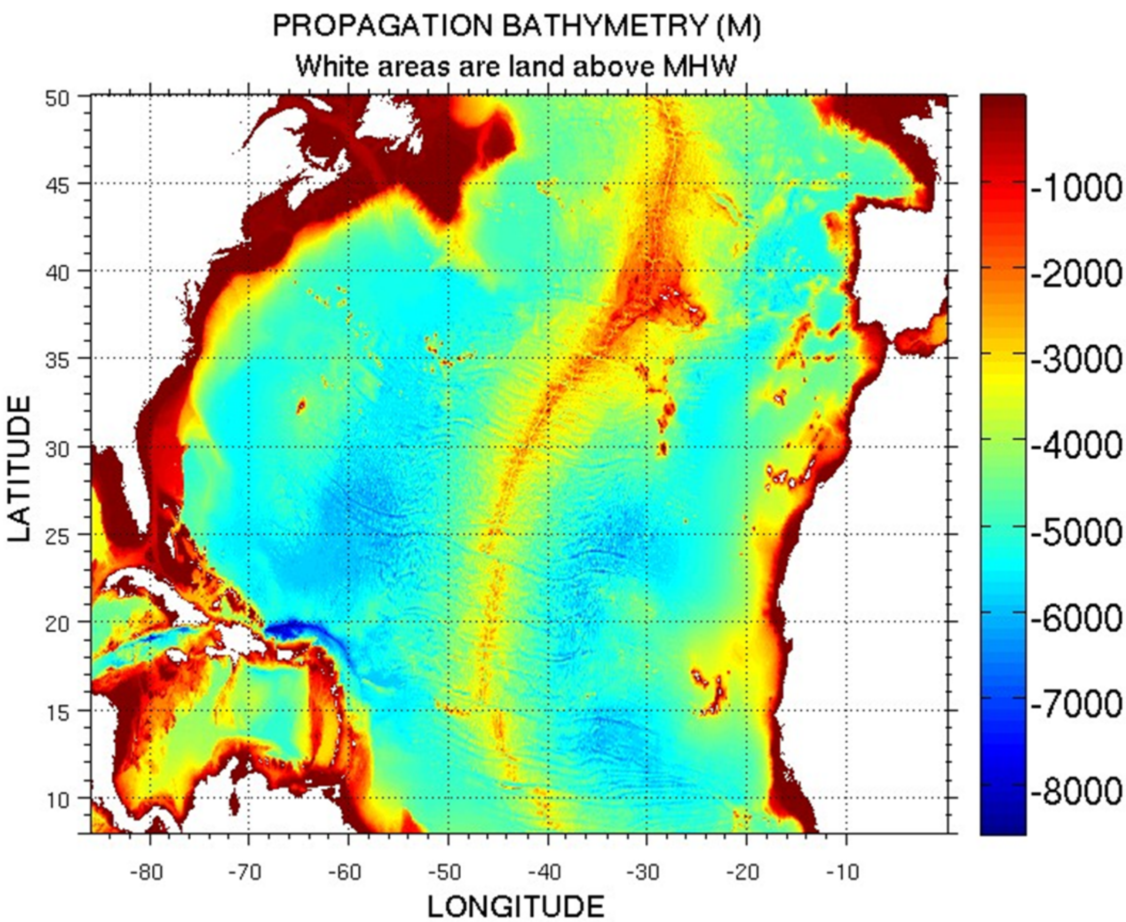

Figure 1 – Propagation grid. Computational cell resolution: 60 arc seconds.

The GEBCO data had to be smoothed six times with the smoothing Fortran program supplied with MOST. This program is called bathcorr.f, and at all times the smoothing parameter was set to 1 (least smoothing). Figure 2 shows the difference between the original, unsmoothed, grid and the smoothed grid. It can be seen that the smoothing is limited to islands, seamounts, trenches, canyons, mostly near the coast. The green color represents the case where the difference (unsmoothed – smoothed) came out positive, and the blue color shows negative values. Positive values (green) imply that the depths of islands and seamounts have been decreased by the smoothing, as expected. Negative values (blue) imply that the smoothing has decreased the depths of seafloor depressions (trenches, canyons, etc.).

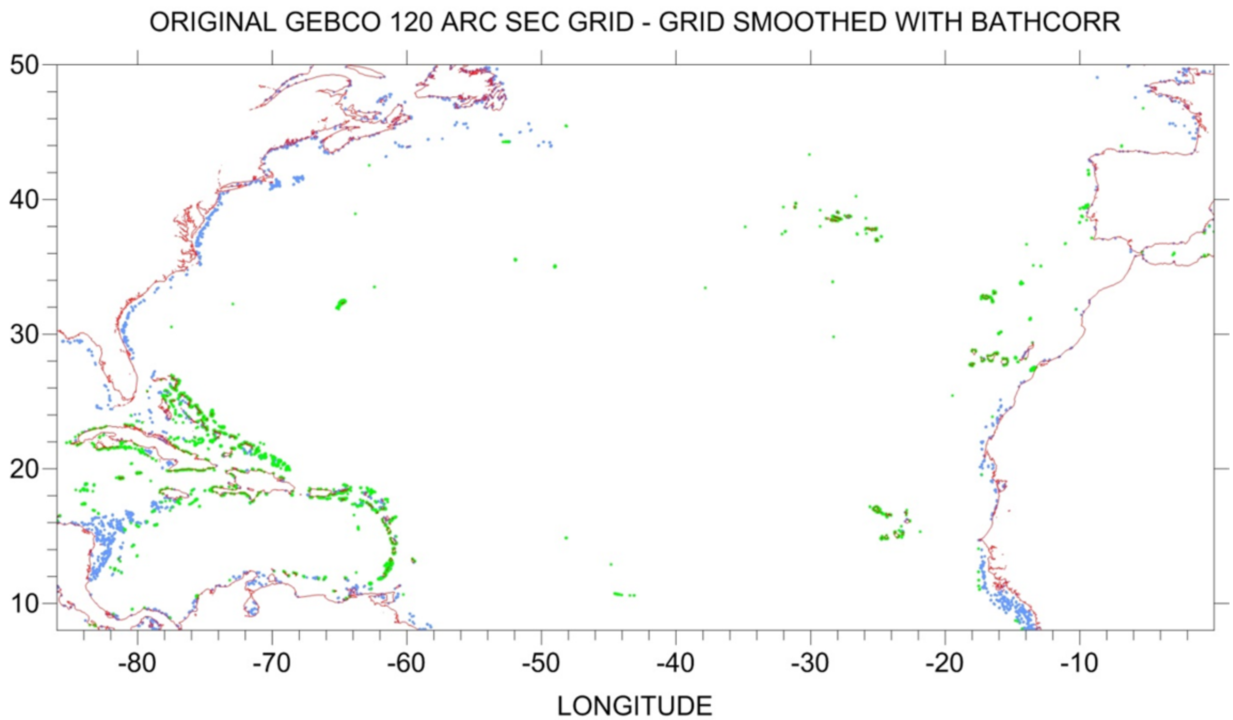

Figure 2 – Green color means smoothing of islands, or seamounts. Blue means smoothing of trenches, or canyons.

The propagation phase was done with a resolution of 120 arc seconds, but results had to be stored at 960 arc seconds resolution due to array size limitations in the inundation version of MOST used. Although the inundation version can handle inundation grids of 3000 x 3000 computational cells, apparently the propagation grid size it can read is much smaller than 3000 x 3000. This implies that the tsunami boundary conditions reaching the outer inundation grid (A) are given at approximately 28.8 km spacing at our geographical latitude.

The second part takes care of the inundation phase. Due to software limitations, and to the desire to do high-resolution inundation modeling (30 m resolution), Puerto Rico (including its two island municipalities at the east: Vieques and Culebra) was broken down into three parts: East, Central, and West. This is shown in Figure 2, which shows the geographical coverage of the three inundation grids. Grid A is the larger, lower resolution, grid. Grid B is the intermediate resolution grid (9 arc seconds; approximately 270 m resolution). The inner grids (Grids C) are three (east, central, west), each with a resolution of 1 arc second (approximately 30 m).

