NUMERICAL RECREATION OF THE 1918 PUERTO RICO TSUNAMI USING NOAA'S MOST MODEL

by

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I. Introduction

In 2003 tsunami flood maps were prepared for the whole island of Puerto Rico as part of a FEMA funded Hazard Mitigation Grant. The TUNAMO 2 Japanese model was used. The bathymetry used was, in some cases, from the early 1900's, and the topography was from the middle of the 20th century. Now, as part of a study sponsored by the USA National Tsunami Hazard Mitigation Program (NTHMP), it is desired to re-do de maps with recently acquired, high-resolution, bathymetry/topography, allowing a higher resolution computational grid. It is the purpose of this study to re-create the 1918 Puerto Rico tsunami (Mercado and McCann, 1998) with the MOST model (Titov and Synolakis, 1998), using recently acquired bathymetry and topography, and compare results with the observations carried out at the time of the tsunami in order to make a decision.

II. The MOST Model

MOST comes in two versions: 1) the generation/propagation version, and 2) the inundation version. The generation/propagation version generates de initial sea surface deformation using Okada's deformation model (1985), and propagates the signal over s single computational grid. In a trio of netcdf files results are stored at every time step all over the grid for the wave height, U velocity (zonal) and V velocity (meridional).

II.A. Generation/Propagation MOST

Figure 1 shows the computational grid used for the generation/propagation code. It has a resolution of 60 arc seconds. The basic statistics for the computational grid are shown in Table 1 below. The value of Δt in the table gives the maximum allowed time step (CFL condition) for this grid. The initial parameters given to the generation/propagation MOST code, which includes the fault parameters, is given in Table 2. Table 3 contains the fault parameters used (Mercado and McCann, 1998).

The propagation simulation was of the first 8 hours of the tsunami, and snapshots of wave height, U and V velocity components were stored every 30 seconds starting 5 seconds after the tsunami generation.

Figure 2 shows the initial sea surface deformation according to Okada's (1985) model, which is included in the generation/propagation MOST code. Figure 3 shows the maximum wave height irrespective of time (Maximum Envelope of Highest Water, or MEOHW) all over the propagation computational grid. Figure 4 shows a zoom into the deformation site. Figure 5 shows a time history of the wave height taken at the location of the filled green circle in Figure 2.

The generation/propagation code writes to the hard disk three netcdf files containing information about the wave height, and U and V velocities, every time step all over the wetted areas of the computational grid. These three files are then read by the inundation code of MOST and do the inundation/runup

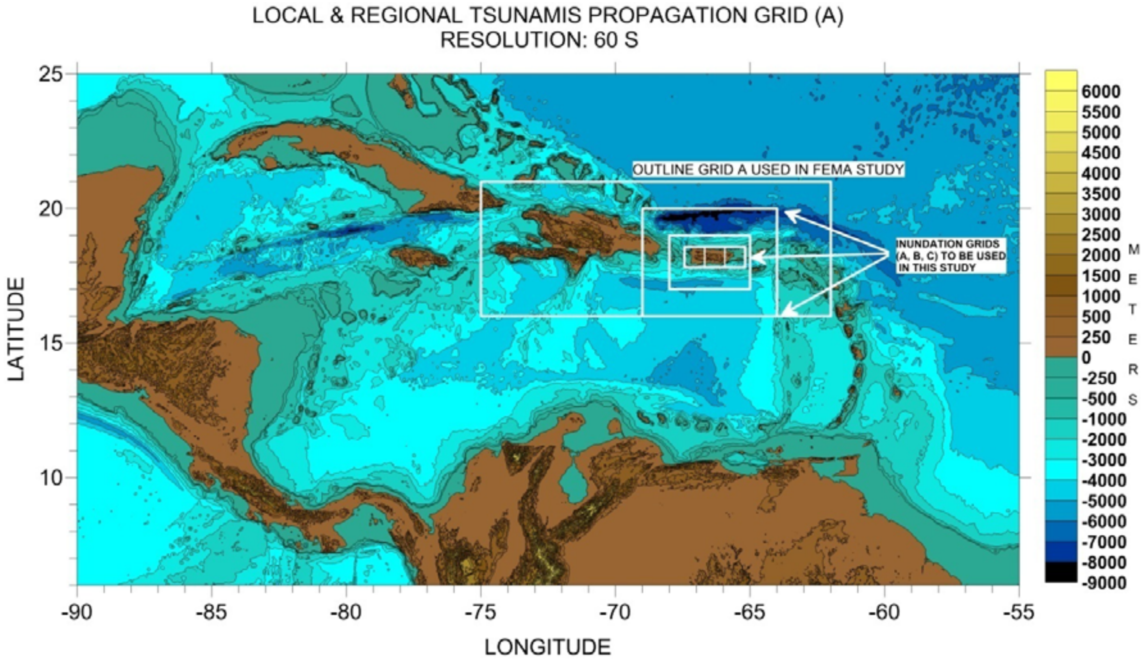

Figure 1 - Propagation grid (A) used for the simulation of the 1918 Puerto Rico tsunami. The grid resolution is 60 s. For reference, also shown is the outline of the geographical coverage of the grid A used for the FEMA project. The outlines of the nested grids A, B, and C for the inundation phase are also shown.

Table 1: Grid Information for the Generation/Propagation Computational Grid A

Grid Information: Propagation Grid for Regional & Local Tsunamis

Grid File Name:	regional&local_prop_A_60s_v2.dat
Grid Size:	1141 rows x 2101 columns
Total Nodes:	2397241
Grid Geometry	
X Minimum:	-90°
X Maximum:	-54.999993°
X Spacing:	0.01666667° = 60 s ≈ 1800 m
Y Minimum:	6°
Y Maximum:	25.000004°
Y Spacing:	0.016666670175439° = 60 s ≈ 1800 m
Grid Statistics	
Z Minimum:	-8497 m
Z Maximum:	5293 m
Δt = 6.06 s	

Table 2: Input parameters supplied to the generation/propagation MOST code in order to simulate the 1918 Puerto Rico tsunami. Fault parameters are taken from Mercado and McCann (1998). Note there are 4 fault segments.

```
# MOST Mode ( 0=location point already in MOST convention,  1=fault origin or epicenter location is in Aki-Richards convention)
1
# Grid Name
Caribbean_region
# Grid axes version
20050825
# Location of bathymetry file
Regional&local_prop_A_60s.dat
# Input minimum depth for offshore (m) [depth threshold for propagation, vertical wall is set at this point]
20
# Input time step (sec) [time step based on CFL]
5.0
# Input amount of steps [total time for simulation based on 'input time step', 8 hours for this case]
5760
# Input number of steps between snapshots [output interval, multiple of 'input time step', every 30 s for this case]
6
# ..Starting from [first output time frame, multiple of 'input time step', 5 seconds for this case]
1
# Save output every n-th grid point [output grid is save every 4th node, 16 arc-minutes in both x and y directions]
1
# Input global b.c.s (1=global, 0=non-reentrant) [use default of 0 if grid is not global]
0
# Output filename prefix (e.g. s_2943_194_ha.nc, s_2943_194_ua.nc, s_2943_194_va.nc)
Puerto_Rico_1918
# Source Zone Name
Puerto_Rico_1918
# Source Zone Code
ca
# Source Column
b
# Source Row
50
# Source Version [versioning we used to keep track of revisions on the same unit source runs]
0
# Input number of fault-planes: [input the desired number of fault planes]
4
############# FAULT-PLANE #1  ########################
# x-integration [default value]
41
# y-integration [default value = 21]
21
# Vp - P-wave velocity [default value = 8.11]
8.11
# Vs - S-wave velocity [default value = 4.49]
4.49
# 'Deform Area X' [size of deformation area in X direction]
500
# 'Deform Area Y' [size of deformation area in y direction]
500
# 'Longitude'     [fault parameters]
292.66
# 'Latitude'      [fault parameters]
19.0
```

```
# 'Length (km):'  [fault parameters]
13.0
# 'Width (km):'   [fault parameters]
23.0
# 'DIP (deg):'    [fault parameters]
85.0
# 'RAKE (deg):'   [fault parameters]
-95.0
# 'STRIKE (deg):' [fault parameters]
185.0
# 'SLIP (m)'      [fault parameters]
4.0
# 'DEPTH (km):'   [fault parameters]
4.674
############# FAULT-PLANE #2  ########################
# x-integration [default value]
41
# y-integration [default value = 21]
21
# Vp - P-wave velocity [default value = 8.11]
8.11
# Vs - S-wave velocity [default value = 4.49]
4.49
# 'Deform Area X' [size of deformation area in X direction]
500
# 'Deform Area Y' [size of deformation area in y direction]
500
# 'Longitude'     [fault parameters]
292.65
# 'Latitude'      [fault parameters]
18.88
# 'Length (km):'  [fault parameters]
4.0
# 'Width (km):'   [fault parameters]
23.0
# 'DIP (deg):'    [fault parameters]
34.0
# 'RAKE (deg):'   [fault parameters]
-146.0
# 'STRIKE (deg):' [fault parameters]
236.0
# 'SLIP (m)'      [fault parameters]
4.0
# 'DEPTH (km):'   [fault parameters]
4.712
############# FAULT-PLANE #3  ########################
# x-integration [default value]
41
# y-integration [default value = 21]
21
# Vp - P-wave velocity [default value = 8.11]
8.11
# Vs - S-wave velocity [default value = 4.49]
4.49
# 'Deform Area X' [size of deformation area in X direction]
500
# 'Deform Area Y' [size of deformation area in y direction]
500
```

```
# 'Longitude'     [fault parameters]
292.62
# 'Latitude'      [fault parameters]
18.86
# 'Length (km):'  [fault parameters]
31.0
# 'Width (km):'   [fault parameters]
23.0
# 'DIP (deg):'    [fault parameters]
82.0
# 'RAKE (deg):'   [fault parameters]
-98.0
# 'STRIKE (deg):' [fault parameters]
188.0
# 'SLIP (m)'      [fault parameters]
4.0
# 'DEPTH (km):'   [fault parameters]
4.336
############# FAULT-PLANE #4  ########################
# x-integration [default value]
41
# y-integration [default value = 21]
21
# Vp - P-wave velocity [default value = 8.11]
8.11
# Vs - S-wave velocity [default value = 4.49]
4.49
# 'Deform Area X' [size of deformation area in X direction]
500
# 'Deform Area Y' [size of deformation area in y direction]
500
# 'Longitude'     [fault parameters]
292.58
# 'Latitude'      [fault parameters]
18.58
# 'Length (km):'  [fault parameters]
18.0
# 'Width (km):'   [fault parameters]
23.0
# 'DIP (deg):'    [fault parameters]
60.0
# 'RAKE (deg):'   [fault parameters]
-120.0
# 'STRIKE (deg):' [fault parameters]
210.0
# 'SLIP (m)'      [fault parameters]
4.0
# 'DEPTH (km):'   [fault parameters]
2.309
```

