ASSESSMENT OF THE TSUNAMI-INDUCED TSUNAMI HAZARD FOR PONCE 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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OBJECTIVE

Carry out a tsunami currents hazard analysis for Ponce Bay using the MOST tsunami model. Figure 1 shows a Google Earth view of the Bay and the locations where current velocities time series were collected. Table 1 shows the coordinates of the locations. A total of 4 hours were simulated.

Figure 1 – Google Earth view of Ponce Bay. The locations where time series were measured are shown by the yellow pins. Geographical coordinates are given in Table 1.

Table 1: Geographical coordinates of the locations where time series were collected.

Station Number	**Longitude(°)**	**Latitude (°)**
1	-66.623630	17.956721
2	-66.654317	17.959052
3	-66.645600	17.977912
4	-66.628392	17.98.0994
5	-66.618576	17.965886
6	-66.619517	17.970974

BATHYMETRY

The bathymetry (and topography) is based on the 10 meters resolution DEM for Ponce prepared by NGDC. Figure 2 shows painted contour plots of the bathymetry and topography. We can see that Ponce Bay is no exception to the complexity of the bathymetry around Puerto Rico.

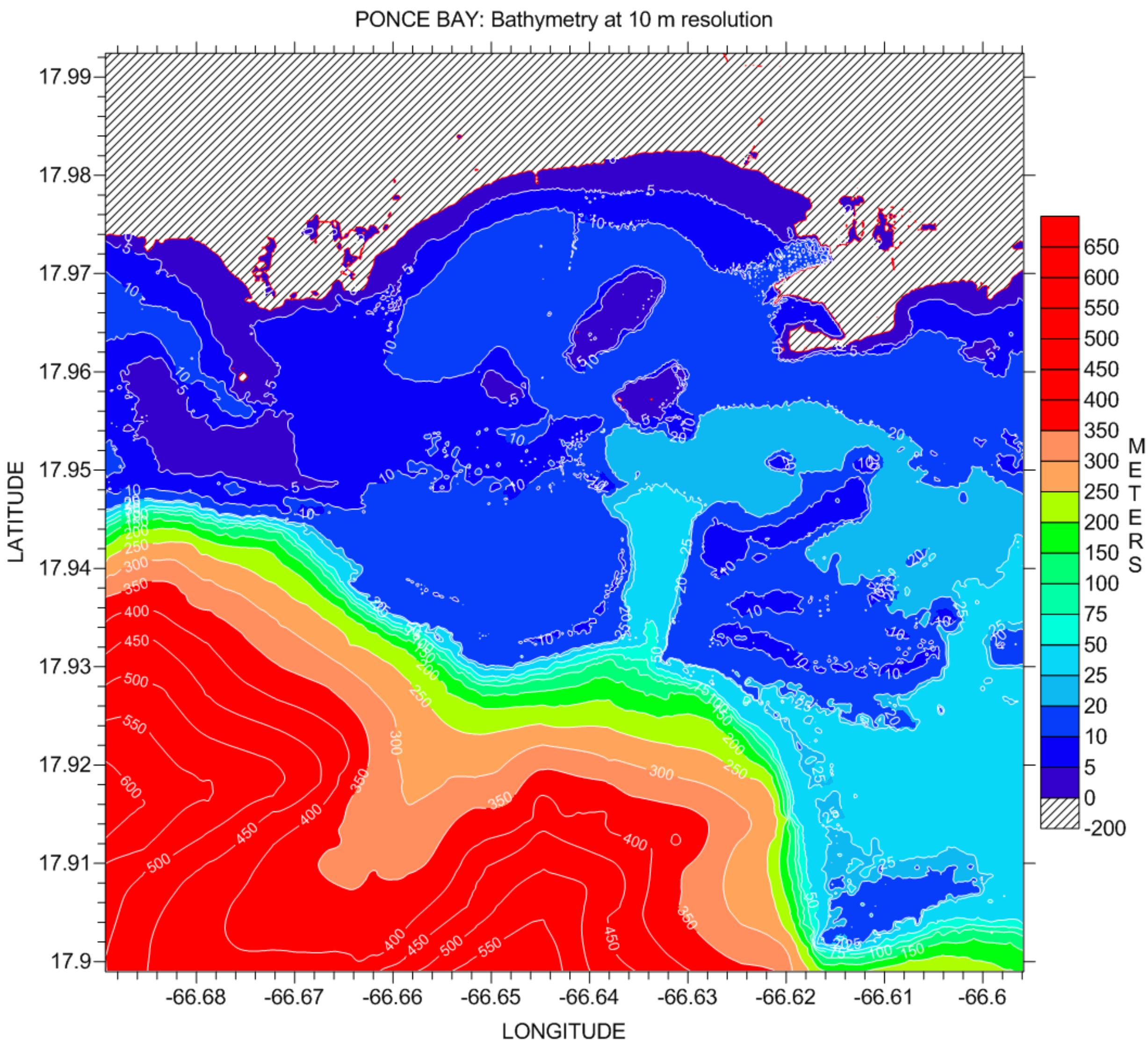

Figure 2 – Contour plot of the bathymetry and topography of the study site.

PREVIOUS WORK

As part of a previous study, a total of 320 local faults were simulated with MOST at a grid resolution of 30 m. With these results the tsunami flood maps for the island were prepared. One of the additional outputs (in addition to the water surface elevation), was the current speed induced by each of the tsunamis. This current speed was output in a netcdf file as the maximum values at each computational cell, irrespective of the time during the event when it occurred. Figure 3 shows the collection of all maximum current speeds for all 320 simulations. The color scale is based on the Mapping & Modeling report publication "Guidelines and Best Practices for Tsunami Hazard Analysis, Planning, and

Preparedness for Maritime Communities – Maritime Planning and Preparedness Guidelines”, draft June 2015.

The Guidelines provide four current speed ranges which should be used for damage assessment:

1. Blue: 0 to 2.9 knots – no observed damage
2. Green: 3 to 5.9 knots – minor to moderate damage
3. Orange: 6 to 8.9 knots – damage observable, transition to major damage
4. Red: larger than, or equal to, 9 knots – major to complete damage

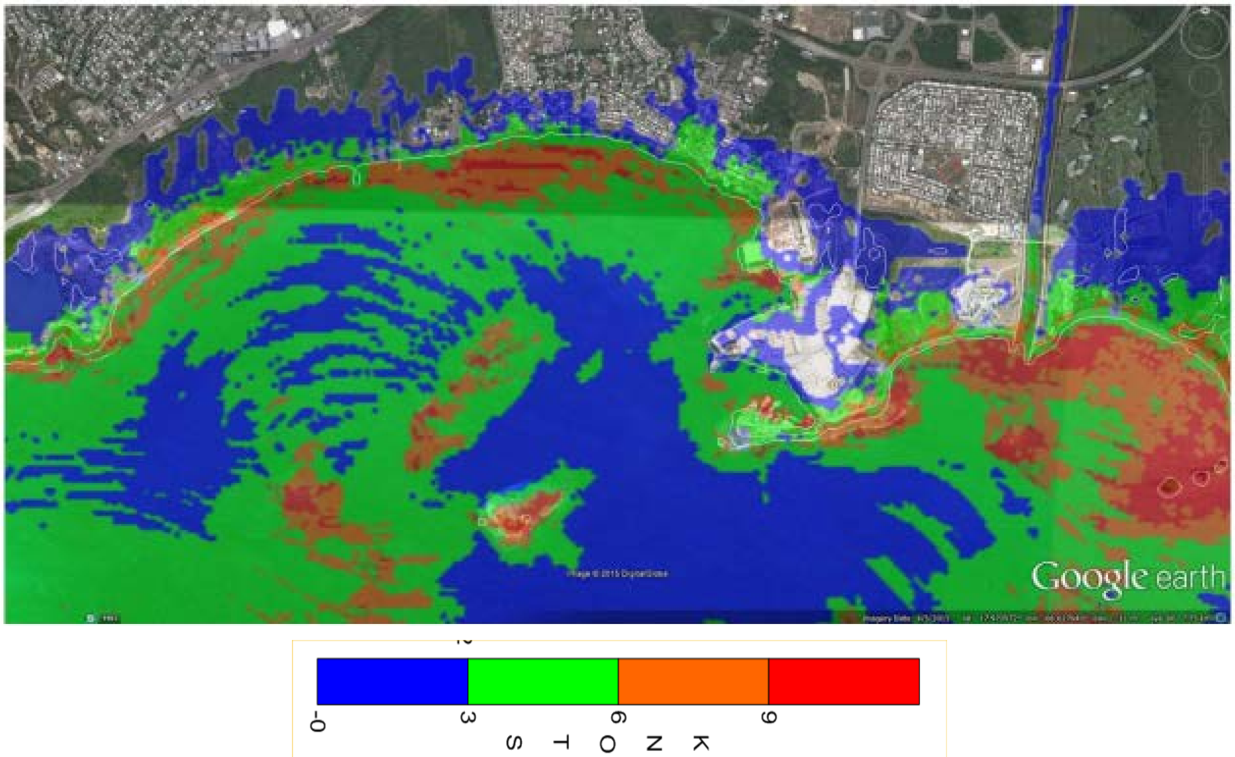

Figure 3 – Maximum tsunami current speed zones for the composite of 320 tsunami simulations.

