Tsunami Hazard and Inundation Modeling and Assessment for the U.S. Gulf Coast

Alyssa Pampell Manis
Texas A&M University at Galveston

OCEAN ENGINEERING
TEXAS A&M UNIVERSITY

Juan Horrillo, Texas A&M University at Galveston
Jens Figlus, Texas A&M University at Galveston

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Outline

- Tsunamis and landslide-generating processes
- Probabilistic approach to determining landslide tsunami sources in the Gulf of Mexico
- Numerical tsunami modeling
- Comparing tsunami inundation and hurricane storm surge inundation

Tsunamis

- Tsunami: a series of ocean waves generated by sudden displacements in the sea floor, landslides, volcanic activity, or weather events (meteotsunami)
- Shallow-water or long waves with wavelengths of several hundred km
- In open ocean, wave amplitude of a few cm to m
- As tsunami waves approach shore, water depth decreases, waves slow down, and wave amplitude increases

Tsunamis as Coastal Hazards

Tsunami wave arriving in Upper Santa Cruz Harbor, CA after 2011 Tohoku-oki earthquake (currents up to 14 knots)

- Tsunamis can also cause destructive currents in ports, bays, harbors, etc., even far from the source and/or with small amplitudes
- Massive destruction from unanticipated events have prompted a full-scale assessment of tsunami hazard along coasts, even in areas with an apparent low risk (e.g. Gulf of Mexico)

Tsunamis in the Gulf of Mexico

- Gulf of Mexico (GoM) coasts have been included in the United States Tsunami Warning System since January, 2005
- A few small tsunamis have been recorded in the Gulf of Mexico (GoM) in the 20th century[1]:
  - October, 1918: small indeterminate amplitude tsunami recorded at Galveston tide gauge from seismic event west of Puerto Rico
  - May 2, 1922: 2.1 ft (0.64 m) amplitude wave recorded at Galveston tide gauge
  - March 27, 1964: 0.6 ft (0.18 m) amplitude waves recorded at Freeport tide gauge, resulting from Gulf of Alaska earthquake

[1] ten Brink, U., Twichell, D., Lynett, P., Geist, E., Chaytor, J., Lee, H., Buczkowski, B., and Flores, C. (2009), *Regional Assessment of Tsunami Potential in the Gulf of Mexico*, U.S. Geological Survey

Earthquake vs. Landslide Tsunamis

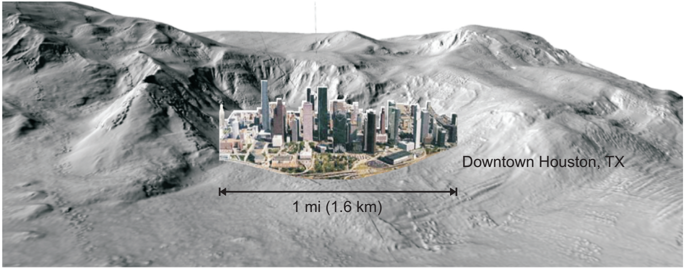
- Earthquake-induced tsunamis are generally well-understood and well-modeled (though prediction is difficult)
- Landslide tsunamis are typically smaller and less frequent, but can cause more localized damage
  - Grand Banks, Newfoundland, 1929: 3-8 m waves, killed 28
  - Papua New Guinea, 1998: 15 m waves, killed > 2200
- Landslide tsunami generation is less well-understood but involves longer time scales and a more dynamic process between sediment flow and water motion, requiring a more complex modeling approach

Landslide Generation Processes

- Submarine landslides can result from:
  - Earthquakes
  - Overpressure due to rapid sediment deposition
  - Presence of weak soil layers
  - Excess pore pressure
  - Wave loading on sea bed from storms/hurricanes
  - Gas hydrate dissociation
  - Groundwater seepage
  - Slope oversteepening

GoM Submarine Landslides

- “Small” submarine failures occur regularly, detected from damaged pipelines, cables, etc.