Table 3:

Long°	Lat°	Depth of Center Of Fault Plane (km)	Average Slip (m)	Strike (°)	Dip (°)	Rake (°)	Width (km)	Length (km)
292.66	19.00	4.674	4	185	85	-95	23	13
292.65	18.88	4.712	4	236	34	-146	23	4
292.62	18.86	4.336	4	188	82	-98	23	31
292.58	18.58	2.309	4	210	60	-120	23	18

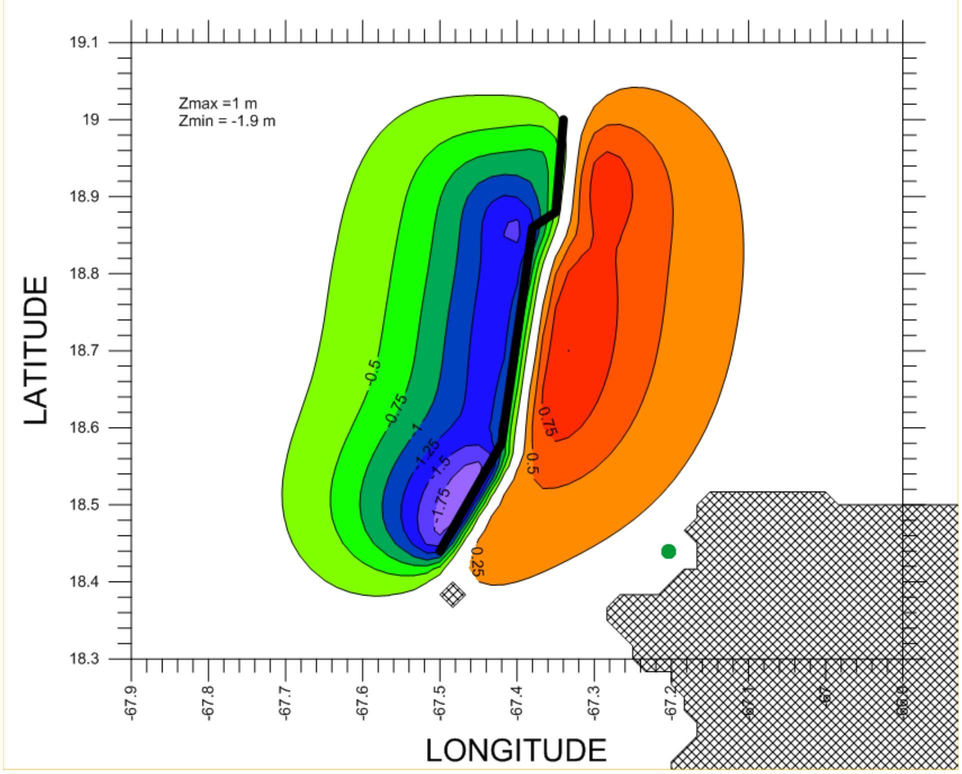

Figure 2 - Initial deformation of the 1918 Puerto Rico tsunami as computed in the generation/propagation grid. The latitude/longitude coordinates for each fault plane have been assumed to follow the Aki-Richards (1980) convention. Green solid circle denotes the location where the time series in Figure 5 was obtained. The black polygon shows the trace of the fault.

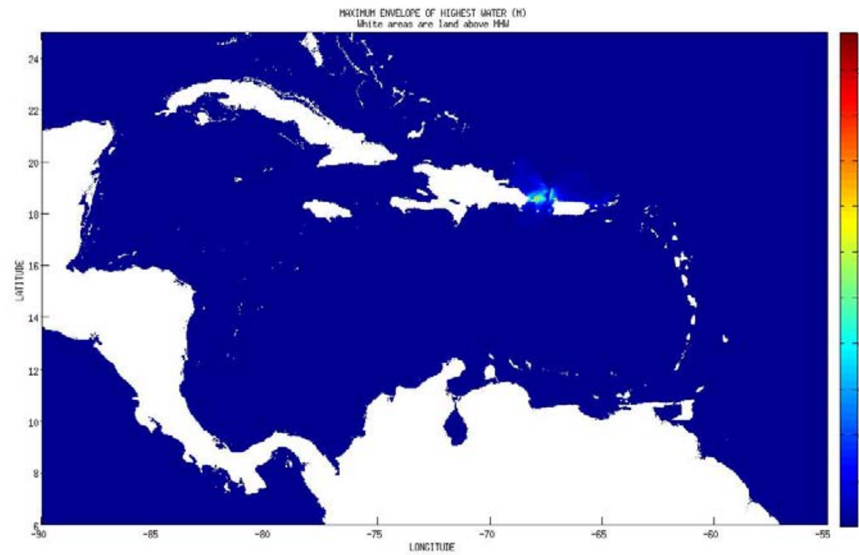

Figure 3 - Maximum wave height irrespective of time (Maximum Envelope of Highest Water, or MEOHW) all over the computational grid.

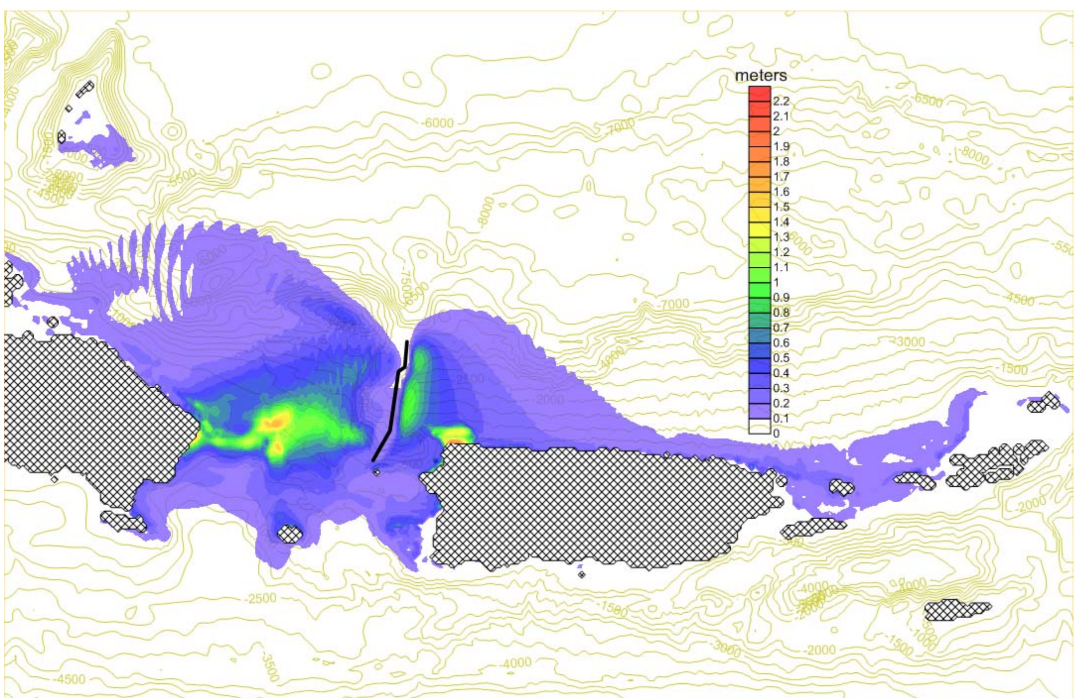

Figure 4 – Zoom of Figure 3. The black polygon shows the trace of the fault.

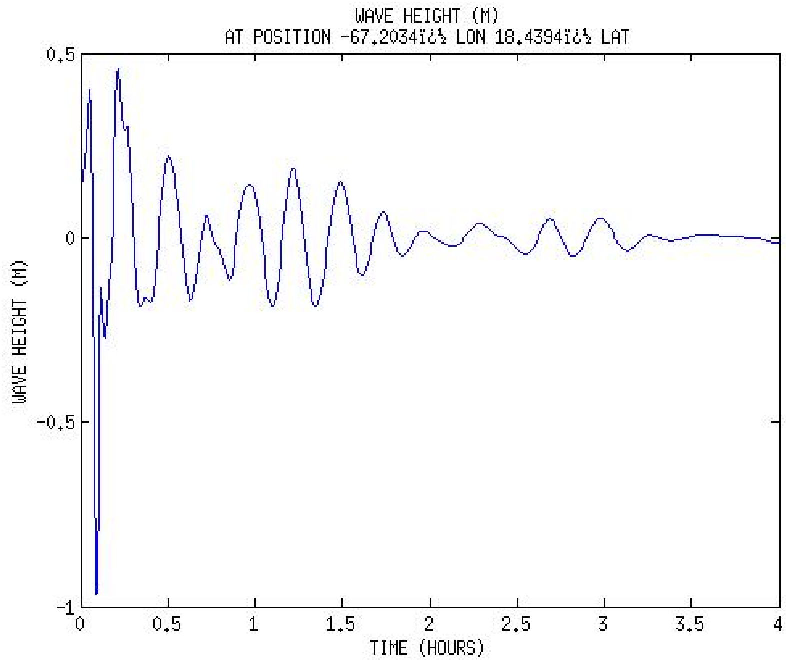

Figure 5 – Wave height time history taken at the location of the green filled circle in Figure 2 (longitude -67.1739° W, latitude 18.4564° N, water depth of 205 m).

