METEOTSUNAMI Guidelines and Best Practices

Part I: METEOSUNAMI MODELING

National Tsunami Hazard Mitigation Program

Mapping and Modeling Subcommittee Written: Nov. 2020

A key outcome specified in the National Tsunami Hazard Mitigation Program (NTHMP) Strategic Plan is the development of “tsunami inundation maps that support informed decision making in tsunami-threatened communities.” To achieve this, the NTHMP’s coordinating committee further specified that all NTHMP-funded models and mapping products should adhere to various goals and strategies defined in the NTHMP Strategy Plans, including following established guidance procedures used in tsunami modeling. The purpose of this document is to describe guidelines that have been developed for meteorological tsunami (meteotsunami, a.k.a. MT) modeling.

As a first attempt to include the MT hazard in the NTHMP’s tsunami effort, the NTHMP’s Mapping and Modeling Subcommittee (MMS) tasked the gulf coast tsunami team at Texas A&M to undertake a MT pilot study in a specific region of the Gulf of Mexico (GOM, see Appendix A). The primary goal of the pilot study was directed at modeling MT, such that the knowledge learned from such an effort would form the foundation on which a MT modeling guidance could be produced for the US states and territories. APPENDIX A provides summary results of a numerical study of a MT event that took place on February 2010 along the Florida gulf coast. From the MT modeling acquired experience, this report summarizes the overall approach, and further efforts needed to be implemented toward the development of a MT hazard assessment at specific regions, example:

- Establish a prioritized list of communities for which to develop MT hazard?
- Assessment of the MT hazards within high-risk zone for DEM mapped coastal region
- Assessment of the MT hazard within high-risk zone for non-DEM-mapped coastal regions

The purpose of this guidance and best practices document is to establish minimum requirements that should be met to meet the NTHMP Strategic Plan goals.

Purpose

Guidance on MT numerical modeling for the purpose of determining hazard regions (inundation zones) and evacuation products is expected to provide consistent products across state and territorial coastal boundaries. Included here, are guidelines for model inputs, outputs, and directions to ensure that numerical codes used are properly applied. In addition to this document, the MMS must develop a checklist for evaluating MT Modeling (models benchmarking) and hazard reports and/or metadata. Recommendations for metadata, project reports, or other forms of documentation related to modeling and MT map development can be taken from previous efforts used to develop tsunami inundation maps.

Intended Audience

This MT guideline and best practices are envisioned for tsunami modelers and trained emergency managers in the science of MT or tsunami with the intent of providing the best attainable products to support state, federal planners and emergency managers in making informed decisions. However, these guidelines also apply to federally funded NTHMP tasks.

Expected Results

The outcome of adherence to the guidelines and best practices set forth for MT modeling will result in more uniform and understandable products. These guidelines and best practices may also serve communities or regions where formal MT mitigation efforts are required or are in development stage.

Meteotsunami Guidelines

The intent of this guidance document is to support the development of MT products that will result in clear, consistent hazard mitigation products.

In this guideline, "Meteotsunami modeling" refers to the numerical computer code(s) used to simulate MT generation, which is forced by atmospheric pressure propagation and wind forcing (wind stress) across a body of water. The outcome of this process is the potential to produce a surge in wave energy at the shoreline with the potential to inundate low-lying coastal regions resulting in damage to infrastructure and/or loss of life; MT may combine with other phenomena, e.g., storm surge resulting in further enhancement in the local sea level.

This guidance document also addresses the primary input of parameters required to successfully model the MT for a specific scenario.

Meteotsunami Definition

As the name implies, the source of a MT is a moving atmospheric pressure disturbance such as a squall line, storm system, derecho, frontal motion, or atmospheric gravity wave train. Unlike seismic sources, these sources change both spatially and temporally. Many MT attributes are otherwise similar to those of their seismic equivalent (Pattiaratchi and Wijeratne 2015). Ground level pressure changes from known squall sources are typically <5 hPa (1 hectoPascal=1 mbar), but can contribute to the rapid formation of a MT over the course of several minutes. Because sea level changes attributed to the "inverted barometer" effect are small, resonance effects are required to produce a damaging MT. As the speed of these squall sources at ground level is typically in the range of 15-30 m/s, resonance can occur where the shallow water wave speed ($c = \sqrt{gd}$) matches that of the moving squall. This restricts the generation zone to ocean depths <90m coupled with significant "fetch" where Proudman resonance can be expected to increase the wave amplitude. Additional means of amplification include shoaling (Green's Law), shelf slope effects (Greenspan resonance), and the matching of atmospheric gravity wave with natural harbor/basin seiche periods. The extensive shelves of some US coasts and lakes (e.g. Great Lakes, East and Gulf Coasts), provide both the area and "fetch" needed for MT generation. In addition, in many MT cases, the wind stress has shown to play a significant role in the contribution of the MT effects in terms of coastal inundation of low lying areas.

Meteotsunami Modeling Best Practices

- The nearshore computational grid should be of a cell size sufficient to resolve significant coastal features (example: long and narrow inlet, harbor, basin, etc.), as available DEMs allow.
- MT potential source regions based roughly on ocean-continental or lake slope orientation, depth and extend should be identified.
- MT modeling should use the best available data and the latest and most feasible modeling techniques. A nonlinear shallow water numerical model in spherical coordinate is believed to perform satisfactorily when modeling MT. Inclusion of the wind stress term into the numerical model physics may be required in some coastal regions or scenarios. The wind stress term could play an important role for the correct prediction of the MT effect.
- Current tides and storm surge effects also could be important for the correct prediction of the MT effect.
- Modeling should include DEMs developed from the highest resolution bathymetric-topographic data available, appropriate computation resolution and credible source (atmospheric pressure disturbance) characterizations.
- Collaboration between forecast atmospheric/climate and MT modeling groups is encouraged to ensure best MT source prediction and accurate model results of hindscast /forecast products.
- As new MT approaches are developed along with improvements in the underlying physics, this should be justified or supported by a technical report or peer-reviewed scientific journal paper.

