ASSESSMENT OF THE TSUNAMI-INDUCED MARINE CURRENTS HAZARD FOR ARECIBO BAY, PUERTO RICO

Report Submitted to

Puerto Rico Component of the USA National Tsunami Hazard Mitigation Program

and the

Puerto Rico Seismic Network

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Introduction

The 2004 Indian Ocean Tsunami claimed more than two hundred thousand lives and caused billions in damages. Since then tsunami-related education and methods for preparing coastal communities from suffering similar destruction have become an area of enormous interest.

A common misconception associated with tsunamis is where the threat lies. Many consider the destructive waves that strike the coast as the only real threat to coastal communities. Even though this idea is accurate for many cases, this train of thought does not account for the damages that can be caused even when a tsunami does not heavily impact the coast.

The National Tsunami Hazard and Mitigation Program (NTHMP) has identified this concern and has made strives to better prepare the maritime community for events of this nature. One major source of concern is the currents that can be generated from tsunami-related events. In a study done by Lynett et al. (2013), an attempt was made to quantify damage due to tsunami currents inside ports, bays, and harbors. When currents were greater than 3 knots, moderate damage could occur, but once the current exceeds 6 knots, severe damage can be caused on the docks and boats. The damage can occur even when a tsunami's epicenter is located a long distance from the area of concern.

In this report, Arecibo Bay, on the north coast of Puerto Rico, was examined. Four points of particular interest were selected for time series extraction (see Figure 1). These points are the bays center, a pier on the bay’s beach and two points on the north and west part of the bay. This bay was evaluated to measure vorticity, current speeds, inundation, angular frequencies of the shed eddies, etc. These results are presented ahead with additional details referring to the methodology used to make this report.

Methodology

Google Maps

Figure 1: Google earth image of the area under study. The time series stations found in the report are presented using yellow pins.

Table 1. Geographical locations for the stations.

Station Number	Station Name	Longitude (˚)	Latitude (˚)
1	Northern Bay	-66.702722	18.479981
2	New Pier	-66.70161	18.47793
3	Central Bay	-66.706111	18.475902
4	Western Bay	-66.710589	18.473241

Numerical Model

The Method of Splitting Tsunamis or MOST was used for generating the data found in this report. This is the principal model used in the NOAA Center for Tsunami Research (NCTR). The MOST model was run using an interface developed by the NCTR, known as ComMIT. This model operates in two parts. The first part consists of assigning the numerical values for several seismic parameters such as geographical location, rake, slip, etc. This information is used to generate the deformation, which in turn generates the propagation across open ocean. The second part works on the inundation phase. This consists of three grids, which go from lowest to the highest resolution. Grid A is the largest in geographical extension and has the lowest resolution, grid B has an intermediate resolution, and grid C has the largest resolution. MOST was setup so that once the tsunami reaches grid C, the MOST program executes the inundation part of its program. This information is used to generate the graphs found in this report.

Bathymetry and Topography Processing

As was previously explained MOST operates using three grids. For this particular study a resolution of 60 arc seconds (1800 m) was used for Grid A, a resolution of 9 arc seconds (270 m) for grid B and a resolution of 1/3 arc seconds (10m) for Grid C. This grid was not edited outside of what ComMIT edits when using a function called Filter Bathymetry (SSL). This operation filters points on a respective grid, which can cause problems when running the MOST executable. This was used once on all grids. In addition, grid C (see Figure 4) was cropped using ComMIT in order to fit under the max allowed grid size 3000X3000 (LINUX) or 2000X2000 (WINDOWS).

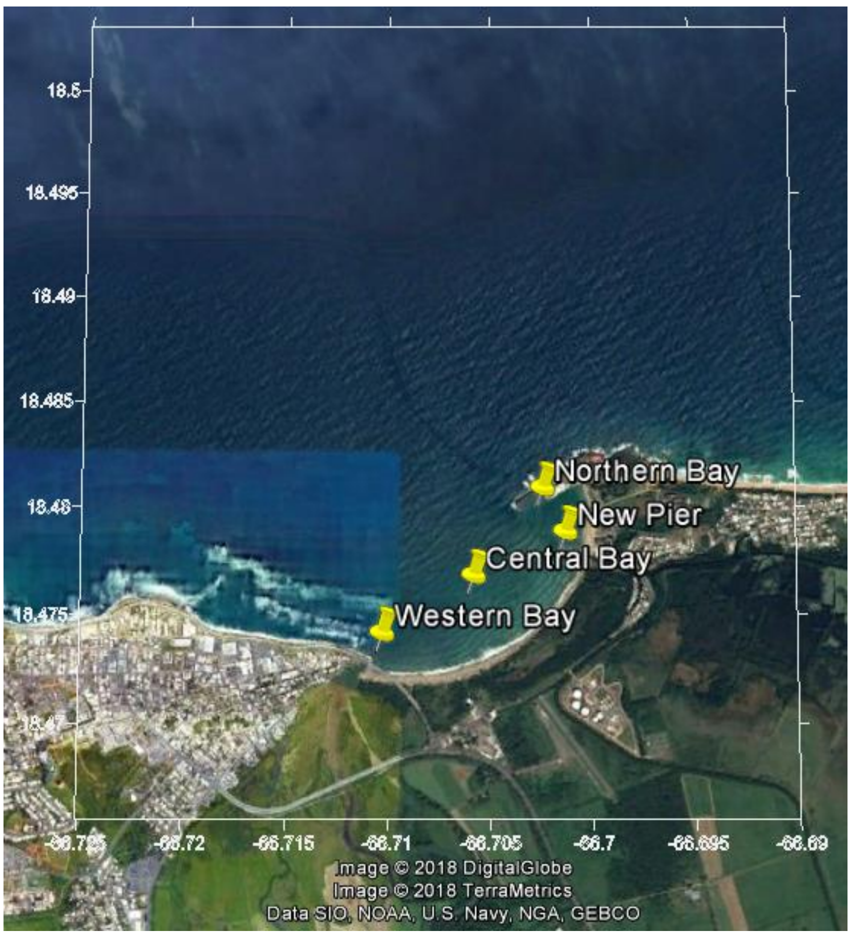

Figure 2: Google earth image displaying a rectangle corresponding to the computational grid C used for modeling the FEMA scenario. Northernmost corner has depths greater than 300 meters.

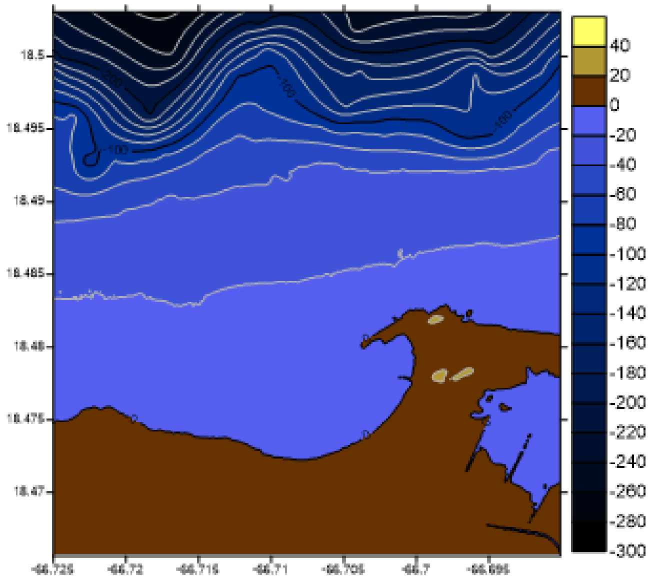

Figure 3: Contour Map displayed in the results section corresponding to Arecibo Bay. The vertical datum adopted by NGDC is Mean High Water (MHW). Grid resolution is 10 m.

Tsunami Scenario

The propagation part of this event was done using ComMIT's custom propagation menu. The first scenario was generated using four fault planes. The seismic information came from a previous report done by Prof. Aurelio Mercado submitted to NTHMP for tsunami flood events from local events. It consisted of a magnitude 8.4 earthquake generated along the Puerto Rico Trench commonly called the FEMA Catastrophic Event. The coordinate system had to be modified from its original Aki-Richards epicenter coordinate system to the system that MOST uses. The Aki-Richards format takes the epicenter from the top left corner, while MOST takes the epicenter from the center of the bottom side of the fault plane.