II.B. Generation/Inundation MOST

The MOST/Propagation code netcdf output files (for the wave height, U and V velocity components), are given as input to the MOST/Inundation code in order to compute the inland inundation in the inner, highest-resolution, Grid C. The nomenclature is that the outer, lowest resolution, grid is called Grid A. The middle, intermediate resolution, one is called Grid B. And the inner, highest resolution, one is called Grid C. They consist of three nested grids.

In the preparation of these grids we made use of a 1 second (approximately 30 m) resolution Digital Elevation Model (DEM) prepared by the National Geophysical Data Center (NGDC) for the preparation of the Puerto Rico Short-term Inundation Models (SIM). For Grid A we used ETOPO1 (Amante and Eakins, 2009).

Grid A:

As grid A for the inundation phase modeling in this study we cropped the 1-min regional propagation grid (A) (see Fig. 1 above) to the following bounding longitudes and latitudes: -69° to -64° W, 16° to 20° N (see Figure 6). Resolution: 60 s (1800 m).

Grid B:

As grid B for the inundation phase modeling we will use exactly the same geographical coverage as the 1 s DEM from NGDC, sub-sampling it to 9 s resolution (see Figure 7). Resolution: 9 s (270 m).

Grid C:

As grid C for the inundation phase modeling we will crop the 1s NGDC DEM to the bounding longitudes and latitudes shown next, and sub-sample the DEM to 1s resolution. This approximately gives computational grid cell sizes of approximately 30 m by 30 m (to be compared with the 90 m by 90 m used in the FEMA study). Since the whole island could not be covered by one Grid C of 1s resolution and still maintain an upper limit in the DIMENSION statements of the source code of 3000 x 3000, the island was divided into three sections: West, Center, and East (see Figures 6 and 7).

Figure 6 shows a contour plot of Grid A. The grid information for this grid is shown in Table 4 below. Figure 7 shows a contour plot of Grid B. The grid information for this grid is shown in Table 5 below. Figures 8-10 show contour plots of the 3 segments into which Grid C has been broken apart. Grid information for each segment is shown in Table 6 below. The white crosses in each plot show the location of tsunami-ready tide gauges. The locations of the tsunami-ready tide gauges were obtained from http://rmsismo.uprm.edu/Estaciones/mare.php.

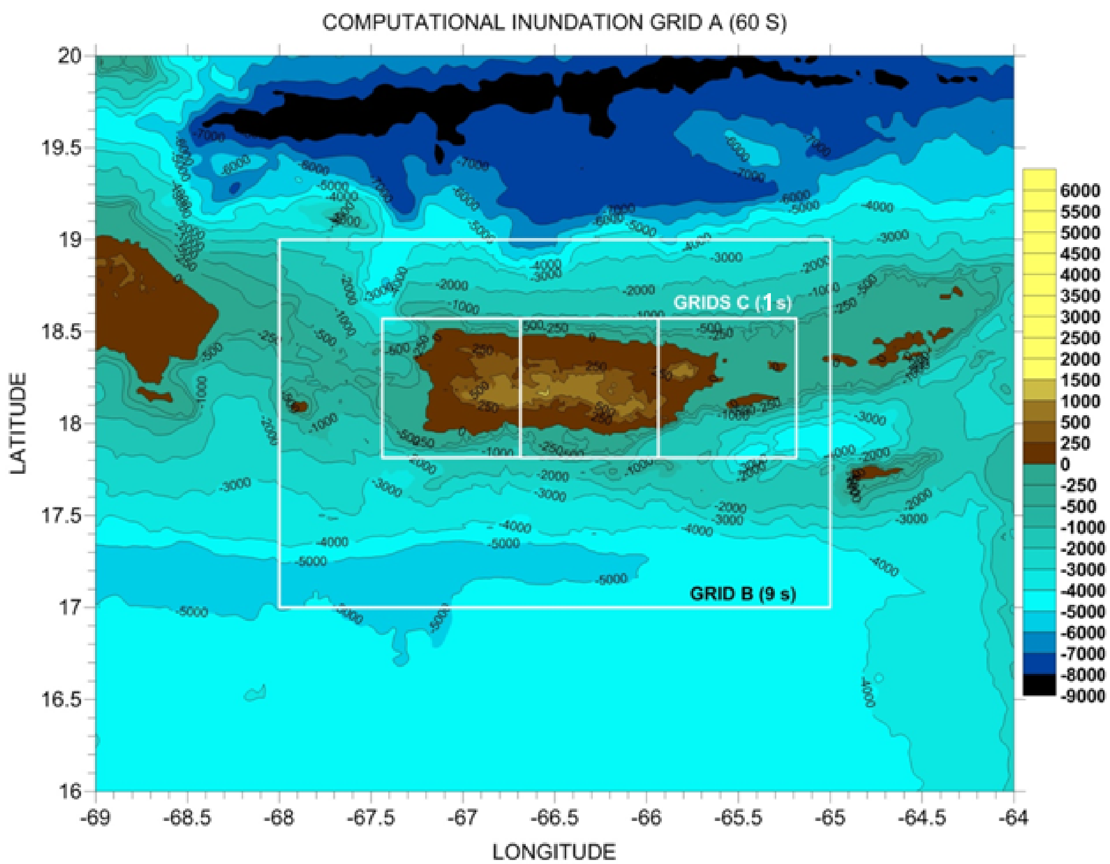

Figure 6 - Computational inundation Grid A. The outlines of the in8undation Grids B and C are also shown.

Table 4:

Grid Information: Grid A for Inundation Code	
Grid File Name:	**Grid_A_60s_inun_v2.grd**
Grid Size:	241 rows x 301 columns
Total Nodes:	72541

Grid Geometry	
X Minimum:	-68.9999958°
X Maximum:	-63.9999948°
X Spacing:	0.01666667 = 60 s ≈ 1800 m
Y Minimum:	16.000002105263°
Y Maximum:	20.000002947368°
Y Spacing:	0.016666670175437 = 60 s ≈ 1800 m
Grid Statistics	
Z Minimum:	-8497 m
Z Maximum:	1145 m
Δt_A = 6.05 sec	

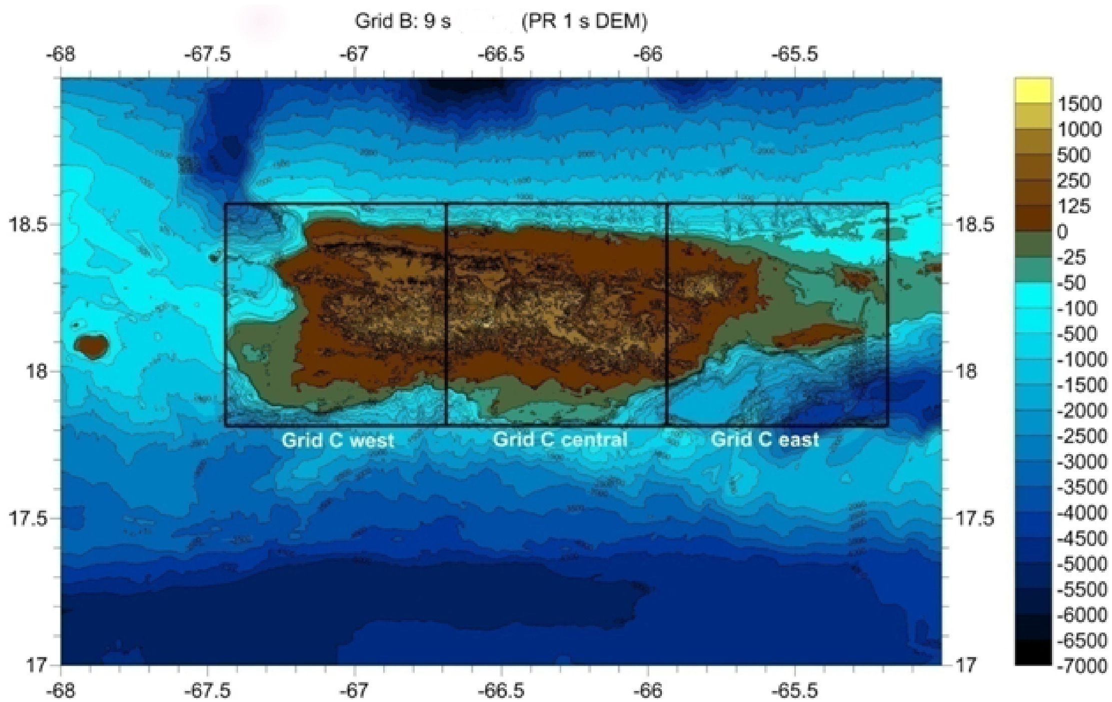

Figure 7 - Computational inundation Grid B. The outlines of the in8undation Grids B and C are also shown.