<u>**Source Characterization**</u>

- Source selection should be based on MT credible scenarios, that consider relevant local and distant sources and generation mechanisms.
- MT squall and climate should be well detailed as necessary to capture the relevant characteristics of the MT waves, e.g.:
  a) atmospheric pressure disturbance, shape or geometry/profile, magnitude/evolution and distribution;
  b) squall path, velocity and direction, squall front line angle with respect to travel direction;
  c) wind field velocity magnitude, direction and distribution;
  d) meteorological/climate time scale, and;
  e) squall forcing time and spatial steps from climate models.

DEM Development

- Modeling global ocean MT propagation should be performed using DEMs with cell sizes <= 1 arcminute (longitude: ~1.85km at the equator).
- Modeling MT expected wave height at coastal regions should be modeled at <= 15 arc second (longitude: ~400m at the equator).
- For modeling detailed MT inundation, spatial resolutions of 1/3 arcsecond (~ 10 m equivalent) is appropriated, However, spatial resolution <1/3 arc second might be required in flat coastal regions, e.g., barrier islands with extended beaches characteristic of the gulf and east coasts.

- DEM and its associated documentation should be described and disseminated online to support its use by other groups (e.g., NCEI's DEM Web Portal: http://www.ngdc.noaa.gov/dem/squareCellGrid/map).

Model Parameters

- Model runtime should be sufficient to capture the maximum MT wave height that might result from the different mode of enhancements, i.e., Proudman resonance, shoaling/Green's law, edge wave/Greenspan resonance and shelf/harbor resonance (seiche).
- The computational grid domain should should be sufficiently large enough (e.g., from a global domain to the local domain of interest) to capture important MT wave dynamics.
- To capture tidal effects, the MT numerical models should consider the actual MHWL/MLWL (or the dynamic tidal condition) of the region for maximum inundation/runup, or maximum current respectively.
- Other physical effects include those caused by the surge and/or the wind stress, which may be required in order to more accurately predict the size(?) of the MT

Model inputs

Model inputs include, but are not limited to:

- The bathymetric and topographic digital elevation models (DEMs).
- Meteotsunami source:
    - Atmospheric pressure disturbance with simple topology of the squall front, direction or other information that define credible local and distant pressure disturbance scenarios, e.g., squall configuration, velocity, direction, angle of the cold front along the travel path, atmospheric pressure disturbance magnitude/evolution and distribution.
    - For better prediction, atmospheric pressure disturbance might be time and space dependent.
    - Climate and wind stresses obtained from direct measurements hindcasted/forecasted by atmospheric models, e.g., temperature distribution, wind field velocity magnitude, direction and distribution.
    - Input from other atmospheric and oceanographic model inputs such as WRFand/or ROMS.
- Tsunami propagation bottom friction and land use friction considerations
- Wind drag coefficient according to storm type (hurricane or squall cold front). This parameter seems to play an important role in MT prediction at a specific location or for specific cases.
- Tides and storm surge effects should be considered for specific location or cases.

Model outputs

- MT maximum coastal wave height or maximum MT sea level elevation.
- MT arrival time (e.g., in many scenarios, the MT arrival time is close to the passing of the pressure disturbance line)
- Credible MT worst case scenario for the area of interest, e.g., pressure disturbance, velocity and direction, cold front angle, etc.

- MT inundation products (flooding extent and inundation depth)
- Other products: MT current/damaging current, Momentum flux and vorticity

NTHMP efforts:

- MT modeling codes should meet benchmark standards adopted by the NTHMP (there are numerous examples of events (e.g. from the Great Lakes) that may be used for benchmarking).
- All relevant and credible MT sources should be considered for modeling the MT hazard in a specific location.
- Model outputs should be tested against historical MT event measurements and other local or more recent MT events where information is available.
- A tentative of MT inundation benchmark problems is provided below:
  February 2010 MT Clearwater, FL
  January 2016 MT in Naples, FL
  2008, Boothbay Harbor MT, Maine
- A list of numerical models that could be used for MT calculations follows (This list of tsunami models can be easily adjusted or modified to account for the MT's physics and input parameters).
  RIFT, MOST, ALASKA GI'-T, ATFM, FUNWAVE, GEOCLAW, HySEA, MOST, NEOWAVE, SELFE, TAMU, FVCOM (use by Great Lakes research group), etc.
- Numerical models should be used appropriately with respect to domain of applicability as identified by benchmarks.
- All modeling efforts and methodology should be described and justified (i.e., in a technical report or journal). This includes input data (e.g., DEM, sources), submodel (e.g., atmospheric/climate and ocean models, and modeling parameters.
- Inputs to model runs from which MT hazard are developed should be archived and made available to ensure reproducibility as it has been done for the tsunami development.
- At a minimum, model output should include the maximum predicted MT height or inundation extend in order to support mapping needs.

This document is part of the "Tsunami Modeling and Mapping: Guidelines and Best Practices" series.

APPENDIX A

A NUMERICAL STUDY OF THE FEBRUARY 2010 METEOROLOGICAL TSUNAMI ALONG THE FLORIDA GULF COAST

Nov 16, 2020

Texas A&M under NTHMP/NWS Award # NA18NWS4670078

1) INTRODUCTION:

This report summarizes a numerical investigation of the Florida gulf coast meteotsunami (MT) of February 2010. It has been undertaken to compare results against both observations and the output of other models. Results also identify coastal regions which may be susceptible to MT events.

As the name MT implies, the source of a meteorological tsunami (meteotsunami) is a moving atmospheric pressure disturbance such as a squall line, storm system, derecho, frontal motion, or atmospheric gravity wave train. Unlike seismic sources, these sources change both spatially and in time. Many MT attributes are otherwise similar to those of their seismic equivalent (Pattiaratchi and Wijeratne 2015).