TSUNAMI SCENARIO

In what follows the assessment of the tsunami induced hazard will be based on is Muerto’ s Trough fault #12 (p.36*, Report on Puerto Rico Tsunami Flood Maps for Local Events submitted to NTHMP and the PRSN*, January, 2014), an Mw 7.5 earthquake generated at the Mona Channel approximately 71 km from the bay (see Figure 4). Figure 5 shows the maximum elevation above MSL in the Ponce Bay area for the event, at 10 m. Figure 6 shows the flood depths (difference between the elevations relative to MSL and the terrain elevation). This will be denominated the Local Water Depth. Figure 7 shows the maximum current speeds for the event.

Figure 8 shows elevation and speed time series at the locations shown in Figure 1. Figure 9 to 11 show stick plots of the current vectors at the same locations.

A useful information, especially for cruise and cargo ships is the minimum water depth reached during the tsunami event. Figure 12 shows such information. This is computed by subtracting the maximum sea surface depression from the water depth at each computational cell (see Figure 13).

Figure 14 shows the Minimum Envelope Of Waters (anti-MEOW), which is the maximum depressions of the sea surface computed irrespective of the time when it occurred. This is the opposite of the MEOWs.

Another one is the Peak-to-Trough water level fluctuation, and shown in Figure 15. 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).

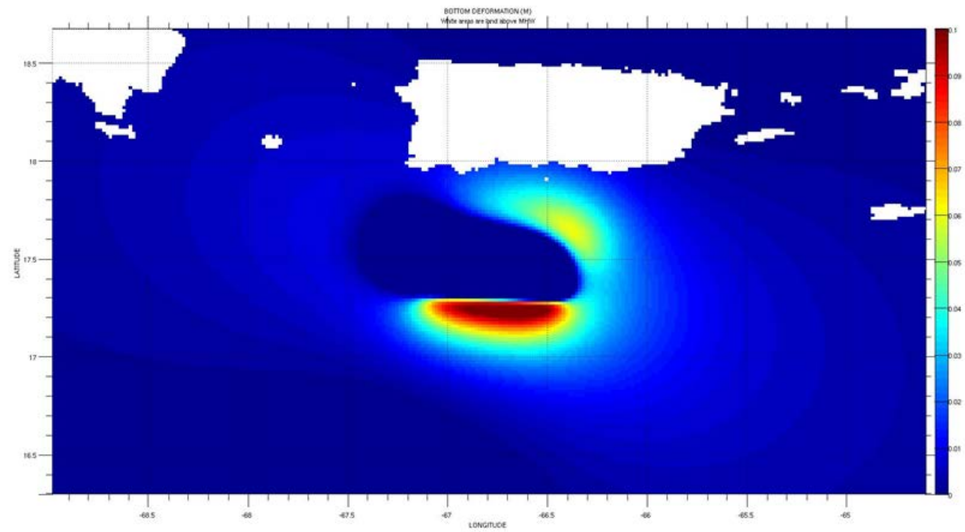

Figure 4 – Initial sea surface deformation Muerto's Trough fault #12 scenario. Elevations in meters.

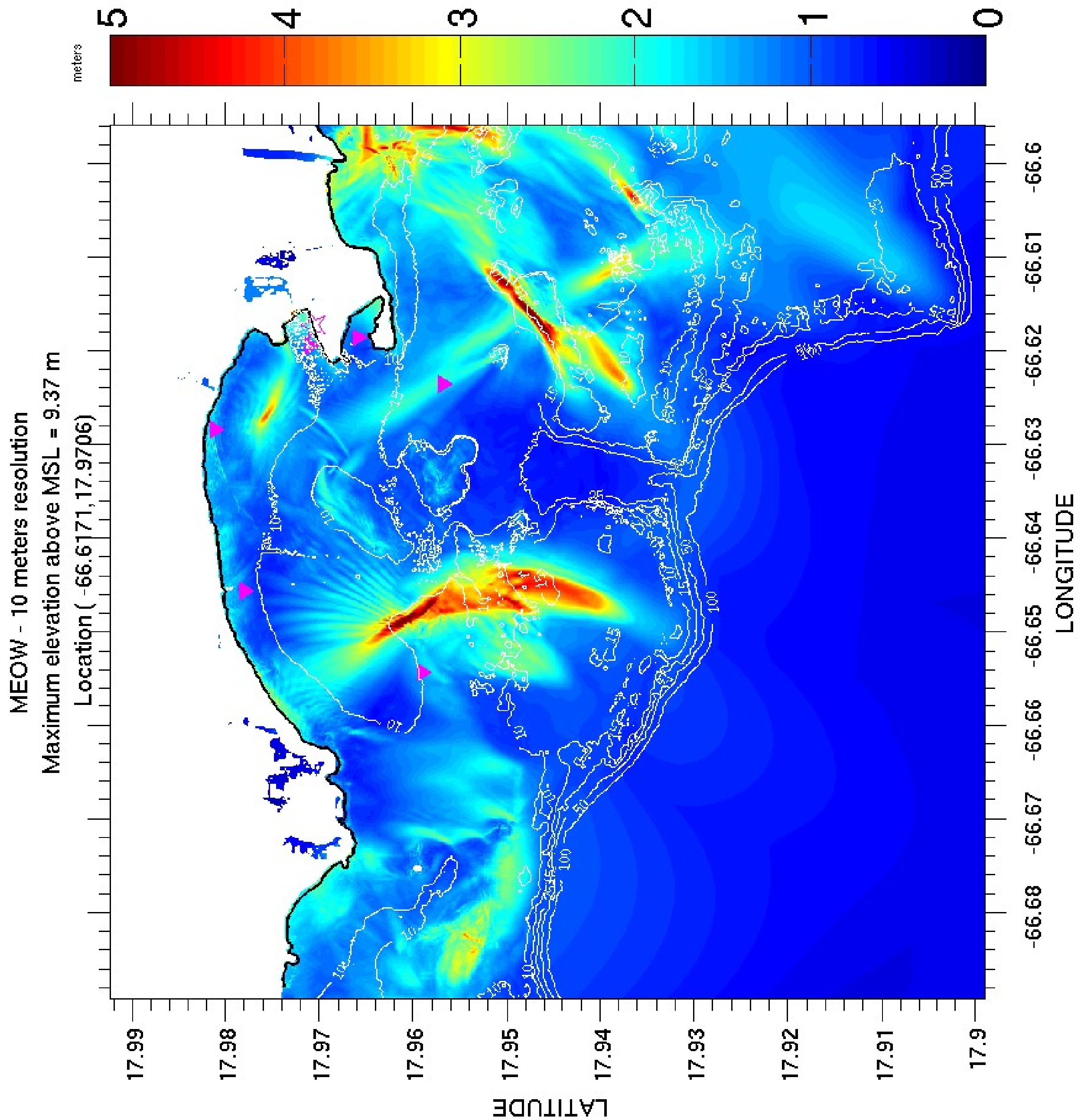

Figure 5 – Maximum sea surface elevation for the Muerto's Trough fault #12. Elevation in meters.

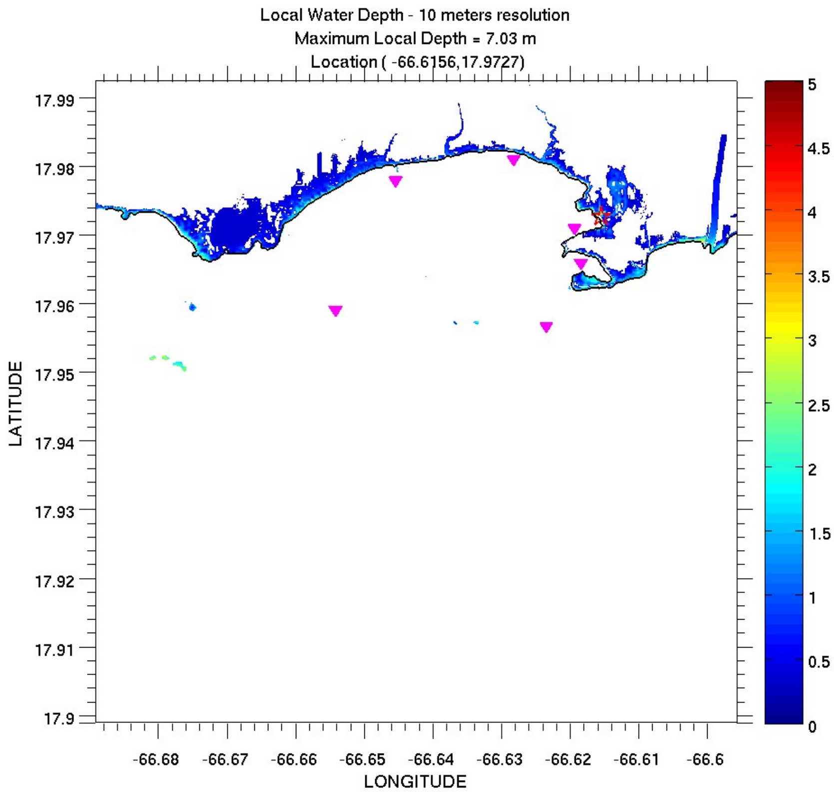

Figure 6 – Maximum Local Water Depth for Muerto's Trough fault #12. Depth in meters.