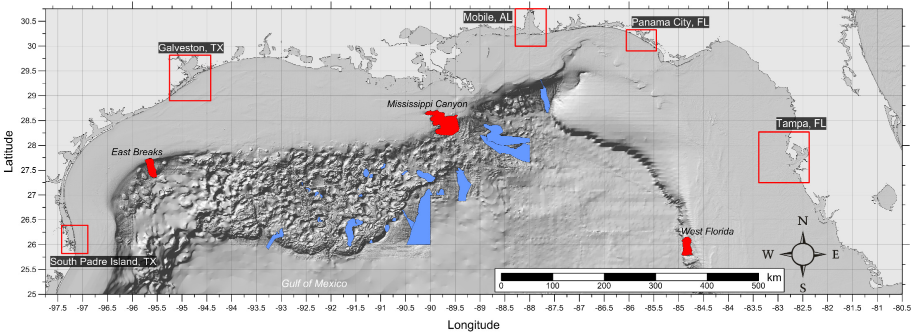


P. Jeanjean, A. Hill, BP America Inc., S. Taylor, BHP Billiton Petroleum (2003), The Challenges of siting facilities along the Sigsbee Escarpment in the Southern Green Canyon Area of the Gulf of Mexico: Frame work for integrated studies, OTC 15156.

- Earthquakes are expected to be the most common and most likely trigger of more massive slope failures which can initiate a tsunami

Past GoM Submarine Landslide Events

- 3 large-scale ancient sources identified as worst-case tsunami scenarios: East Breaks, Mississippi Canyon, and West Florida
- 24 additional identified landslide events [2] used for GoM assessment
- Since there is limited data on past GoM landslide tsunamis, a probabilistic approach is necessary to determine hazard regions: Monte Carlo Simulation



[2] McAdoo, B. G., L. F. Pratson, and D. L. Orange (2000), Submarine landslide geomorphology, US continental slope, Mar. Geol., 169, 103-136.

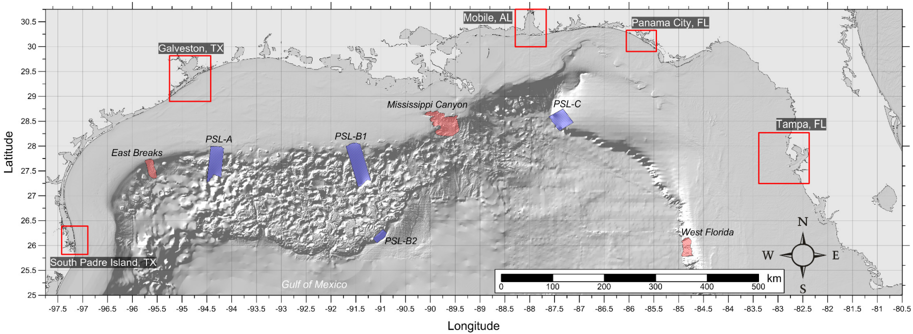
Monte Carlo Simulation

1. Calculate a set of possible landslide configurations based on distributions for Depth (D), Area (A), Volume (V), and Length (L)
    - GoM data show A, V, and L are mutually very well correlated
    - To capture these trends as well as the uncertainty in the parameters, we implement a Cholesky decomposition for random correlated variables of A, V, and L
2. Perform sediment stability analysis (i.e. Factor of Safety) for each possible source using size/location, sediment characteristics, Peak Horizontal Ground Acceleration (PHA) as the failure trigger
3. Trial configurations that fail and produce a tsunami amplitude above a threshold value (20 cm) are considered tsunamigenic

MCS tsunamigenic failures

- Each tsunamigenic scenario is associated to a probability and rate of recurrence
  - Probability of tsunamigenic failure is calculated as the joint probability of slope failure (# of failures/total trials) and annual probability of the triggering PHA
- Worst-case scenarios are determined as the most likely extreme events:
  - Largest tsunami amplitude
  - Shortest return period $\leftrightarrow$ highest probability
- 4 probabilistic maximum credible sources have been identified to “fill the gaps” between the 3 ancient worst-case failures

Sources and Mapped Communities



- 7 landslide configurations used for tsunami modeling: 3 historical (Red), 4 probabilistic (Blue)
- 5 communities where tsunami inundation modeling has been completed: South Padre Island, TX, Galveston, TX, Mobile, AL, Panama City, FL, Tampa, FL

Tsunami Generation Modeling

- 3D-2D coupled models for tsunami modeling
- 3D model (TSUNAMI3D) for tsunami generation by submarine landslide
  - 3D model based on classical Navier-Stokes equations [3]
  - Both water and landslide material are modeled as incompressible Newtonian fluids (deformable landslide)
  - Hydrostatic/nonhydrostatic pressure
  - Explicit scheme applied to momentum and continuity equations, implicit scheme for nonhydrostatic pressure term
  - Uses Volume of Fluid (VOF) method to track fluid-fluid or fluid-air interfaces
  - Resolution: $\sim$ 400m in x, y, $1- \sim$ 50m in z