Ground level pressure changes from known MT sources are typically under 5 hPa, but can build rapidly over the course of several minutes. Because sea level changes attributed to the "inverted barometer" effect are small, resonance effects are required to produce a damaging MT. As the speed of these sources at ground level is typically in the range of 15-30 m/s, resonance can occur where the shallow water wave speed ($c = \sqrt{gd}$) matches that of the moving source. This restricts the generation zone to ocean depths <90m and with significant "fetch" where Proudman resonance can be expected to increase wave amplitude. Additional means of amplification include shoaling (Green's Law), shelf slope effects (Greenspan resonance), and the matching of atmospheric gravity wave and harbor seiche periods. The extensive shelves of the Gulf of Mexico, shown in figure 1 provide both the area and "fetch" for MT generation.

Olabarrieta et al. [2017] analyzed several MT events recorded by northeastern GOM NOAA tide gauges and found seasonal variance in MT occurrence in different regions, as well as a link to climate variability associated with El Nino. One of the prominent events mentioned in Olabarrieta et al. [2017] is the Florida gulf coast MT of February 2010 that generated a 1.0 meter high wave at Clearwater Beach. Here we present the model's physics, setup, and numerical results of this event. A web-based MT tool or numerical model has been developed to facilitate calculations, which can also be used for both hindcasting and forecasting.

Meteotsunami Atmospheric Pressure calculation

The atmospheric pressure source used in this study for the Clearwater Beach case is based on a surface pressure function of general form as:

$$P(x,y) = \begin{cases} A_c * x * exp(-(y)^2 - \left(\frac{x}{L_c}\right)^2) & ,x<0 \\ A_t * x * exp(-(y)^2 - \left(\frac{x}{L_t}\right)^2) & ,x>0 \end{cases} \qquad 1)$$

where subscript *c* indicates crest and *t* indicates trough. Parameters A and L are amplitude and length respectively, which are chosen to produce a compact pressure footprint with a leading edge trough and trailing edge crest. Coordinates x, y are taken to be longitude and latitude excursions from the source center. The pressure distribution propagates at 20 m/s in a SSE direction following the shelf break and is curved slightly along the travel direction (Fig. 1). In this case, we used Ac = 5 mbar, At = 1 mbar, Lc = 0:7 arcdegree, Lt = 1:05 arcdegree. The pressure disturbance travels from (-85.6070, 30.7470) degree to (-82.0620, 23.4480) degree. The pressure distribution is curved slightly upward (Radius of arc = 8 arcdegree ~= 900km and length of the arc = 5 degree ~ = 500km). There is a final rotation of P(x, y), added next to align the axis of the pressure distribution with the direction of travel.

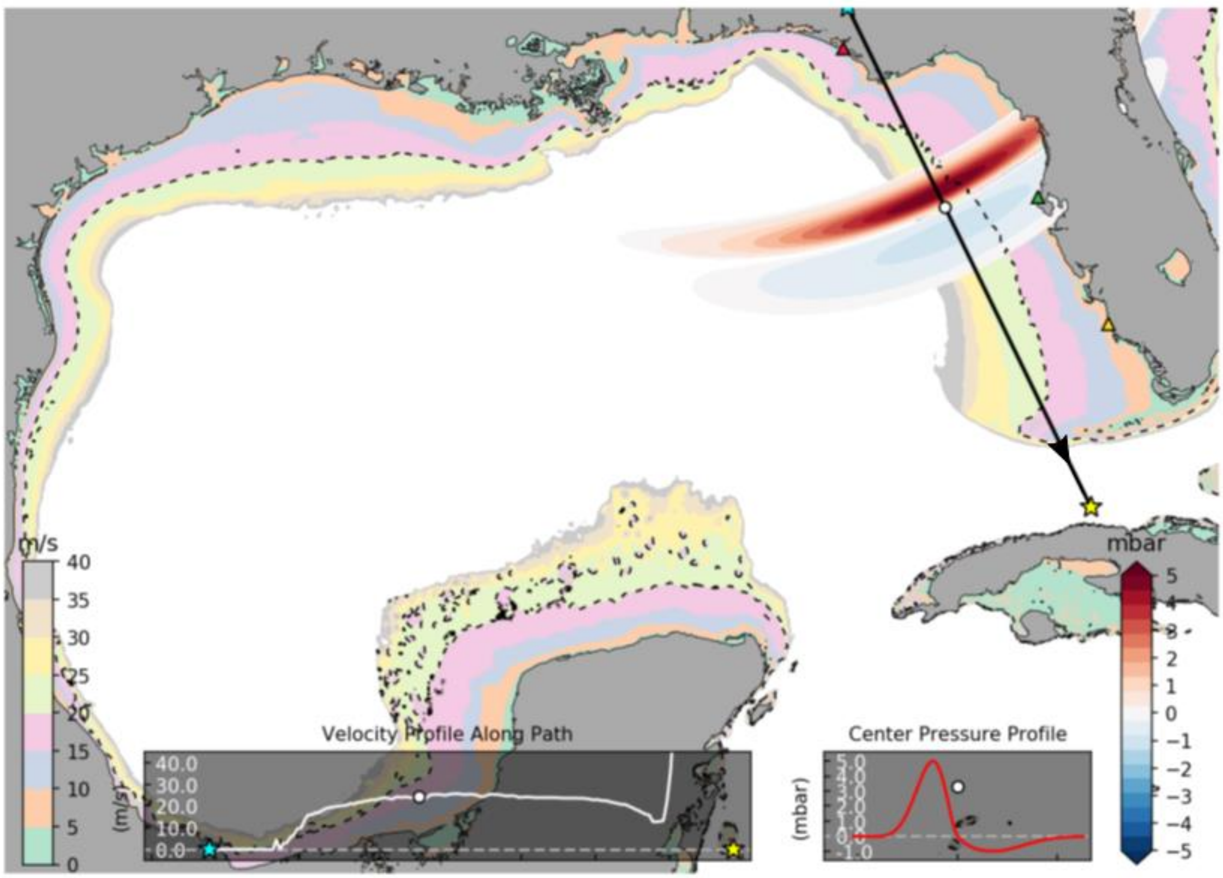

Figure 1: Meteotsunami atmospheric pressure contour plot and travel path. Black solidstraight line shows the path on which pressure disturbance travels (from blue to yellow star).