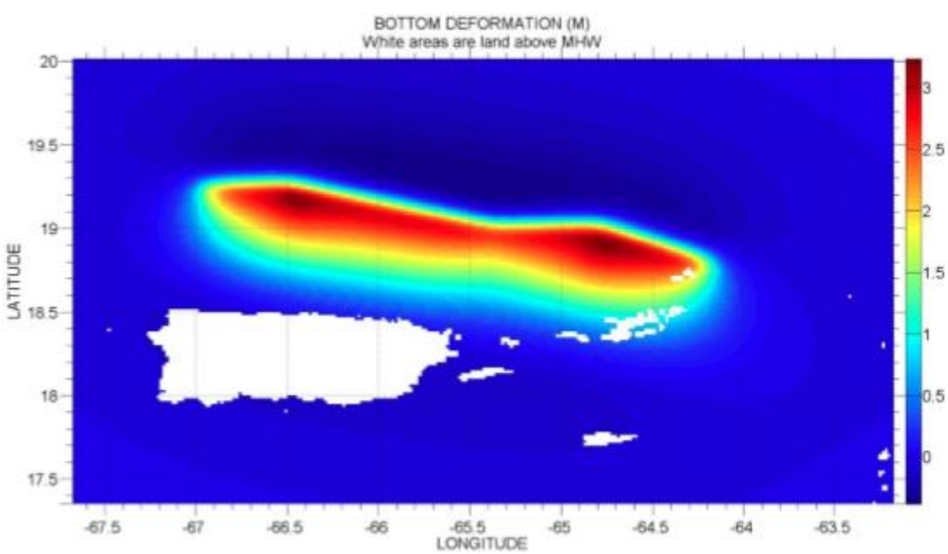

Figure 4: Initial sea surface deformation for the FEMA Catastrophic Scenario. Elevations in meters.

Table 2. Summary of parameters relating to the Tsunami Source, DEMs and the Numerical Method used.

Tsunami Source				
• Location	Puerto Rico Trench			
• Number of Scenarios	1			
• Magnitude	8.4			
• Segment	1	2	3	4
• Longitude (degree)	295.3423	294.8999	293.9418	293.25
• Latitude (degree)	18.4653	18.5381	18.6791	18.7882
• Rupture Length (km)	66.92	63.08	118.9	52.49
• Rupture Width (km)	72.59	72.59	72.59	72.59
• Dip (degree)	45	45	45	45
• Rake (degree)	90	75	85	75
• Strike (degree)	109	90	103	90
• Slip (m)	5.473	5.473	5.473	5.473
• Depth (km)	10	10	10	10
Digital Elevation Models (DEM)				
• Source of Data	National Geographical Data Center (NGDC)			
• Resolution in Inundation	1/3” (~10m)			
• DEM quality control	NOAA/NGDC			
• Structured/non-structured grid	Structured			
• Smoothing	Filtered using SSL (available in program)			
• Buildings/vegetation filters/bald earth	Ports incorporated with bare earth			
Numerical Method				
• Model	MOST-type using ComMIT interface			
• Interface	ComMIT 1.7.7a			
• Initial Condition Variables	Sea surface = earthquake static crustal deformation			
• Propagation	linear shallow water equation			
• Inundation	Non-linear shallow water equation			
• Manning’s Coefficient	0.03			

Results

The section will provide the visual data acquired from modeling the earthquake parameters and DEMs previously explained. These images will be presented in the following manner:

- Images pertaining to Arecibo Bay using the FEMA tsunami scenario (Figures 5-17)

The elevation and current speeds corresponding to the stations in Figure 1 are presented in Figure 8. Figures 9 and 10 correspond to the stick plots of the vectors at the stations previously specified.

Maximum Envelope Of Water (MEOW)

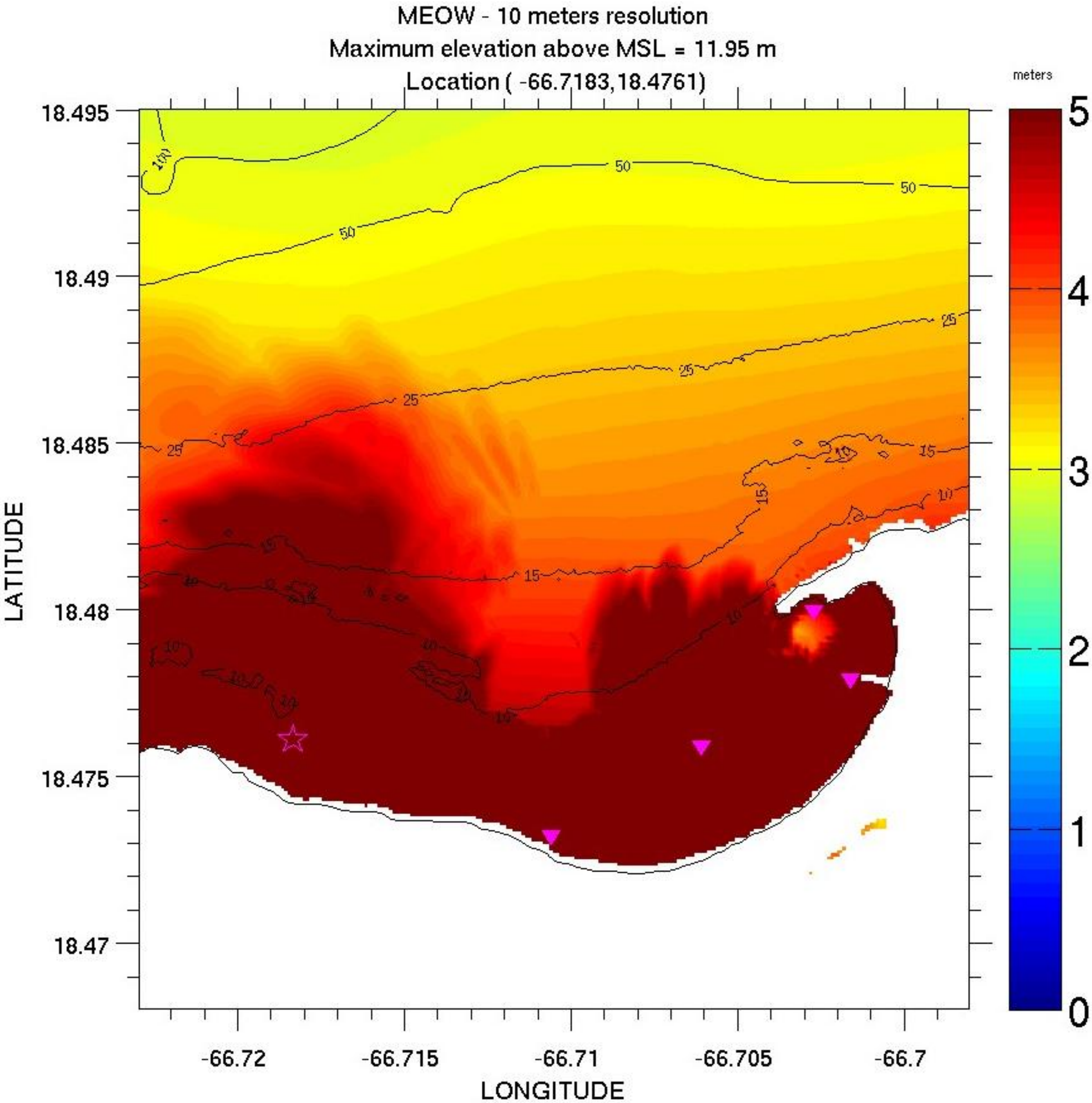

Figure 5: Maximum sea surface elevation above MSL for the FEMA scenario in the Puerto Rico Trench. Elevations in meters. Grid resolution is 10 m. MEOW inland of the mean high water line not shown.