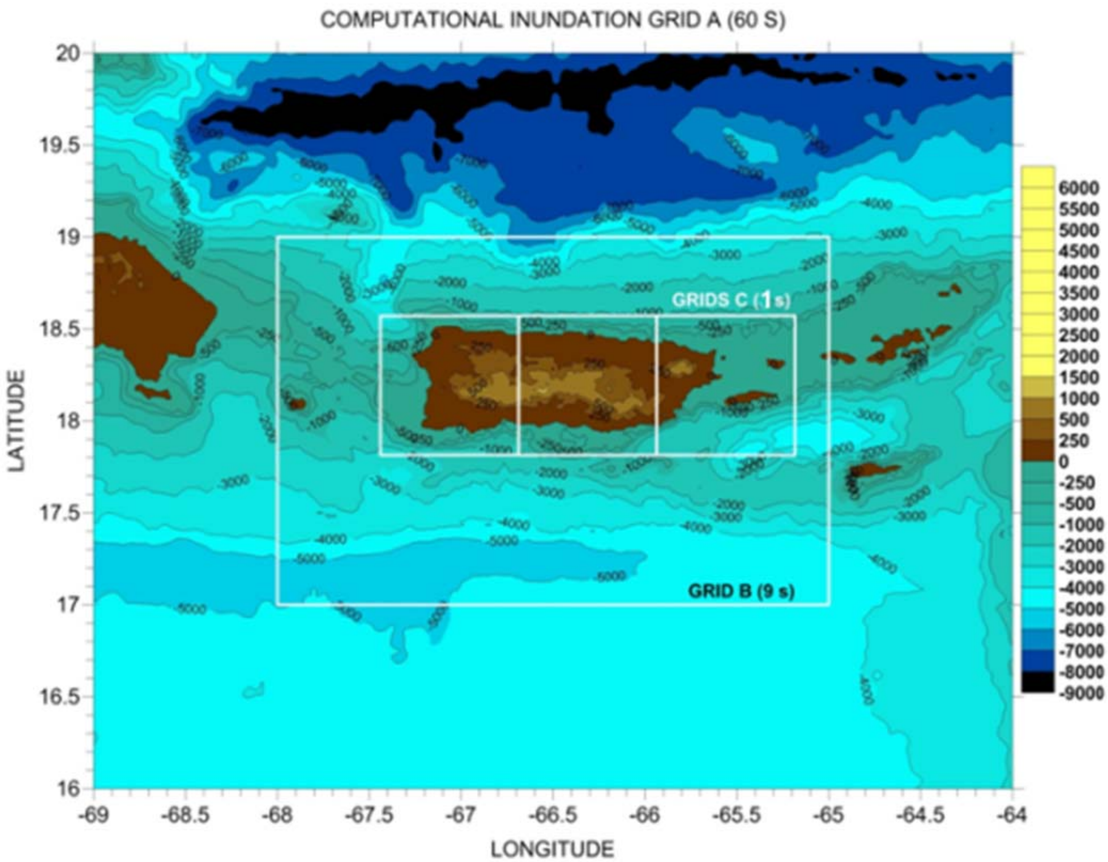

Figure 3 - Computational inundation Grid A. The outlines of the in8undation Grids B and C are also shown.

Figures 4 to 6 show each individual inundation grid. They also show the location of tsunami-ready tide gauges (white crosses) and a few additional virtual ones placed for coverage purposes. Below each figure the parameters describing each grid are given. Tables 1 to 3 show individual basics statistics for each inundation grid.

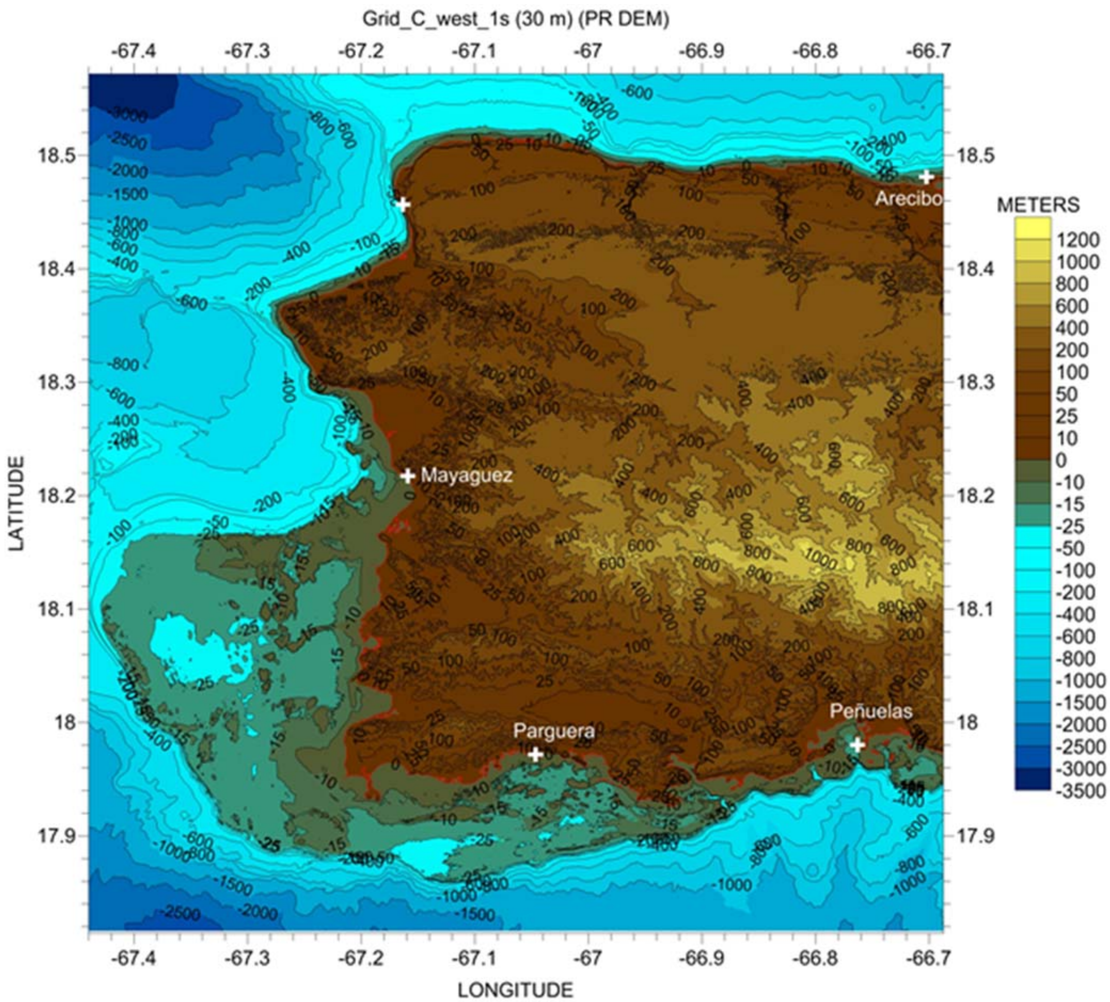

Figure 4 – High-resolution Grid C west used for inundation modeling. White crosses indicate location of tsunami-ready tide gauges.

Table 1: Basic statistics for the West inundation grid.

Cwest	
Grid File Name:	west.grd
Grid Size:	2752 rows x 2845 columns
Total Nodes:	7829440
Grid Geometry	
X Minimum:	-67.360972212943
X Maximum:	-66.570972209053
X Spacing:	0.00027777777914557 (30 m)
Y Minimum:	17.81625001
Y Maximum:	18.58041668
Y Spacing:	0.00027777777898946 (30 m)
Zmin:	-2999.49993302
Zmax:	1330.41986484
Δt:	0.17 sec

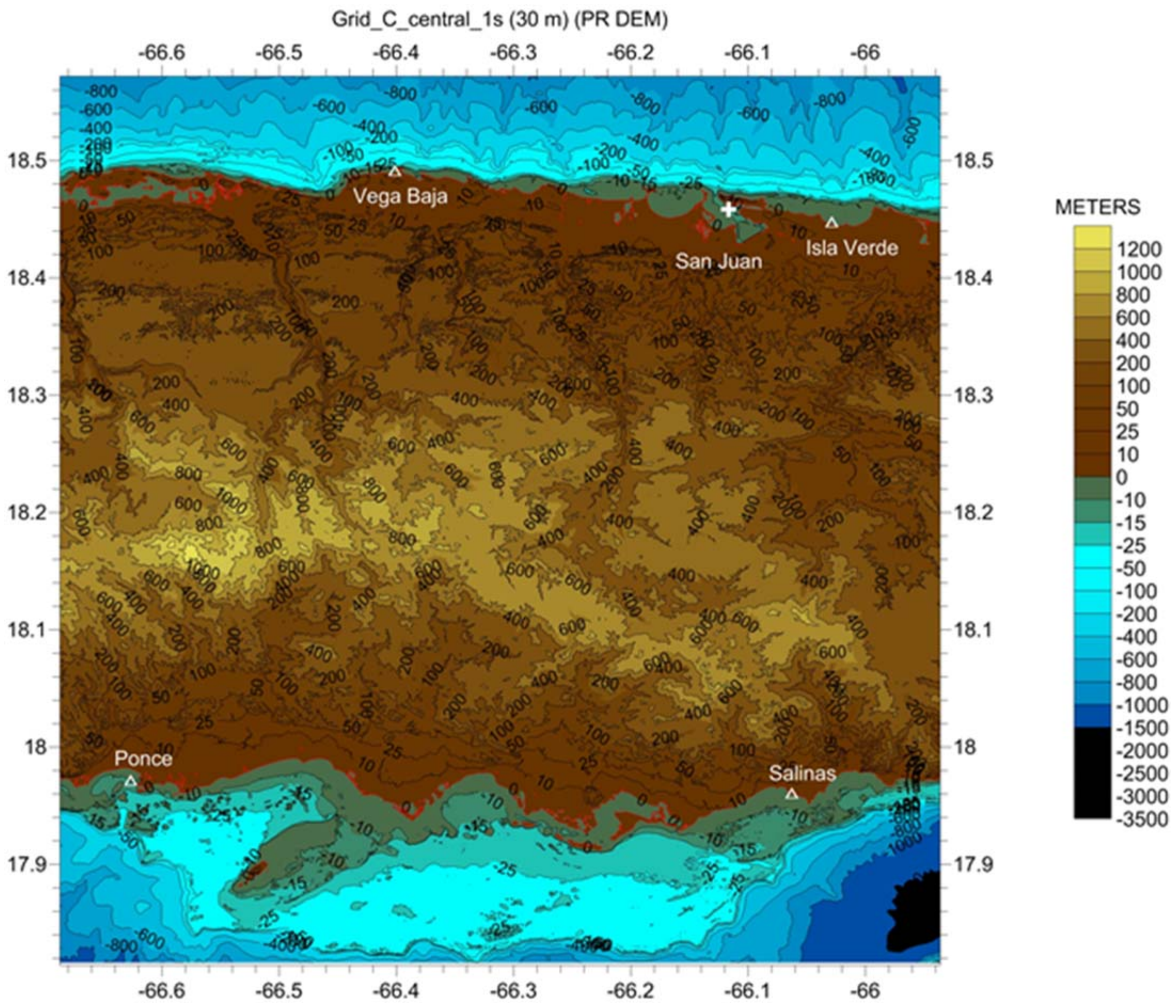

Figure 5 -High-resolution Grid C west used for inundation modeling. White crosses indicate location of tsunami-ready tide gauges. White triangles are supplementary virtual tide stations.