Pressure disturbance is plotted in red-blue contours in mbar. The bottom right inset plot depicts the pressure profile along the path, where the crest amplitude is 5 mbar and the leading trough amplitude is 1 mbar. The bathymetry is plotted in term of shallow water wave celerity $c = \sqrt{gd}$, ranging from 0 - 40 m/s, where d is depth of ocean floor. Bottom left inset plots the velocity profile along the travel path. In this case scenario, it follows more or less the 20 - 25 m/s celerity contour lines. The white dots appearing in all three plots mark the same center of pressure location. Three synthetic or numerical gauges, Panama City, Clearwater Beach, and Naples, FL, are marked by red, green, and yellow triangles, respectively.

Model Setup

The TAMU web based numerical model used for this MT study is a non-linear shallow water wave model in spherical coordinate, modified to include time and space dependent atmospheric pressure. Bottom friction is based on the Manning model with Manning coefficient of 0.025 $sm^{1/3}$. The model domain covers the full Gulf of Mexico as shown in Fig.1. Bathymetry data was downloaded from the Etopo1 dataset https://maps.ngdc.noaa.gov/viewers/wcs-client/, and was interpolated to 15 arcsecond. A coastal wall is set up at water depth of 0.3 m to avoid runup. Marigrams are computed at several near coastal tide gage locations and moved as needed to the nearest point close to 5 m water depth. The Alaska Tsunami Forecast Model (AFTM) model [Knight, 2011] is also used for simulations and to verify results. Details can be found in (Knight 2011, and Wei, et.al., 2020 (in review)). The model has been extended to include atmospheric forcing terms of the form $-\frac{1}{\rho}\nabla P_a - \frac{1}{\rho D} C_d \boldsymbol{W}|W|$ where P_a is the atmospheric disturbance pressure at the ocean surface, C_d is the drag coefficient, D the local bathymetry, and W is the wind speed at 10 m from the water free surface. The drag coefficient is based on Garratt - Bryant (2016). Previous researches indicate that inclusion of wind stress produces a modest (~6% to ~20%) increase in computed MT wave heights due to the shallow shelf regions investigated. Therefore, tides and wind have not been included in the computation. More detailed analyses of selected sites may use higher resolution nested sub-meshes, which is the focus of future work. To compare one minute tsunami gage data with model results, numerical sea level data points are averaged over 60 second time segments prior to output. ATFM model was run on an ASUS windows laptop. Typical computing speed is about two hours of run time per hour of wave propagation. On the other hand, the TAMU web-based model was run on an Unix supercomputer blade with 4 cores x 8 processors. The computing speed was 4h for 20h of wave evolution. We compared both numerical model results (TAMU vs ATFM) and found the modeled wave profiles at Clearwater Beach were vitually identical. Accordingly, we do not distinguish the model outputs in this study and from now on, we refer to them as simply the model results.

Model Results

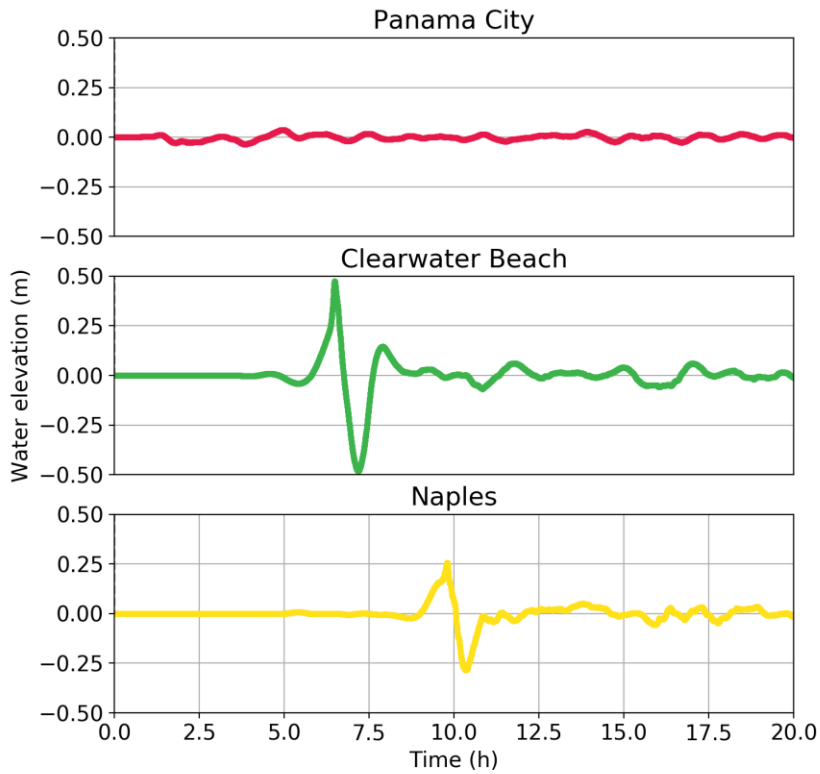

Figure 2. Numerical gauge water elevation time evolution, corresponding to Panama City, Clearwater Beach, and Naples, FL. Results are marked by red, green, and blue colors, respectively. Refer to Fig.1 for location.

Model results show a combination of refraction, reflection, resonance, and shoaling, producing a wave amplitude up to 0.5 m at Clearwater Beach. Fig. 2 shows the time evolution of water levels in the three numerical gauges at Panama City, Clearwater Beach, and Naples, FL. Clearwater Beach and Naples both recorded a prominent wave, with wave height of approximately 1.0 m and 0.5 m, respectively.