Local Water Depth (meters)

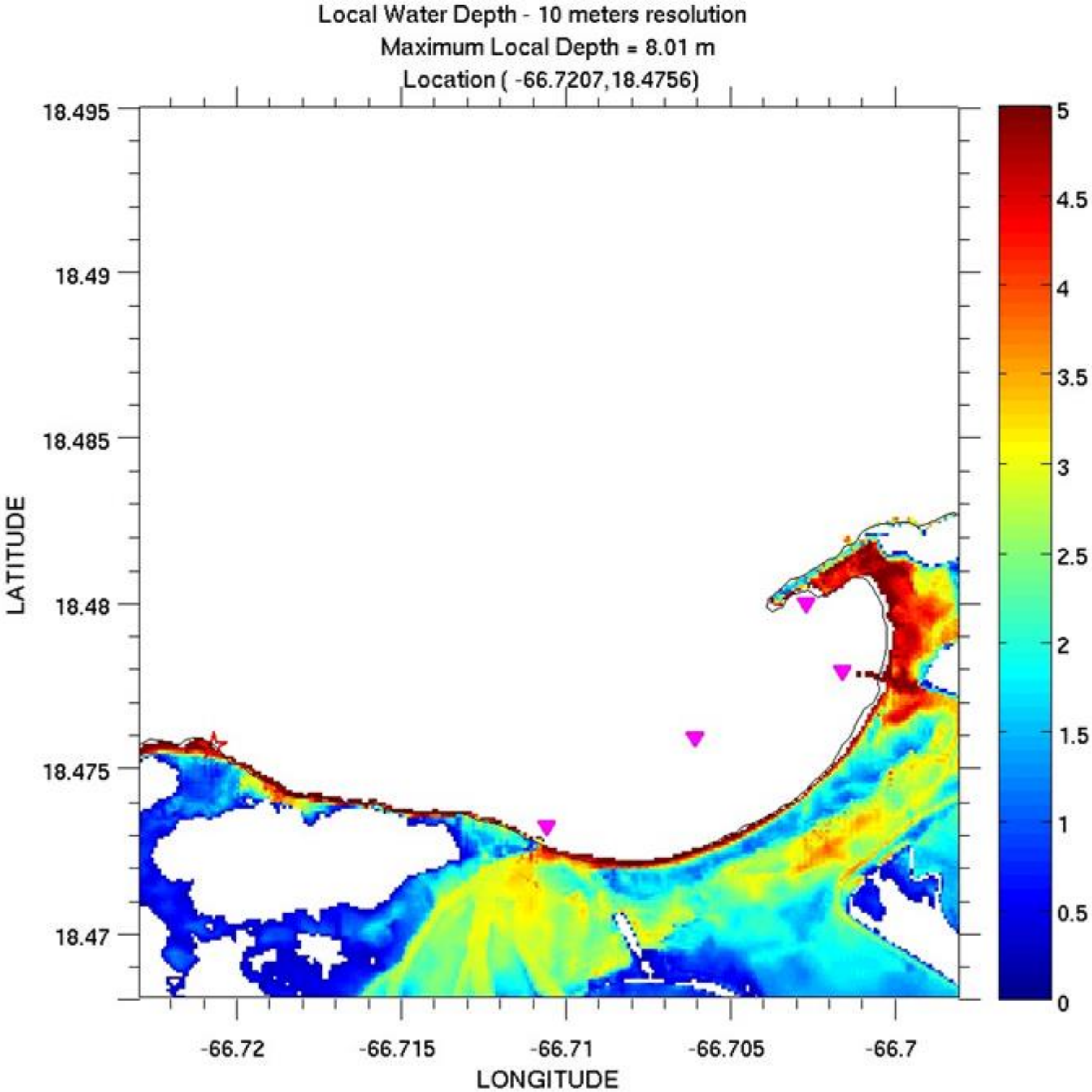

Figure 6: Maximum Local Water Depth for the FEMA scenario in the Puerto Rico Trench. This is inundation water depth. Depths in meters. Star indicates the location of the maximum inundation depth.

Local Tsunami Current Speed Hazard Zones

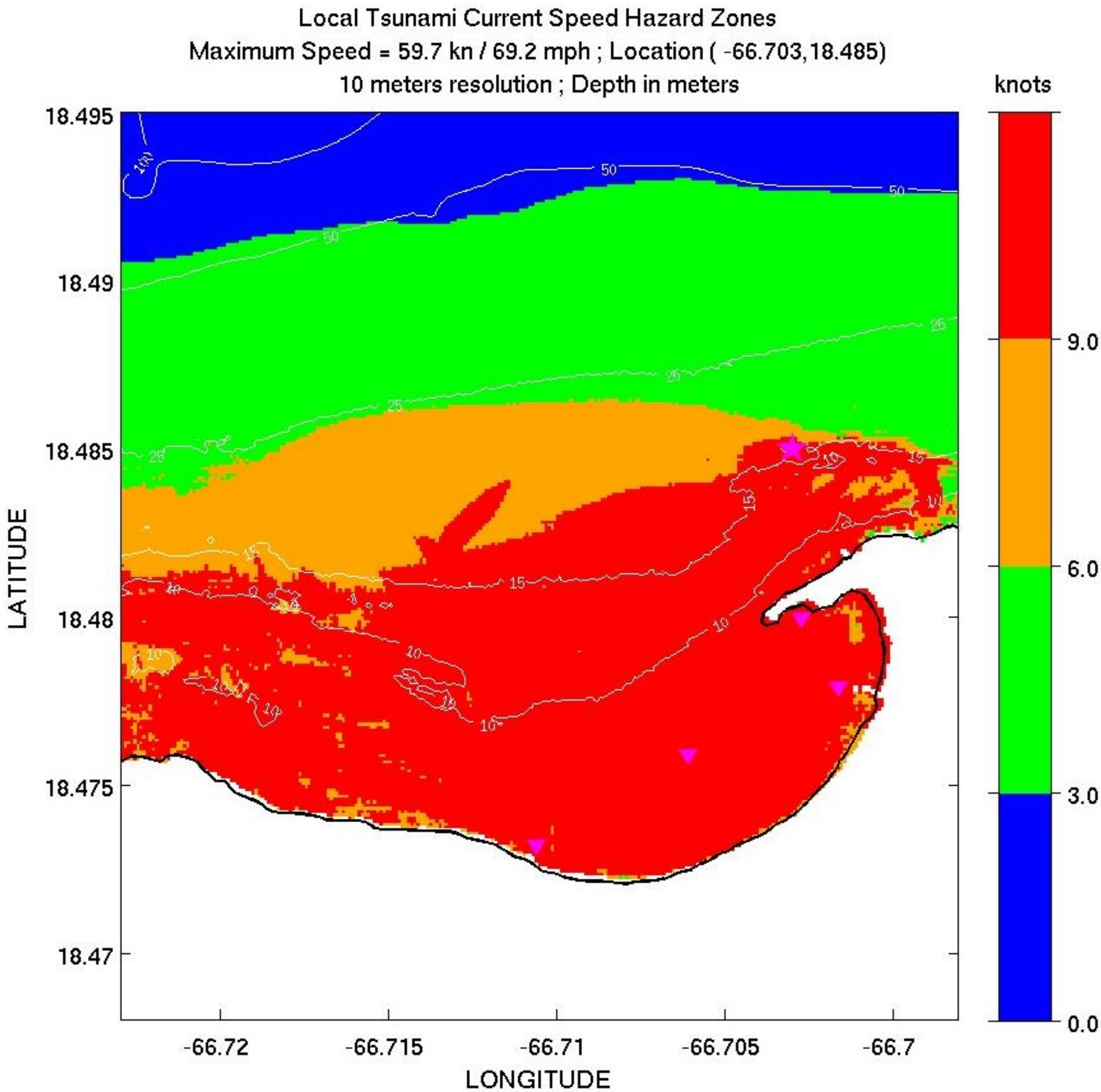

Figure 7: Tsunami current speed hazards zones for the FEMA scenario in the Puerto Rico Trench. Star indicates location of maximum current speed.