Table 2: Basic statistics for the Central inundation grid.

Ccentral	
Grid File Name:	central.grd
Grid Size:	2752 rows x 2843 columns
Total Nodes:	7823936
Grid Geometry	
X Minimum:	-66.57208332017
X Maximum:	-65.782638871838
X Spacing:	0.00027777777914567 (30 m)
Y Minimum:	17.81625001
Y Maximum:	18.58041668
Y Spacing:	0.00027777777898946 (30 m)
Zmin:	-1989.91999738
Zmax:	1300.88983793
Δt:	0.21 sec

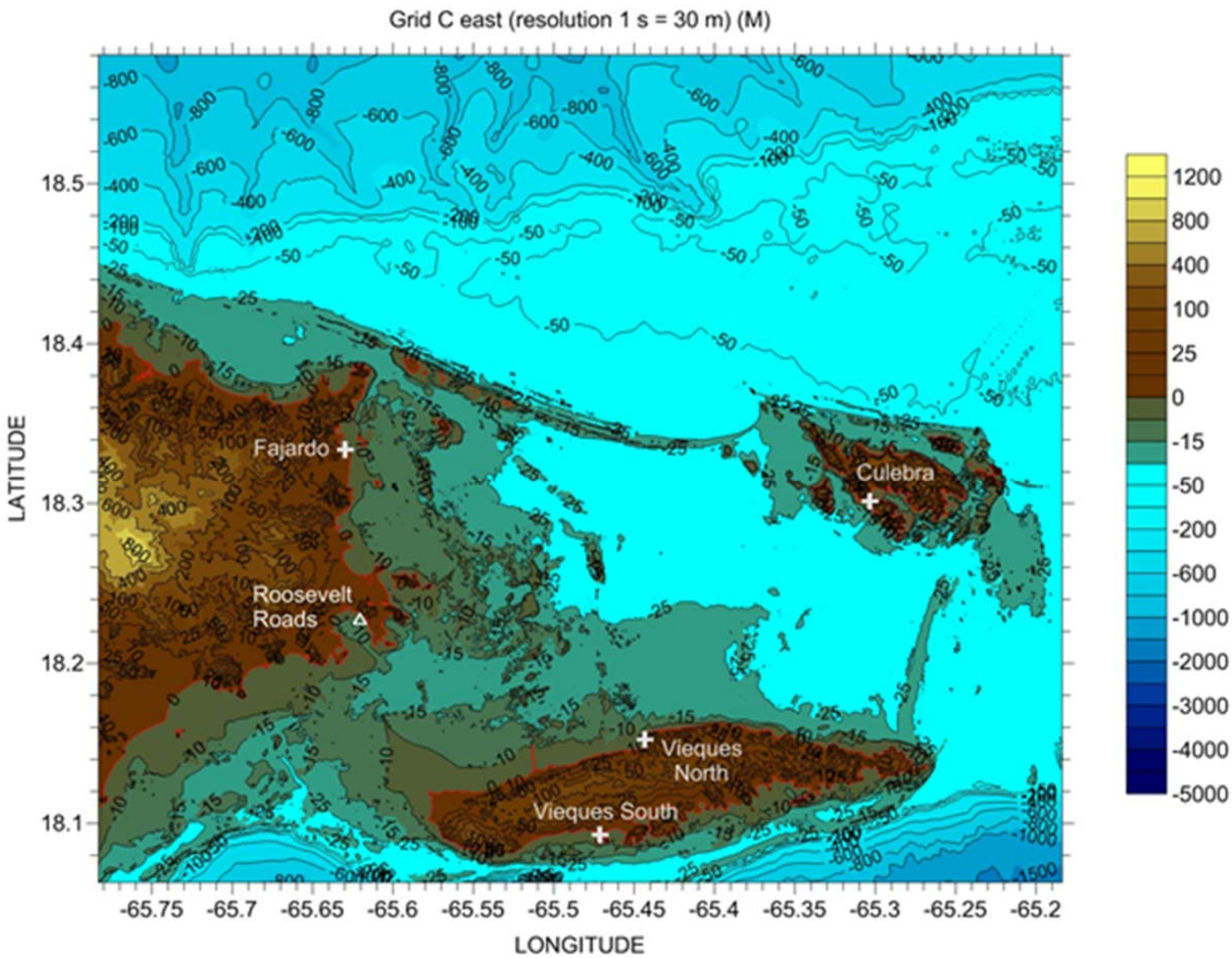

Figure 6 - **High-resolution Grid C west used for inundation modeling. White crosses indicate location of tsunami-ready tide gauges. White triangles are supplementary virtual tide stations.**

Table 3: Basic statistics for the East inundation grid.

Ceast	
Grid File Name:	east.grd
Grid Size:	1863 rows x 2159 columns
Total Nodes:	4022217
Grid Geometry	
X Minimum:	-65.783194427396
X Maximum:	-65.18374998
X Spacing:	0.0002777777791455 (30 m)
Y Minimum:	18.063194455522
Y Maximum:	18.58041668
Y Spacing:	0.00027777777898926 (30 m)
Zmin:	-1796.88990318
Zmax:	1041.68996102
Δt:	0.22 sec

Finally, Figure 6 shows the mosaic generated by joining the three grids. Model results will be shown for each individual grid, and for the mosaic. Movies can only be shown for the individual grids.

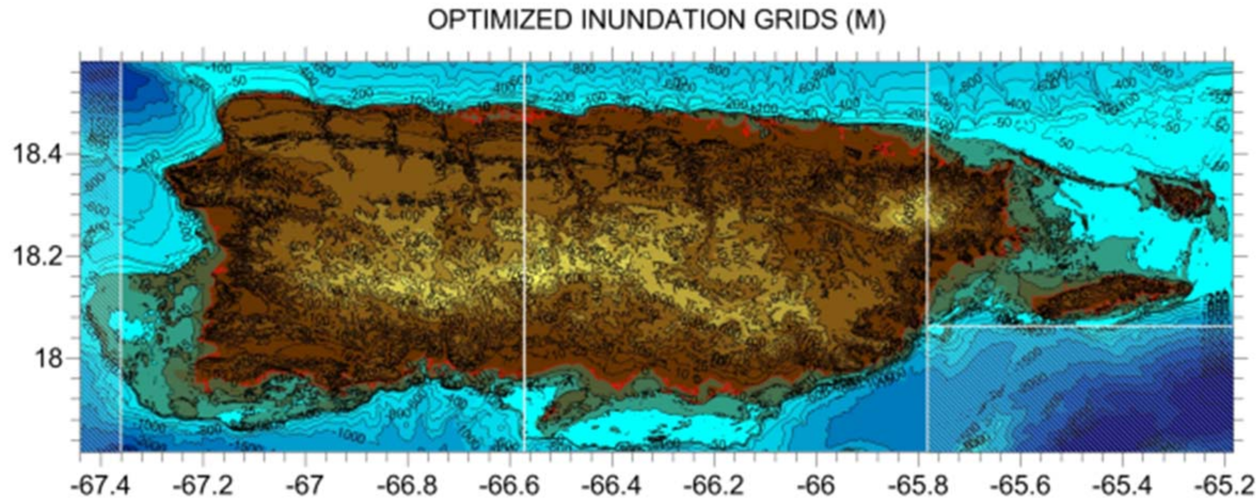

Figure 7 – Mosaic of the three inundation grids. In the final east grid the southern part was cutoff in order to speed up the computations. The section that was cutoff corresponds to the rectangle at the southeast corner of the mosaic.

In order to have an idea of the strength of the tsunami signal reaching the island, and its duration, virtual gauges were placed offshore of each one of the four coasts at a sufficient water depth so that nonlinear effects should not be manifested. The location of each gauge is shown in Table 4.

Table 4: Location of offshore virtual tide gauges for propagation purposes

Gauge	Longitude (°)	Latitude (°)	Water Depth (m)
North coast	-66.48332863	18.500000263	224
West coast	-67.24999545	18.2000002568421	150
South coast	-66.48332863	17.850002494	50
East coast	-65.44999509	18.300002589474	31

Figure 7 shows the location of the gauges.

Figure 8 – Google Earth view of the location of offshore wave bouys used for observing propagation time series.

For each tsunami scenario we will present a table listing the input parameters used to execute the generation/propagation runs, and another table showing the input parameters used to execute the inundation runs. For the propagation results three figures will be shown:

- Figure of the initial bottom deformation. In this figure the lower and upper limits of the color bar is set based on the minimum and maximum deformations.
- Figure of the maximum water elevation attained in each computational cell, relative to Mean High Water (this is the vertical datum of the NGDC DEM). This is what is called the Maximum Envelope of Highest Waters (MEOHW). In this figure the upper limit of the color bar is set based on the maximum sea surface elevation computed anywhere in the computational grid.
- The four offshore time series mentioned above.

For the inundation runs, and for each one of the three inundation grids, three figures will be shown:

- A figure showing the MEOHW for that grid (relative to MHW). In these figures the upper limit of the color bar is fixed at a value of 2 m above MHW. But each figure will list the maximum water relative to MHW attained somewhere in the grid, and its location.
- A figure showing the inundation water depth (that is, relative to the local terrain elevation). These are symbolized by the string LWD. The upper limit of the color bar is also set at 2 m.
- A figure showing the time series of water elevation at each of the water gauges for each of the three inundation grids.
- A figure showing a mosaic (that is, all three inundation grids put together) of the MEOHW.