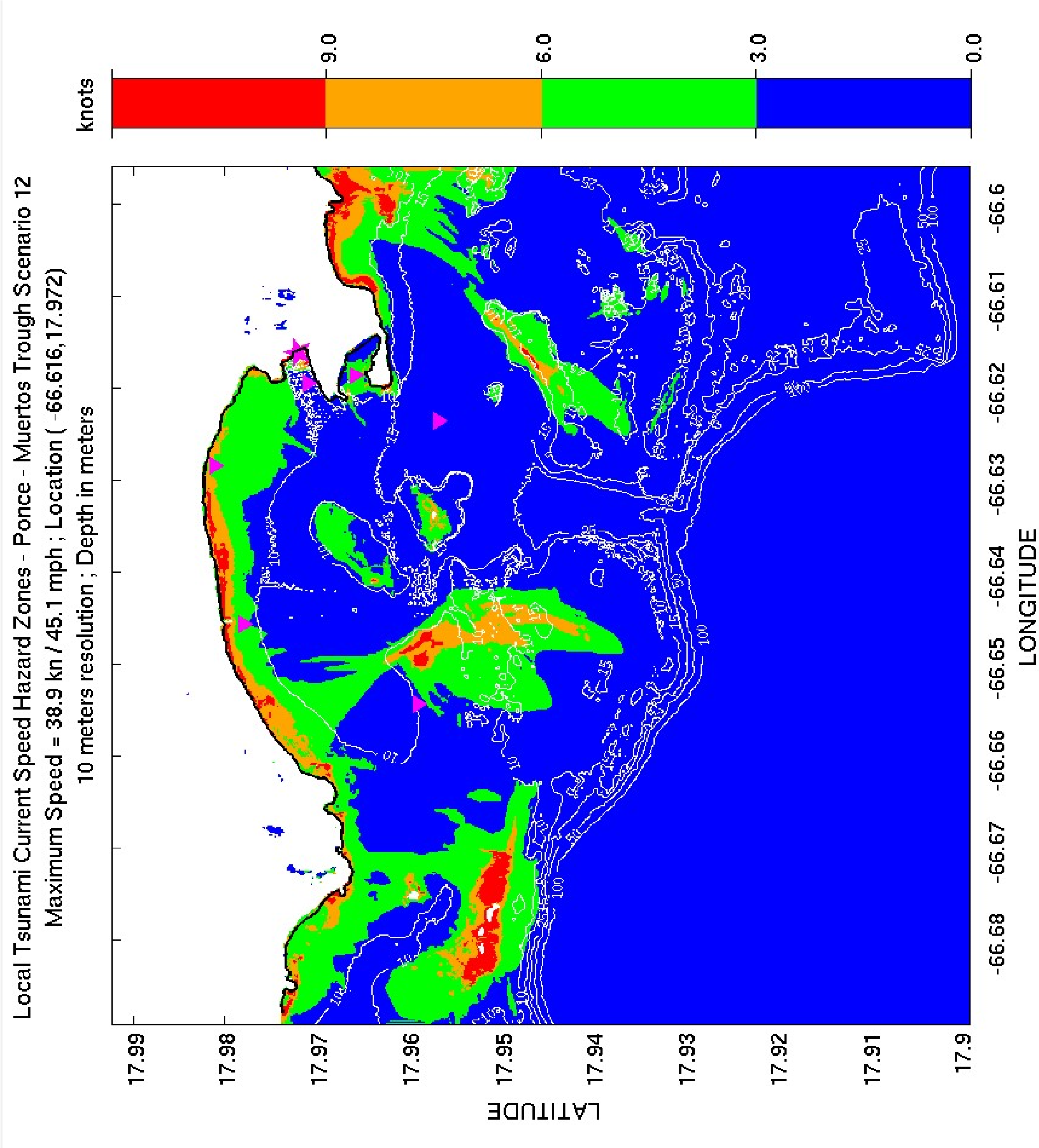

Figure 7 – Tsunami current speed hazards zones for the Muerto's Trough fault #12. A kmz version is given in Appendix I.

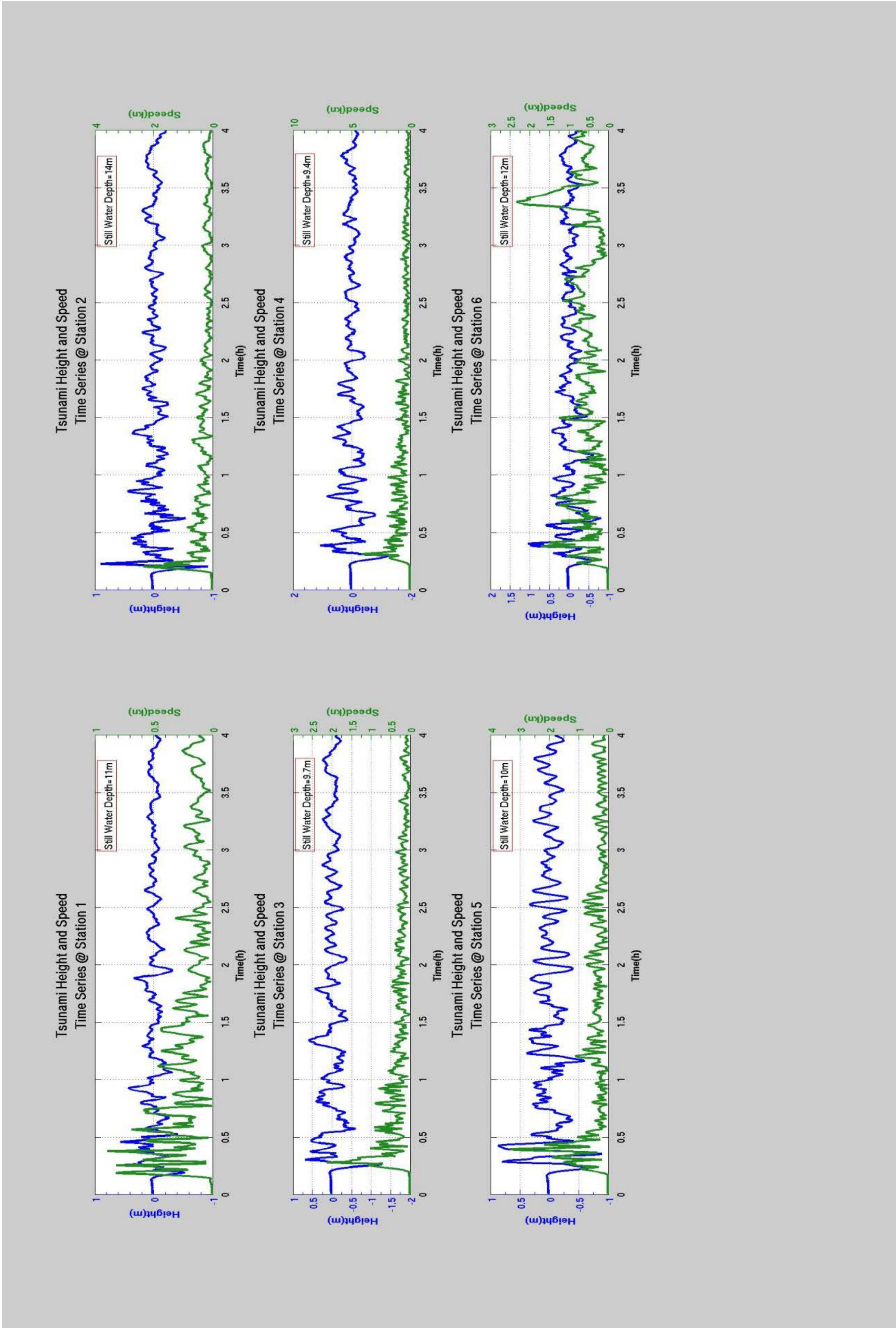

Figure 8 – Tsunami wave height relative to MSL (blue) and tsunami current speeds (green), at stations shown in Figure 1. Grid resolution is 10 m.