Tsunami wave height relative to MHW and tsunami current speeds

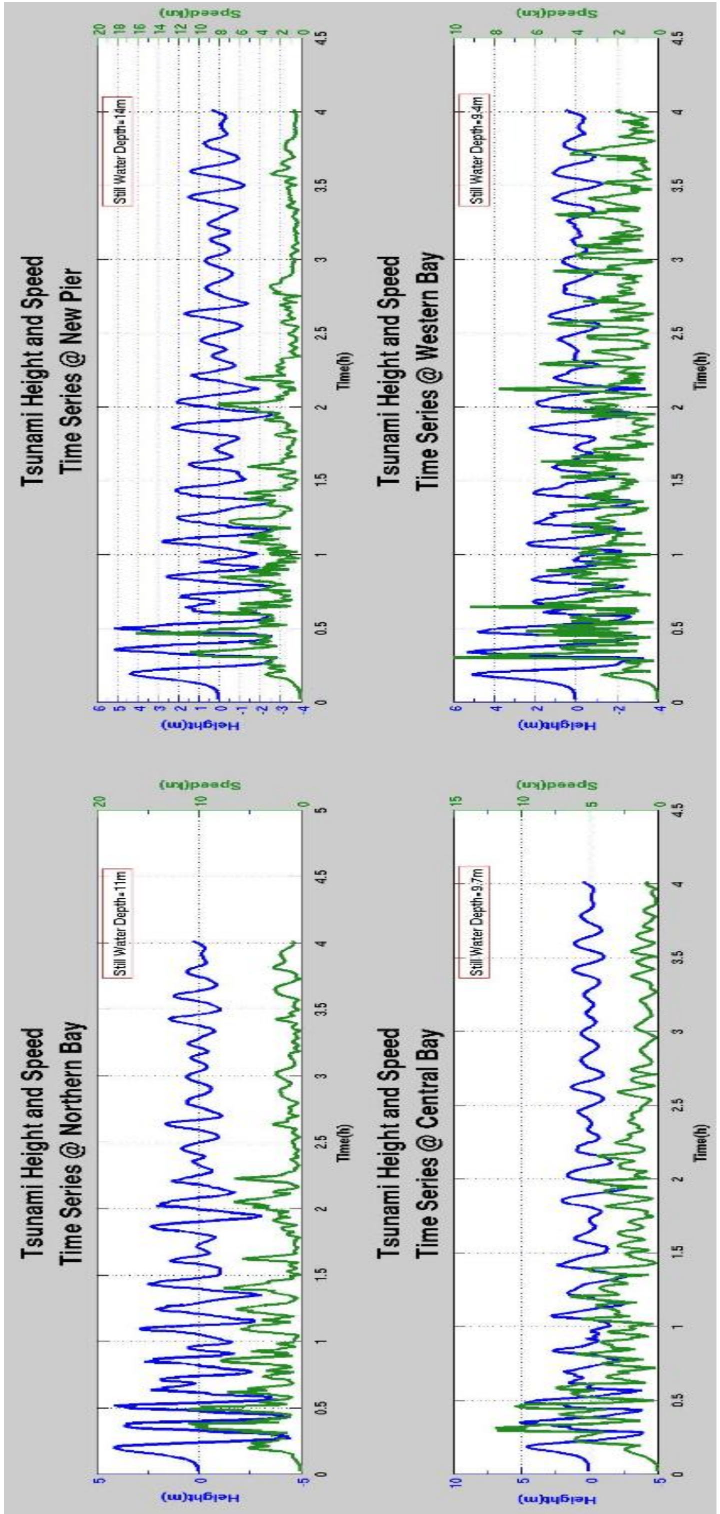

Figure 8: Tsunami wave height relative to MHW (m; blue) and tsunami current speeds (kts; green), at stations shown in Figure 1. Grid resolution is 10 m.

Stick plots of tsunami current for Stations 1 and 2

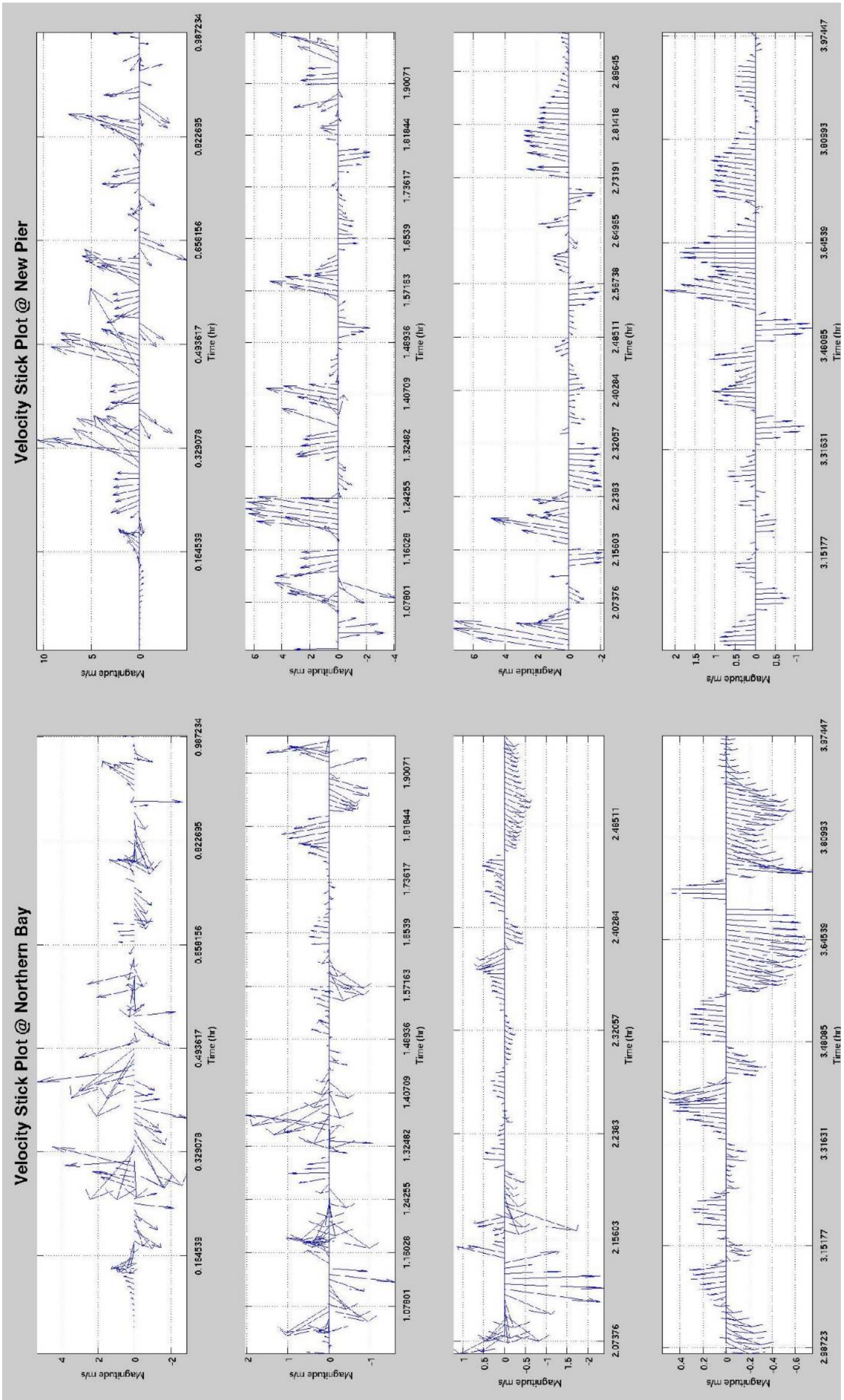

Figure 9: Stick plots of tsunami current speeds at Stations 1 – Northern Bay (left rows) and 2 – New Pier (right rows).