- A figure showing a mosaic of the inundation water depth (that is, relative to the local terrain elevation). This is symbolized by the string LWD.
- A figure showing a mosaic where areas with sea surface elevations above 1 m are painted red, sea surface elevations between 0.3 and 1 m are painted gold, sea surface elevations above 0 m and 0.29 m are painted blue, and areas not flooded are painted white.
- In addition, for each of the three inner grids movies and kmz files are available. A kmz is also available for the mosaics.

We next proceed with showing the results.

FAR-FIELD SCENARIO

The only far-field trans-Atlantic scenario in recorded history has been the 1755 Lisbon tsunami. There has been a lot of research about the location of this tsunami. For our purpose, which is to have an idea of the worst case scenario affecting Puerto Rico's coast due to an event coming from the known 1755 event generation region, it is then best to make use of the results obtained by Barkan et al. (2009). They examined, and made computer simulations, for several sources, including rotating the fault strike over 360° at 15° interval. They concluded that the "A fault strike of 345° yields the highest amplitude in the Caribbean in accordance with historical records" (see page 115, section 4.2 of their paper). They then examined different possible source locations and concluded that the modeling pointed towards their sources 5 and 8 in the Horseshoe Plain (see page 115, section 4.3). These two sources are relatively close to each other (28.8 km apart), as shown in Figures 9 and 10. As mentioned in their paper, these locations correspond to the center of the upper border of the deformation plane.

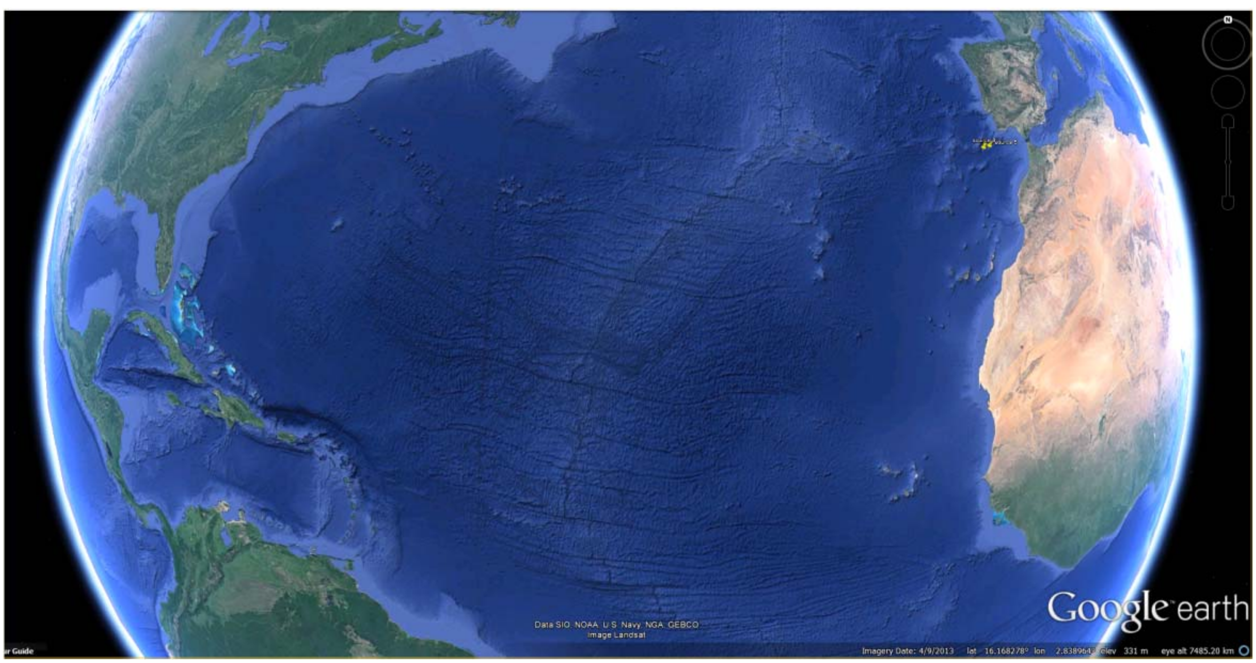

Figure 9 – Google Earth view of the location of two potential sources for the 1755 event.

Figure 10 – Google Earth view of the location of two potential sources for the 1755 event. Zoom of Figure 9 near source location.

For our purposes we will use scenario 5. The fault parameters are taken from their Table 4, shown below as Table 5.

Table 5: Fault parameters as given by Barkan et al. 2009.

Depth (km)	Length (km)	Width (km)	Average Slip (m)	Rake (°)
5	200	80	13.1	90

The depth corresponds to the top of the fault plane.

As mentioned above, the strike is taken as 345°, and the center of the finite fault for scenario 5 is (see their Table 3) -10.753° longitude and 36.042° latitude. Based on these coordinates and the strike, we determined the coordinates of the origin of the fault by moving along the direction 345° – 180° = 165° (SSE) for half the strike length (200/2 = 100 km) (see Figure 11). Recall that the location coordinates given were of the center of the fault. These new coordinates came out as -10.468° longitude and 35.173° latitude. The new coordinates were obtained using the Matlab function **reckon.m**. Overall, the fault parameters used for the simulation are given in the table below.

Table 6 shows the input fault parameters for the propagation version of MOST. Table 7 shows the input parameters for the inundation version of MOST.

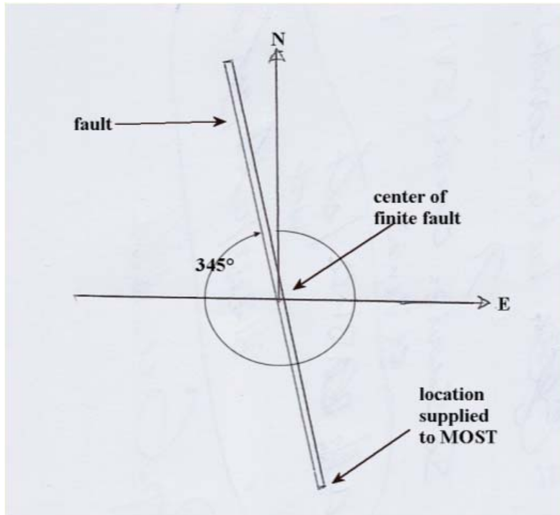

Figure 11 – Schematic of the chosen fault strike.

LISBON 1755?

As stated above, the following fault parameters are taken from Barkan et al. (2009). The question mark at the end of LISBON 1755 is due to the fact that there is yet no general agreement as to the location, nor parameters, of the 1755 event. This is just one of several that have been postulated.

Table 6: Input parameter file for generation/propagation run.

```
######################## SEGMENT 1 ####################################################
Longitude: -10.4682578518
Latitude: 35.172984
Length (km): 200.
Width (km): 80.
DIP (deg): 40.
RAKE (deg): 90.0
STRIKE (deg): 345.
SLIP (m): 13.1
DEPTH (km): 5.0
```

Table 7: Input parameter file for inundation runs (one for each computational grid: West, Central, East)

WEST	
0.0050	Minimum amp. of input offshore wave (m)
5.0	Minimum depth of offshore (m)
0.1	Dry land depth of inundation (m)
0.0009	Friction coefficient (n**2)
1	Let A-Grid and B-Grid run up
200.0	Max eta before blow-up (m)
0.12	Time step (sec)******** reduced (from 0.16) time step to see if we get rid of garbage
60000	Total number of time steps in run (2 hrs)
48	Time steps between A-Grid computations
8	Time steps between B-Grid computations
240	Time steps between output steps (28.8 s)
1	Time steps before saving first output step

```
1          Save output every n-th grid point
'/home4/amercado/NTHMP_PR/inundation/grids/grid_A_60s_inun_v2.dat'
'/home4/amercado/NTHMP_PR/inundation/grids/grid_B_9s_inun_v2.dat'
'/home4/amercado/NTHMP_PR/inundation/grids/west_v3.dat'
'/home4/amercado/Regional_tsunamis/Caribe_Wave-Lantex_2013/propagation/'
'./'
0 0 1 1 Produce/Suppress netCDF output for grids (default: 1 1 1 0)
0      Number of timeseries locations
3 1008 1430 timeseries index (grid number, i, j)
```

CENTRAL

```
0.0050  Minimum amp. of input offshore wave (m)
5.0     Minimum depth of offshore (m)
0.1     Dry land depth of inundation (m)
0.0009  Friction coefficient (n**2)
1       Let A-Grid and B-Grid run up
200.0   Max eta before blow-up (m)
0.18    Time step (sec)
40000   Total number of time steps in run (2 hrs)
30      Time steps between A-Grid computations
5       Time steps between B-Grid computations
90      Time steps between output steps (18 s)
1       Time steps before saving first output step
1       Save output every n-th grid point
'/home4/amercado/NTHMP_PR/inundation/grids/grid_A_60s_inun_v2.dat'
'/home4/amercado/NTHMP_PR/inundation/grids/grid_B_9s_inun_v2.dat'
'/home4/amercado/NTHMP_PR/inundation/grids/central.dat'
'/home4/amercado/Regional_tsunamis/Caribe_Wave-Lantex_2013/propagation/'
'./'
0 0 1 1 Produce/Suppress netCDF output for grids (default: 1 1 1 0)
0      Number of timeseries locations
3 1008 1430 timeseries index (grid number, i, j)
```