Table 5: Grid B Basic Information

Grid Information: Grid B for Inundation Code	
Grid File Name:	**grid_B_9s_inun_v2.grd**
Grid Size:	800 rows x 1200 columns
Total Nodes:	960000
Grid Geometry	
X Minimum:	-68.00013889
X Maximum:	-65.00263886

X Spacing:	0.0025000000250208 = 9 s ≈ 270 m
Y Minimum:	17.00208333
Y Maximum:	18.99958335
Y Spacing:	0.0025000000250313 = 9 s ≈ 270 m
Minimum:	-6611.589 m
Maximum:	1315.722 m
Δt_B = 1.035 s	

Table 6: Grid C Basic Information

Grid Information: Grid C for Inundation Code (WEST)

Grid File Name:	**grid_C_west_1s_inun.grd**
Grid Size:	2752 rows x 2712 columns
Total Nodes:	7463424

Grid Geometry

X Minimum:	-67.44013888441
X Maximum:	-66.68708332283
X Spacing:	0.00027777777999999 = 1 arc sec ≈ 30 m
Y Minimum:	17.81625000653
Y Maximum:	18.58041667931
Y Spacing:	0.00027777778 = 1 arc sec ≈ 30 m
Minimum:	-3505.59 m
Maximum:	1190.08 m
Δt_C = 0.158 s	

Grid Information: Grid C for Inundation Code (CENTRAL)

Grid File Name:	**grid_C_central_1s_inun.grd**
Grid Size:	2752 rows x 2709 columns
Total Nodes:	7455168

Grid Geometry

X Minimum:	-66.68791665617
X Maximum:	-65.93569442793
X Spacing:	0.00027777778 = 1 arc sec ≈ 30 m
Y Minimum:	17.81625000653
Y Maximum:	18.58041667931
Y Spacing:	0.00027777778 = 1 arc sec ≈ 30 m
Minimum:	-1831.66 m
Maximum:	1330.42 m
Δt_C = 0.220 s	

Grid Information: Grid C for Inundation Code (EAST)

Grid File Name:	**grid_C_east1_1s_inun.grd**
Grid Size:	2752 rows x 2710 columns
Total Nodes:	7457920
Grid Geometry	
X Minimum:	-65.93624998349
X Maximum:	-65.18374997747
X Spacing:	0.00027777778 = 1 arc sec ≈ 30 m
Y Minimum:	17.81625000653
Y Maximum:	18.58041667931
Y Spacing:	0.00027777778 = 1 arc sec ≈ 30 m
Minimum:	-4535.7 m
Maximum:	1066.11 m
Δtc = 0.140 s	

It can be seen that at the northwestern and southeastern corners of Grid_C_1s_west_inun.grd and Grid_C_1s_east_inun.grd, respectively, lie in very deep waters, which produces the result that the computational time step for both grids is constrained to be very small. This has the result of very long wall clock times in the simulations. When many runs are required we will have to come up with different inundation grids arrangements in order to avoid these extremely large water depths which force very small time steps. But now we just want to recreate one event, the 1918 tsunami, and we will continue using these three C grids.

III. Results of recreation of the 1918 Puerto Rico tsunami using MOST

Figure 11, 12, and 13 show the MEOHW for western Puerto Rico, demonstrating that it was northwestern part of the island which suffered the worst impact. Figure 14 shows that the maximum runup of 11.7 m above MSL occurred on the north facing side of the island. Figure 15 shows a Google Earth view of the northwest tip of the island, showing where the location of the maximum runup (according to the simulation), and the location of two locations mentioned in the report by Reid and Taber.

Figure 16 and 17 show the MEOHW results for Grid C central, while Figures 18 and 19 show the same for Grid C east. And Figure 20 shows the whole island. It can be seen that the entire north coast was affected, with wave heights on the order of at least 1 meter.

We will now look at zooms of different locations. Figure 21 shows a zoom of Aguadilla Bay, showing that the brunt of the wave energy in the Aguadilla city area was received just south of the city, in what is still a not too developed area (see Figure 22). Figure 23 shows Mayaguez Bay, Figure 24 shows Boqueron Bay, and Figure 25 show Puerto Real Bay and Buye Beach, where we can see wave energy concentration.

Finally, Figure 26 we show the maximum computed runup vs latitude along the west coast of the island. Shown in the same figure is the outline of the west coast, with the runup values as given by Reid and Taber. The model output is shown in both its original resolution of 30 m, and also as a 3 point running average.

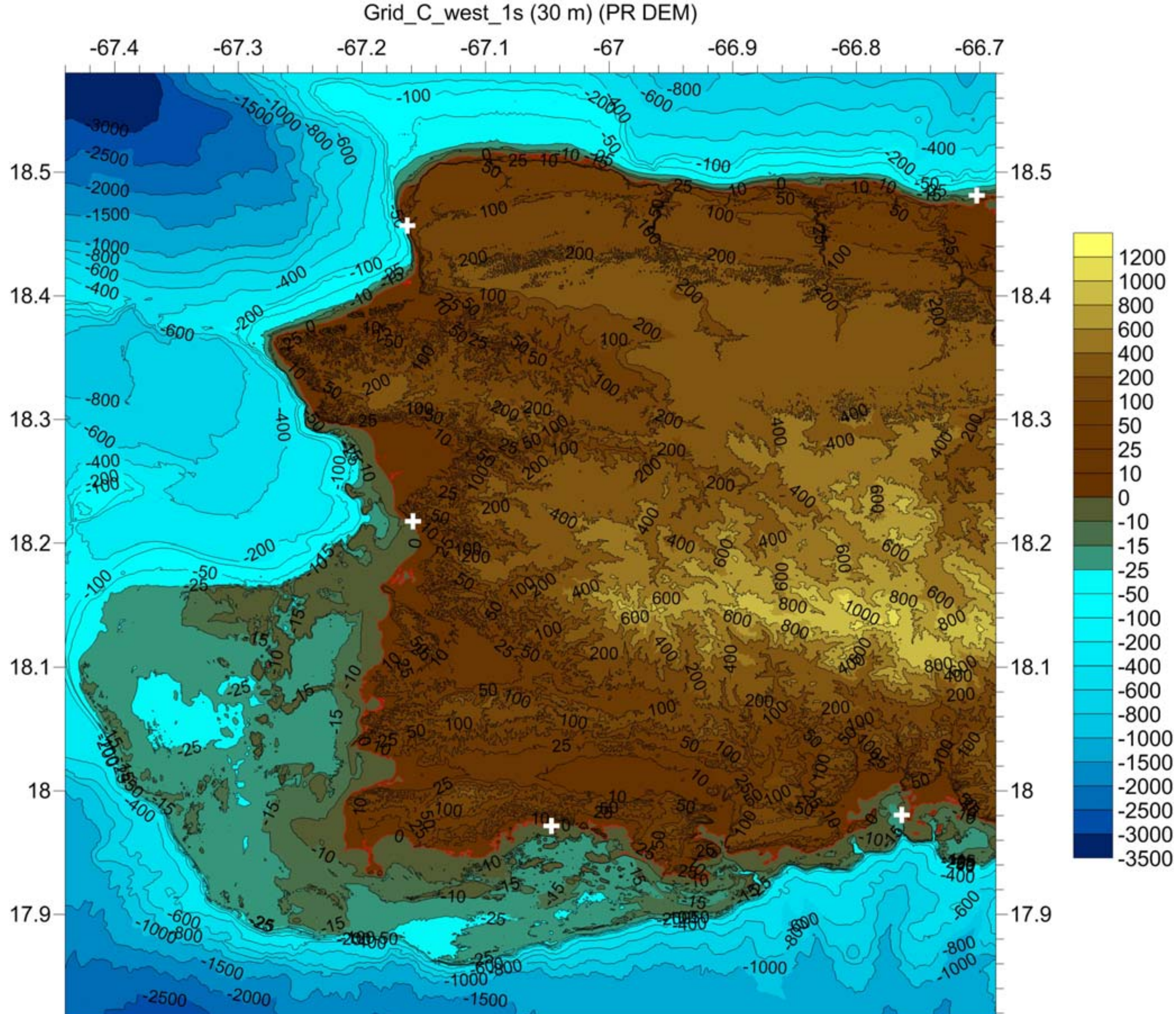

Figure 8 – High-resolution Grid C west used for inundation modeling. White crosses indicate location of tsunami-ready tide gauges.

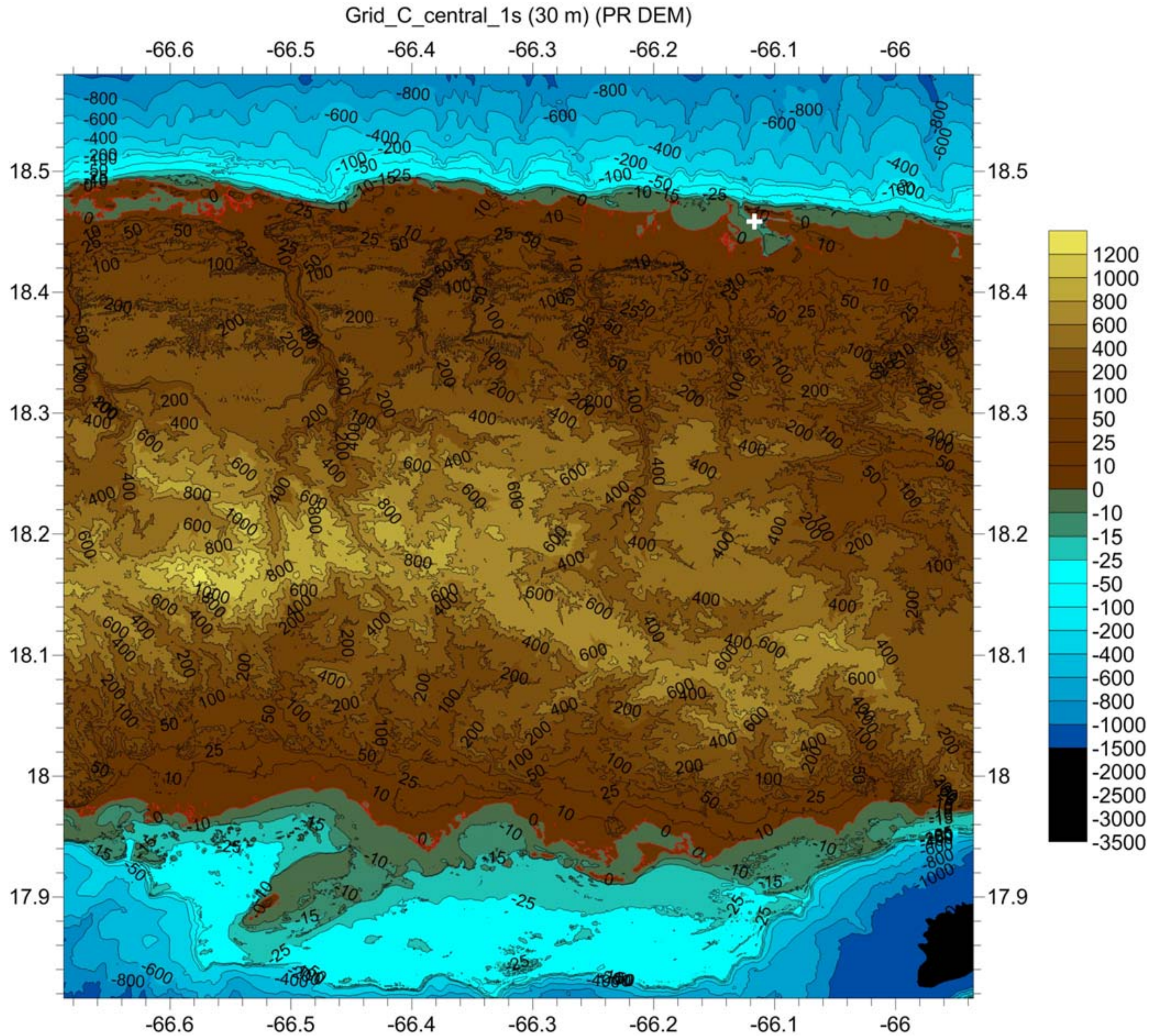

Figure 9 – High-resolution Grid C west used for inundation modeling. White crosses indicate location of tsunami-ready tide gauges.

