Project Progress Report
Period March /2014 to August/2014

TAMUG Contract Number: 10-480471
Sponsor Award No.NA12NWS4670014
Contract Sponsor: National Tsunami Hazard Mitigation Program (NTHMP-NOAA)
Title: **Construction of five (5) tsunami inundation maps in the Gulf of Mexico**.

Project Dates:	September 1, 2012 – August 31, 2015
Recipient:	Texas A&M University at Galveston (TAMUG)
Contact:	Dr. Juan J. Horrillo Texas A&M University at Galveston Maritime Systems Engineering (MASE) 200 Seawolf Park or P.O. Box 1675 Galveston, TX 77553-1675 Phone: (409) 740-4465 horrillj@tamug.edu
Website:	http://www.tamug.edu/

PI
Name: Juan J. Horrillo
Contribution to Project: Lead TAMUG's team for the numerical model application and probabilistic methodology for the entire project.

Research Associate
Name: Alyssa Pampell
Contribution to Project:
Dr. Pampell is a research associate working in the probabilistic approach to determine credible tsunami-landslide sources. The existing tsunami-landslide sources together with those determined from the probabilistic approach are used to obtain detailed runup and inundation at five specific locations along the US GOM's coastline.

Graduate Student
Name: Lisha Parambath
Contribution to Project:
Mrs Lisha Parambath was an ocean engineering student under the guidance of Dr. Juan J. Horrillo. Mrs. Parambath finished her Master Thesis. Her work contributed to determine three additional tsunami-landslide sources. The existing tsunami-landslide sources (see ten Brink et al., 2009) together with the determined by the probabilistic approach are used to obtain detailed runup and inundation at five specific locations along the US GOM's coastline.

Project Collaborator:
Name: Yoshinori Shigihara
Contribution to Project:
Dr.Shigihara, from the Military Academic of Japan, Japan, is helping improve the basic methodology for the probabilistic approach (using Monte Carlos simulations) to define tsunami-landslide sources for several return periods or probability of exceedance.

Project Emergency Manager:
Name: Amy Godsey
Contribution to Project:
Mrs. Amy Godsey serves as an emergency manager consultant to ensure overall results, inundation maps and findings are relevant to practical application for response and preparedness strategies.

OBJECTIVES

The main goal of this project is to construct five tsunami inundation maps at specific locations along the US GOM coastline. The inundation maps are constructed based on three credible (ancient) submarine landslide scenarios, which have been described and characterized by ten Brink *et.al*., 2009. Additional landslide scenarios (three more) are created using a probabilistic method for a total of six cases or scenarios. Locations for the construction of tsunami maps are selected according to a preliminary study aiming to determine vulnerable regions along the US GOM coastline. Our new grant NA13NWS4670018 (**A probabilistic Methodology for Hazard Assessment of Tsunami Generated by Submarine Landslide and for Construction of Tsunami Inundation Maps in the Gulf of Mexico**) funded through the sustainability of current tsunami activities, FY13 NTHMP grants, is giving us the opportunity to increase our soil database and develop new tsunami-landslide sources and scenarios using the probabilistic approach. Thus, we will be able to increase the resolution for the probabilistic estimation of tsunami-landslide sources.

BACKGROUND

Our first project NA09NWS4670006, ***Construction of the first tsunami inundation map in the Gulf of Mexico***, (Horrillo et al., 2010) funded by NTHMP has shown that tsunamis generated by ancient landslides (*Regional Assessment of Tsunami Potential in the Gulf of Mexico* by ten Brink *et.al*., 2009) have indeed the potential to cause severe flooding to the Gulf of Mexico (GOM) coastal communities. Our study proved that such landslide sources can cause inundation of the order of 6 - 8 feet (~1.8 - 2.4 m) in Port Aransas, TX, comparable in term of inundation, to severe storm surge. Tsunami energy focusing has been identified in several regions along the US GOM coastline. Regions most impacted are located at the southern tip of South Padre Island TX, Grand Isle LA., and the coastal strip from Pensacola to Cape San Blas FL. Consequently, the goal of this project is to establish for first time a systematic production of tsunami inundation maps along the GOM US coast aimed to provide guidance to state emergency managers and optimize real-time tsunami warnings to communities along the GOM coastline. Construction of tsunami maps are based on identified past events of local submarine landslides and other local landslide sources determined by means of a probabilistic approach. It is projected that five (5) new tsunami inundation maps will be completed during the estimated project period.