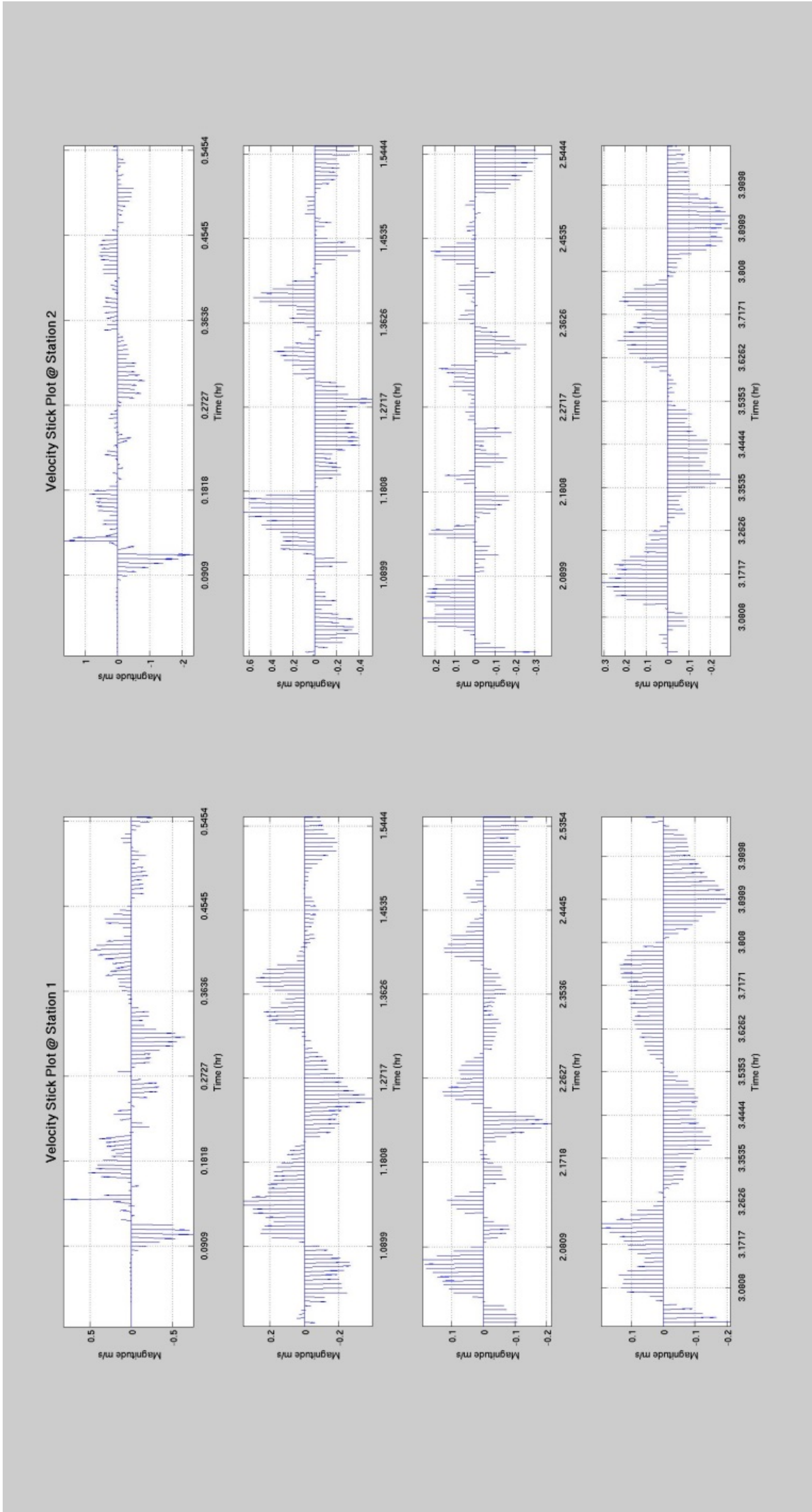

Figure 9 - Stick plots of tsunami current speeds at Stations 1 (left column), and 2 (right column).

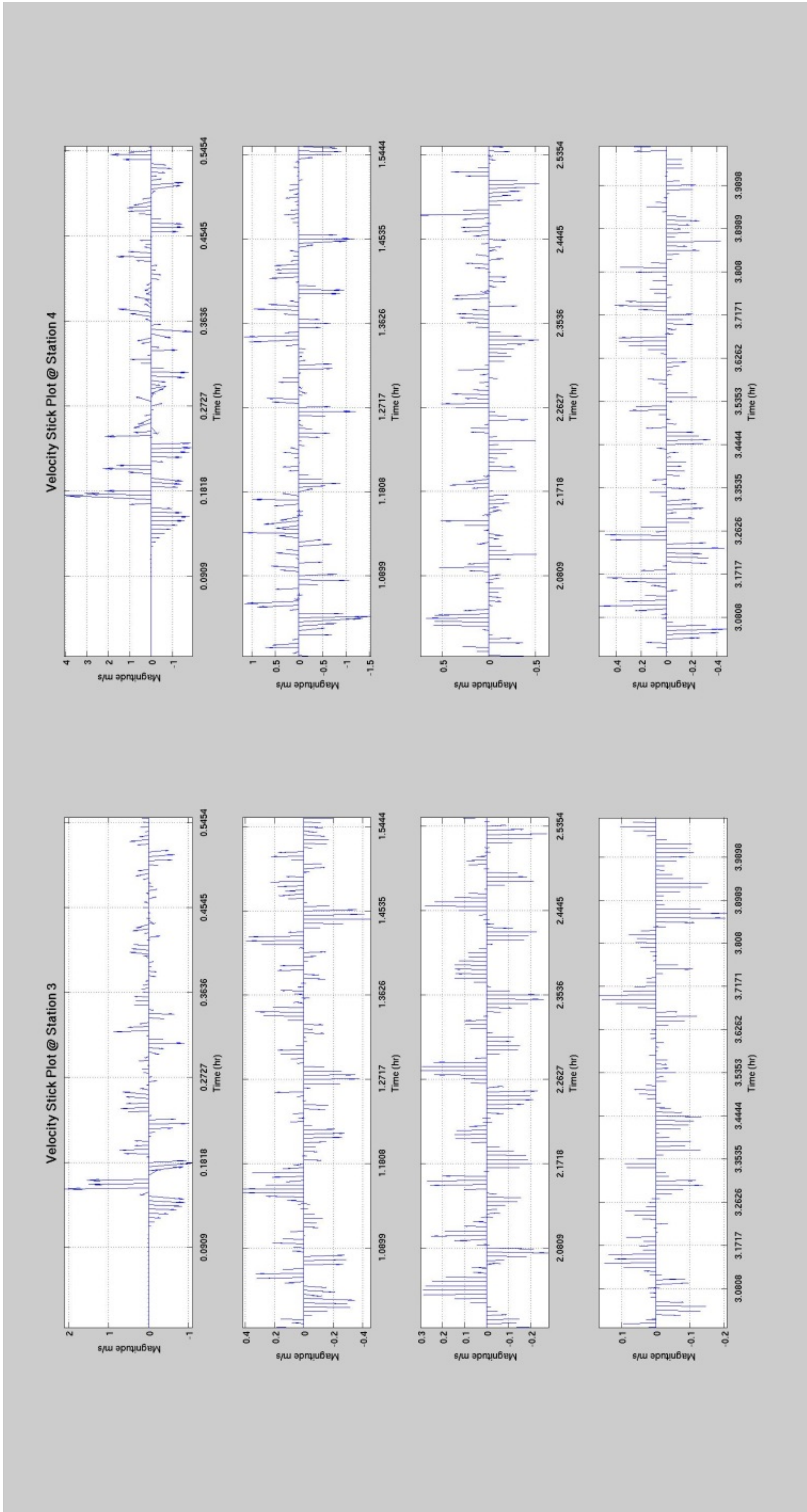

Figure 10 – Stick plots of tsunami current speeds at Stations (left column), and 4 (right column). Grid resolution is 10 m.

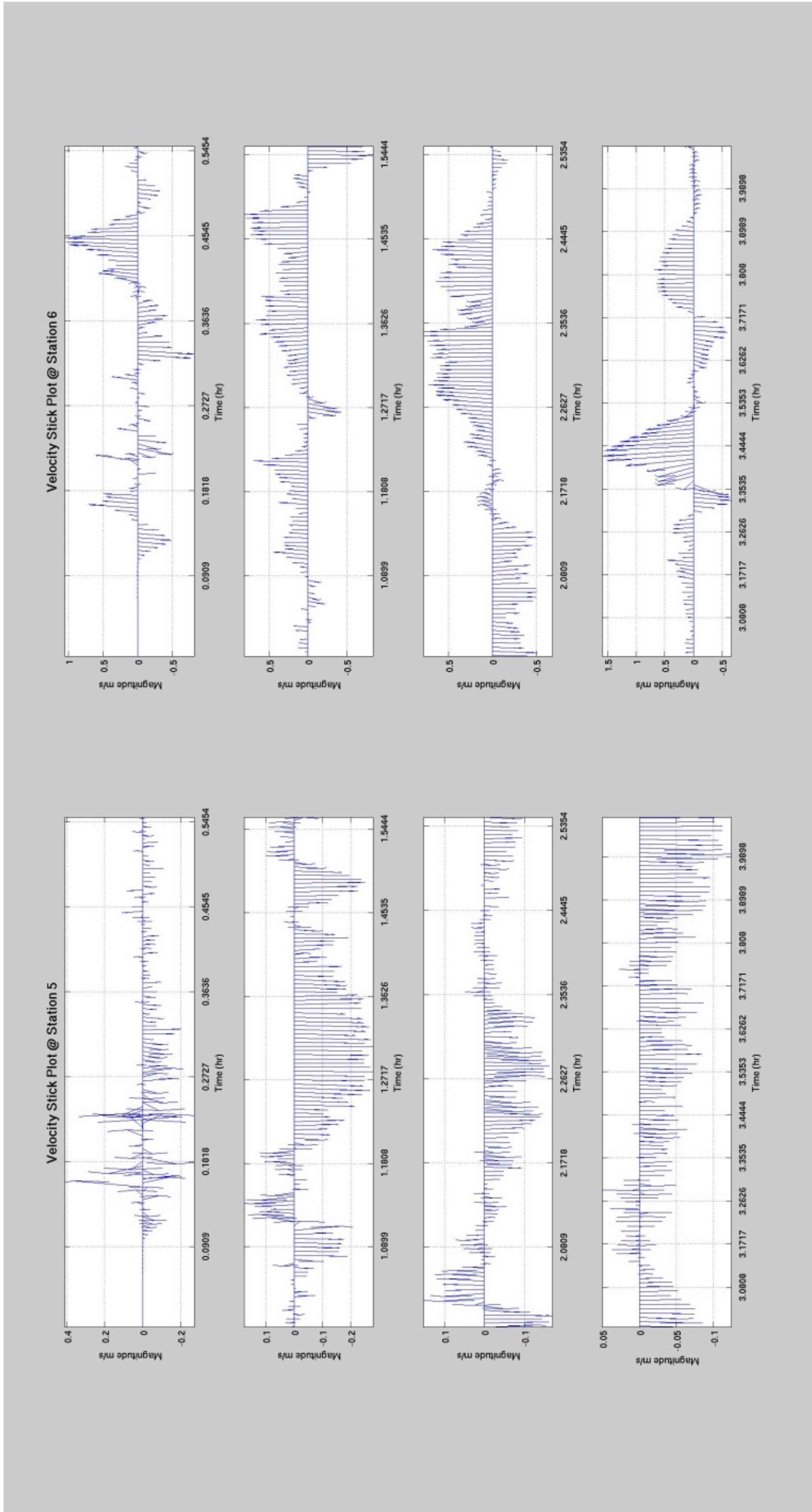

Figure 11 – Stick plots of tsunami current speeds at Stations (left column), and 6 (right column). Grid resolution is 10 m.