EAST

```
0.0050  Minimum amp. of input offshore wave (m)
5.0     Minimum depth of offshore (m)
0.1     Dry land depth of inundation (m)
0.0009  Friction coefficient (n**2)
1       Let A-Grid and B-Grid run up
200.0   Max eta before blow-up (m)
0.17    Time step (sec)
42353   Total number of time steps in run (2 hrs)
35      Time steps between A-Grid computations
5       Time steps between B-Grid computations
140     Time steps between output steps (23.5 s)
1       Time steps before saving first output step
1       Save output every n-th grid point
'/home4/amercado/NTHMP_PR/inundation/grids/grid_A_60s_inun_v2.dat'
```

```
'/home4/amercado/NTHMP_PR/inundation/grids/grid_B_9s_inun_v2.dat'
'/home4/amercado/NTHMP_PR/inundation/grids/east.dat'
'/home4/amercado/Regional_tsunamis/Caribe_Wave-Lantex_2013/propagation/'
'./'
0 0 1 1 Produce/Suppress netCDF output for grids (default: 1 1 1 0)
0       Number of timeseries locations
3 1008 1430 timeseries index (grid number, i, j)
```

RESULTS

Figures 12 and 13 show the sea surface deformation according to the Okada model included in MOST. It can be seen that the deformation had a ridge of more than 7 m in elevation (7.7 m the maximum)

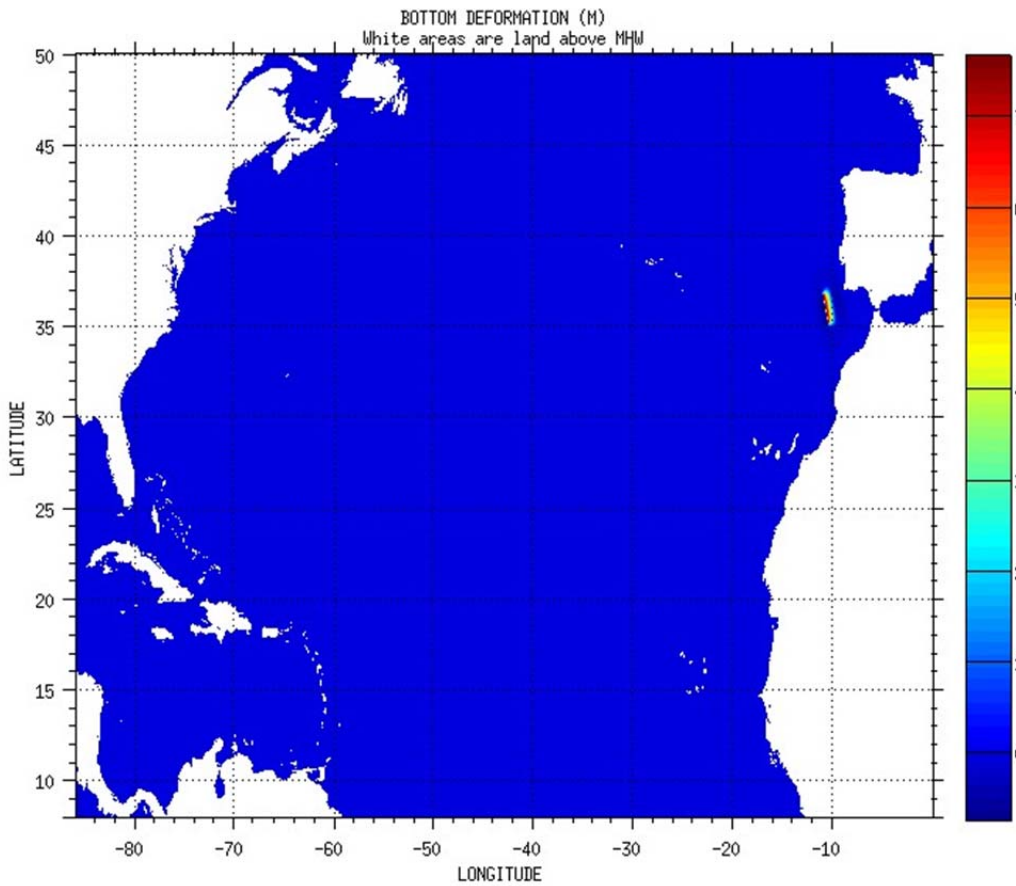

Figure 12 – Sea surface deformation for fault parameters given in Table 6.

Figure 14 shows Propagation grid Maximum Envelope of Waters (MEOW). Figure 15 shows the time series at the four offshore virtual tide gauges whose locations are given in Table 4. Figure 16 shows the MEOW for the West inundation grid. Figure 17shows the LWD for the West inundation grid. Figure 18 shows the MEOW for the Central inundation grid. Figure 19 shows the MEOW for the West inundation grid. Figure 20 shows the MEOW for the East inundation grid. Figure 21shows the LWD for the East inundation grid.

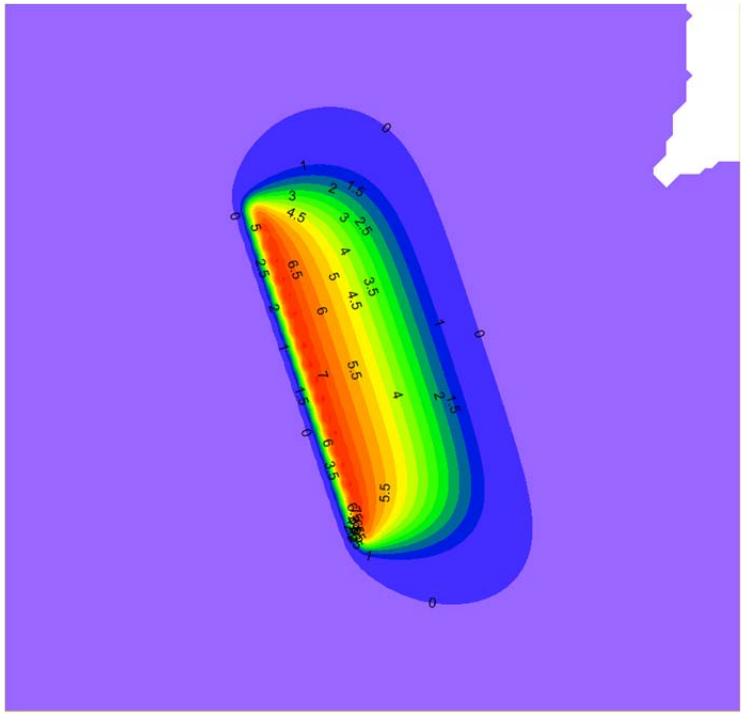

Figure 13 – Zoom of bottom deformation for scenario 5 in Barkan et al. (2009).

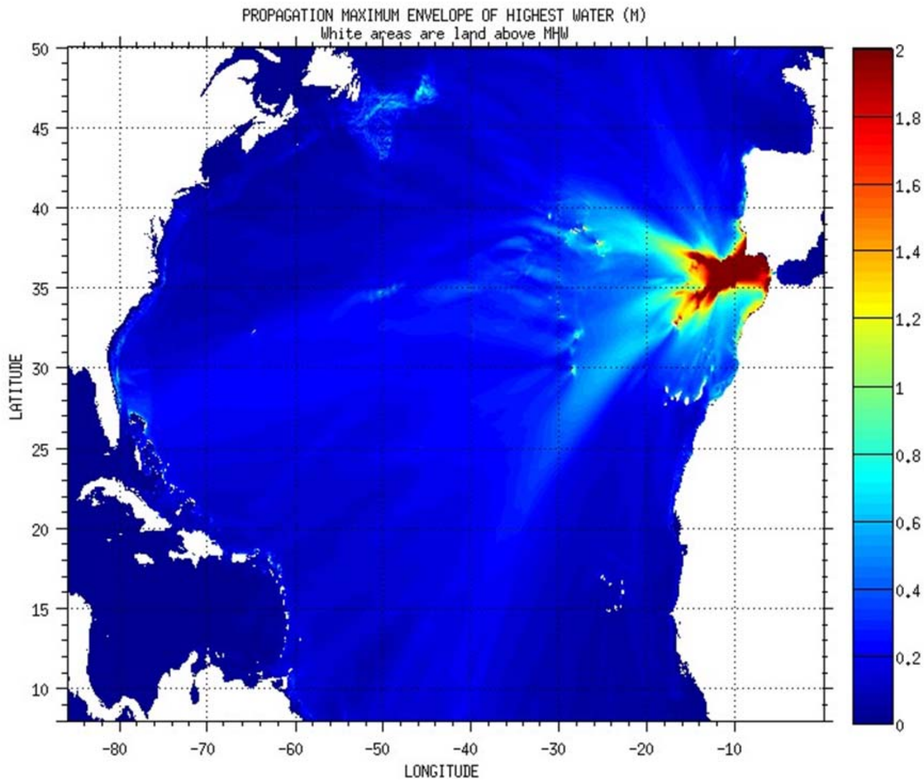

Figure 14 – Propagation grid Maximum Envelope of Waters (MEOW). The upper limit of the colorbar was forced to stay at a maximum of 2 m in order to better discern the energy propagating towards the Caribbean region.