Stick plots of tsunami current for Stations 3 and 4

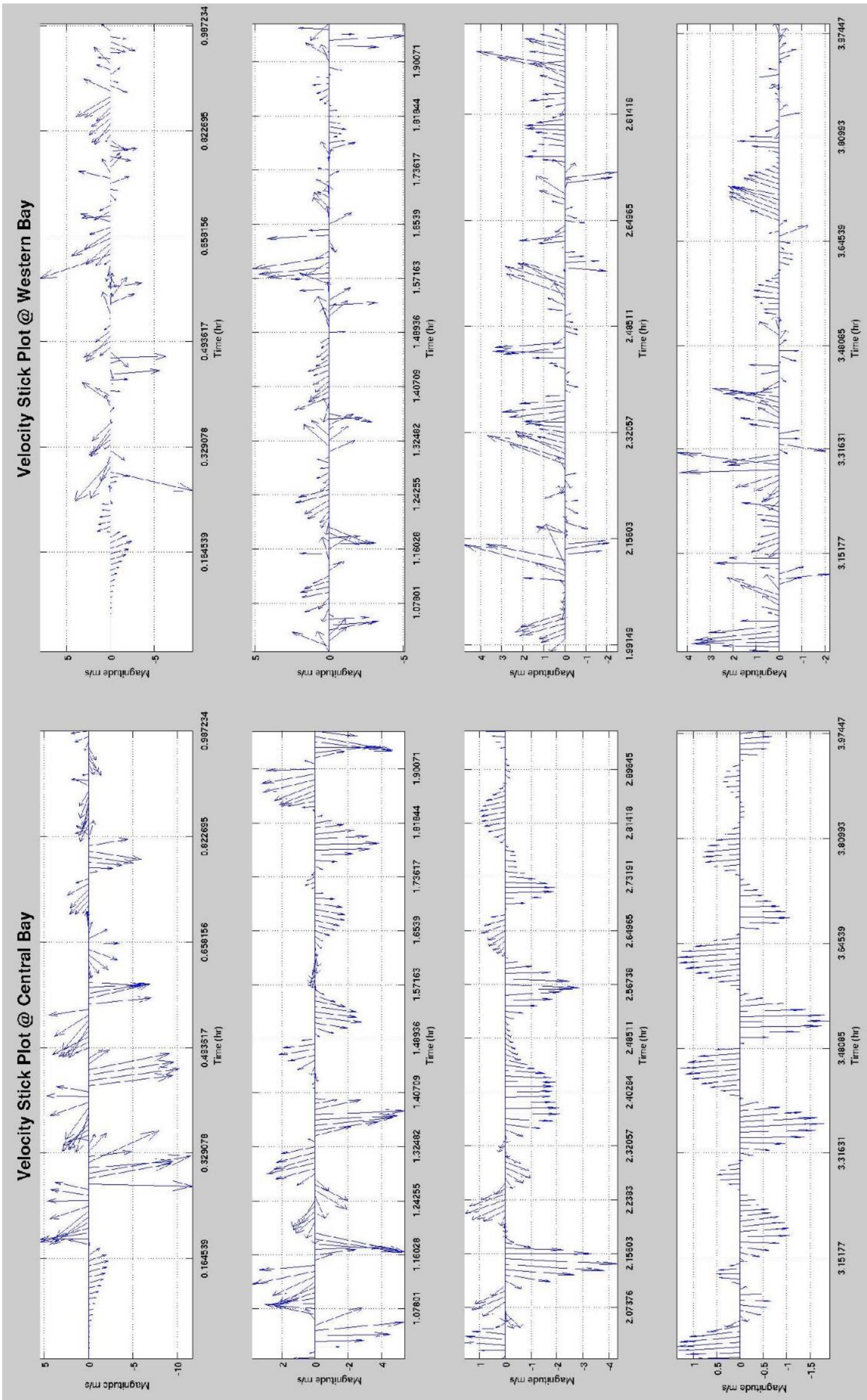

Figure 10: Stick plots of tsunami current speeds at Stations 3 – Central Bay (left rows) and 4 – Western Bay (right rows).

Minimum Water Depth (relative to MHW)

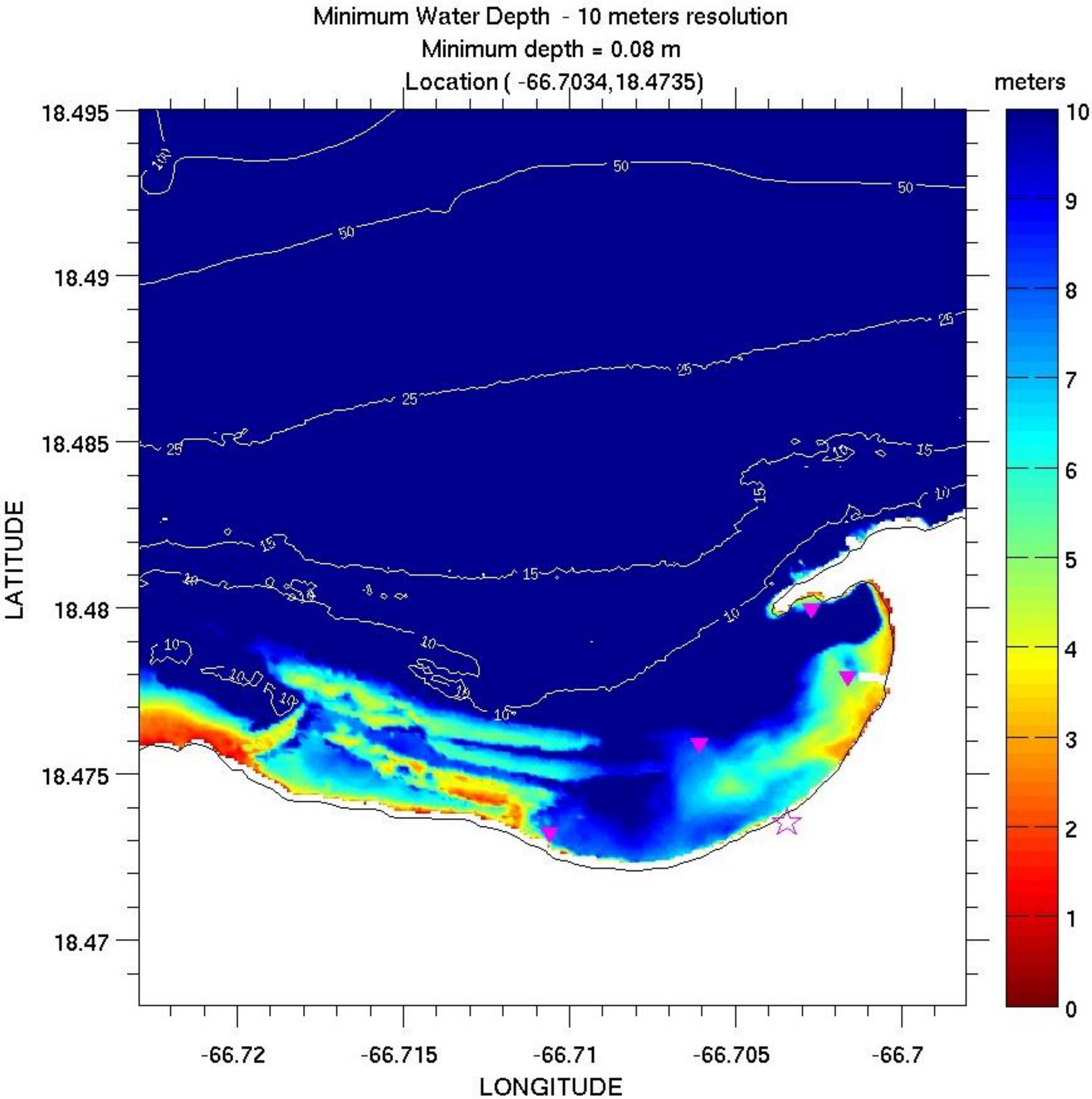

Figure 11: Minimum remaining water depth. This is computed by subtracting the absolute value of the maximum sea surface depression from the absolute value of the mean water depth at each computational cell. Use the image found in the appendix in order to visualize this calculation. Grid resolution is 10 meters.

Minimum Envelope Of Water (anti-MEOW)