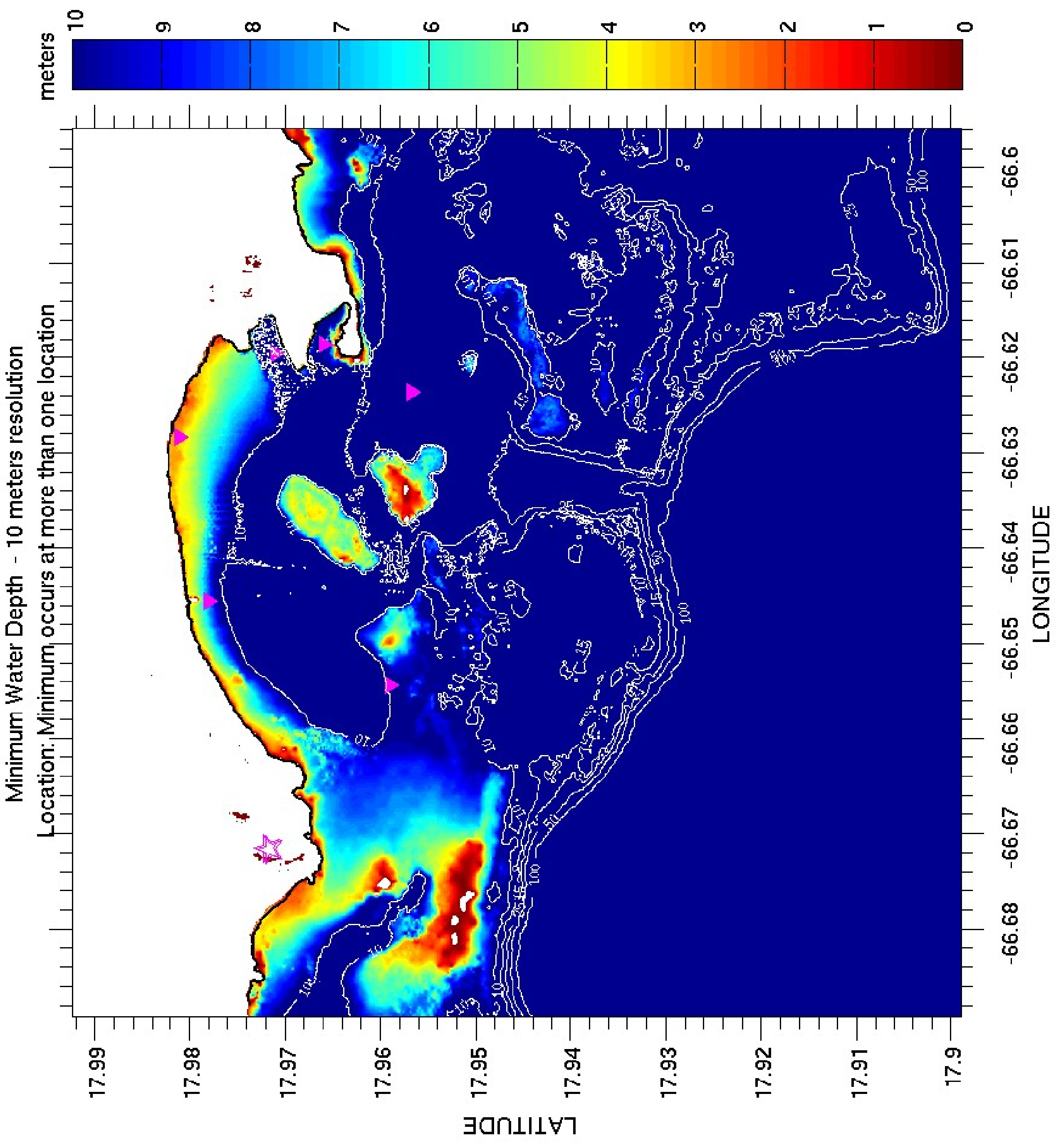

Figure 12 – Minimum remaining water depth. See Figure 13 for a schematic of how it is computed.

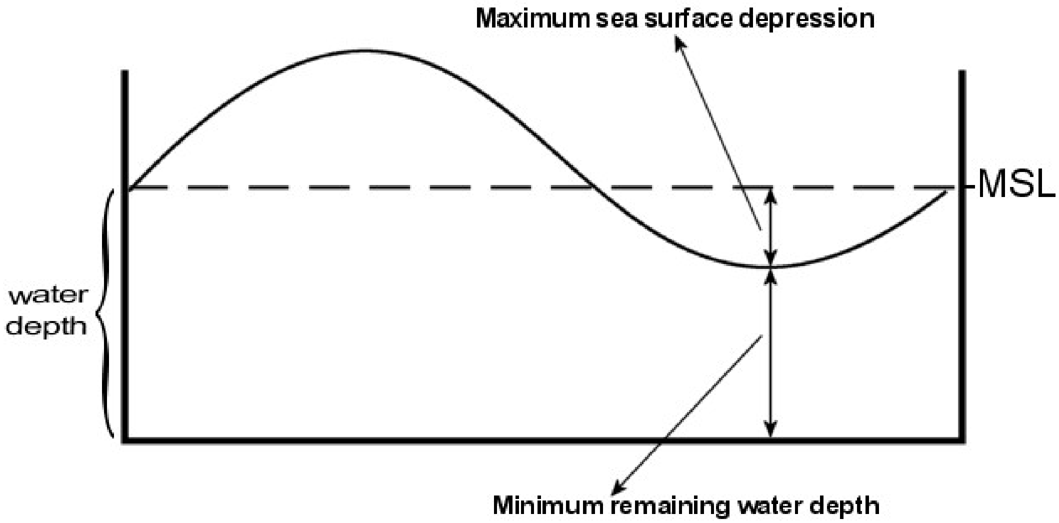

Figure 13 - Schematic of how to evaluate the minimum remaining water depth at each computational node. Minimum remaining water depth = MSL water depth – maximum sea surface depression.

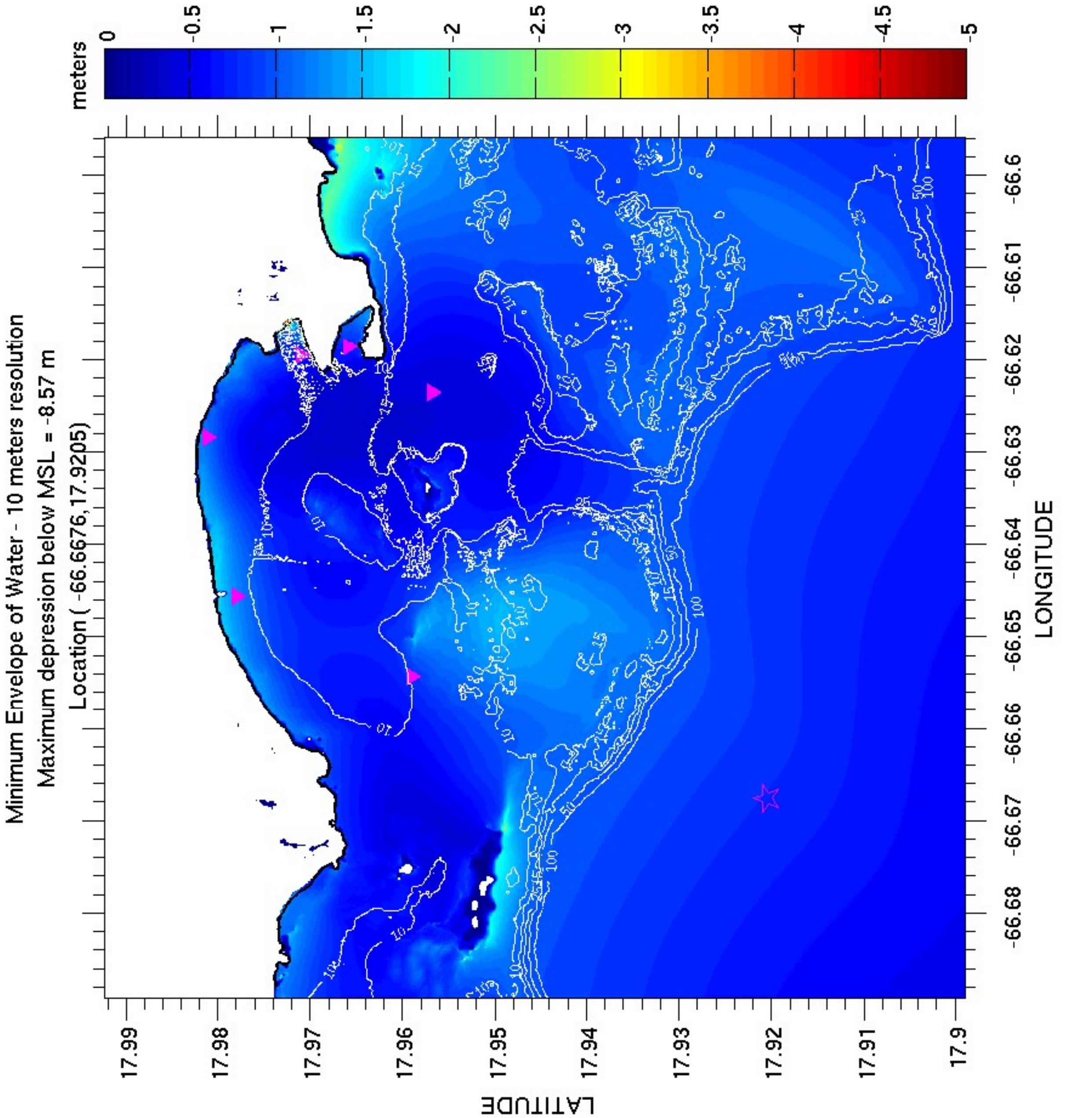

Figure 14 – Minimum envelope of waters (anti-MEOW).

