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Invited review

Tsunami deposits of the Caribbean – Towards an improved coastal hazard assessment

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ABSTRACT

Coasts worldwide experience considerable population pressure and the demand for reliable hazard management, such as of tsunamis, increases. Tsunami hazard assessment requires information on long-term patterns of frequency and magnitude, which are best explained by inverse power-law functions. In areas with a short historical documentation, long-term patterns must therefore be based on geological traces. The Caribbean tsunami hazard is exemplified by >80 events triggered by earthquakes, volcanic activity, or mass wasting within the region or in the far-field during the last 520 years. Most of these tsunamis had regional or local impacts. Based on two numerical hydrodynamic models of tsunamis spawning at the Muertos Thrust Belt (MTB) and the South Caribbean Deformed Belt (SCBD), which are two scenarios only marginally considered so far, we show that pan-Caribbean tsunamis can also be taken into account. We furthermore review almost 60 sites for possible geological evidence of tsunamis in the Caribbean including fine-grained subsurface deposits and subaerial coarse clasts, and re-evaluate their implications for tsunami hazard assessment against state-of-the-art models of onshore sediment deposition by tsunamis and extreme storms. The records span the mid- to late Holocene, with very few exceptions of Pleistocene age.

Only a limited number of reliable palaeotsunami records with consistent and robust age control were identified, hampering inter-island or interregional correlation of deposits of the same event. Distinguishing between storm and tsunami transport of solitary boulders is very difficult in most cases, whereas those clasts arranged as ridges or incorporated into polymodal ridge complexes, which line many windward coasts of the Caribbean, can mainly be attributed to long-term formation during strong storms, overprinting potential tsunami signatures. The quantification of tsunami flooding parameters such as flow depth, inundation distance or flow velocities, by applying inverse and forward numerical models of sediment transport is still very limited and needs to be extended in the future. Likewise, sediment-derived hazard implications still await implementation in spatial planning. As extreme-wave deposits are clearly understudied in the Caribbean, there is great potential for coastal hazard assessment to be developed and improved. Thus, further studies using common standards of high-resolution methods of bedform and stratigraphical documentation and robust chronological models with independent age control, combined with refined inverse and forward models of sediment transport and deposition are required to reconstruct reliable patterns of magnitude and frequency of palaeotsunamis in the Caribbean and to map hazard-prone areas. To date, known palaeotsunami deposits from the Caribbean probably represent only a fraction of actually happened prehistoric tsunamis and, therefore, do not reflect major tsunami inundations of the past adequately.

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1. Introduction

Coasts around the globe experience high population growth, resulting in an increasing number of humans exposed to hazards associated with the sea and continental margins (Brückner, 2000; Adger et al., 2005). With >700 islands and 55,383 km of coastline (UNEP, 2004), and most of its population, infrastructure, and tourist facilities concentrated in close proximity to the sea (McGregor and Potter, 1997; von Hillebrandt-Andrade, 2013), the Caribbean region is disproportionally vulnerable to coastal hazards (Fitzpatrick, 2012).

The traditional triad of rapid-onset hazards in the Caribbean, as perceived some decades ago and summarized in Tomblin (1981), comprises earthquakes, volcanism and hurricanes. This was once more exemplified by the devastating earthquake of Haiti in 2010 with a death toll of >230,000 (Bilham, 2010; Fritz et al., 2013), the eruption of Mount Pelée on Martinique in 1902, which destroyed the former principal town of the island and killed around 28,000 inhabitants (Tanguy, 1994), and the Great Hurricane of 1780 with a similar number of fatalities along the Lesser Antilles island arc (Rappaport and Fernandez-Partagas, 1997).

However, history tells that the Caribbean is also highly susceptible to the hazard of tsunamis, which is closely linked to the high seismic activity and volcanism, coastal and submarine landslides, and teletsunamis generated in the open Atlantic Ocean. Even though 127 potential tsunamis were revealed for the Caribbean by O'Loughlin and Lander (2003) based on historical accounts (Fig. 1), the Caribbean is still lacking well-founded information regarding long-term occurrence patterns of high-magnitude tsunamis (Rowe et al., 2009). However, a regional early warning system has been installed for the Caribbean and adjacent regions, relying on >115 seismic stations, 55 sea-level stations, five DART buoys, detailed local evacuation maps, as well as several community engagement programs (von Hillebrandt-Andrade, 2013).

Similar to other types of natural hazards (Korup and Clague, 2009; Corral et al., 2010), frequency-magnitude patterns of tsunamis can be explained best by inverse power-law functions, but without upper truncation (Burroughs and Tebbens, 2005). The tsunami record of the Caribbean (1498–2014) (NGDC/WDS, 2016) is mainly compiled of a rather low number of non-verifiable eyewitness observations on tsunami height, which usually do not distinguish between wave height, flow depth and run-up height. While this record matches the power-law function inadequately, the fit of the larger, global dataset for the same time period is much better (Fig. 2a). By disregarding run-up measurements and unspecific eyewitness records and only considering tide-gauge measurements as well as flow depth and tsunami height derived from post-tsunami measurements from the global dataset, the confidence level rises to >0.95 (Fig. 2b), therefore corroborating the inverse power-law relationship.

The spatial distribution of tsunami hazard in the Caribbean based on historical accounts and instrumental data is irregular, focusing on the Greater Antilles islands of Jamaica, Hispanola, and Puerto Rico, followed by the Lesser Antilles island arc (Zahibo and Pelinovsky, 2001; Parsons and Geist, 2009) (Fig. 3). Nevertheless, a number of uncertainties are associated with these data:

- Information on historical tsunamis or earthquakes is mainly based on colonial reports. These reports have to be considered incomplete, since population density was lower and thus events may have occurred unnoticed. Civil authorities only noted events if they severely affected the economic activities of the colony (O'Loughlin and Lander, 2003).
- The quality and reliability of sources on tsunami occurrence varies greatly, partly due to the fact that the concept of tsunamis and their trigger mechanisms were not well understood in the past (O'Loughlin and Lander, 2003).