Since a practical hazard assessment was not contemplated in our first work NA09NWS4670006 (Tsunami inundation for Port Aransas, TX), herein was proposed to include, in addition to the worst case scenarios approach, a probabilistic analysis to identify potential submarine landslides with higher hazard of generating tsunamis. The probabilistic analysis aims to estimate the hazard expressed in terms of slope failure, following the work described in Maretzki, Grilli and Baxter, 2007. The scope of this specific effort has been enhanced by the recent grant NA13NWS4670018 obtained through the FY13 NTHMP sustainability of current tsunami activities.

Our first project, NA09NWS4670006 (Tsunami inundation for Port Aransas, TX), established the foundation for model setup and source characterization. These results are still vital for the subsequent construction of tsunami inundation maps on selected communities along the GOM coastline. It is projected that the new set of inundation maps (5 additional maps) will promote a line of investigation in comparing the project's outcomes with results of other flooding phenomena that are more common in the GOM, i.e., extreme storm surge. This effort has been envisioned in our current proposal for FY14, funding opportunity Number: NOAA-NWS-NWSPO-2014-2004049 (**Development and implementation of temporal-low-order inundation maps for tsunami hazard areas where inundation studies have not yet been assigned/executed or where little bathymetric and elevation data exists**) which has been already funded. This effort will contribute to combine flooding preparedness, criteria and emergency procedures.

Locations for construction of the five (5) inundation maps were selected according to a preliminary study aiming to determine vulnerable areas affected by the identified past events (ten Brink *et.al*., 2009) and those estimated by the probabilistic approach. The selection of the locations depend on the proximity of submarine landslides and the quality of the existing local topographic data and geotechnical information. Tsunami flooding inland-extent, maximum inundation depth, momentum flux and tsunami arrival time are determined within the hazard areas of the selected locations. The selected location are: South Padre Island, TX; Freeport, TX; Galveston, TX.; Mobile, AL; and Panama City, FL.

PROJECT FINDINGS SUMMARY

In addition of the ancient landslide scenarios identified by tenBrink, (2009) (East-Breaks, Mississippi Canyon and West Florida), three new landslide scenarios (named in our study as Transects A, B and D) have been determined using the probabilistic methodology. Figure 1 depicts some of the landslides scenarios obtained by using the probabilistic approach and some of those identified by tenBrink, (2009). Our findings suggest that the rate of recurrence of these landslides determined by the probabilistic approach are around 10,000 years; result that is consistent with recent studies carried out by the USGS research team, Geis, et al., 2013.
As an example of this scenarios, the 3D simulation result of the landslide-induced tsunami waves for the Mississippi Canyon scenario is presented in Figure 2. Top-left panel on the Figure 2 shows a snapshot of the underwater landslide at 20 min after the initiation of the submarine landslide; the top-right panel shows the free water surfaces deformation generated by the motion of the submerged landslide. As can be observed (readers should use the color bar as a reference), the outgoing wave of 20m (66ft) of amplitude is propagating offshore but immediately refracting toward the coastline located to the sides and behind. The outgoing positive wave is followed by a complex negative wave or surface depression of approx. 28m in average (approx. 92ft) caused by the fast downslope motion of the underwater slide. At this stage (20 min), an emerging positive wave in the depression region is still not visible or developed.