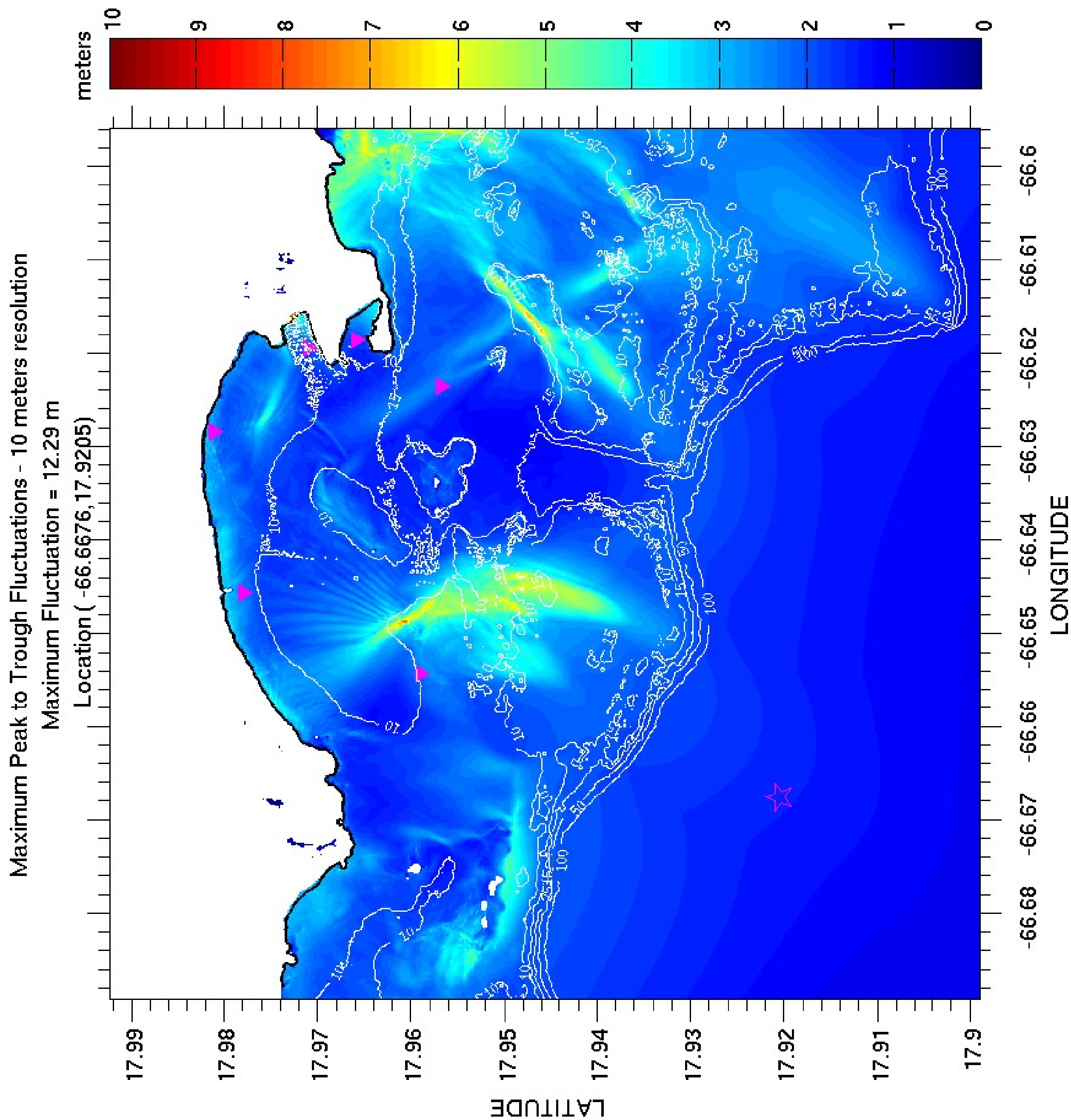

Figure 15 - Peak-to-Trough water level fluctuation. See text for an explanation. Grid resolution is 10 m.

Gyres/eddies within and near the bay have been shown to be a hazard. Figure 16 shows the magnitude of the maximum angular frequency of the eddies (what is actually computed is the flow vorticity, in radians/sec; this is changed to angular velocity by dividing by 2 and changing from radians/sec to degrees/sec). A movie was prepared that shows the eddies and as they spin off from the generation area.

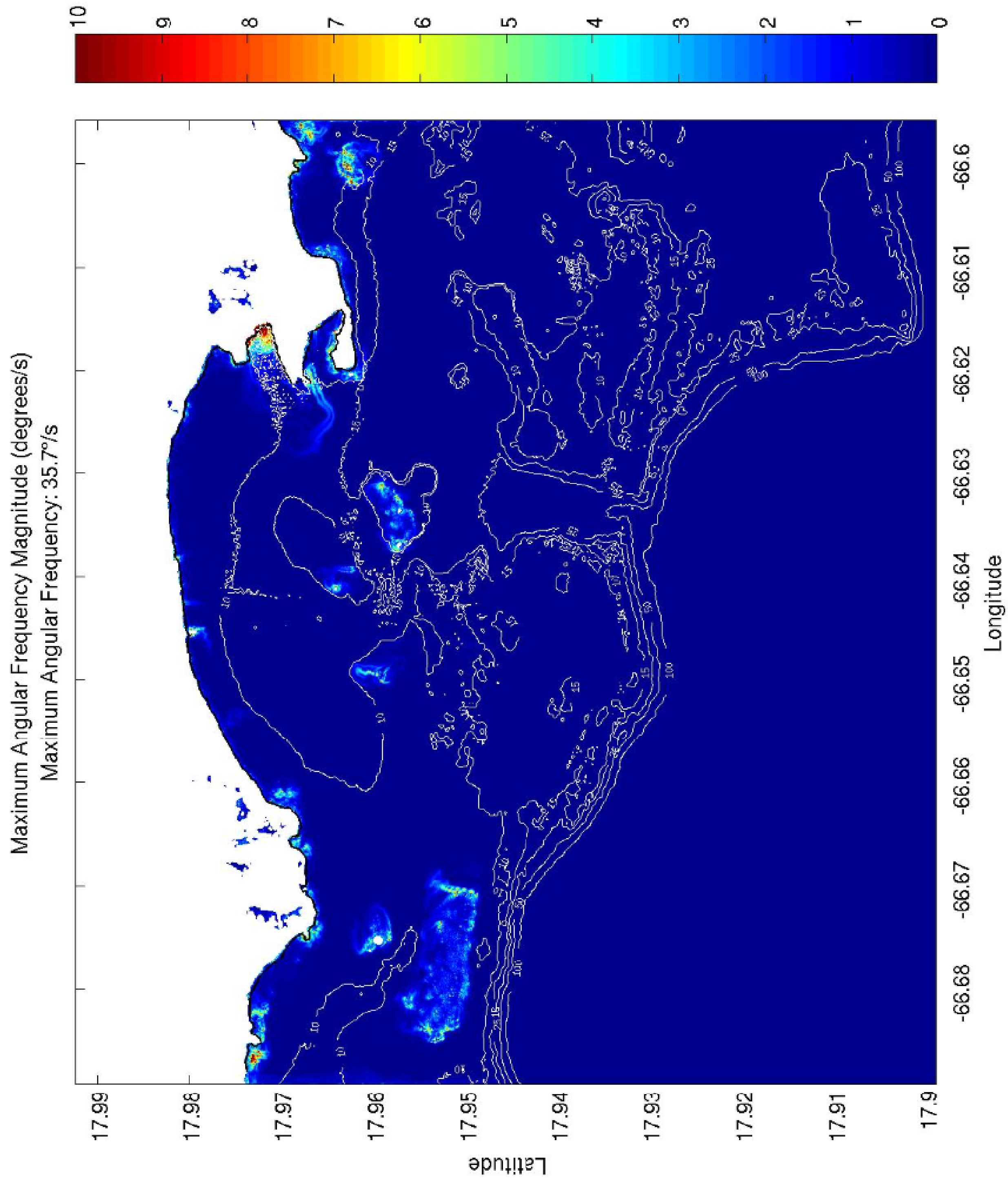

Figure 16 – Figure showing the magnitude of the maximum angular frequency of the eddies induced by the tsunami. Grid resolution is 10 meters.

A petition of the Mapping and Modeling sub-committee of NTHMP is to present the so-called Time Threshold Maps (TTM). Quoting from the M&M document titled "Guidelines and Best Practices for Tsunami Hazard Analysis, Planning, and Preparedness for Maritime Communities", developed by NTHMP Mapping and Modeling Subcommittee, Mitigation and Education Subcommittee, and Warning Coordination Subcommittee, Maritime Planning and Preparedness Guidelines – Version 3 (07-22-15), Draft June 2015,

To show the duration of damaging currents, "time-threshold" maps can be generated. For a specified current velocity level, these maps will show the time duration during which the velocity is exceeded based on numerical modeling results run for a 60 hour tsunami scenario. It is recommended that the duration represent the time period between the first and last time a particular velocity is exceeded, not the sum of times the threshold is exceeded. While this type of information should be very useful for harbor personnel to estimate the duration of dangerous conditions, the estimates will be highly source dependent and scenario specific.