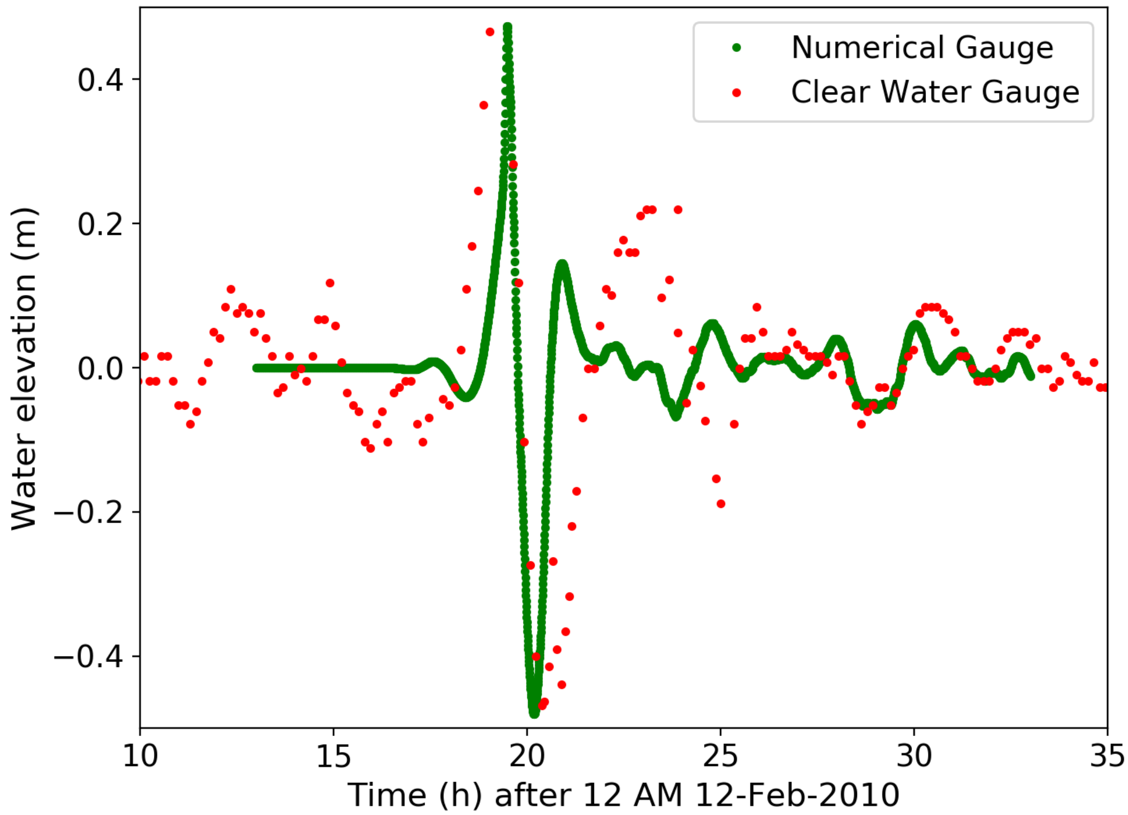

Figure 3: Numerical result (green) and NOAA gauge (#872672) record (red dots) comparison at Clearwater Beach, FL.

For the sake of simplicity, we will focus our study on Clearwater Beach, FL where the MT event had the greatest effect. Fig. 3 compares the numerical result and NOAA tide gauge (#872672) record at Clearwater Beach, FL. Good agreement can be seen for the first major wave crest and trough, especially the peak and trough amplitude. However, the second wave is not reproduced well. This indicates that additional investigation of the parameters in the simplified disturbance wave profile in Eq.1 is needed to resolve the discrepancy. For example, while obtaining the crest and trough amplitudes of the MT wave was reproduced , the wave crest and trough lengths did not match well. According to Hibiya and Kajiura [1982], the more abrupt the pressure jump, the stronger is the amplification of MT wave generation, and thus, the pressure disturbance wave lengths play an important role. In addition, the simplification of the pressure disturbance profile of only one wave could also be an important point for further investigation. The omission of the wind stress may also have had an additional impact on the results.