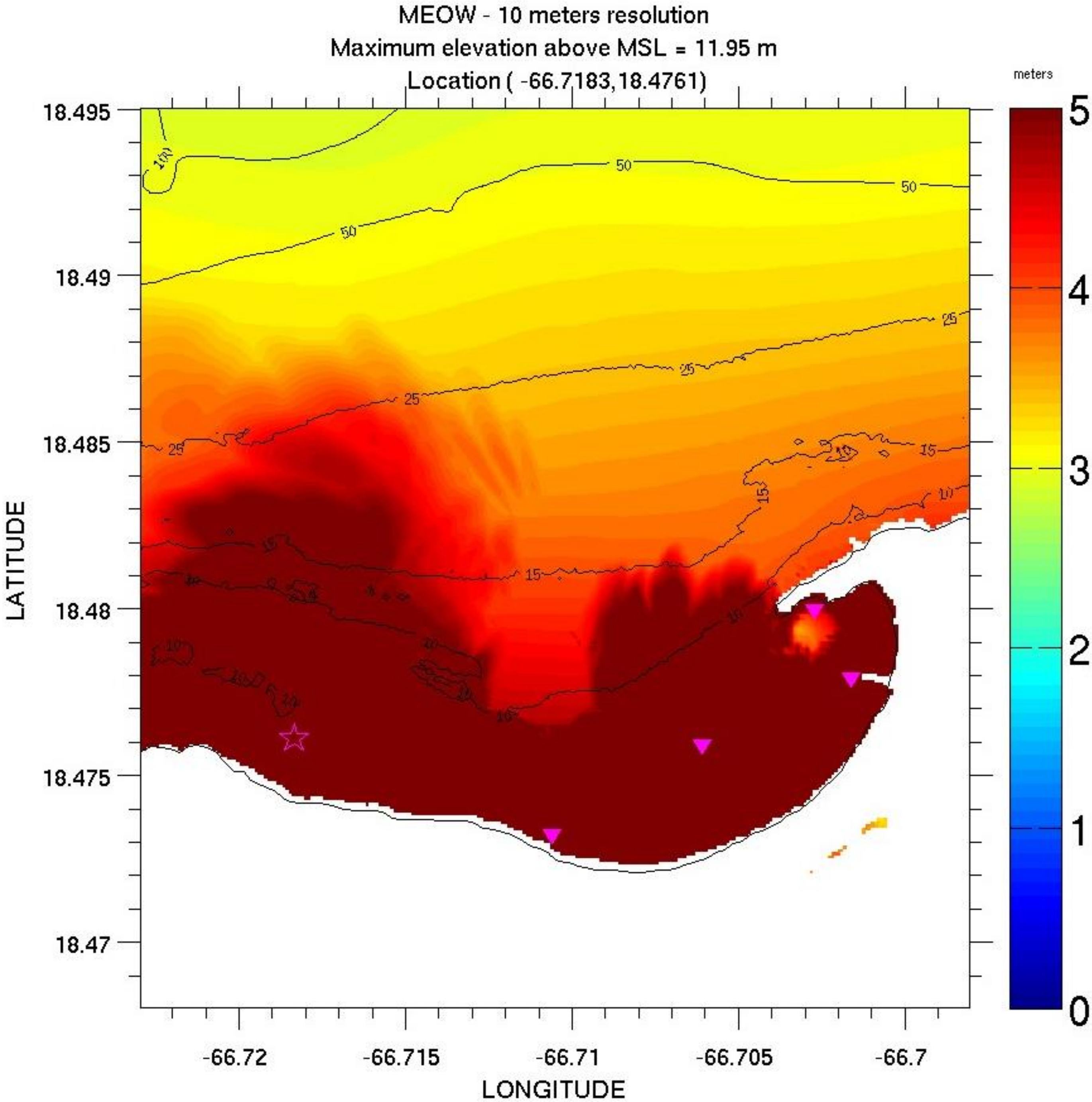

Figure 12: Also known as the maximum sea surface depression. This corresponds to the greatest decrease in sea level relative to MSL. The image found in the appendix can be used to facilitate visualization. Grid resolution is 10 meters.

Maximum Peak to Through Fluctuations

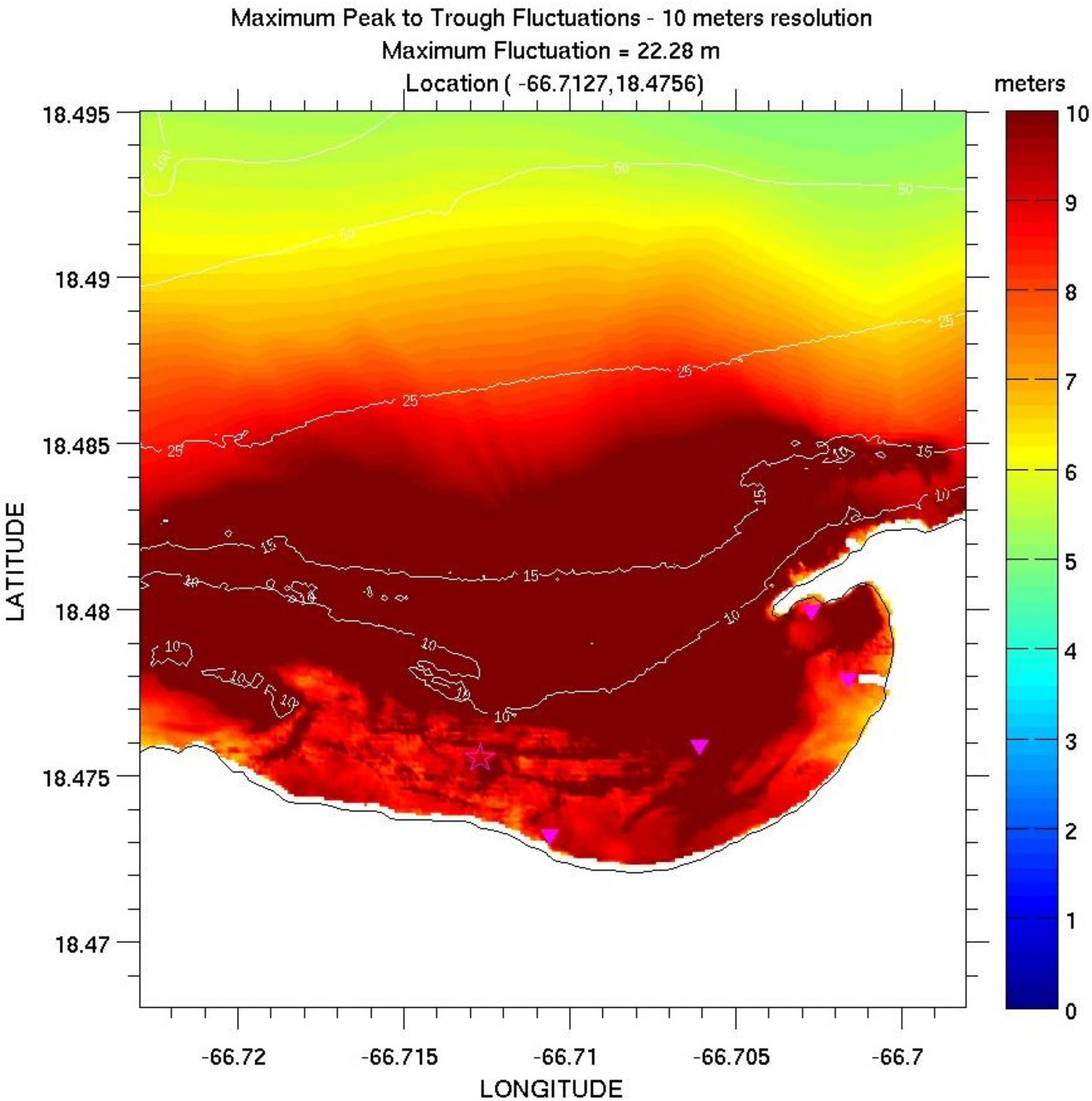

Figure 13: Peak-to-Trough water level fluctuation. This is computed by subtracting the maximum sea surface depression (irrespective of time) from the maximum sea surface elevation (irrespective of time – MEOW minus anti-MEOW). The image found in the appendix can be used to facilitate understanding this calculation. Grid resolution is 10 m.

Maximum Angular Frequency (degrees/s)