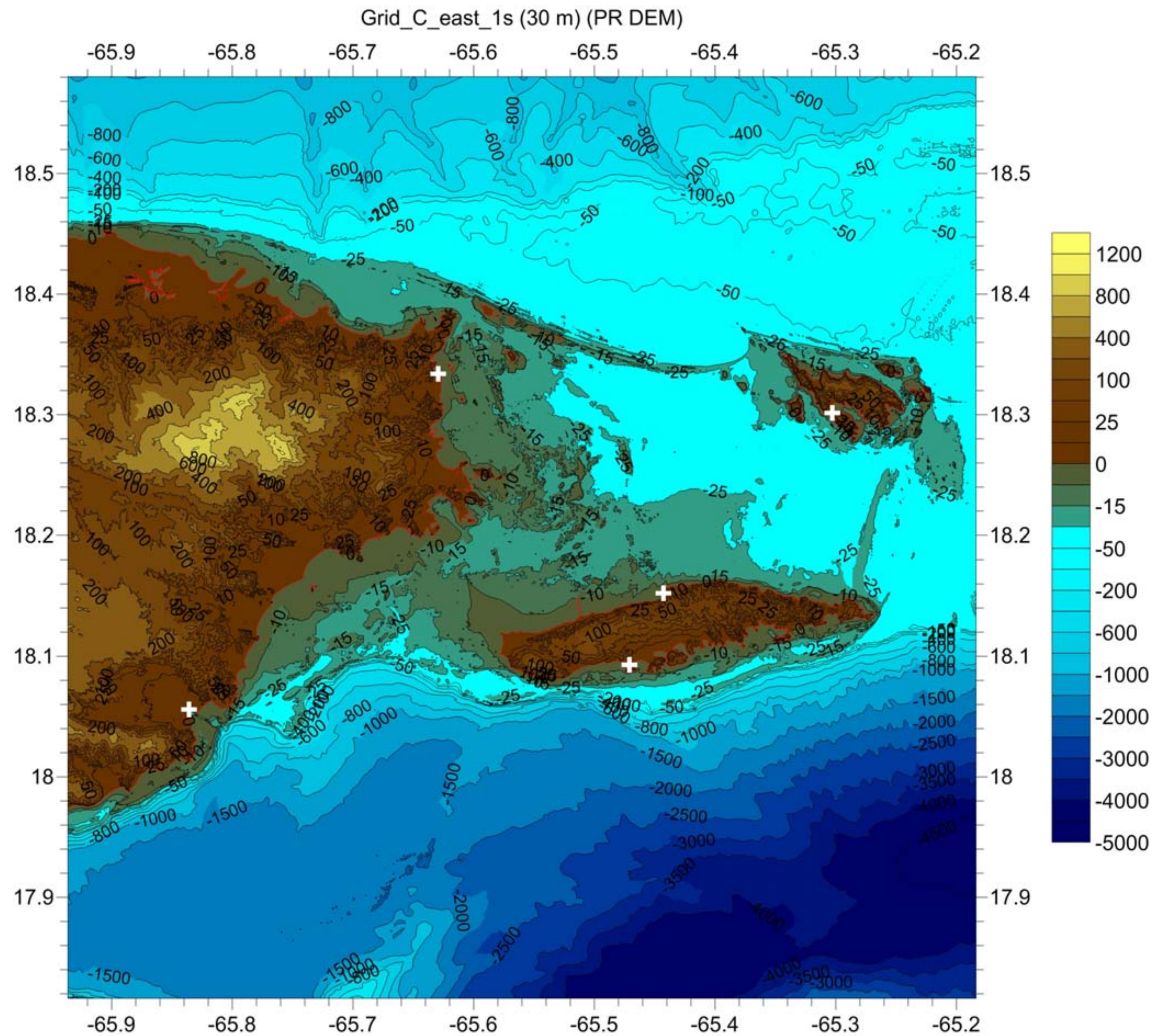

Figure 10 – High-resolution Grid C west used for inundation modeling. White crosses indicate location of tsunami-ready tide gauges.

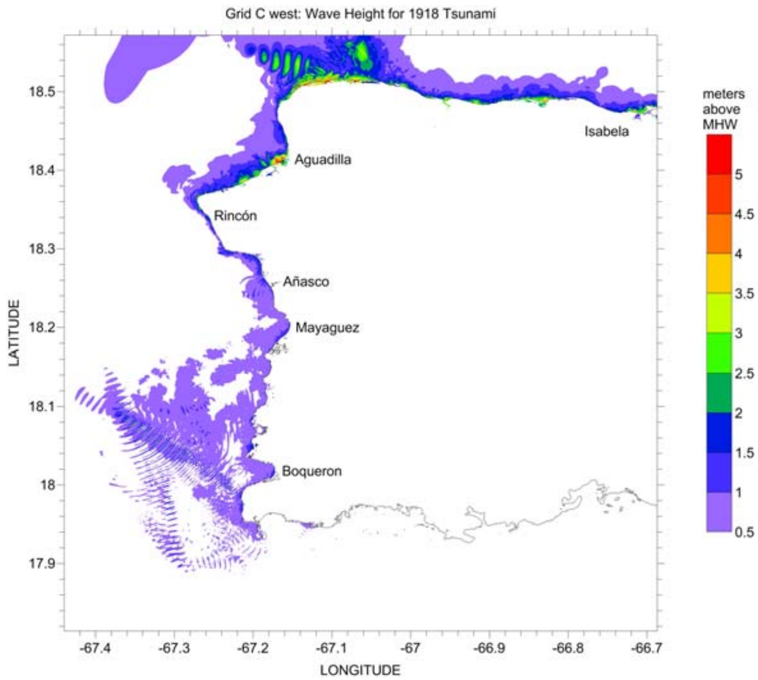

Figure 11 – MEOHW for Grid C west.

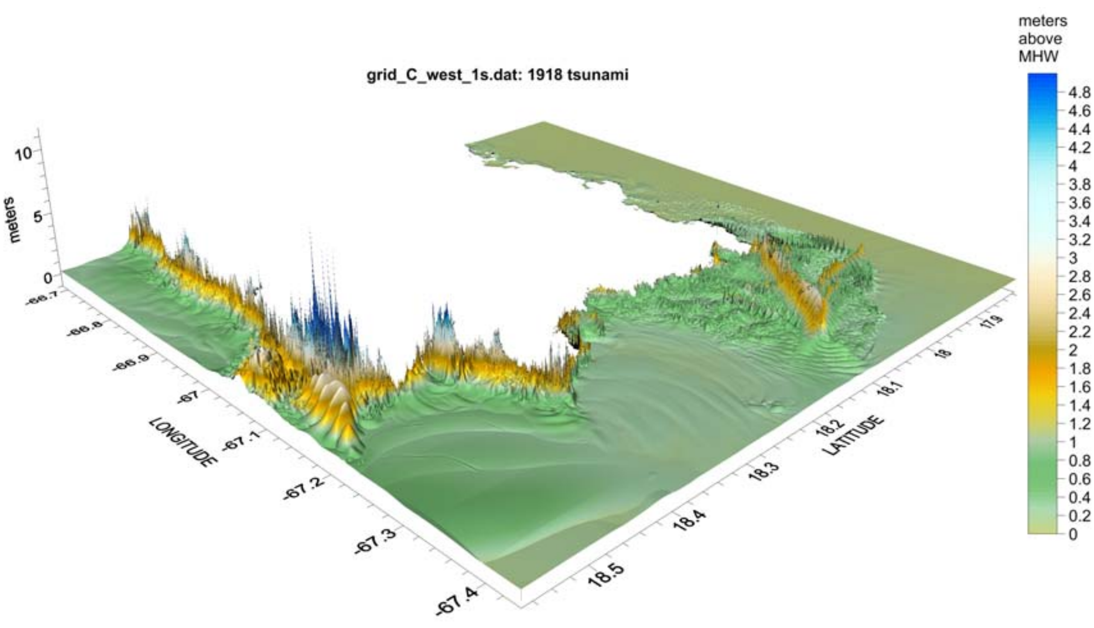

Figure 12 – 3-D view of the MEOHW for Grid C west.