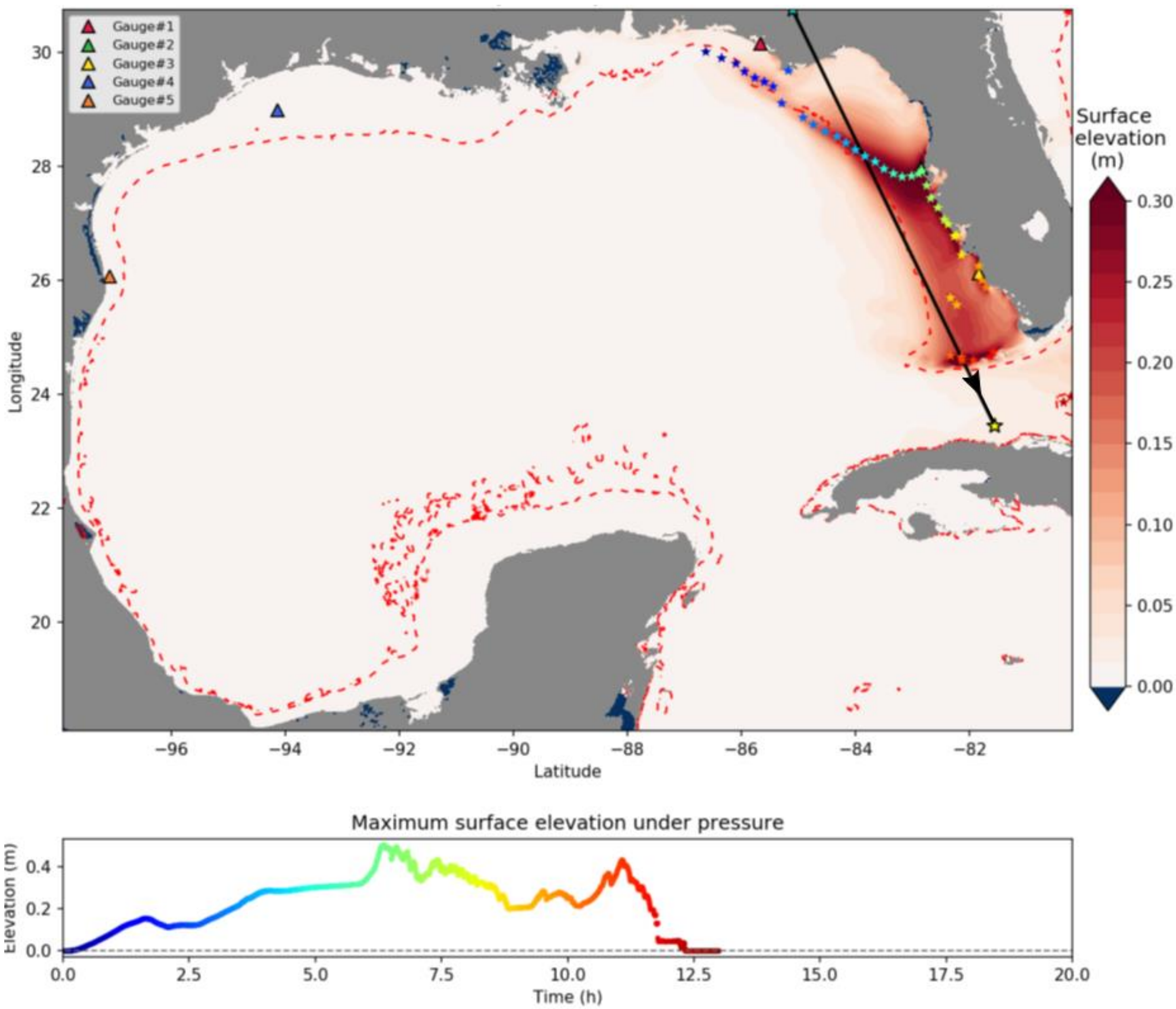

Figure 4: Contour plot (red) showing the maximum surface elevation at each grid point after 20 hours simulation of the 2010 Florida MT event. Black solid straight line shows the path on which pressure profile moves from the blue star toward yellow. Red dashed line marks the contour line where Proudman resonance would occur (20 m/s). Colored stars track the location with the maximum elevation of all grid points at 15 min intervals. Bottom plot shows the time evolution of this maximum elevation with color matching the star locations.

Fig. 4 plots the maximum wave amplitude after 20 hours of the 2010 Florida MT event. It can be observed that energy is focused toward Clearwater Beach and the south Florida coastline (around Key West Islands). Colored stars indicate the path of the maximum wave amplitude at 15 min intervals with the first section of stars directed toward Clearwater Beach, and the second group of stars tracking parallel to the coastline (like an edge wave) toward Naples. The first section aligns well with the velocity contour line at 20 m/s because of Proudman resonance. The wave energy built up, continues straight and refracts toward Clearwater Beach, producing the highest water elevation during this event. We noticed that the MT wave is almost traveling in phase with the atmospheric pressure. The bottom subplot shows the time evolution of this tracked maximum wave amplitude, with the first peak detected at the Clearwater Beach tide numerical gauge (green color). Less than four hours later, a 0.25 m wave reached Naples, FL. (orange color). Moreover, Florida Keys also took a strong hit by catching the remnant wave energy that was trapped or generated by the south-western Florida shelf (red color).

Numerical Experiment for Meteotsunami Effect in West Florida

In order to gain a better understanding of the MT effect on the west Florida coastline from different source regions in the GOM and under different pressure disturbance velocity and path direction conditions, we carried out the following numerical experiments. The US GOM coast is divided into several MT potential source regions based roughly on continental slope orientation (Fig. 5). Within each region, a series of parallel travel paths are established, and for each path, pressure disturbance travel speed is varied from 10 m/s to 40 m/s. For this study, the pressure disturbance's geometric parameters and magnitude are kept the same as the 2010 Florida case. For instance, the experiment indicated in Fig. 5(h), uses pressure disturbances traveling from NW to SE. Results of this experiment (Fig. 6) show the maximum wave amplitude recorded at each numerical gauge (#01, #02 and #03 correspond to Panama City, Clearwater Beach, and Naples, FL, respectively). We found that for Clearwater, FL. (see Fig. 6 panel numerical gauge #2 and Fig. 5(h)) the pressure disturbance traveling at 20 m/s from NW to SE that caused maximum MT corresponds to path # 7 and # 8. These paths match the closer offshore paths to Clearwater, FL.

