STRATEGIC POSITIONING OF SEA LEVEL GAUGES FOR EARLY CONFIRMATION OF TSUNAMIS IN THE INTRA-AMERICAS SEA

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ABSTRACT. The potential impact of past Caribbean tsunamis generated by earthquakes and/or massive submarine slides/slumps, as well as the tsunamigenic potential and population distribution within the Intra-Americas Sea (IAS) was examined to help define the optimal location for coastal sea level gauges intended to serve as elements of a regional tsunami warning system. The goal of this study was to identify the minimum number of sea level gauge locations to aid in tsunami detection and provide the most warning time to the largest number of people. We identified 12 initial, prioritized locations for coastal sea level gauge installation. Our study area approximately encompasses 7°N, 59°W to 36°N, 98° W. The results of this systematic approach to assess priority locations for coastal sea level gauges will assist in developing a tsunami warning system (TWS) for the IAS by the National Oceanic and Atmospheric Administration (NOAA) and the Intergovernmental Oceanographic Commission's Regional Sub-Commission for the Caribbean and Adjacent Regions (IOCARIBE-GOOS).

KEY WORDS: Caribbean Sea tsunamis sea-level gauge

1. INTRODUCTION

Historical data suggest that tsunamis have occurred in the Intra-Americas Sea (IAS) region approximately once every 3-yr, and destructively once every 21-yr [*O'Loughlin and Lander*, 2003]. According to Bryant [2005], approximately 14% of all tsunamis have occurred in the Caribbean. When considering only Hawaii, Alaska, the U.S. West Coast, and the Caribbean, about 2,590 victims or 83% of all tsunami fatalities in these regions over the last 150 years occurred in the Caribbean [*O'Loughlin and Lander*, 2003]. As a result of these recorded fatalities and the rise of Caribbean population by almost 300% from 1950 to 2000 [*CIAT, et al.*, 2005], protection of human life is a primary reason for establishing a TWS in this region. In this work, historical tsunamis in the IAS were analyzed with the aid of a numerical ocean model and the results were used to suggest locations for coastal sea level gauges for the most efficient implementation of a TWS for the IAS region.

While tsunamis are usually generated in deep water, they are considered shallow-water waves because the typical wavelength of a tsunami is 220,000-m and the average depth of the Caribbean is approximately 2600-m. Tsunamis propagate at the shallow water gravity wave phase speed of $c = (g\,H)^{1/2}$, which can be in excess of 222 m s^{-1} (~ 800 km hr^{-1}), until they dissipate or encounter a shelf and shallow coastal water where they slow to 8 – 14 m s^{-1} (~ 30 – 50 km hr^{-1}). This study sought to understand how and where tsunamis are generated in the IAS, how they travel through this region, and where a minimum number of sensors should be installed to most efficiently confirm or deny the presence of an impending tsunami.

The predominant tsunamigenic events are earthquakes; however landslides, avalanches, submarine slumps or slides, volcanic eruptions, volcano flank failure, and oceanic meteor impact can also cause a tsunami [Lander, et al., 2002; McCann, 2006; Pararas-Carayannis, 2004]. Often, a tsunami is the result of coinciding events, thus it can be difficult to identify the actual tsunamigenic process.

When designing a tsunami warning system it is critical to understand the types of tsunamigenic mechanisms, the coastlines that are more likely to be affected by a tsunami, tsunami travel time to those coasts, and the resulting effects from historical tsunamis [Lander, et al., 1999]. However, the historical record is incomplete. Here, we simulated tsunamigenic events with the potential to have far-field (greater than 1000-km) impacts. The results were combined with information on human population concentrations around the Caribbean to determine the most critical and advantageous locations for the installation of coastal sea level gauges.

Historical Tsunamis in the IAS Region

The historical record of tsunami origins and affected areas is sparse. The data used in this study is from both O'Loughlin and Lander [2003] and the National Geophysical Data Center [NGDC, 2005]. These original tsunami origin data have 0.1-degree precision, and while there are historical records of areas affected by some of these events, for others there is no information regarding effects or arrival location.

The Caribbean and Surrounding Tectonic Plates

Tectonic activity due to plate movement is the principal cause of earthquakes, 80% of which occur along the plate boundaries in the oceanic crust [Woods Hole, 2005]. Figure 1 shows the plates in the Caribbean region, their boundaries, and summarizes their interactions [Lander, et al., 2002; McCann, 2006; O'Loughlin and Lander, 2003; Pararas-Carayannis, 2004]. A detailed description of tsunamigenic potential of these areas is provided in Henson et al. [2006].