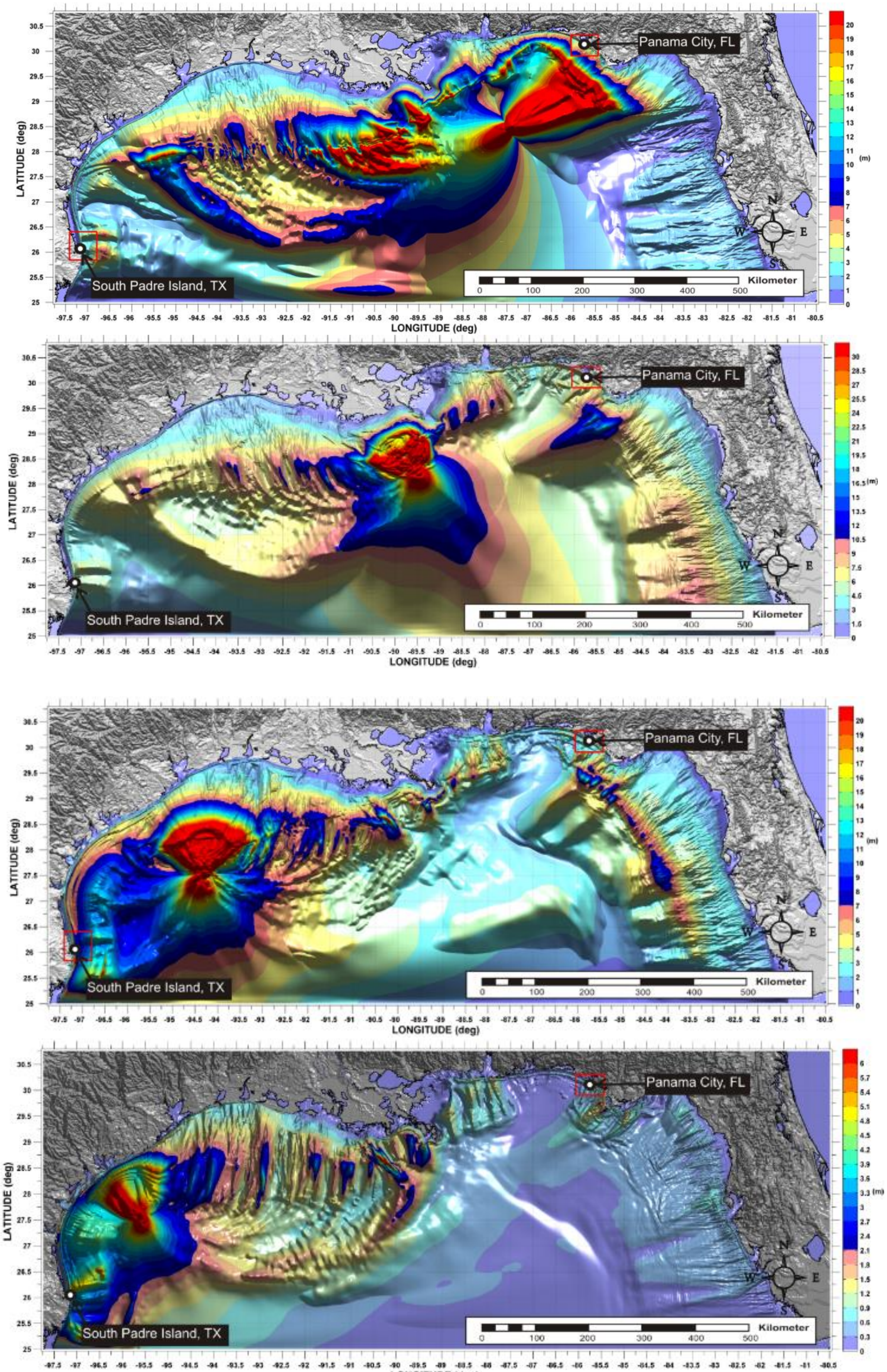

Figure 1. Maximum wave amplitude: Top panel, Transect D (probabilistic landslide); second panel, Mississippi canyon landslide; third panel, Transect A (probabilistic landslide); last panel, East-Breaks landslide.