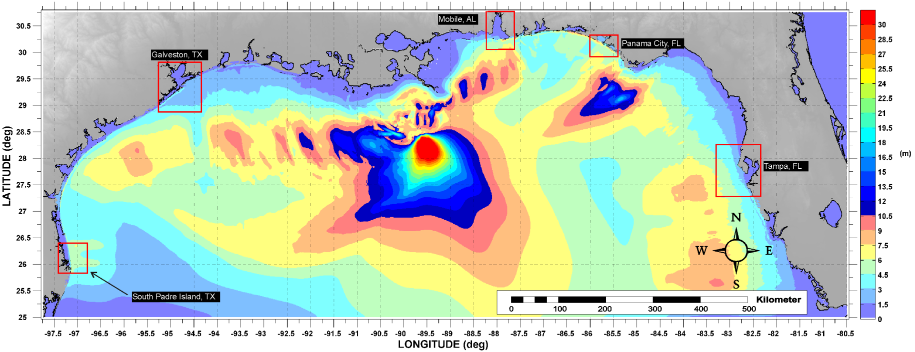
[3] Horrillo, J., Wood, A., Kim, G.-B., and Parambath, A. (2013), A simplified 3-D Navier-Stokes numerical model for landslide-tsunami: Application to the Gulf of Mexico, *J. Geophys. Res., 118*, 6934-6950

Wave Propagation Modeling

- Coupled with 2D model (NEOWAVE) for wave propagation and inundation
  - 2D (x,y) depth-averaged model based on nonliner shallow water equations [4]
  - Similar treatment of governing equations (hydrostatic/nonhydrostatic, explicit/implicit)
  - Momentum conserved advection scheme to model wave breaking
  - Two-way nested grids for modeling higher-resolution wave runup and inundation
  - Uses free surface elevation and depth-averaged wave velocities from TSUNAMI3D as initial condition (“hot-start”)
  - Resolution: 15 arcsec $\rightarrow$ 1/3 arcsec

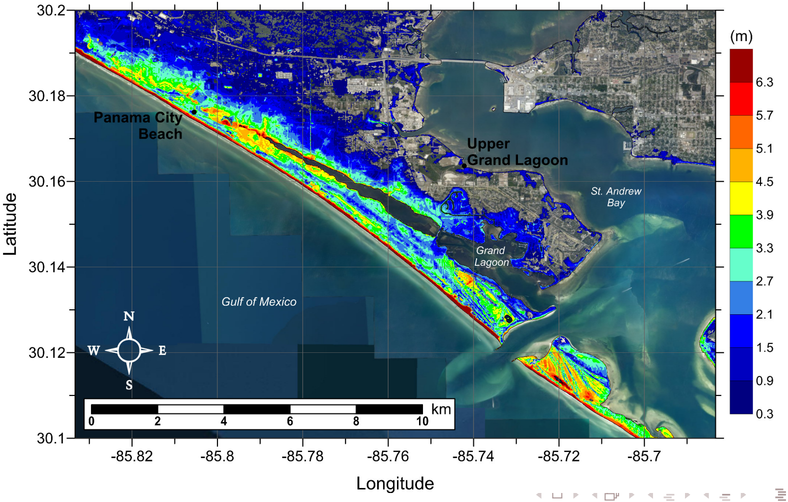
[4] Yamazaki, Y., Kowalik, Z., and Cheung, K. F. (2008), Depth-integrated, non-hydrostatic model for wave breaking and run-up, *Int. J. Numer. Meth. Fluids, 61*, 473-497

Example: Mississippi Canyon Landslide Maximum Tsunami Amplitude

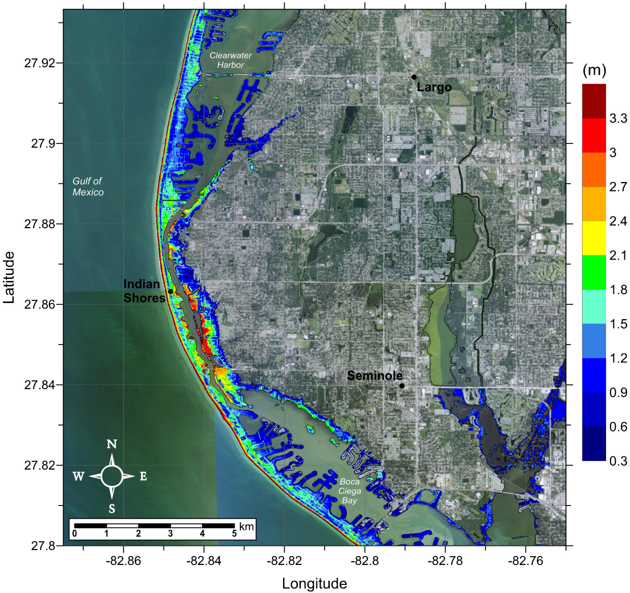


Tsunami Inundation: Panama City, FL

- Maximum of Maximums (MOM) inundation: maximum inundation depth from an ensemble of all seven tsunami sources