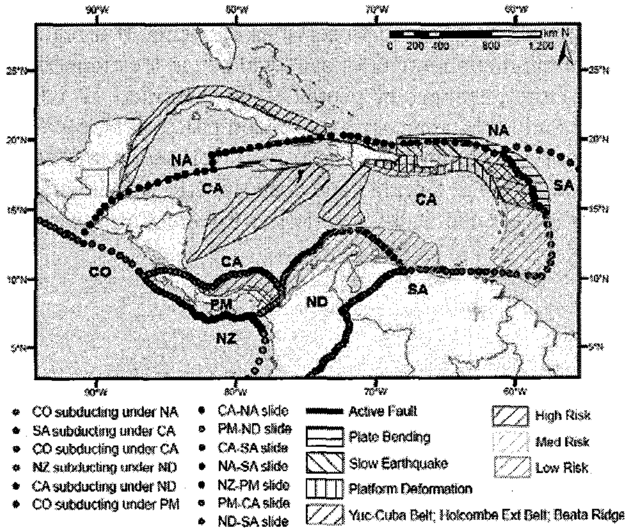

Figure 1 – Plate boundaries and interactions from Bird [2003] and tsunamigenic source regions from McCann [2006].

Sea Level Gauges in the Caribbean Sea

Over approximately the past 10 years, some 60 sea level gauge stations were installed in the Caribbean and surrounding countries by NOAA, programs such as RONMAC (Water Level Observation Network for Latin America), CPACC (Caribbean Planning for Adaptation to Global Climate Change), and other locally and internationally-funded programs to examine local sea level changes. Government organizations, educational institutions, and independent companies had offered to maintain these stations, but as of February 2006, most stations were in various states of disrepair. Out of the 60 stations that had been deployed historically throughout the IAS region, 17 were fully operational and transmitting data, 16 were not operational but the equipment was accounted for, and 10 were questionably operational. The remaining stations are either no longer operational or are missing altogether [Henson and Wilson, 2005]. To contribute to a tsunami warning network, most stations will need to be replaced, while others need to be upgraded with additional hardware such as a GPS card and/or GOES transmitter [Henson and Wilson, 2005]. The IAS TWS (IOC UNESCO, 2005) proposal recommends integration of an infrastructure including 31 upgraded sea level stations throughout the wider Caribbean Sea.

Puerto Rico has aggressively pursued the development of a tsunami-ready sea level gauge network. The Puerto Rico Seismic Network (PRSN) group has begun installing 10 sea level gauge stations around the island [von Hillebrandt-Andrade, 2006, personal correspondence]. A base station located in Mayagüez, Puerto Rico, will be capable of processing data from these and other sea level stations throughout the IAS.

2. METHODS

This study sought to determine where the minimum number of sea level gauges should be located to maximize the warning time to the largest amount of people. We analyzed how and where regionally destructive tsunamis form, propagate, and impact a coastline, in the context of the coastal population distribution. We developed an assessment of where coastal sea level gauges are operational, in order to minimize duplication in a prioritized list of locations that should be monitored for sea level. A complete description of the methods used is provided in Henson et al. [2006].

Without pinpointing specific tsunami origin locations, we examined areas where a tsunami is more likely to occur by using a tsunamigenic event source map [McCann, 2006]. An analysis of risk is based on the known or assumed origins of 42 historical tsunamis (Figure 2). Propagation, travel time, and impact analyses are accomplished through the simulation of the historical tsunamis with the Navy Coastal Ocean Model (NCOM).

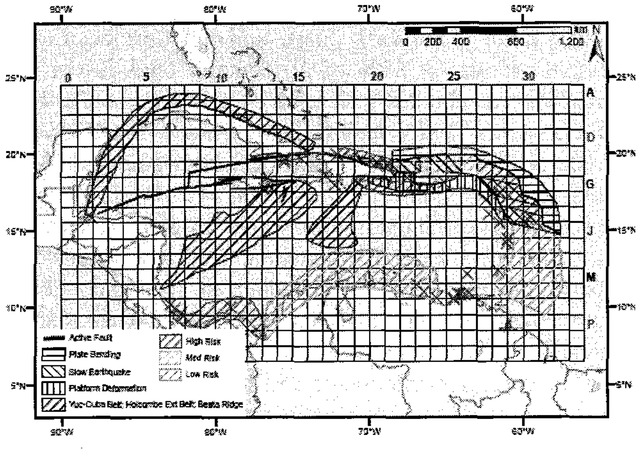

Figure 2 – 1-degree grid used to define regional tsunamigenic potential. Includes map of the IAS, historical tsunami origins "X" (simulated here), and tsunamigenic source regions. (see Henson et al., 2006).

Determination of Coastal Grid Points (CGP), Population Data, and Time Series Analysis

Custom programs were used to determine impact locations and calculate the travel time to the coastlines throughout the IAS. We used the ETOPO2 bathymetric dataset for the numerical simulations and to identify the first grid point just off the coast.

Population data was obtained from the Latin American and Caribbean Population Database [CIAT, et al., 2005].

Efficient use of a limited number of sea level gauges requires that each gauge warn the greatest number of people possible. A population center, due to the high and variable resolution of the population data set, was defined as a grid point having a population of over 500.

Sea Level Gauge Location Determination

A sea level gauge for a tsunami warning system should be positioned to maximize warning time. Several factors such as population centers, locations where a tsunami may occur, travel time or propagation speed, and wave dissipation are considered when calculating warning time. The Pacific Tsunami Warning System was designed to detect a tsunami within 30-min after the generating earthquake [Bernard, et al., 2001]. The IAS TWS proposal, accepted by the IOC (Intergovernmental Oceanographic Commission), recommends at least 15-min of warning time [IOC-UNESCO, 2005]. We calculated warning time by subtracting travel time to the population center from the travel time to a sea level gauge. A population center is considered to be warned if it can be notified within 30-min after tsunami generation. The closer the gauge is to the tsunami origin, the more warning time available to remote population centers.