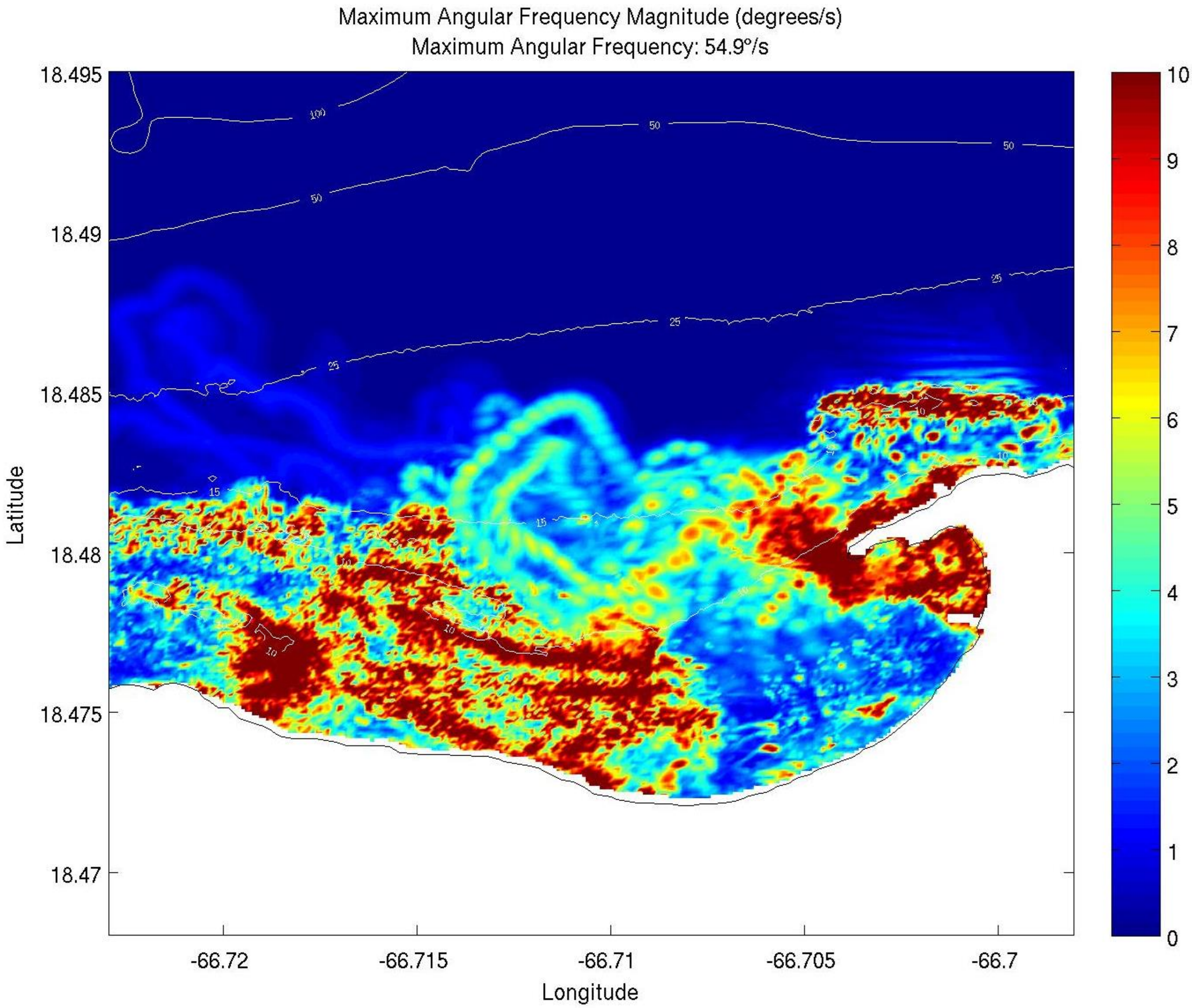

Figure 14: Figure showing the magnitude of the maximum angular frequency of the eddies induced by the tsunami. Grid resolution is 10 meters.

Current Speed Duration Greater than 3 knots

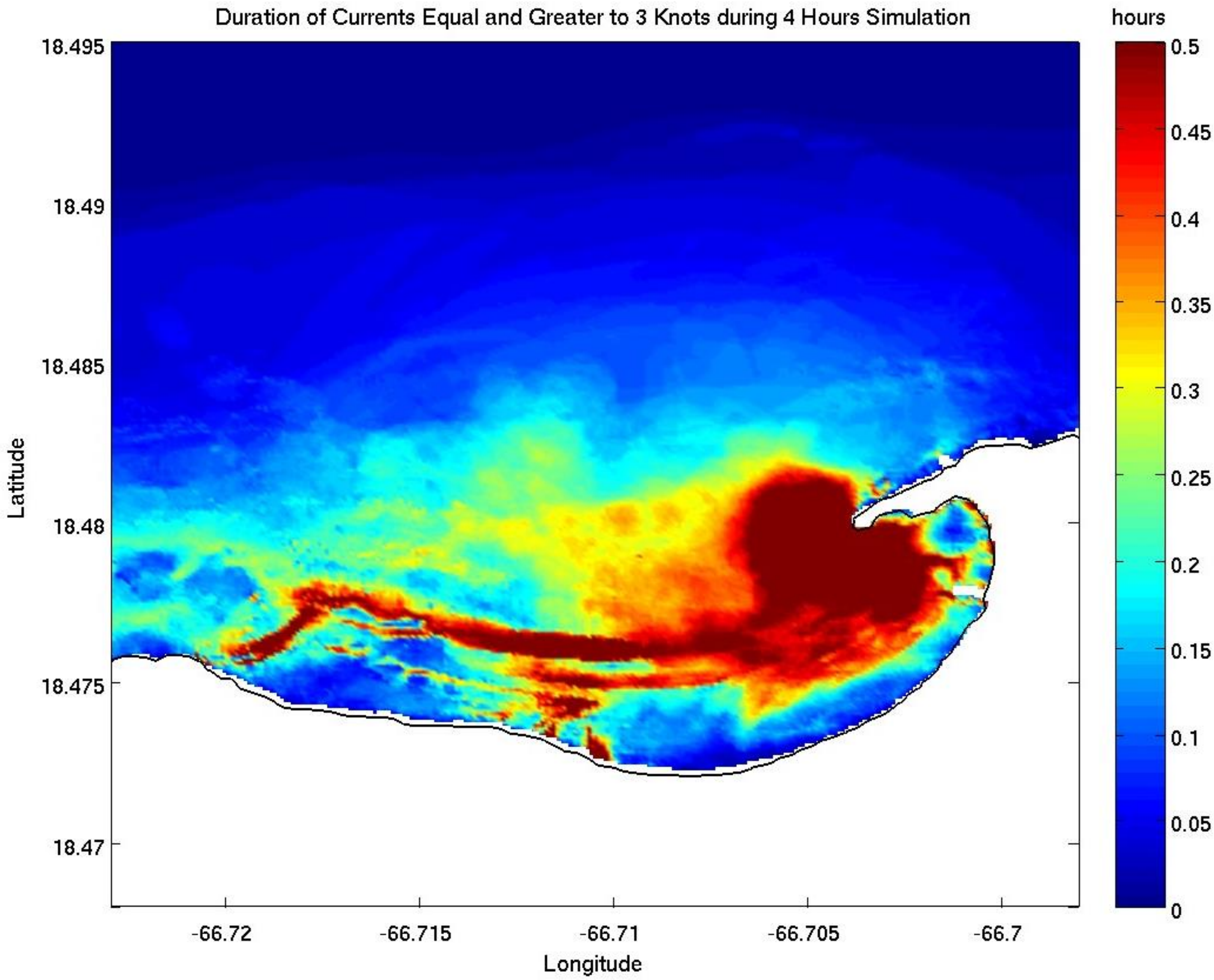

Figure 15: Duration of tsunami-induced currents ≥ 3 knots during the 4 hours of simulation with a color bar cap of 0.5 hours. Grid resolution is 10 m.

Current Speed Duration Greater than 6 knots

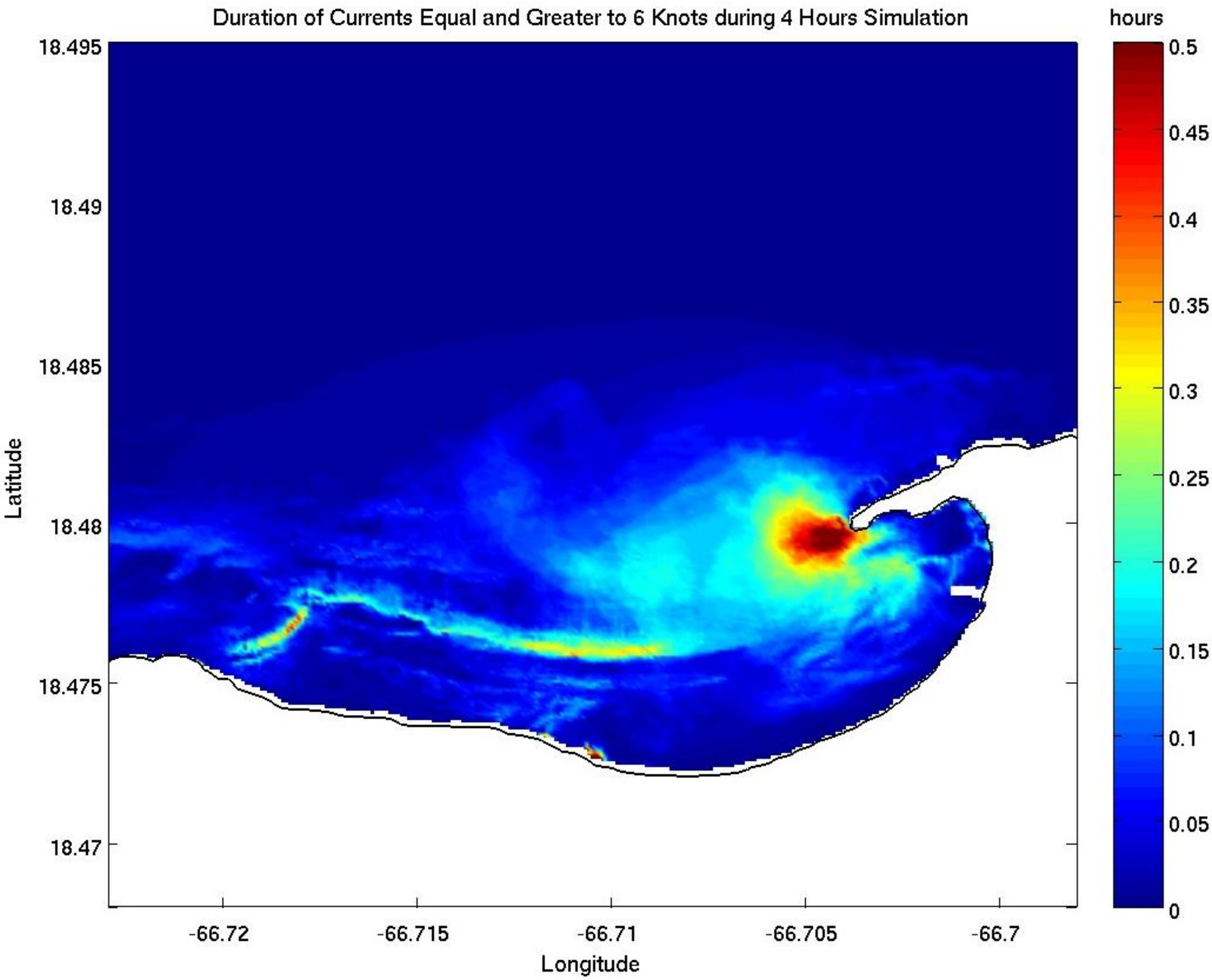

Figure 16: Duration of tsunami-induced currents ≥ 6 knots during the 4 hours of simulation with a color bar cap of 0.5 hours. Grid resolution is 10 m.