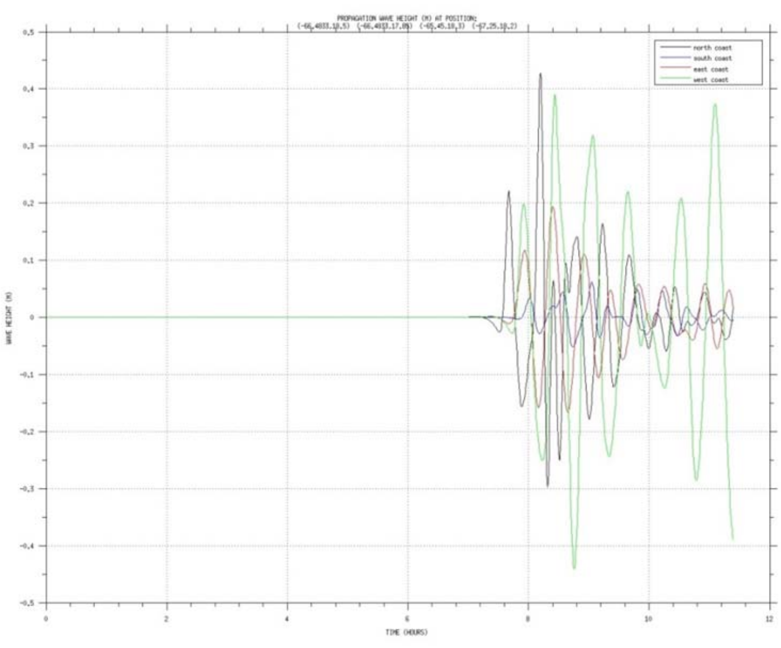

Figure 15 - Time series at the four offshore virtual tide gauges whose locations are given in Table 4.

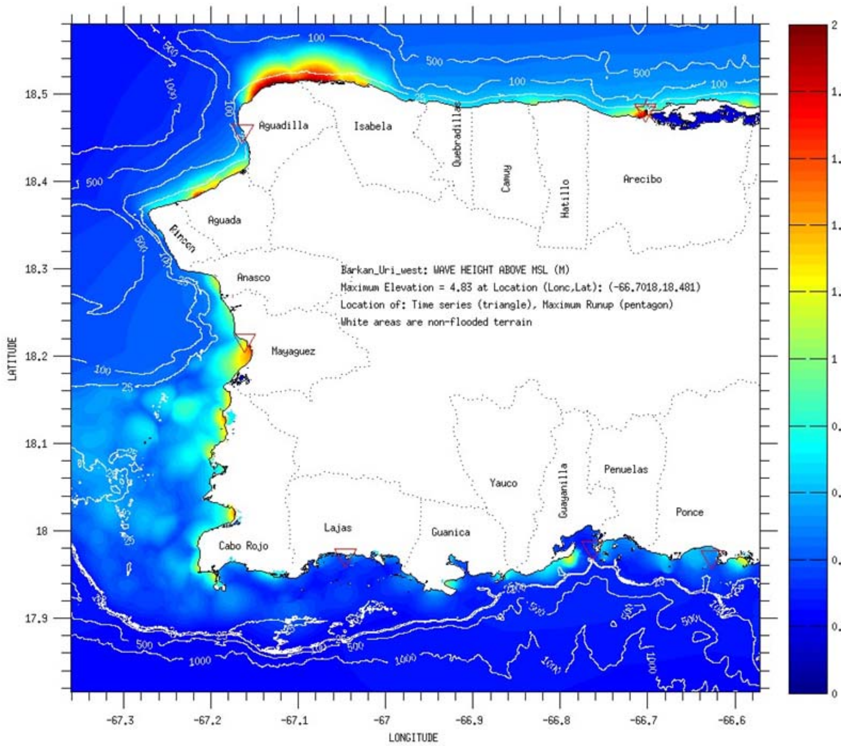

Figure 16 – MEOW for the West inundation grid.

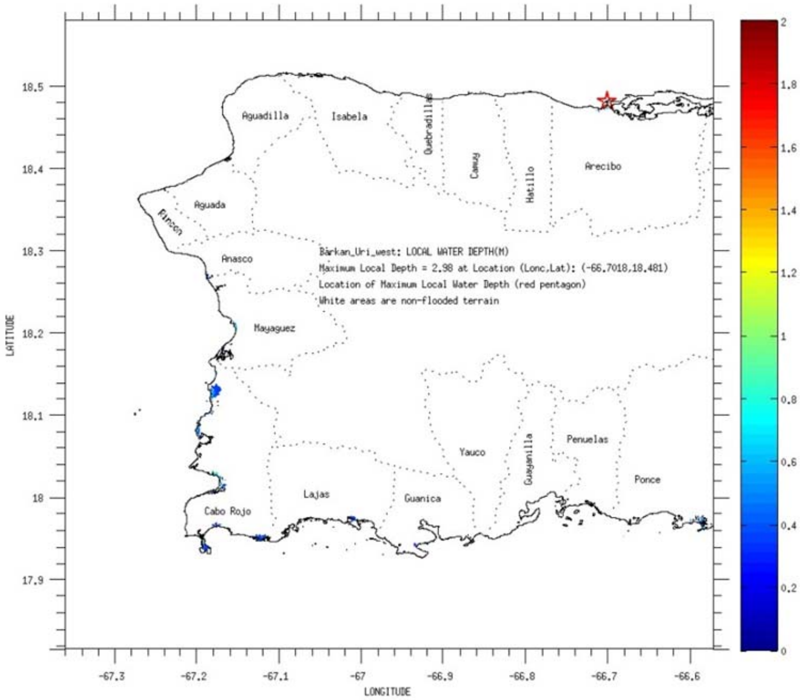

Figure 17– LWD for the West inundation grid.

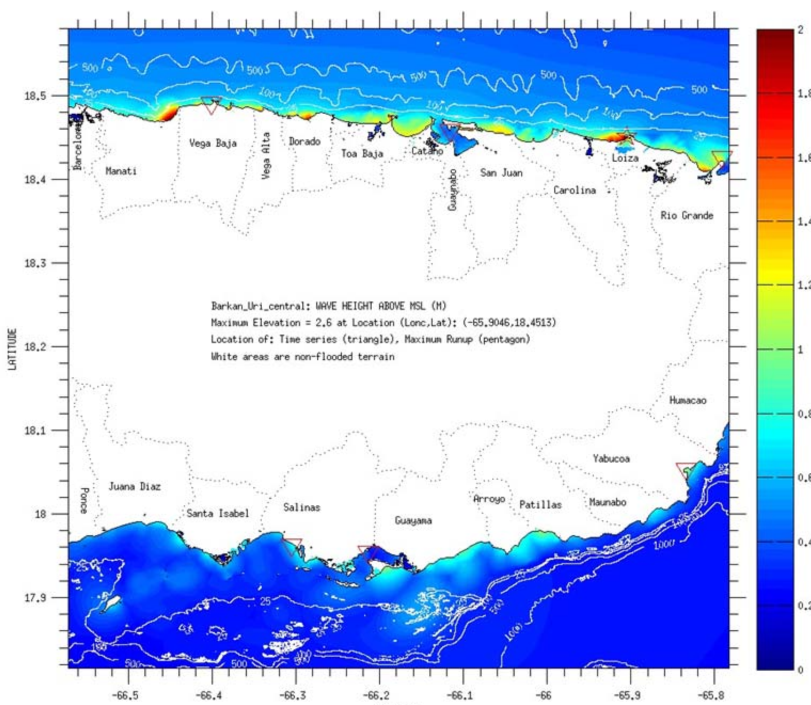

Figure 18 – MEOW for the Central inundation grid.

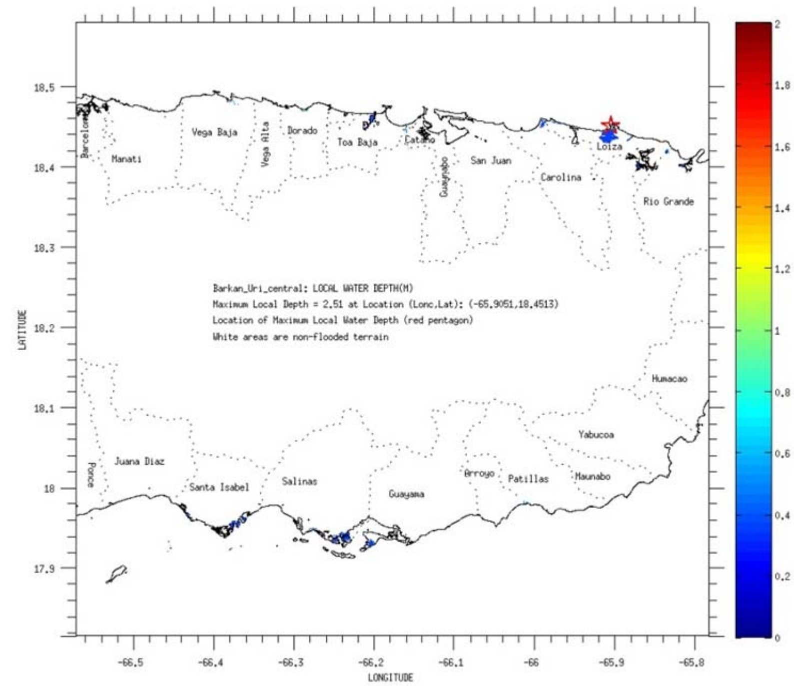

Figure 19 – MEOW for the West inundation grid.