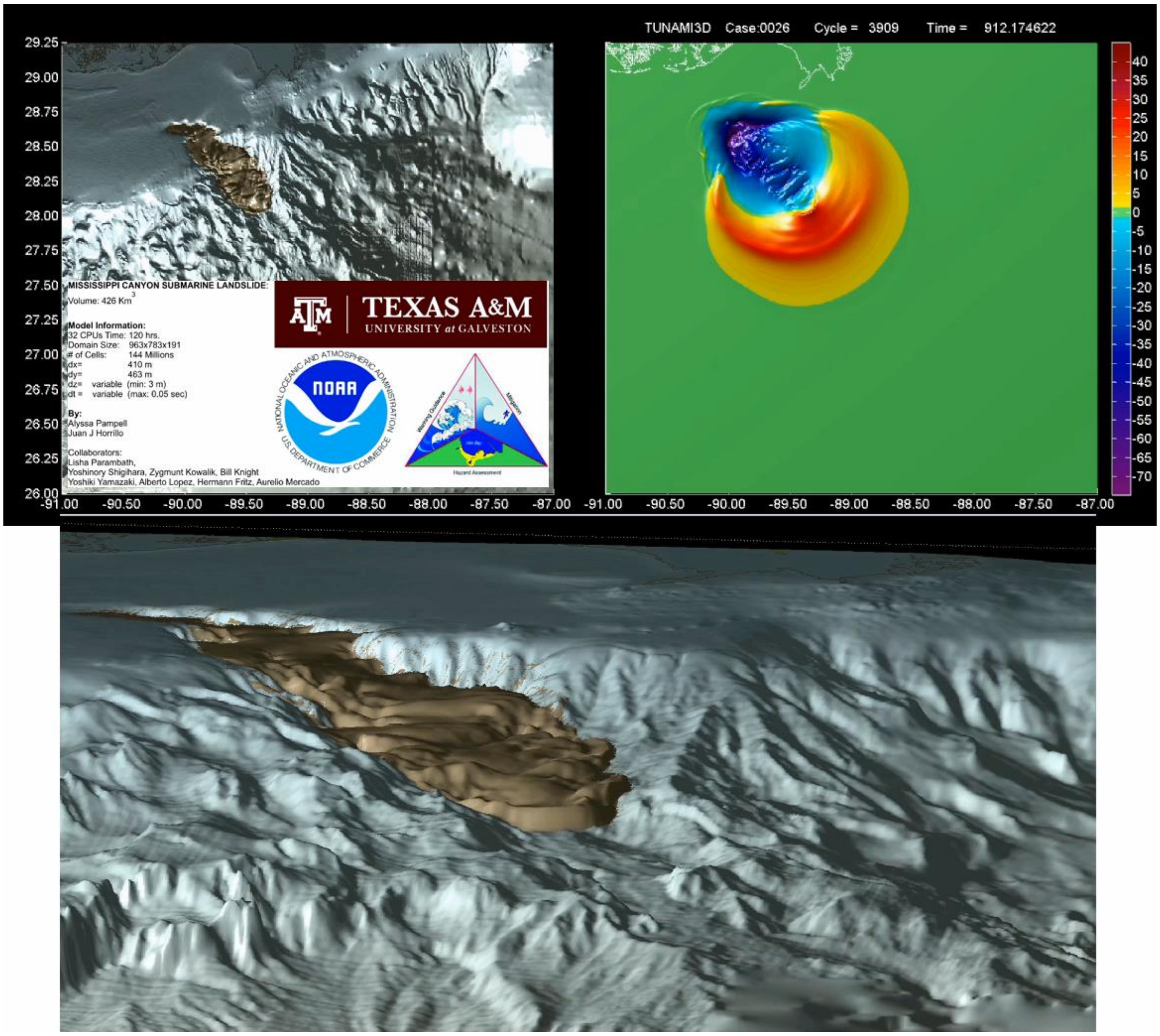

Figure 2. Three dimensional (3D) simulation results for the Mississippi Canyon tsunami source scenario. Top-left panel underwater landslide at 20 minutes from its initiation; top-right panel, free water surfaces deformation generated by the motion of the subsea landslide; bottom panel, perspective view of the submarine landslide.

For the construction of inundation maps, we combine the 3D model (TSUNAMI3D for the landslide-induced tsunami waves) with the 2D depth integrated non-hydrostatic model (NEOWAVE for the wave propagation and runup) (coupled model). The 3D model provides a full representation of the wave kinematic (velocity field) and the free surface configuration for the initial tsunami wave generated by the landslide, which is then inputted as the initial condition (hot start) to the more simplified but more numerically efficient 2D model for the calculation of the wave propagation and detailed runup in the region of interest.

One critical step in the coupling process of the models is to determine the right moment of transferring the full 3D wave kinematic and free surface deformation field to the 2D model. The 3D domain must be large enough to fully develop the generated waves without leaving the domain boundaries, also the energy budget of the domain need to be calculated to verify if the generated waves are fully or mostly developed. The 3D field information or variables are converted to two dimension by a simple column wise depth averaging and inputted as an initial condition to the 2D numerical model. This step is achieved by performing a certain number of simulations (through trial and error) that ultimately yield the most appropriate time and domain size.

For example, by using the nested grid capability of the code NEOWAVE, detailed tsunami runup was obtained in Panama City FL and South Padre Island TX, i.e., maximum sealevel elevation (runup), water depth (inundation) and maximum momentum flux. However, in this bi-annual report and for sake of simplicity, we are presenting only inundation depth and maximum momentum flux results.