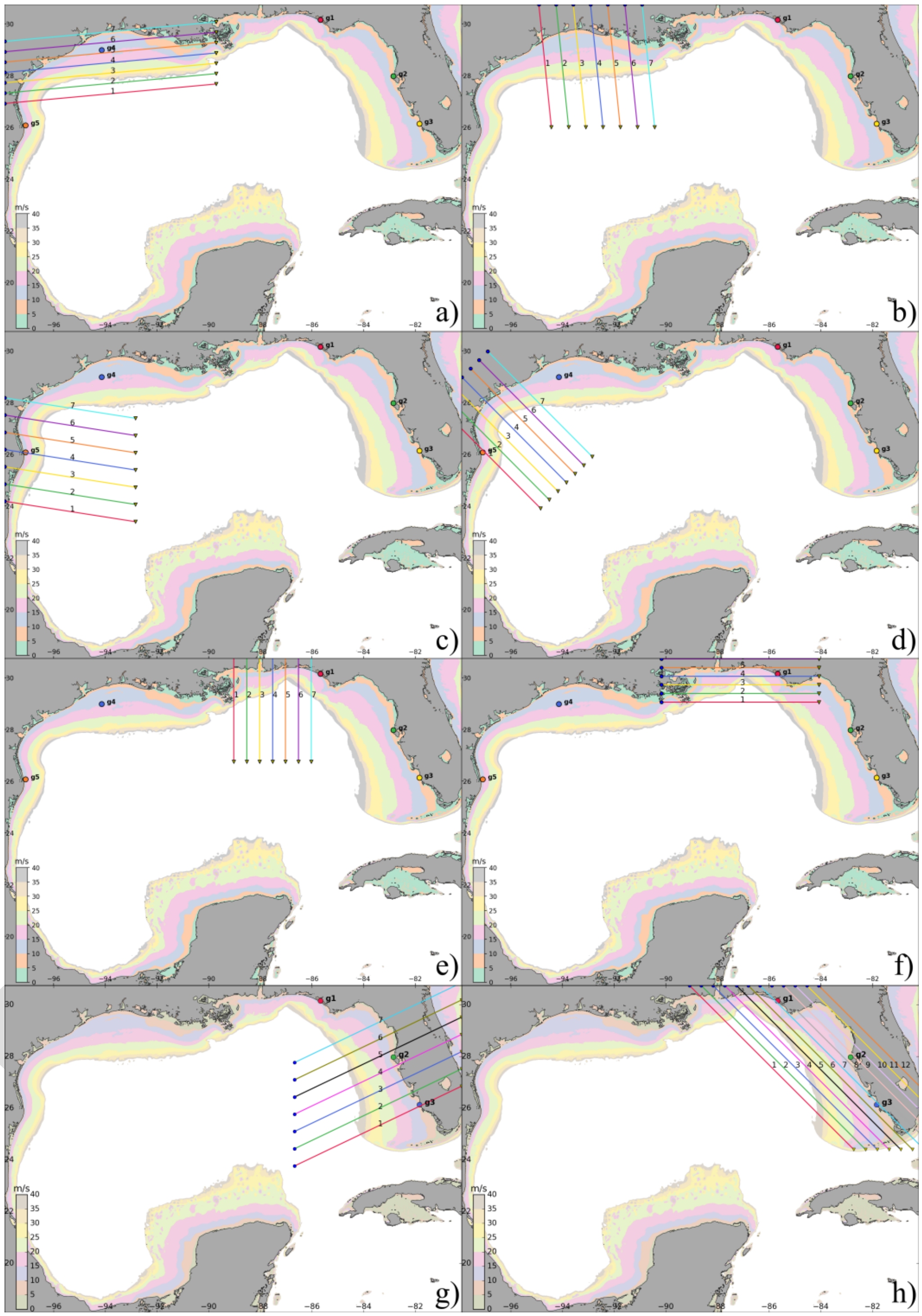

Figure 5: Numerical experiment of meteostusnami pressure disturbance transects covering the U.S. Gulf of Mexico continental shelves. Numerical gauges #01, #02 and #03 correspond to Panama City, Clearwater Beach, and Naples, FL, respectively

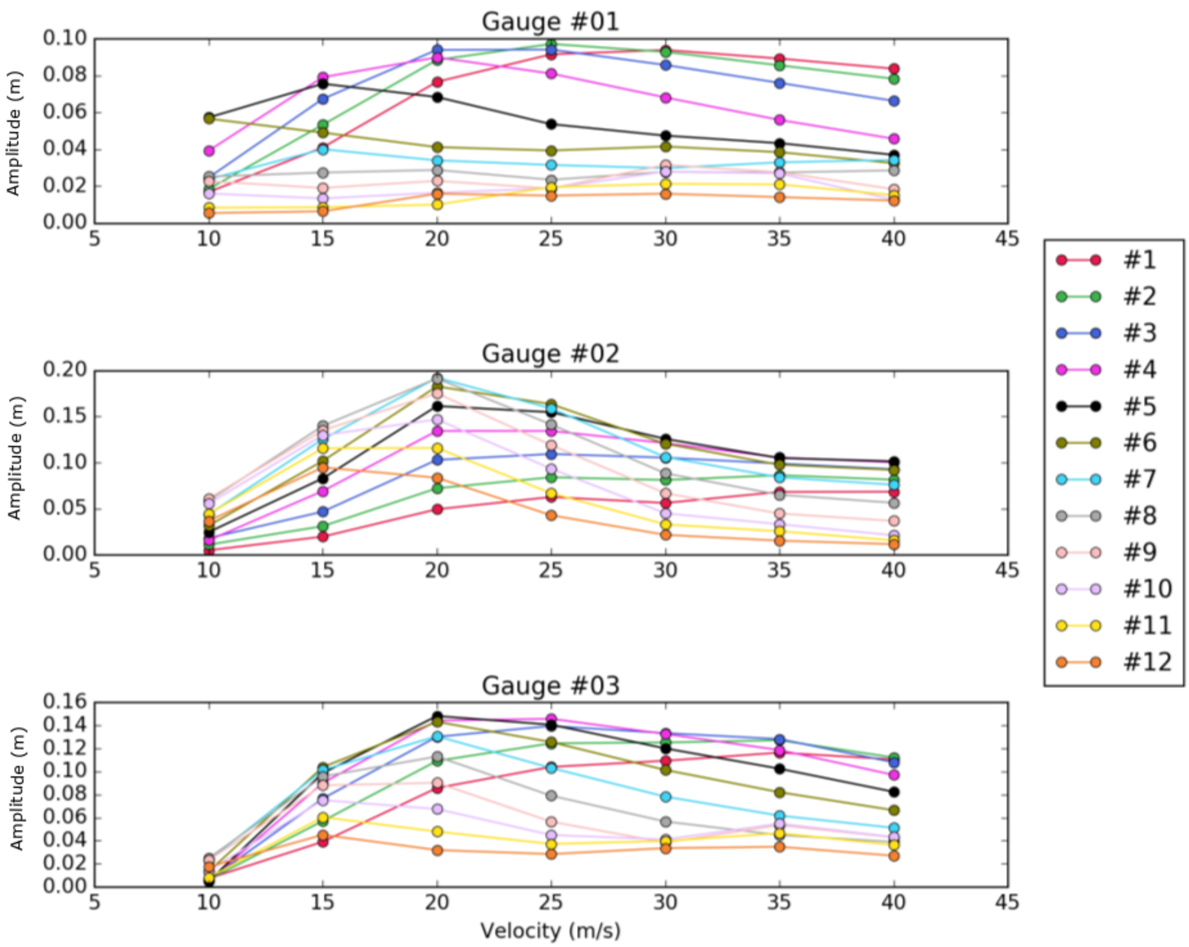

Figure 6: Maximum wave amplitude (meter) recorded at each numerical gauge for each travel path and velocity in Fig. 5h. Numerical gauge #01 #02 #03 corresponds to Panama City, Clearwater Beach, and Naples, FL, respectively. In each subplot, x-axis is velocity and colored lines represent the different atmospheric pressure travel paths indicated in Fig.5h .