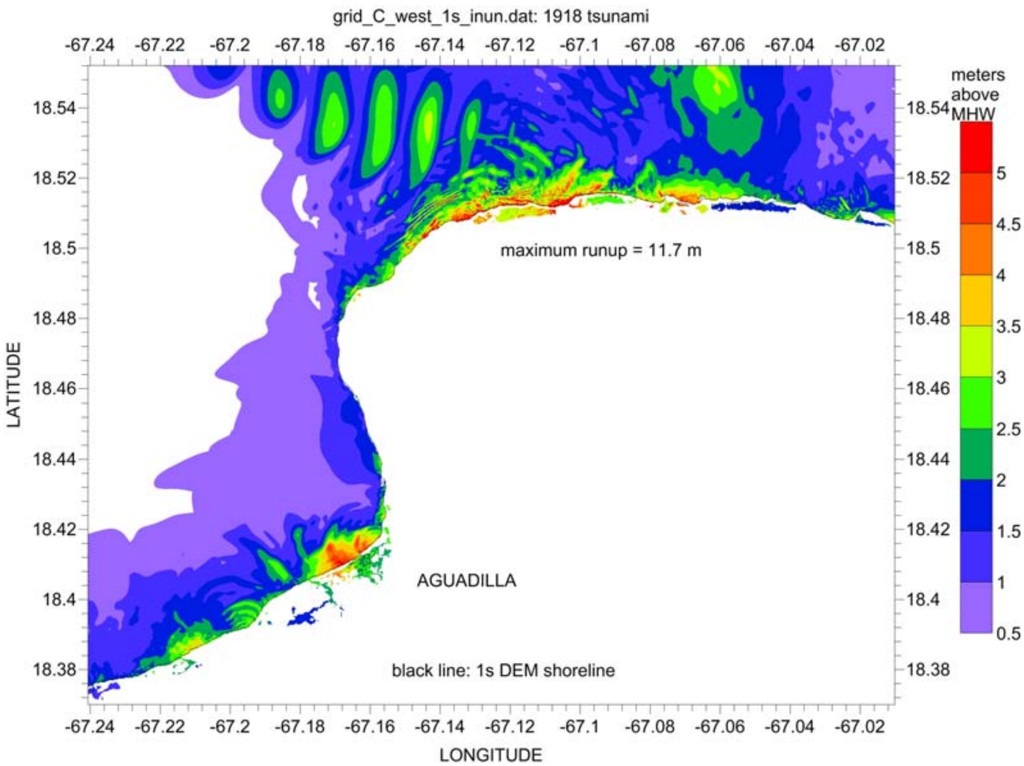

Figure 13 – Zoom into the northwest corner (Aguadilla) of the MEOHW of grid C west.

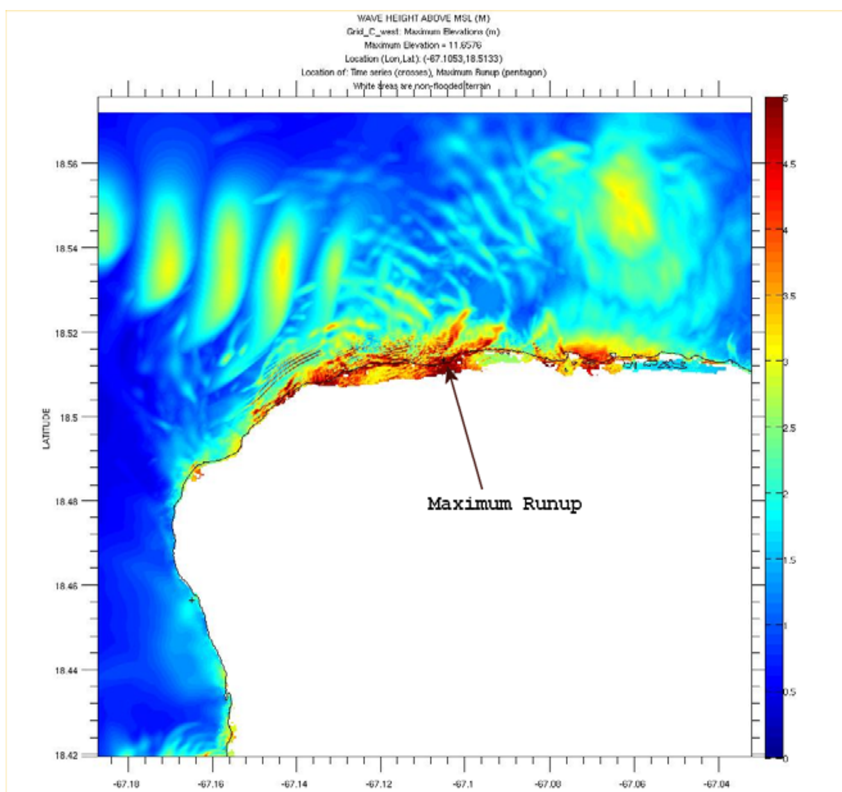

Figure 14 – Zoom into the northwest corner (Aguadilla) of the MEOHW of grid C west.

Figure 15 – Google Earth view of the northwestern tip of Puerto Rico, showing the locations of sites mentioned in Reid and Taber (1919).

IV. Conclusion

Overall we can see that the maximum runup (11.7 m) according to the model occurred further east than the location where Reid and Taber measured their maximum runups of between 5.5 and 6 m (Punta Agujereada; see Figure 15). Note that both sites are backed by an inland vertical cliff, seen as a heavy dark line in Figure 15.

Making reference to Figure 26,

- Reid and Taber measured elevations of 5.5 to 6 m at what they called Punta Agujereada, which is well matched by the model.
- At Punta Borinquen they observed a runup 0f 4.5 m, which is again well matched by the model. At the sites they called Aguadilla they documented that “at no place were the measurements less than 2.4 meters above sea level, and near the head of the bay the crest of the wave must have at least 3.4 m in height”, which is, again, in general agreement with the model output.
- Slightly further south, at the mouth of Rio Culebrinas, they state that “the wave could not have been less than 4 m high”, which is not disagreement with the model output.
- Near the Punta Higuero lighthouse they noticed a fish between the railroad tracks, at an elevation of 5.2 m. Here the model gives a maximum elevation of about 4 m.

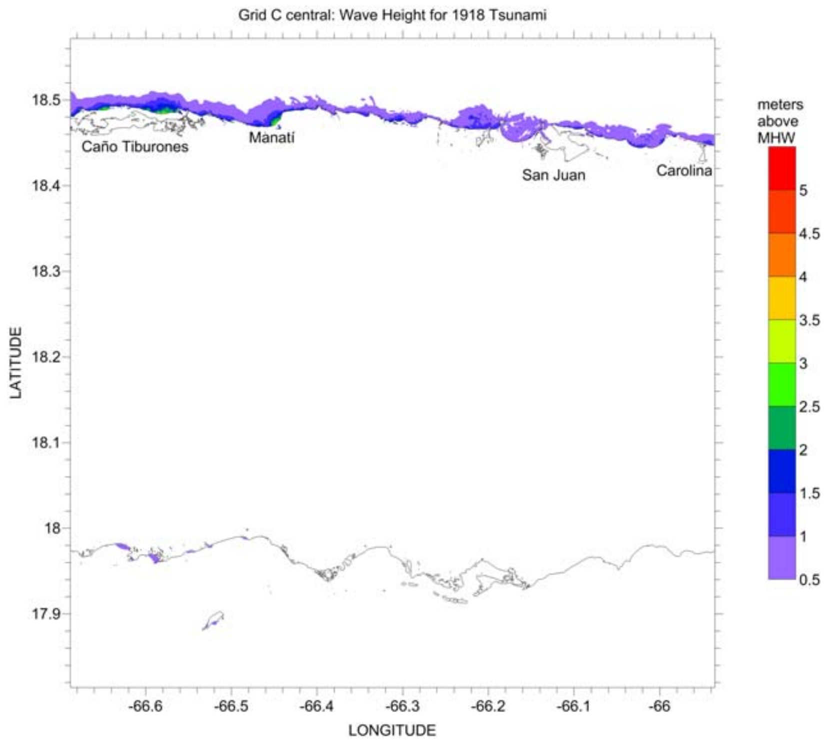

Figure 16 – MEOHW of grid C central.

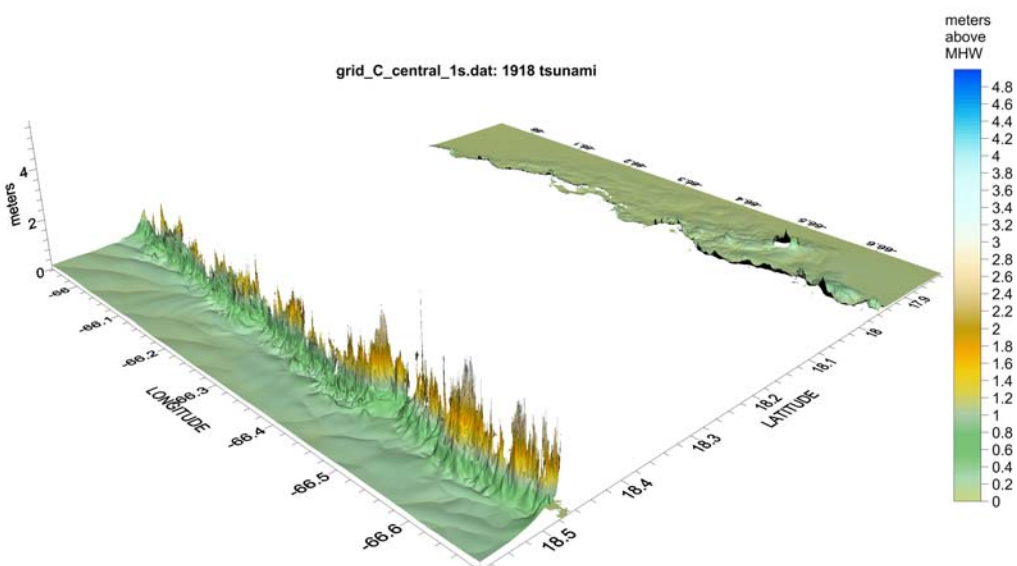

Figure 17 – 3D view of grid C central.