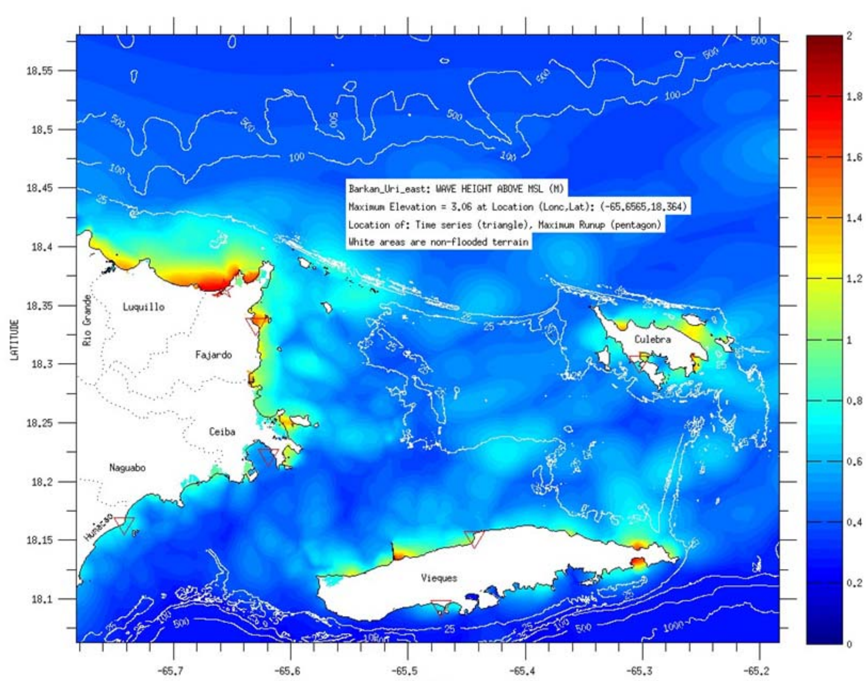

Figure 20 – MEOW for the East inundation grid.

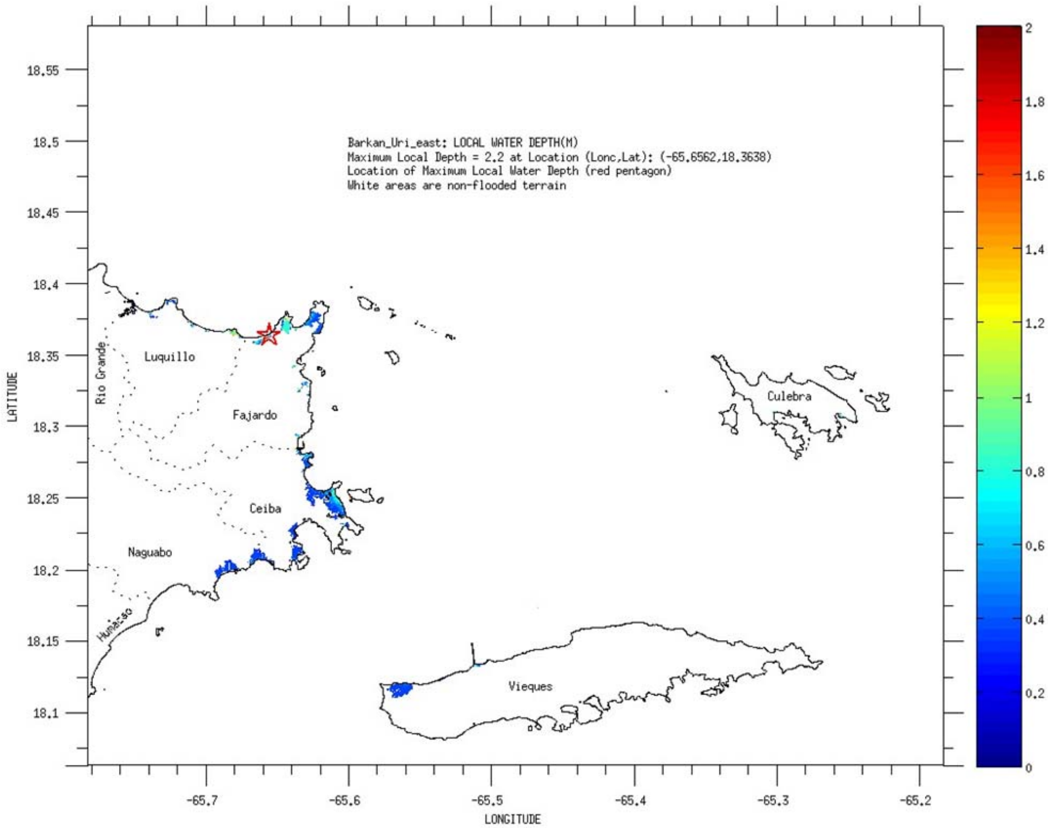

Figure 21– LWD for the East inundation grid.

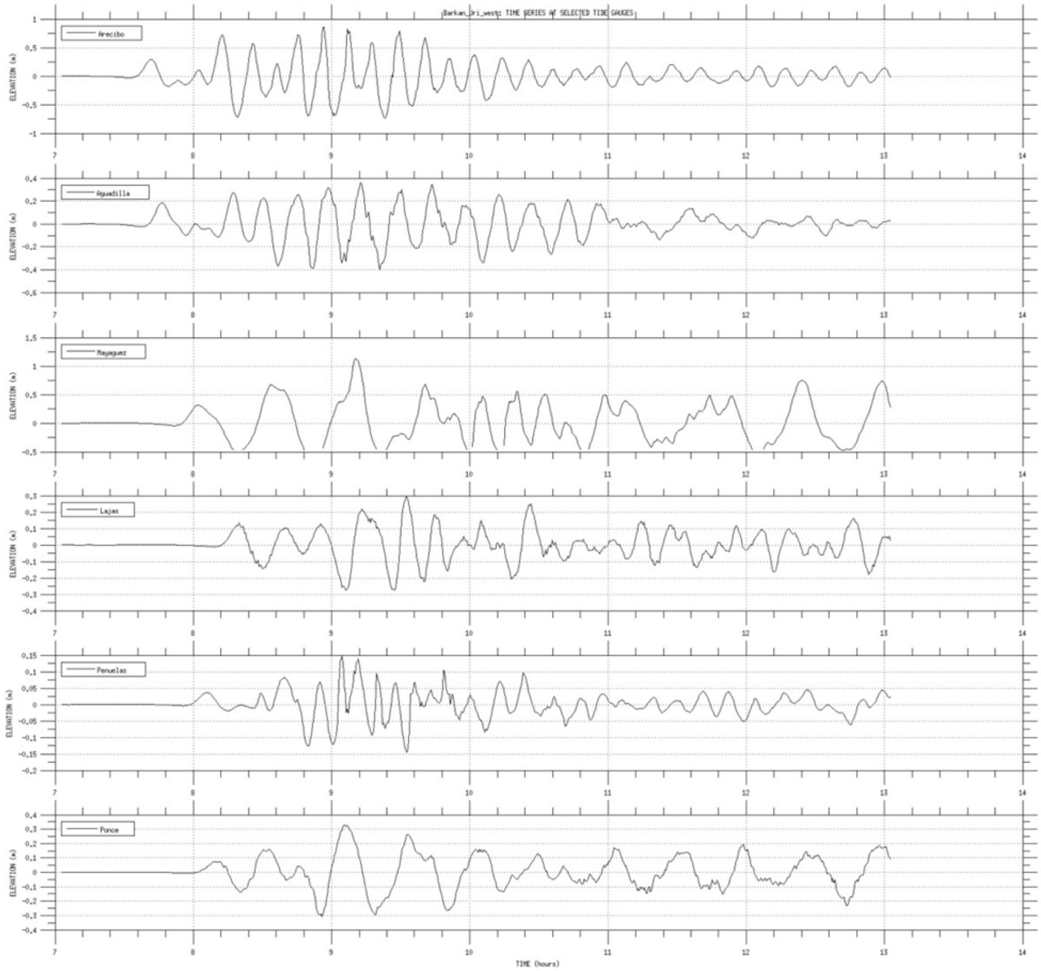

Figure 22 – Inundation time series for the West grid.