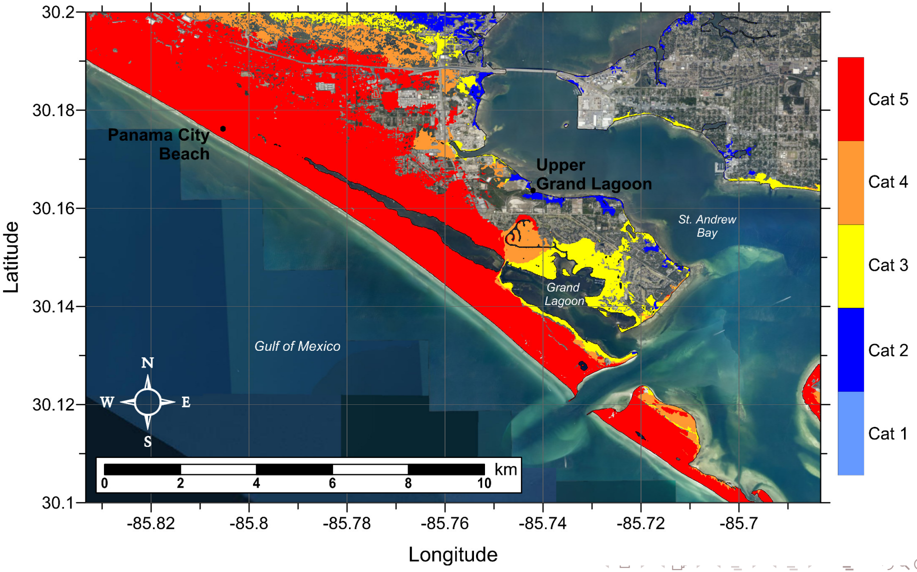
Tsunami Inundation: Tampa, FL



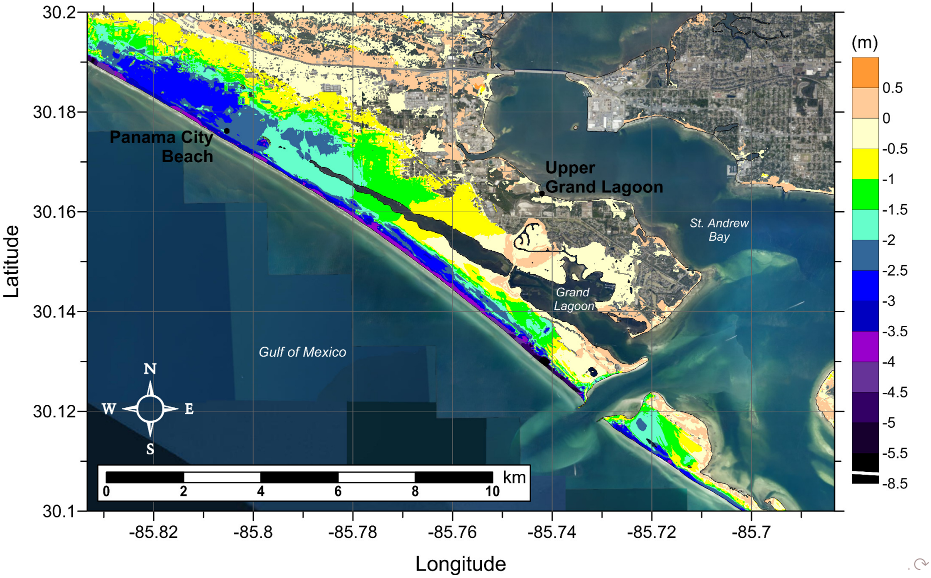
Comparing Tsunami Inundation and Hurricane Storm Surge Inundation