Figure 3 and 4 show the tsunami inundation results in Panama City, FL caused by the Mississippi Canyon and the Transect D-probabilistic landslide scenarios respectively. Tsunami effects by these sources are calculated in great detail on the innermost grid 1/3 arc-second resolution of the nested grid domain. Left panels on Figure 3 and 4 portrait the inundation depth defined as difference between maximum sealevel elevation and the land elevation. Numerical results show that the overall maximum water inundation in the populated area of Panama City FL reaches 3.8m (approx.12.5ft) in average. It is important to mention that regions with inundation depths shallower than 0.30m (~1ft) are not indicated in the figures.

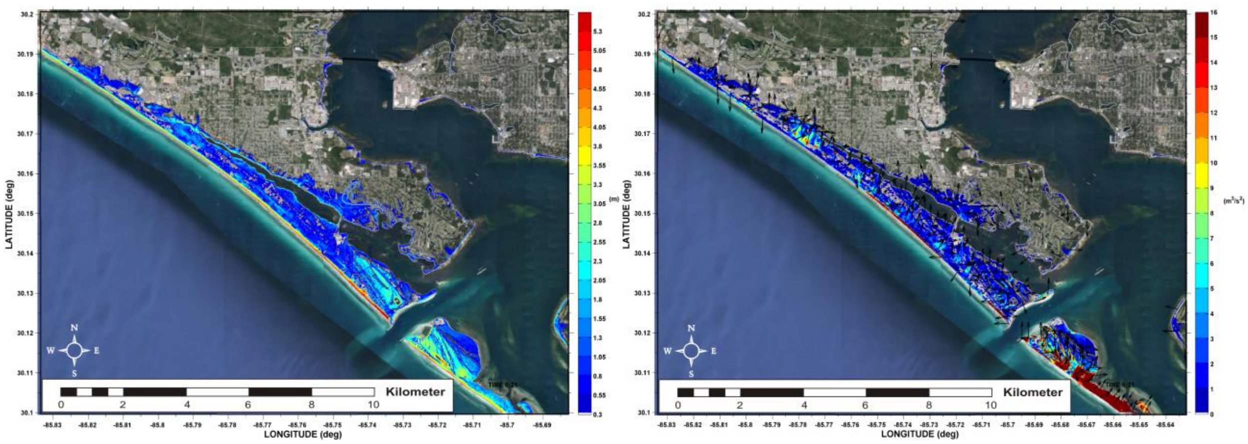

Figure 3. Inundation and momentum flux maps for Panama City, FL produced by the Mississippi Canyon tsunami source scenario. Left panel, Inundation depth; right panel, maximum momentum flux.

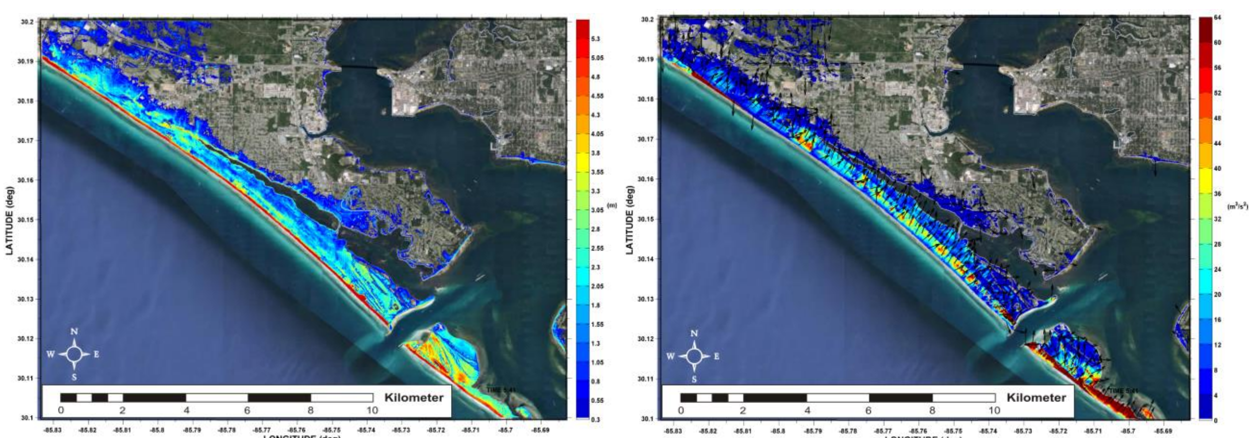

Figure 4. Inundation and momentum flux maps for Panama City, FL produced by the Transect D Probabilistic tsunami source scenario. Left panel, Inundation depth; right panel, maximum momentum flux.