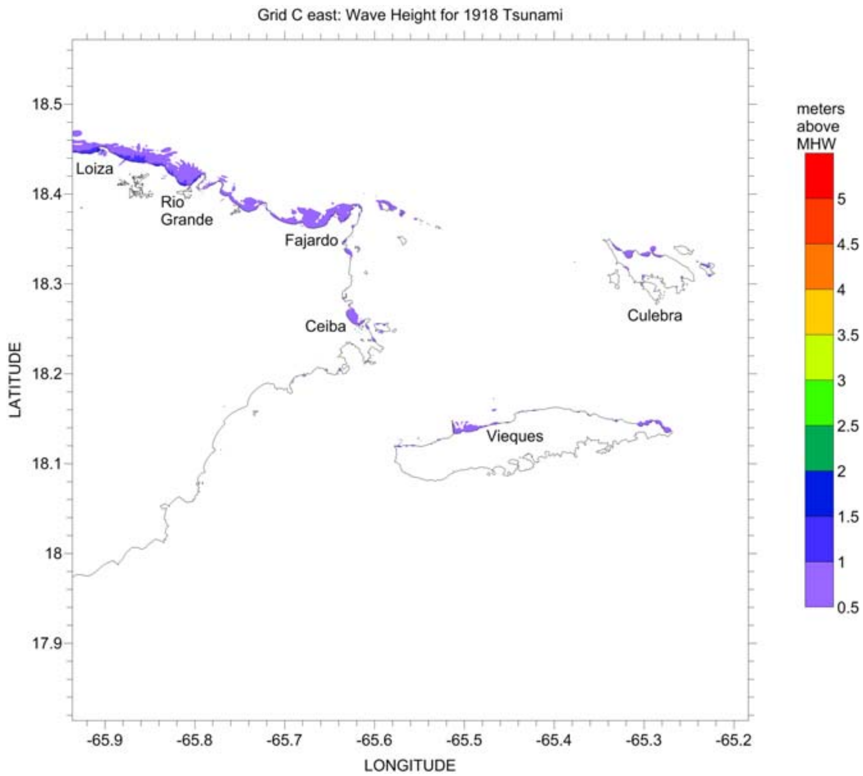

Figure 18 – MEOHW of grid C east.

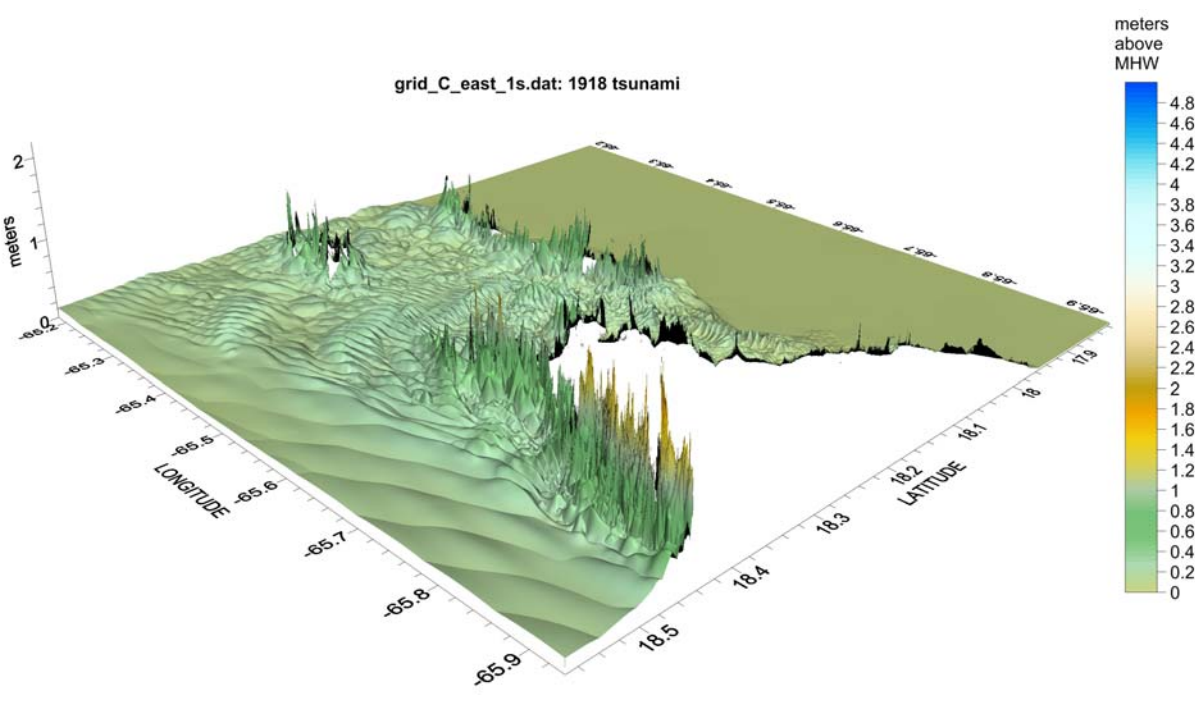

Figure 19 – 3D view of grid C east.

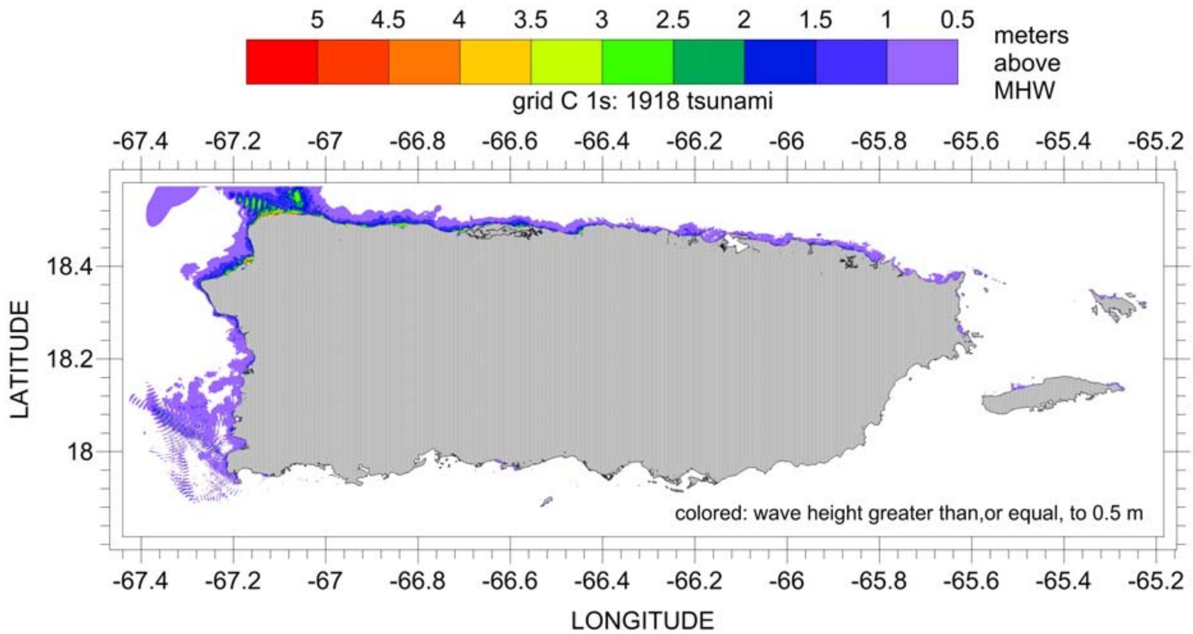

Figure 20 – MEOWH of the whole island. 1918 tsunami.

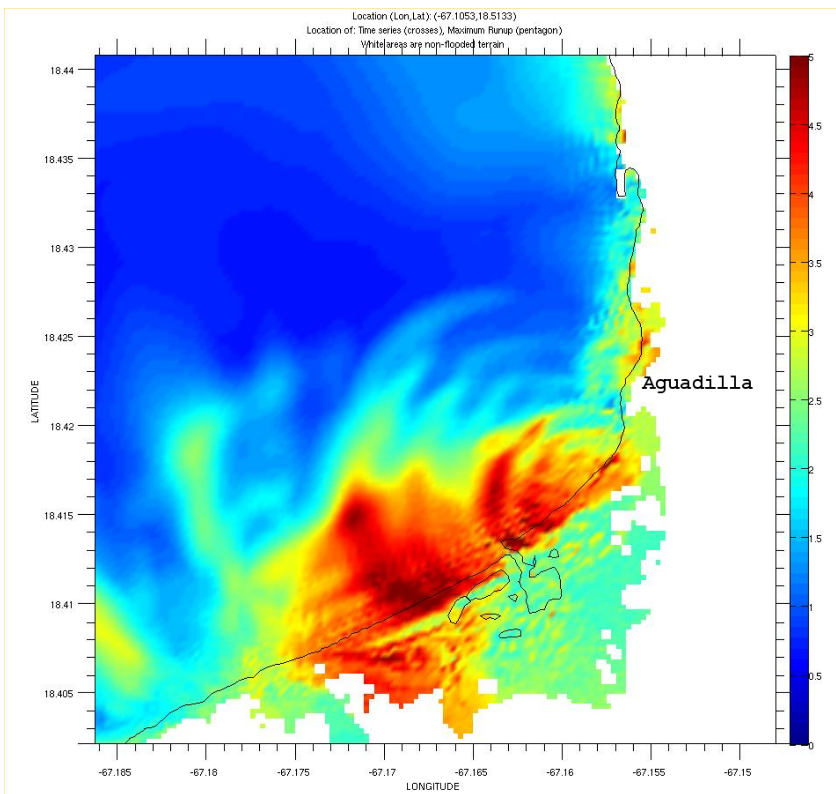

Figure 21 – Zoom into the MEOHW at the city of Aguadilla.

Figure 22 – Google Earth view of the present city of Aguadilla.

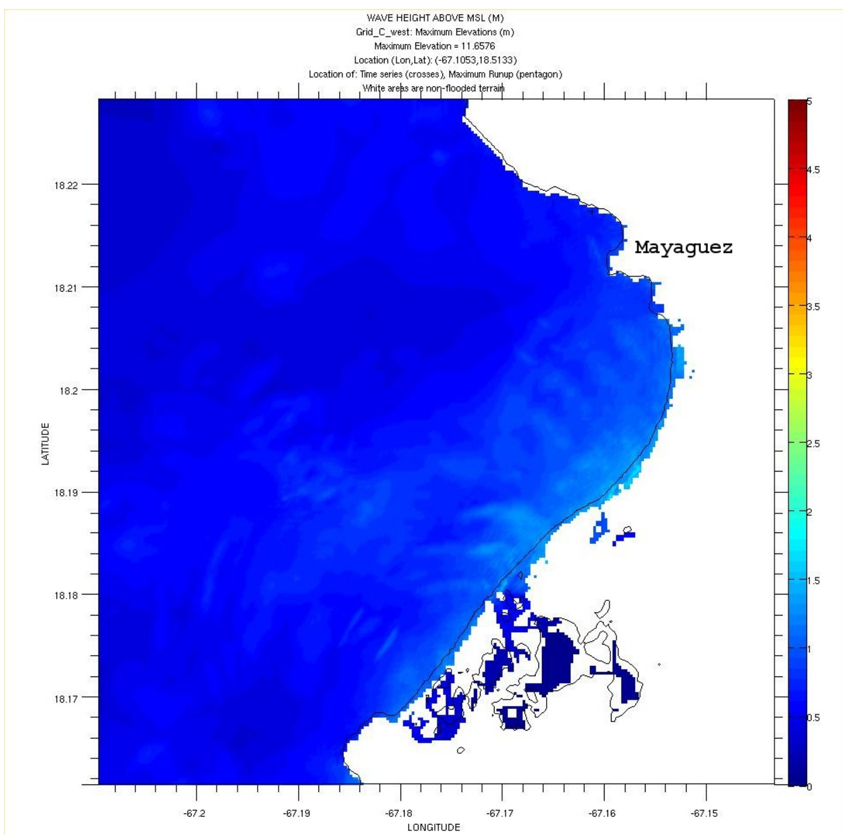

Figure 23 - Zoom into the MEOHW at the city of Mayaguez.