The following steps can be taken to produce time-threshold maps:

1) Use the modeled time-history data for various scenarios to determine the length of time specific current thresholds (3/6/9 knots for well-maintained harbors; 2/5/8 knots for older, poorly maintained harbors) are active.

2) Maps can be created that show the same time-threshold for multiple scenarios, or multiple time-thresholds for the same scenario.

3) When displaying multiple time-thresholds on a maps, the colors used for the times should have a consistent scale for the best comparison.

In our case, we only present the TTM for just 4 hours of simulation. Figures 17to 19 show the TTMs using a colorbar cap of 0.5 hours, and a current threshold $\geq$3, 6, and 9 knots, respectively.

Based on Figures 16 – 19 we can conclude that Ponce Bay seems to be less problematic than the San Juan and Mayaguez Bays. Notwithstanding the fact that Ponce Bay is more open to deep waters than the other two bays. It is less protected. At this moment it is not clear why this is so. It could be the strange form of the initial sea surface deformation shown in Figure 4. Or it could be that being less enclosed, it provides less opportunity for resonance effects that is expected to play an important factor in the Time Duration values. This should be tested with another tsunami scenario.

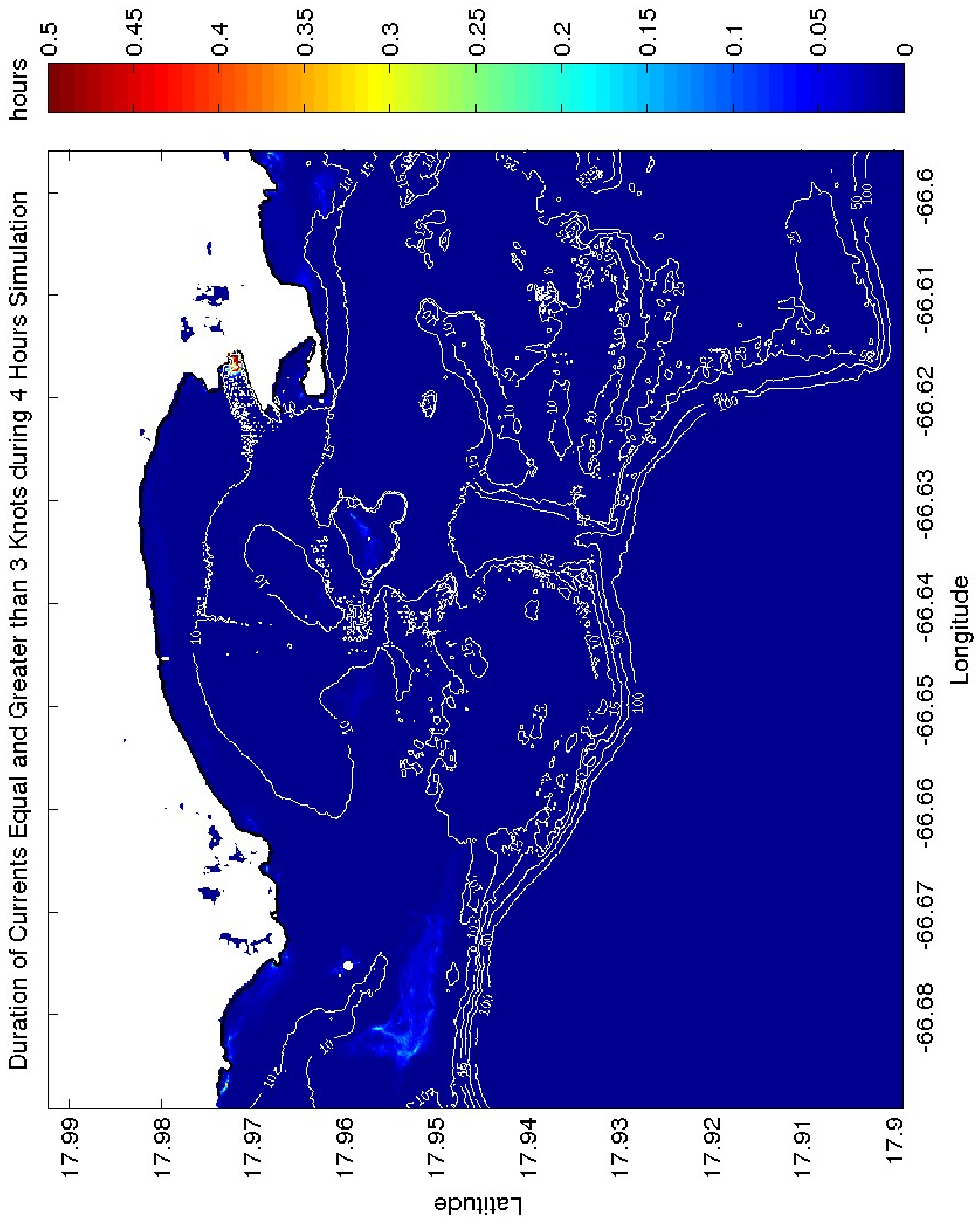

Figure 17 – Duration of tsunami-induced currents ≥ 3 knots during the 4 hours of simulation with a colorbar cap of 0.5 hours. Grid resolution is 10 m.

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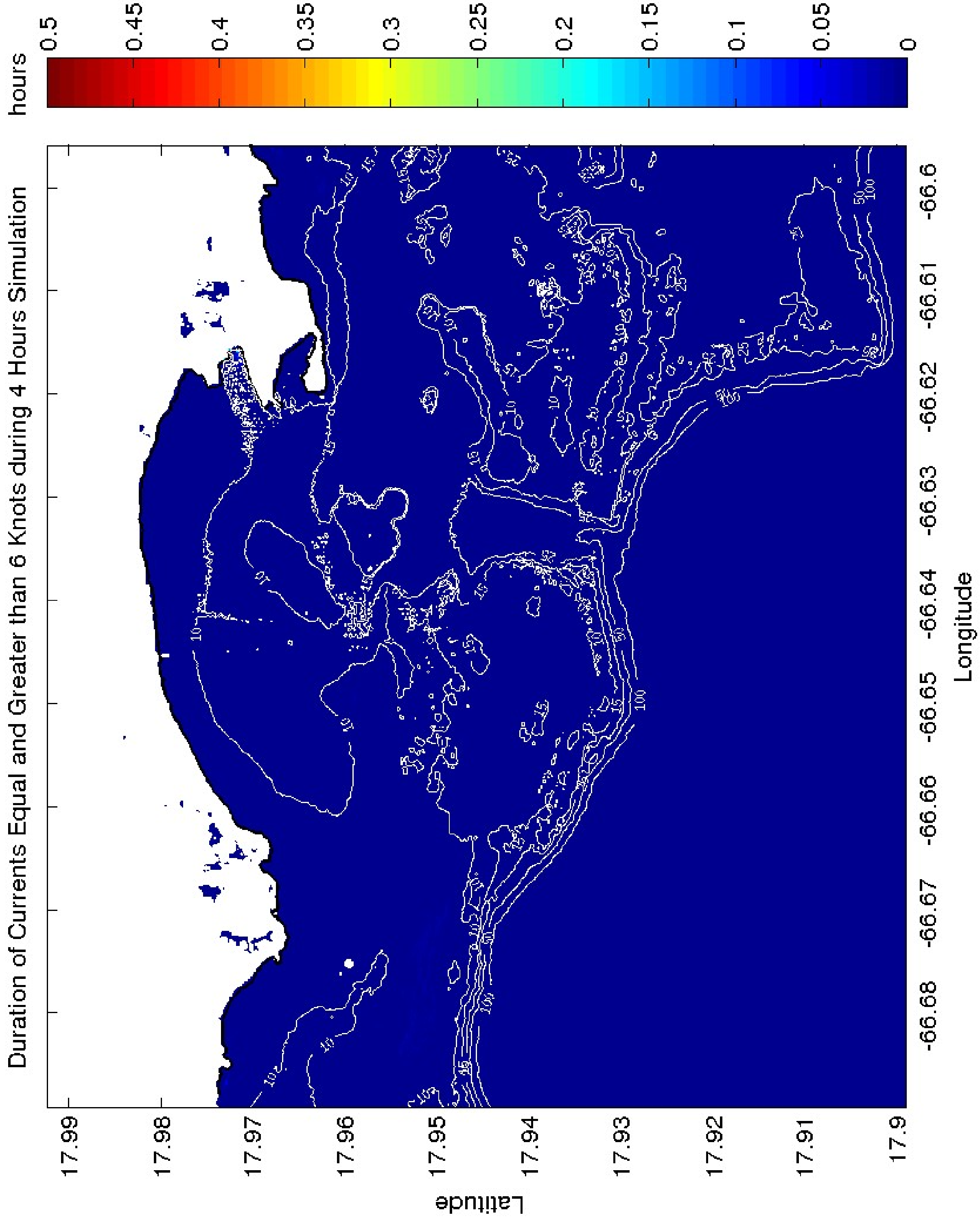

Figure 18 – Duration of tsunami-induced currents ≥ 6 knots during the 4 hours of simulation with a colorbar cap of 0.5 hours. Grid resolution is 10 m.