Right panels on Figures 3 and 4 show the "maximum momentum flux" ***hu²***, where ***h*** and ***u*** are the inundation depth and velocity corresponding to the maximum momentum flux. As it can be seen from Figure 4 (left panel), momentum flux values can go up to 60 m×(m/s)^2 in average for the Transect D landslide scenario.

It is important to mention that forces on structures can be determined based on hu^2 values as

$$F = \frac{1}{2}\rho C_d b(hu^2)$$

Where, ρ is the sea water density, C_d is the drag coefficient which depends on the shape or geometry (wet area perpendicular to the flow) of the structure and b is the structure width.

Figure 5 and 6 show the tsunami inundation results in South Padre Island, TX caused by the Transect D-probabilistic and the East-Breaks landslide scenarios respectively. Numerical results show that the overall maximum water elevation in the populated area of South Padre Island can reach 3.9m (approx. 13ft), see left panels on Figure 5. Right panels on Figure 5, the “maximum momentum flux” or hu^2 can reach values up to 110 m×(m/s)^2 in average.

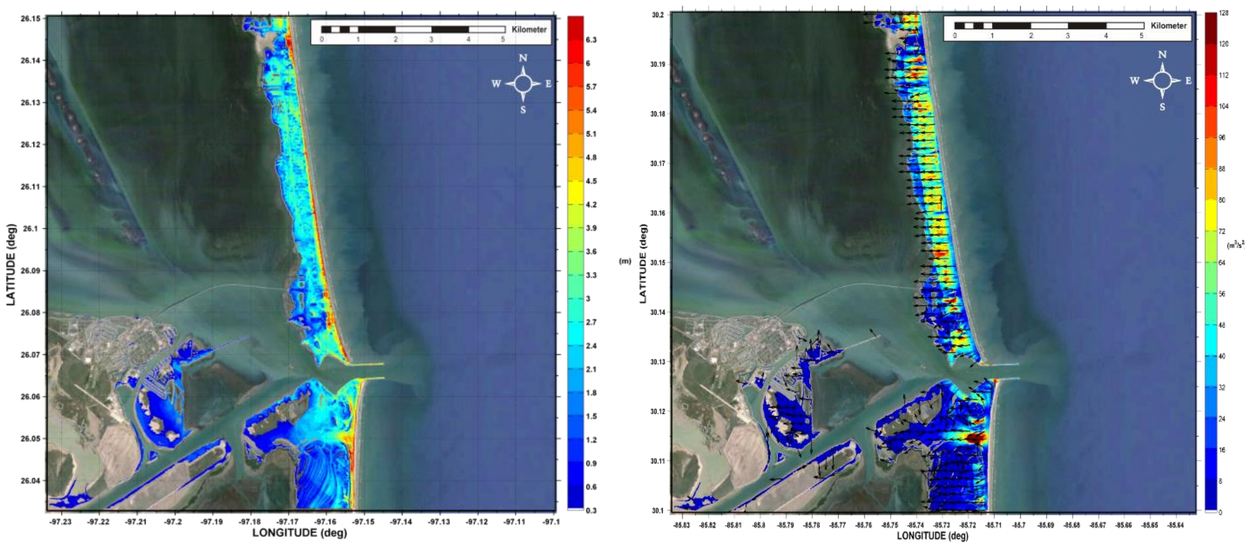

Figure 5. Inundation and momentum flux maps for South Padre Island, TX produced by the East-Breaks tsunami source scenario. Left panel, Inundation depth; right panel, maximum momentum flux.