To further understand how different travel paths influence the maximum MT wave amplitude at selected locations, we performed a path vs location sensitivity experiment (see Fig. 7) where three travel paths are selected, with the middle one (#2) being the same as the 2010 Florida event, and the rest with different travel velocities of the pressure disturbance. The atmospheric pressure disturbance amplitude and geometry parameters are kept the same as the Florida case.

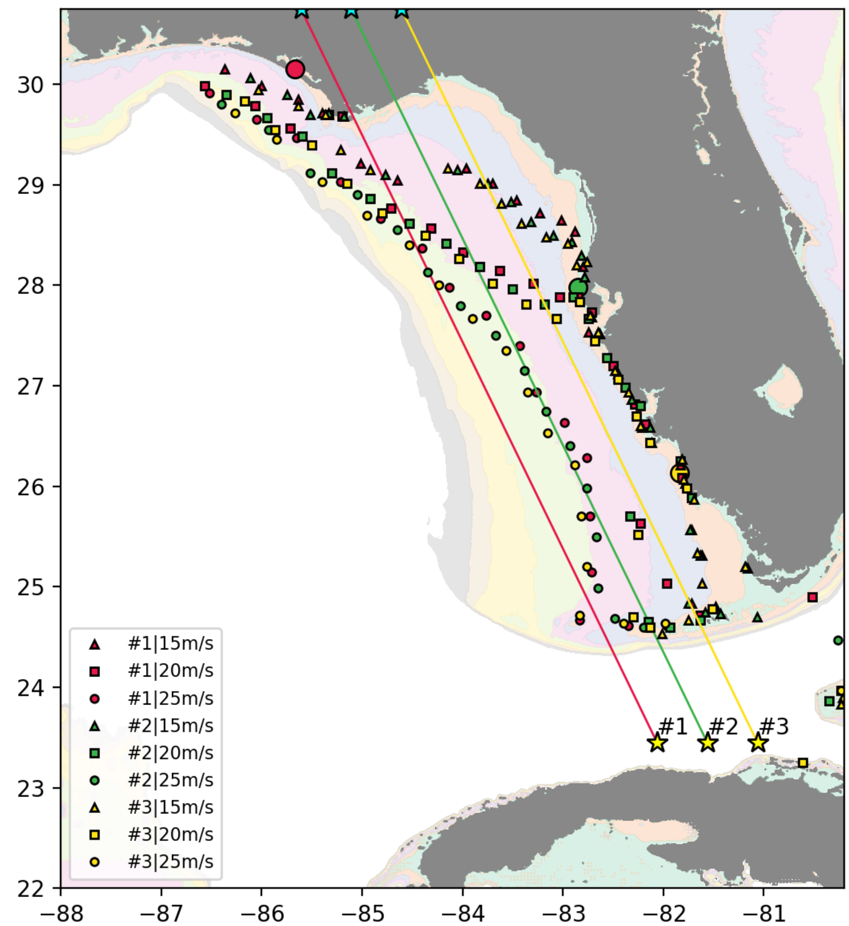

Figure 7: Maximum wave amplitude tracking at 15 min intervals for three different travel paths and three different velocities. Different shapes mark velocities and colors correspond to travel paths.

Fig. 7 shows the track of maximum wave amplitude at 15 min intervals for three pressure travel paths and three velocities. Different shapes reflect the three velocities, while the colors correspond to travel paths. At Clearwater Beach (larger green circle), for both 15 m/s and 20 m/s velocities, all travel paths resulted in the maximum wave amplitude track striking Clearwater Beach. However, the 25 m/s velocity track hits Florida Keys directly. For this particular experiment, the sensitivity of MT maximum wave track with respect to pressure travel path demonstrates that shelf configuration (depth and shape, etc.) is the dominant factor, under the assumption of a straight pressure disturbance travel path with a constant velocity.

Summary

In this pilot MT study, we successfully recreated the 2010 Florida Gulf of Mexico MT, and carried out numerical experiments to investigate the influence of pressure disturbance travel path and velocity on selected Florida locations. Good agreement can be found from the first major wave crest and trough, especially the peak and trough amplitude. However, the second wave is not reproduced well in our model results. Model results demonstrate a combination of refraction, reflection, resonance, and shoaling, which combine to produce wave amplitude varying from near zero up to 0.5 m. We noticed that the MT wave is almost traveling in phase with the atmospheric pressure in most of the cases. Secondly, we carried out numerical experiments to investigate the influence of pressure disturbance travel path and velocity for select Florida locations. For this particular experiment, the mismatch of MT maximum wave track with respect to pressure travel path demonstrates that shelf configuration (depth and shape, etc.) is the dominant factor, under the assumption of a straight travel path with a constant velocity. For future work, we plan to expand to other locations, increase the parameter range to gain a better understanding of the pressure disturbance profile, path and velocity, and possibly include additional parameters including: variability of the travel path direction, velocity variability , and different or multiple pressure disturbance profiles. Additionally, wind stress has been incorporated into the model and will be tested in the future to further investigate its effects.

In summary, the numerical study could aid in predicting MT impact, identifying vulnerable coastal communities, estimating water inundation levels, enabling emergency managers to better understand the hazard and thus, potentially mitigate its effect prior to an event taking place by evacuating high risk beaches.

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