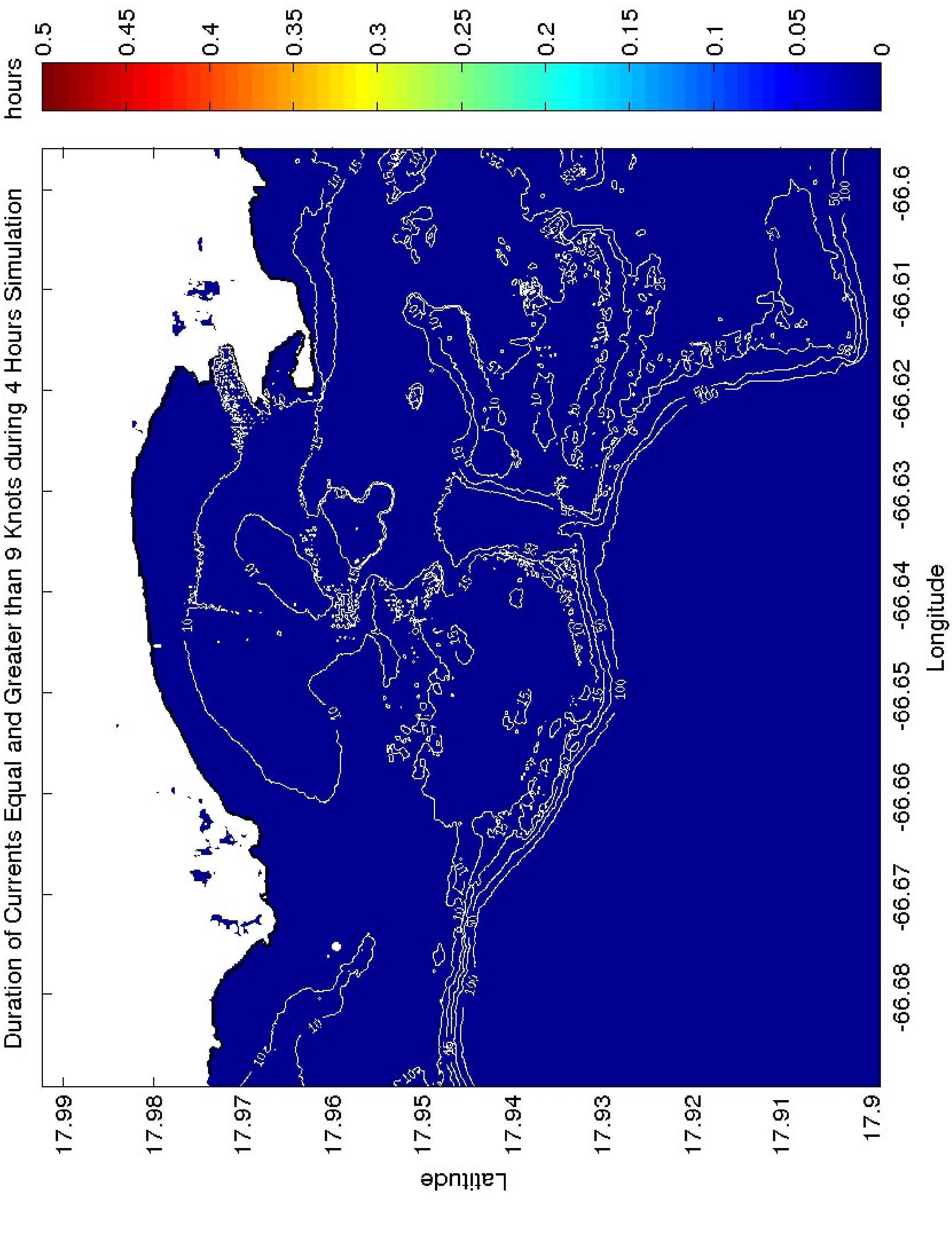

Figure 19 – Duration of tsunami-induced currents ≥ 9 knots during the 4 hours of simulation with a colorbar cap of 0.5 hours. Grid resolution is 10 m.

As was mentioned in the San Juan Bay current hazard assessment, we would like to point out certain aspects of this study that differ from the original assessment of tsunami-induced current hazards (P. Lynett et al., 2014). The assessment done here is based on a local source tsunami with a magnitude of Mw 7.5 while the original NTHMP currents assessment referred to transoceanic tsunami events. Also, we modeled the tsunami for a total of 4 hours since the original deformation, while the original assessment modeled the tsunami for up to 60 hours. The combination of the complex bathymetry around Puerto Rico and the fact that we used a local and very strong tsunami event shows drastic results in terms of magnitude of current speeds and sea surface elevations. The duration of the tsunami induced currents is much lower in our case possibly due to the fact the transoceanic events have a longer period which helps maintain steady currents for longer time, and could induce resonance effects inside the bays. The constant in and out-flux of tsunami waves due to our local event results in unsteady currents that do not last long periods of time. As part of future work, we should assess the effects of far-field sources.

There is also the concern of whether a model like MOST has all of the Physics required to simulate the extremely high currents reaching Ponce Bay.

For a better understanding of the behavior of tsunami-induced currents inside Ponce Bay, please see the currents and vorticity movies. Finally, these images – with the exception of Figure 3 - were based on just one event. If it is desired to explore the consequences for all scenarios, use Figure 3, which is based on a composite of 320 events.

ACKNOWLEDGEMENTS

We would like to acknowledge the technical help and support of Mr. Harry Justiniano. Also, the support of Dr. Victor Huerfano, of the Puerto Rico Seismic Network, is greatly appreciated. And also of NOAA's Center for Tsunami Research, especially Dr. Diego Arcas and Dr. Chris Moore.

APPENDIX I

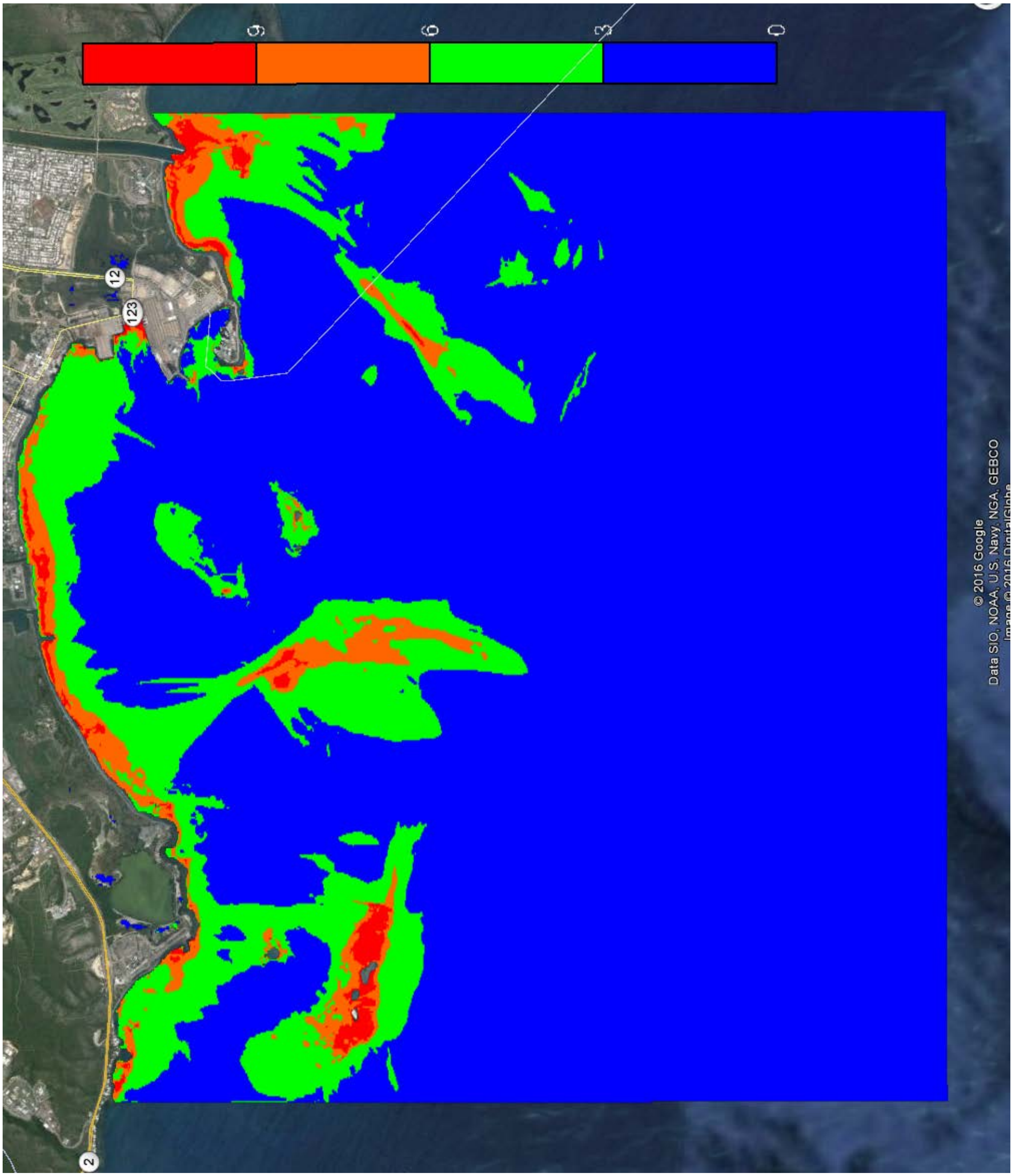

Figure 20 – kmz version of Figure 7 above.