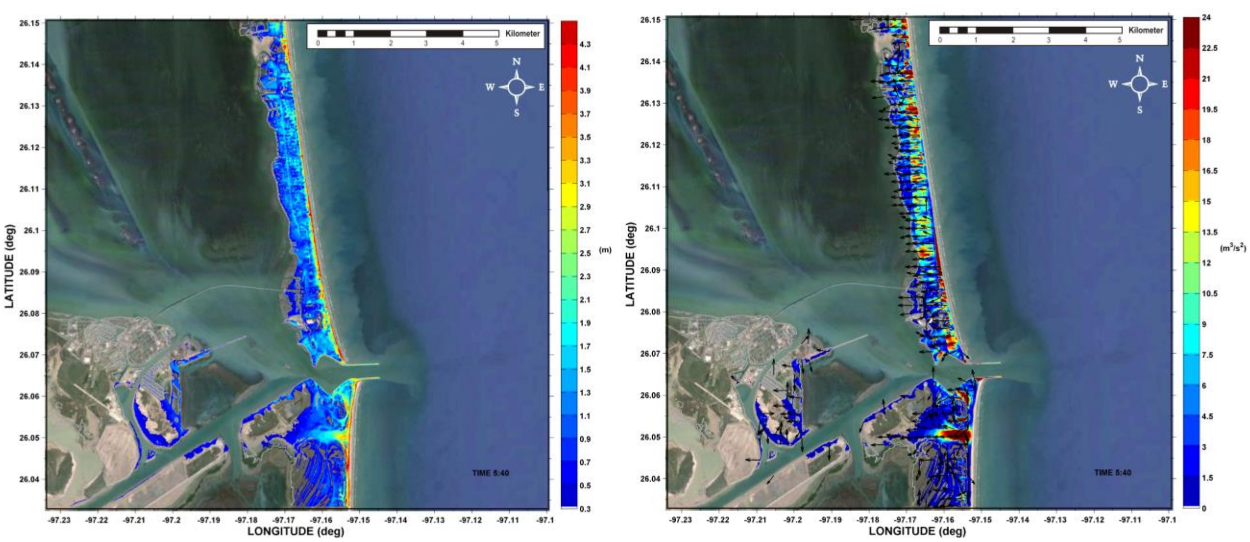

Figure 6. Inundation and momentum flux maps for South Padre Island, TX produced by the Transect D Probabilistic tsunami source scenario. Left panel, Inundation depth; right panel, maximum momentum flux.

ACCOMPLISHMENT SUMMARY

- Draft inundation maps have been generated for Panama City, FL and South Padre Island, TX.
- Most of the publicly available geotechnical information necessary for the characterization of soil by regions in the GOM has been gathered. We were able to obtain sediment information to determine additional landslide failure transects and therefore tsunami sources through the FY13 NTHMP sustainability project (NA13NWS4670018)
- Our tsunami team has established and refined the methodology for conducting a probabilistic tsunami hazard assessment to identify potential submarine landslides with higher possibility of generating tsunamis. The estimate of rate of recurrence seems to be around 10000 years in average.
- The current sediment stability methodology has been constantly improved, as sediment information is added to the database, distributions of sediment parameters now are better defined.
- The Methodology has been presented in the IUGG Meeting, Gocek, Turkey and Rhodes, Greece, 25-28 September, 2013. "Identification of Landslide-Tsunami Sources: A Probabilistic Approach for the Gulf of Mexico", Yoshinori Shigihara, Juan Horrillo and Lisha Parambath, International Tsunami Symposium (ITS). In addition, the probabilistic approach is planned to be presented this coming December in AGU.
- The Monte Carlos algorithm and the programming routines (Matlab) have been parallelized reducing considerably the calculation time.
- Four landslide scenarios have been re-characterized again to reflect the (e.g., location, water depth, volume, etc.,) with period of returns around 10000 years.
- Sediment information has been collected to generate one additional landslide transect (this effort belongs to project NA13NWS4670018, FY13 NTHMP -sustainability of current tsunami activities-).

PROJECT SCHEDULE and Percentage of EXECUTION to August 31/2014

Project Dates: **September/01//2012- August/31/2015**
PI: **Dr. Juan J. Horrillo**
Research Associate (RA): **Dr. Alyssa Pampell**
MS. Student: **Mrs Lisha Parambath**
International Collaborator (IC)**: Dr. Yoshinori Shigihara**
Emergency Management Representative (EMR): Mrs. **Amy Godsey**