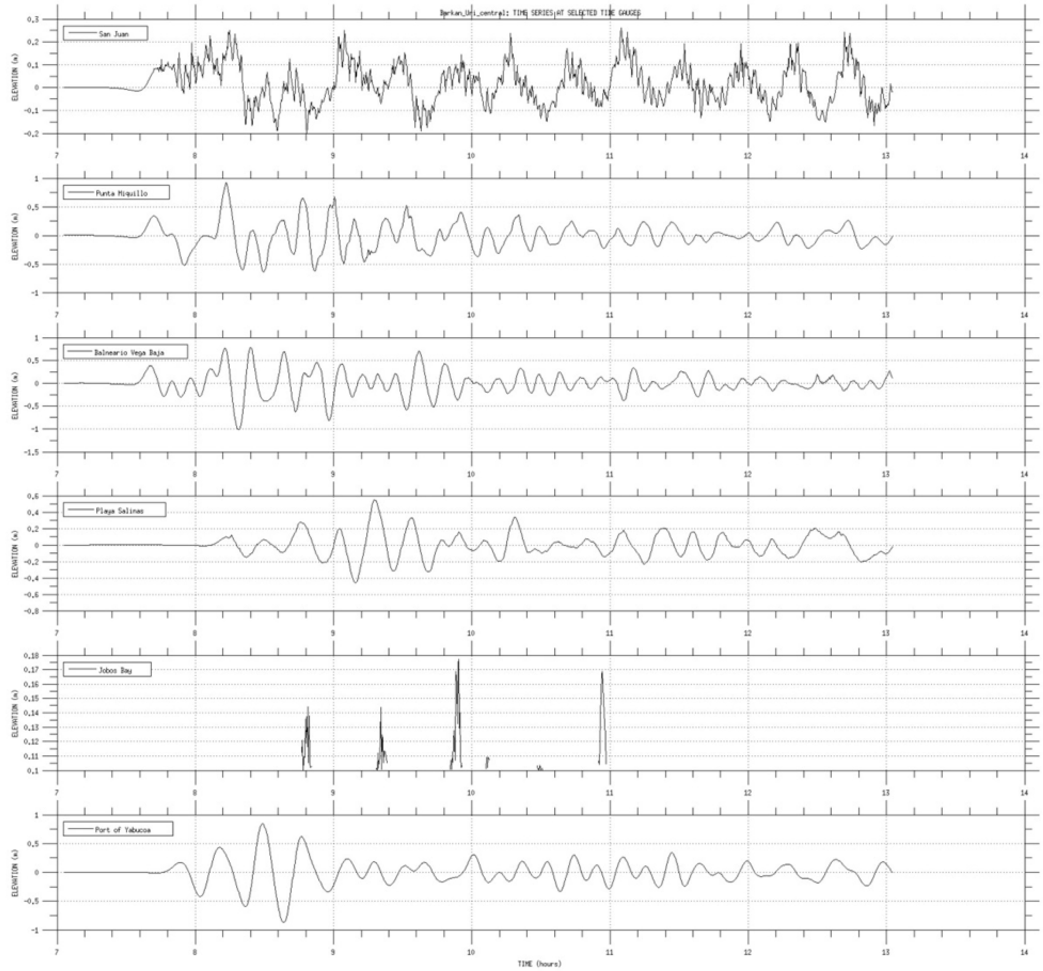

Figure 23 - Inundation time series for the Central grid.

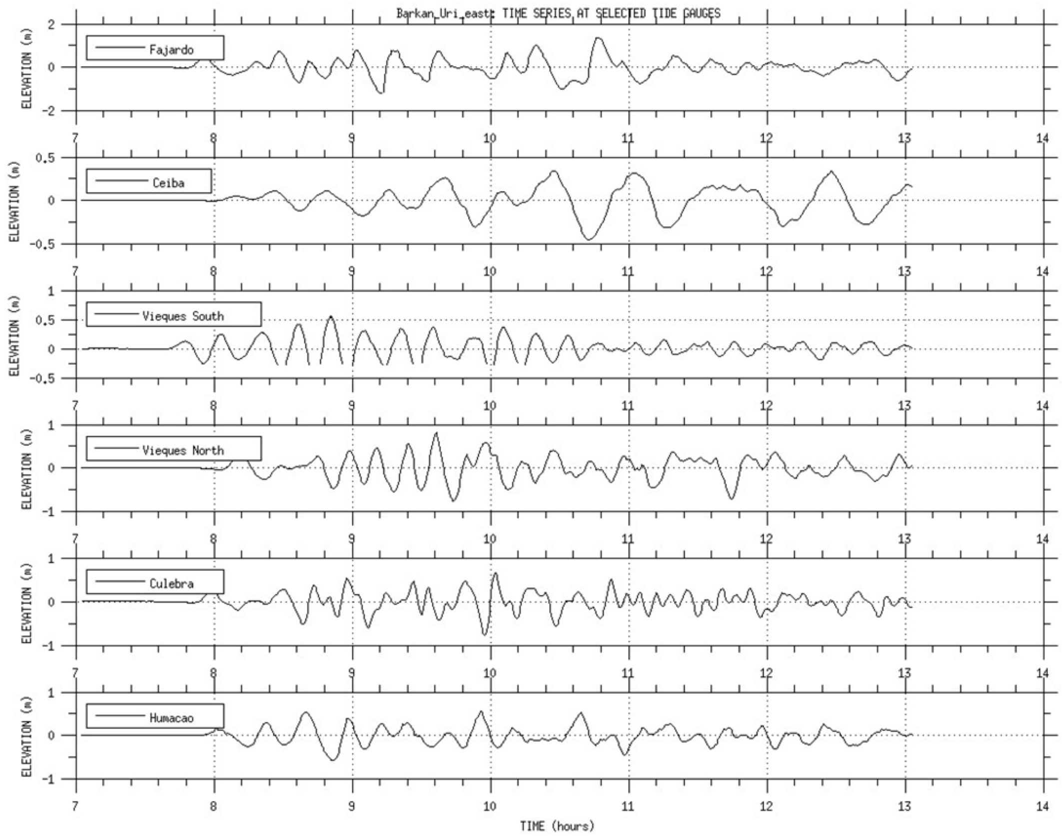

Figure 24 - Inundation time series for the East grid.

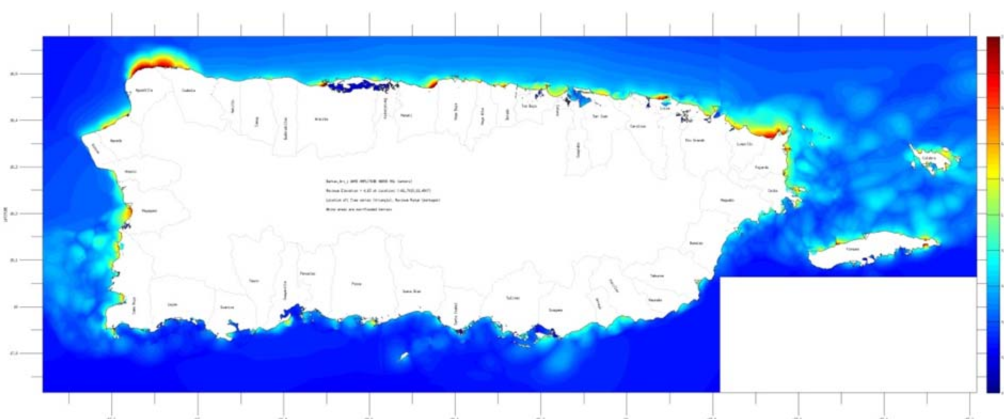

Figure 25 – MEOW mosaic for scenario 5 in Barkan et al. (2005).

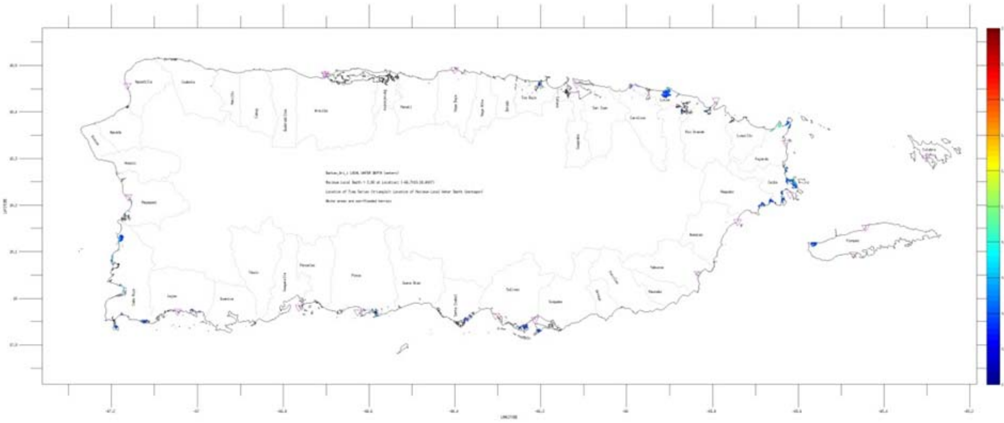

Figure 26 - LWD mosaic for scenario 5 in Barkan et al. (2005).

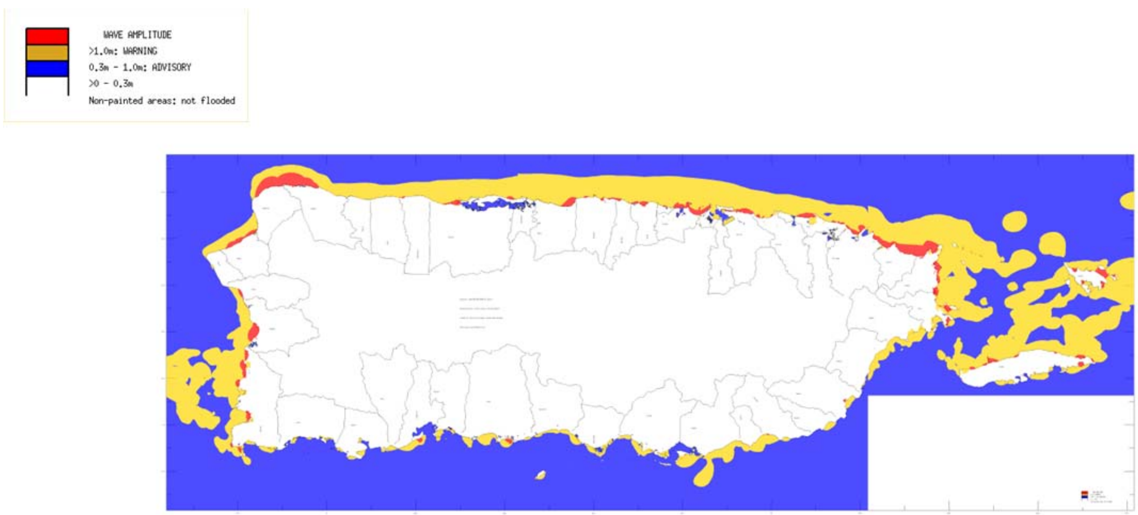

Figure 27 – Figure showing the distribution of Advisories versus Warnings around Puerto Rico for scenario 5 of Barkan et al. (2005).

REFERENCES

Barkan, R., U. S. ten Brink, and J. Lin., 2009. Far field tsunami simulations of the 1755 Lisbon earthquake: Implications for tsunami hazard to the U.S. east coast and the Caribbean. *Marine Geology*, 264:109-122.