- Due to the limitations on availability of high-resolution bathymetry data, detailed inundation maps for all Gulf Coast communities are not yet possible
- To develop a first-order estimate of potential tsunami inundation for those locations, we compare tsunami inundation to hurricane storm surge data: SLOSH model
- SLOSH Maximum of Maximums (MOM) results provide the worst-case storm surge for a given hurricane category and initial tide level
- Determine hurricane category whose MOM storm surge ζ_h best matches tsunami MOM inundation ζ_t
- Absolute difference between hurricane storm surge and tsunami inundation $\Delta\zeta = \zeta_h - \zeta_t$ shows how close of a match the best-match category actually is
  - $\Delta\zeta > 0$: hurricane storm surge higher
  - $\Delta\zeta < 0$: tsunami inundation higher

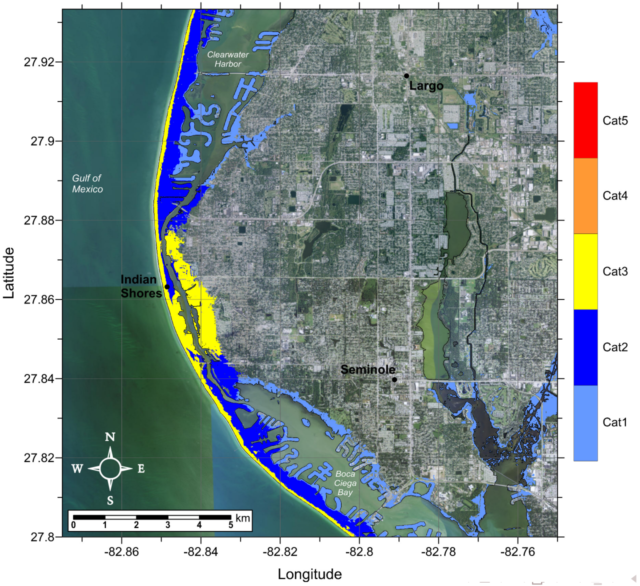
Panama City, FL Hurricane Category Best Matching Tsunami Inundation



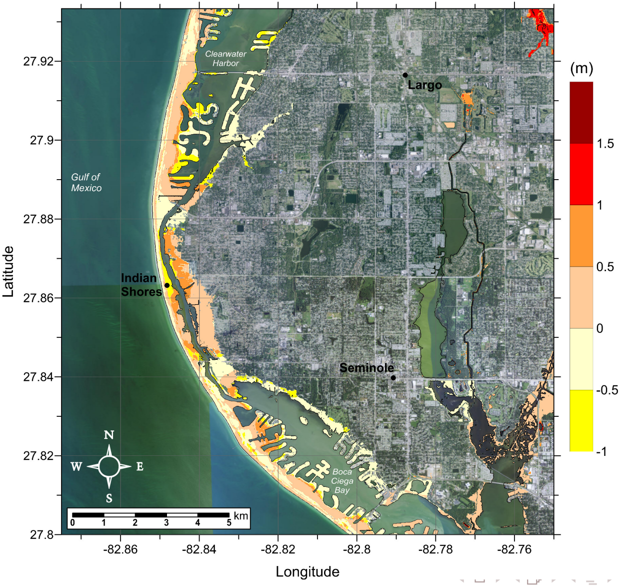
Panama City, FL Hurricane – Tsunami Difference $\Delta\zeta$



Tampa, FL Hurricane Category Best Matching Tsunami Inundation



Tampa, FL Hurricane – Tsunami Difference $\Delta\zeta$



Conclusions

- Level and extent of tsunami inundation varies depending on the regional variations in bathymetry/elevation
- Immediate beachfront areas are inundated at levels comparable to major hurricane ($\geq$ Category 3)
- Barrier islands and near where the continental shelf is relatively narrow (e.g. Panama City) see tsunami inundation that is well above Category 5 levels (up to 5m higher or more)
- Where the continental shelf is wide or where the community is located more inland (e.g. Tampa), tsunami inundation depths are generally comparable to a Category 3 hurricane at the immediate beachfront and down to a Category 1 inland

Current Work

- Inundation maps for Key West, FL and Pensacola, FL (pending DEM development)
- Maritime products (maximum current velocity and vorticity in ports, harbors, bays, etc.) for all 5 currently mapped communities

Acknowledgements

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- Implementing NTHMP-MMS Strategic Plan in Tsunami Hazard Mitigation Products for the Gulf of Mexico (NA14NWS4670049)
- A Probabilistic Methodology for Hazard Assessment Generated by Submarine Landslide in the GOM (NA13NWS4670018)
- Construction of Five Additional Tsunami Inundation Maps (NA12NWS4670014)