Outcome	Strategy	Schedule	Tasks	Resources Execution %
Develop initial condition grids for submarine landslide scenarios based on parameters defined in ten Brink, et.al., (2009) report as input to numerical modeling.	Compilation of all publicly-available bathymetry/topography, documents & research papers on the topic prior to execute this activity.	Sep. 1 to Sep. 15 2014	Research literature & NRC report studies.	PI, IC, RA and Students 97%
		Sep. 16 to Sep. 25 2014	Obtain GOM bathymetric and topographic data.	78%
		Sep. 26 to Oct. 20 2014	Determine location and shape (from landslide mapping) of seabottom initial deformation for each case scenario.	75%
Execute analysis of submarine landslide scenarios to determine static and dynamic initial tsunami wave configurations. Collection of geotechnical info for probabilistic approach	Collection and review of all technical references on the subject.	Oct. 21 to Oct. 30 2014	Determine simple tsunami wave configuration based on volume and morphology of the subsea landslide.	PI, RA, Students, IC 80%
	Submit computer model jobs to Texas A&M (TAMUG) Cray computer.	Nov. 1 to Nov. 20 2014	Model 2D debris flow analysis (Newtonian and Bingham viscous-plastic behaviors) to determine dynamic tsunami wave configuration.	96%
			Post-processing: plotting initial wave profile, result comparisons and landslide evolution (movies).	10%
Perform preliminary large-scale calculation using "low resolution"	Three case submarine landslide scenarios and two different models for wave propagation	Nov. 21 to Dec. 20 2014	Develop initial GOM global grids and locate numerical gauges at	RA, Students, PI, IC and Collaborators

numerical models (hydrostatic and non-hydrostatic) to determine regions along the US coast of GOM with higher tsunami impact for the given landslide scenarios.	(hydrostatic and non-hydrostatic) will be used.		predetermined critical locations along coastline.	
		Dec. 21 to Jan. 31 2014-2015	Static model setup: Create sealevel grid and input sealevel deformation.	25% 20%
Initiate Probabilistic approach study (**Concurrently task**)		Feb. 01 to Feb. 15 2015	Dynamic model setup: Create sealevel grid and input sea bottom deformation in time.	100% 20%
	Plotting results at each gauge and doing comparison of different model results and source scenarios will facilitate visualization of coastal regions with higher tsunami energy concentration.	Feb. 16 to Feb. 31 2015	Select critical coastal regions with higher tsunami energy concentration.	30%
Select the region with the higher tsunami hazard considering: proximity to submarine landslides, preliminary sea level results and extent of flooding, infrastructure and population density and quality/resolution of existing bathymetric and topographic data.	Create a table with all variables e.g., wave height, population density, infrastructure and quality of bathy/topo data for each critical coastal region to assist in selecting the location to perform inundation mapping.(mainly constrained by DEMs availability)	Mar. 1 to Mar. 7 2015	Study previous activity results to select one specific location for the construction of the inundation map.	PI, RA, Students & EMR 60%
		Mar. 8 to Mar 15 2015	Consensus meeting to select the location to construct the inundation map.	40%
Compile publicly-available fine	Document locations with high resolution	Mar. 16 to Mar. 28	Obtain selected-location's	PI, RA, Students

resolution bathymetric and topographic data of the selected location.	bathymetry/topography data for future inundation mapping studies	2015	bathymetric and topographic data.	40%
Perform high resolution numerical modeling (nesting) to determine: tsunami flooding-inland-extent, maximum flooding depth, momentum flux and duration at maximum flow within the hazard regions of the selected locations.	Submit computer model jobs to Texas A&M (TAMUG) Cray Supercomputer.	Apr. 1 to May. 31 2015	Model setup. Integrate fine resolution grid to low resolution GOM grid. Input sealevel or seabottom deformation.	PI, RA, Students 25%
			Program execution.	25%
			Post-processing: creation of figures, result comparisons, tsunami propagation and runup maps.	10%
Construct a tsunami inundation draft-map for the selected region.	Include construction of a poster for future presentation.	Jun.1 to Jun. 15 2015	Post-processing-results to construct the hazard map.	PI, RA, Students, 0%
Analyze a possibility for higher inundation due to resonance amplification of the sealevel (if this occurrence is applicable to the selected location)	Apply same procedure described in Horrillo et. al. 2008	Jun.16 to Jun. 30 2015	Determine natural mode of oscillation (if this is applicable) e.g., using response function or eigenvalue problem.	PI, RA and Students 0%
Prepare a report for publication on possible tsunamis in the GOM by submarine landslides		Jul. 1 to Aug. 31 2015	Result Assemble and document	PI , RA, Students, IC and EMR 0%

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