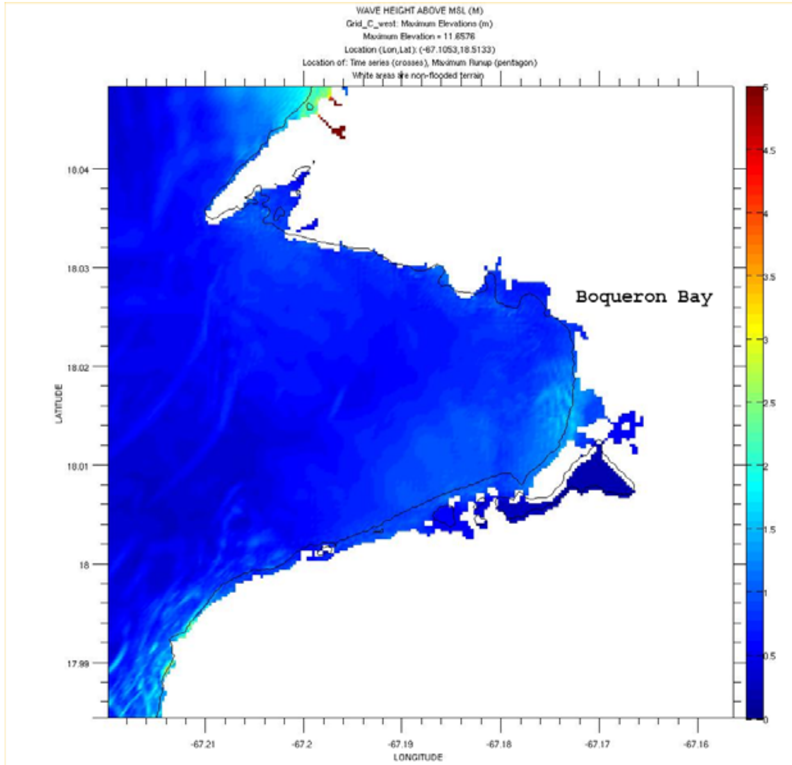

Figure 24 - Zoom into the MEOHW at Boqueron Bay.

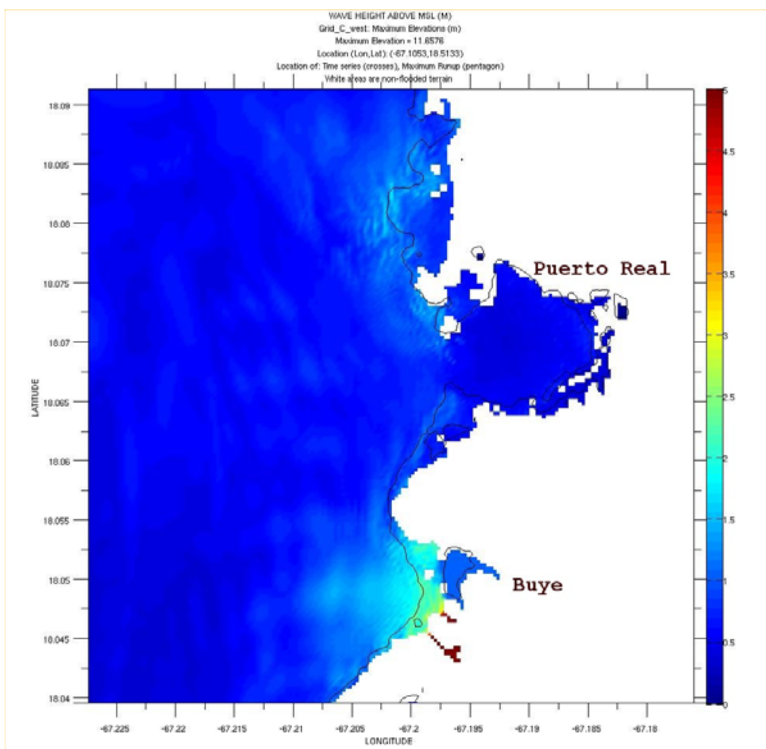

Figure 25 - Zoom into the MEOHW at Puerto Real and Buye Beach.

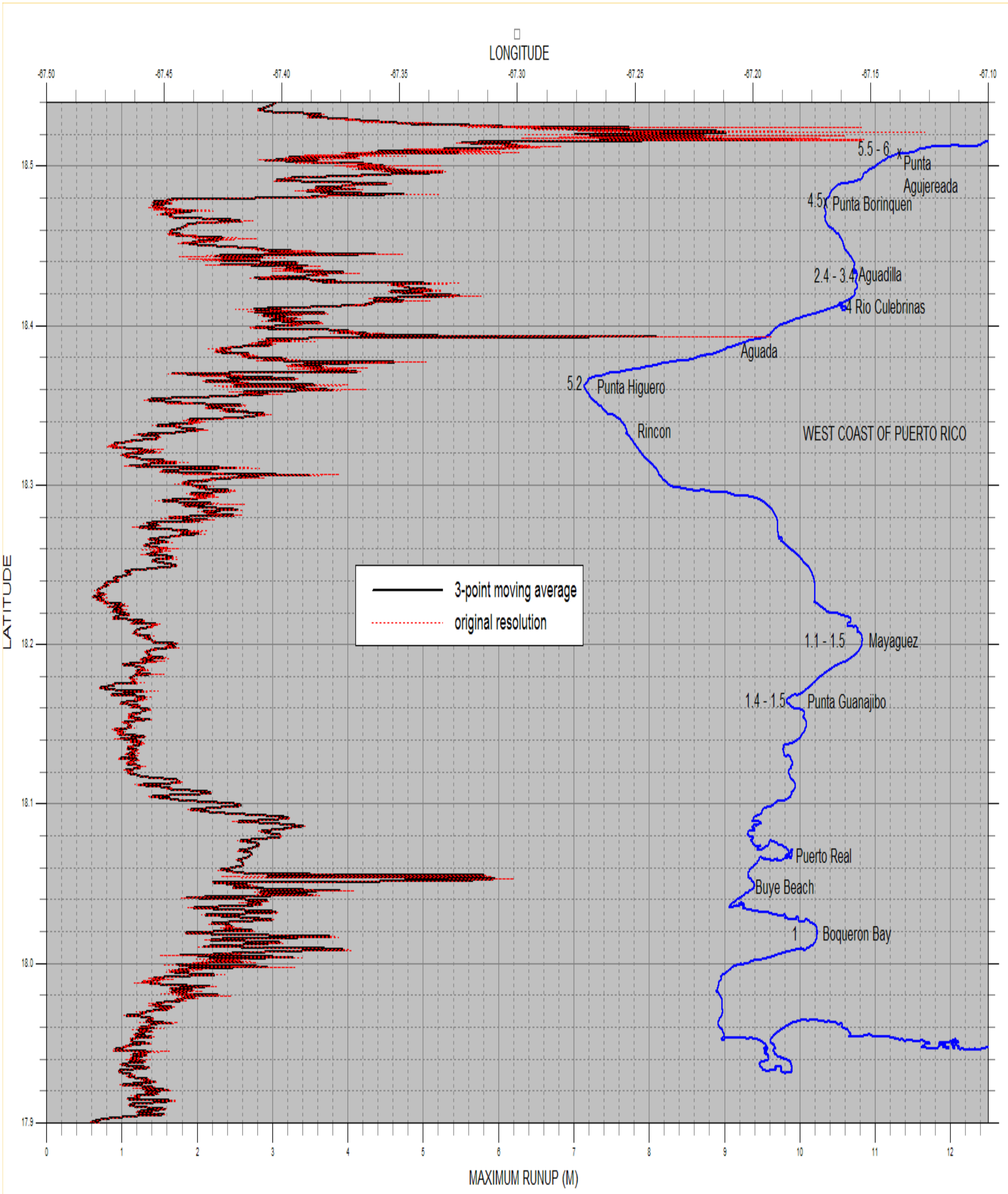

Figure 26 – Maximum runup vs latitude along the west coast of Puerto Rico. Red, dotted, line is the original curve at 30 m grid resolution. Black line is a 3 point running average.

- At the city of Mayaguez, in the northern part of the city, they documented a runup of 1.1 to 1.2 m, which is in good agreement with the model. Further south they observed elevations up to 1.5 m, again in good agreement with the model.
- At a distance of 4 km southwest of the city of Mayaguez (which should be approximately Punta Guanajibo) they documented a wave height of 1.4 to 1.5 m, which is, again, well matched by the model.
- The southernmost point where they measured was in Boqueron Bay. No runup was given, but they a drawdown of at least 1.5 m 50 m offshore. The model gives approximately 3 m of maximum runup at the head of the bay.

From the model output we can see at least two locations where the runup was large, but not measured. One of them was near the town of Aguada, with a maximum of at least 8 m. The other was at Buye Beach, just south of Puerto Real, with a value close to 6 m. It should be stated that tsunami deposits have been found inland at Aguada, but they have not been dated.

VI. Acknowledgment

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V. References

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