Current Speed Duration Greater than 9 knots

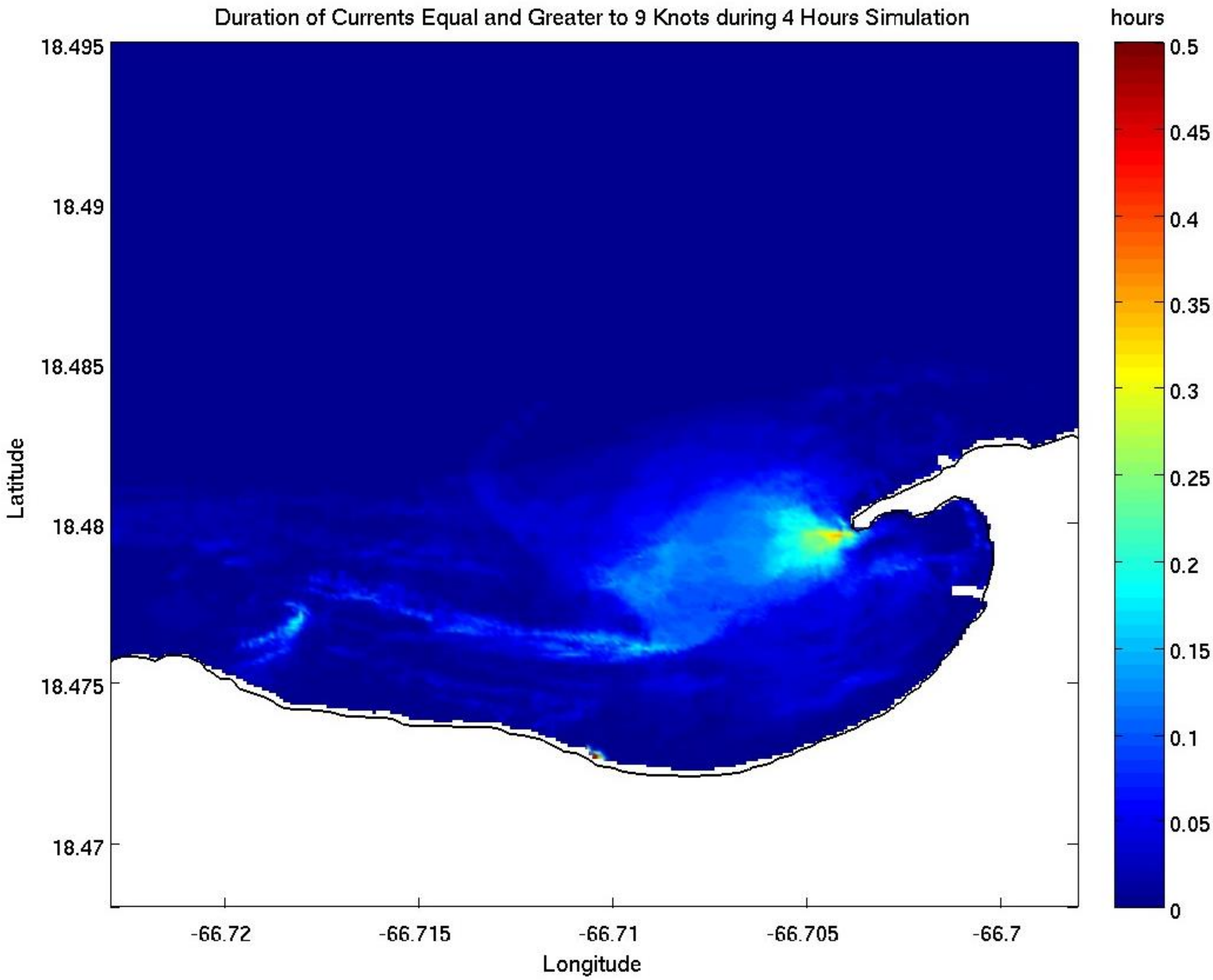

Figure 17: Duration of tsunami-induced currents ≥ 9 knots during the 4 hours of simulation with a color bar cap of 0.5 hours. Grid resolution is 10 m.

Discussion

It is important to take into account when referencing the data found in this report, that some results may not fully correspond to the results found in a real life event. Among the factors that contribute to this reality is the fact that the tsunami event being modeled is generated by a magnitude 8.4 earthquake, which is considered for Puerto Rico as the worst case scenario by FEMA. This can cause the currents, inundation, etc. generated by this event to be more extreme than those generated by a more likely event. Additionally, it is still unknown if MOST can simulate accurately such extreme currents and vorticity.

References

[1] Lynett, P., Borrero, J., Son, S., Wilson, R., and Miller, K., 2013, Assessment of current-induced tsunami hazards for maritime planning: Geophysical Research Letters.

Acknowledgements

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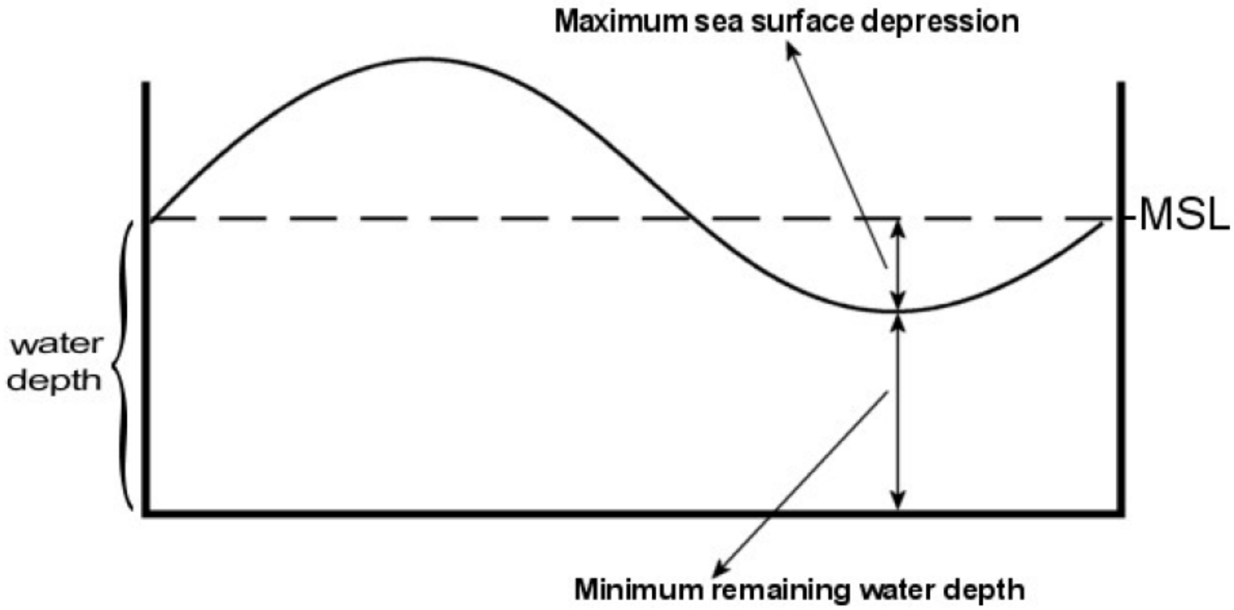
Appendix


Maximum sea surface depression
MSL
water
depth
Minimum remaining water depth