The McCann [2006] tsunamigenic source map appears to have a gap in a tsunami risk region just north of Venezuela in sectors N25 and N26 (Figure 2). An additional low risk value is added to the value of sectors N25 and N26 as if completely covered by a low risk area.

Location Priority for Coastal Sea Level Gauges

Through an iterative experimental process a simple decision matrix was developed to evaluate the relatively highest risk sectors in the following categories:

i. Sector risk value
ii. Number of population centers the sector's gauge can warn in time
iii. Number of population centers less than 1000-km away
iv. Number of sectors closest to one potential gauge location
v. Number of sectors sharing a border

Each sector is assigned a rank in all categories, the ranks are added together, and the sector with the lowest number is assigned an overall rank of 1, the second lowest a rank of 2, etc. The final priority list includes all aspects with equal consideration since all ranks are summed.

The sector risk values are ranked so the sector with the highest relative risk receives first priority. This means that, to a first order, a sea level gauge is most useful within or nearest to a sector that is the most likely to generate a tsunami. Additional details of the risk assessment and location prioritiztion method are provided in Henson et al. [2006].

3. RESULTS AND DISCUSSION

Table 1 shows the prioritized list of initial locations for sea level gauges recommended to provide an efficient warning system.

Table 1 – Initial sea level gauge locations recommended for a tsunami warning system. Locations are listed in order of highest to lowest priority groups. Location coordinates should only be used as a guideline.

Sector	Approximate location for gauge installation	Priority
F21	Arena Gorda, Dominican Republic (18.78°N, 68.52°W)	1
G22	Isla Mona, Puerto Rico (18.09°N, 67.89°W) or Boquerón, Puerto Rico (18.02°N, 67.17°W)	2
G28, G29	Barbuda (17.64°N, 61.80°W)	3
H29, I29, I30	La Désirade, Guadeloupe (16.32°N, 61.05°W)	4
F22	Aquadilla, Puerto Rico (18.50°N, 67.15°W)	5
G20 G21	Boca Chica, Dominican Republic (18.45°N, 69.61°W) Isla Saona, Dominican Republic (18.11°N, 68.57°W)	6
N25	Punta Arenas, Venezuela (10.97°N, 64.4°W)	7
G19	Las Calderas, Dominican Republic (18.20°N, 70.5°W)	8
O10	Portobelo, Panama (9.55°N, 79.65°W)	9
G24	Isla de Vieques, Puerto Rico (18.10°N, 65.45°W)	10
O7	Punta Manzanillo, Costa Rica (9.63°N, 82.64°W)	11

3. CONCLUSION

The goal of a tsunami warning system is to mitigate loss of life and property caused by a tsunami. Different types of systems/networks are currently being successfully employed to measure, record, and telemeter both oceanographic and meteorological data for tsunami warning. This study determined prioritized locations for coastal sea level gauges in the IAS based on tsunami generation risk factors, tsunami propagation throughout the region, population distribution, and tsunami travel time to population centers. These locations will give the maximum warning time to the largest number of people in the most efficient manner.

A database of all sea level gauges installed or thought to be installed was compiled and used to coordinate the recommended locations. The expansion of the IAS regional tsunamigenic event risk analysis was accomplished by combining the spatial frequency of 42 historical tsunamis with a modified tsunami source map from McCann [2006]. This study assumes that the 42 tsunamis were generated by either a dip/slip earthquake or massive slide/slump and were regionally destructive. Each historical tsunami was modeled with the NCOM enabling estimations of where historical tsunamis have had the potential to affect and the travel time to 10,623 coastal locations. Animations of select simulations are available at http://imars.usf.edu/tsunami/. Throughout this work a GIS database was created which will also be useful to those planning the IAS tsunami warning system.

This study established that, initially, 12 sea level gauges are recommended, and 3 of those locations already have or are planned to have a gauge. These locations correspond to the land closest to the center of the relatively higher risk sectors and should serve as a guide for installation. The list provided in Table 1 is not all-encompassing, but represents a start and will primarily warn against tsunamis that originate in the higher risk sectors. To determine exactly where a sea level gauge should be installed a thorough site evaluation is necessary. During the site evaluation, factors that need to be considered include access to open water, proximity to a reef or other shoaling feature, infrastructure and security of site, and ease of station maintenance.

Sea level gauges are a part of a larger system that records, processes, and telemeters data. These stations can provide meteorological and oceanographic data to support other projects such as hurricane and storm surge monitoring and prediction, climate change monitoring, and assist in improving numerical models [*Alverson*, 2005]. These types of systems in other areas around the US are already used by harbor pilots, ship captains, the Coast Guard, recreational and commercial divers and fishermen, the surfing and sailing industry, scientists, and the general public. Therefore, to guarantee continued existence and viability, these stations must have a multi-mission purpose to garner multifaceted support because thankfully, tsunamis do not occur very often.

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