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Analytical model of sea level elevation during a storm: Support for coastal flood risk assessment associated with cyclone passage

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ABSTRACT

Sea level oscillations are a result of continuous astronomic, oceanographic, and atmospheric interactions on different time and intensity scales. Thus, the collective action of forcing factors such as tide, wind, atmospheric pressure, and wave action may lead to elevated sea levels during cyclone events over the continental shelf, abruptly impacting adjacent coasts. The objective of this study is to evaluate the potential risks of sea level rise and coastal flooding associated with the passage of cyclones in southern Brazil. An analytical model was developed based on extreme storm events from 1997 to 2008. The model identifies the impact of each forcing factor during temporary sea level rise. Through the development of a digital terrain model, it was possible to identify the areas most vulnerable to flooding by superimposing the terrain model onto calculated sea levels. During storm events, sea level elevations ranged from 2 to 5 m and show wind as the major forcing factor, followed by swells waves, astronomical tide and finally atmospheric pressure.

1. Introduction

Sea level oscillations continuously respond to astronomical, oceanographic and atmospheric interactions, with a wide range of periodicity (Gill, 1982). Thus, all sea level records contain a complex signature spectrum that includes the tides with periods of less than 1 day to the global eustatic secular changes that occur with longer periods (Goring, 1995). In the intermediate range between 3 and 15 days, atmospheric pressure and wind variations affect sea level. This meteorological influence produces low oscillating flows in the sea level, known as storm surges, which can propagate along or towards the coastline (Truccolo et al., 2006). According to Pugh (1987), meteorological tides can be defined as the difference between the observed and astronomical tides, which may be negative or positive (“storm surge”). The storm surge is therefore responsible for the increase or decrease in sea level in relation to the astronomical tide observed at a given location. This phenomenon is positive and generally more important when the records exceed those provided by the astronomical tide, which implies seawater intrusion into places where this usually does not happen, causing major flooding (Marone and Camargo, 1994). However, when negative, the storm surge has considerable effects on port activities.

The storm surge phenomenon consists of two major components: the wind friction on the sea surface allows momentum transfer from the atmosphere to the ocean, and strong winds blowing along an oceanic track towards the mainland leads to the “pile up” of water in the coastal zone (“wind set-up”), while the low barometric pressure associated with the cyclonic rotation increases the level of the ocean (the inverted barometer effect - “barometric set-up”, Pugh, 1987; Benavente et al., 2006).

Additionally, a third factor, the increase in the wave height, also acts to increase the water level in the surf zone (“wave set-up”), allowing the waves to reach further in land than normal waves do, which transfers the surf zone towards the coast (Benavente et al., 2006). Thus, according to Marone and Camargo (1994), positive storm surges may be intensified depending on the amplitude and period of the waves that often accompany these events when they are most significant.

During high-energy conditions (storm cycles), the average level of the sea water increases by a combination of the tide, wind, wave and pressure. Thus, the beach and dunes are strongly attacked by the incident waves, which generally causes erosion. When storm waves reach the beach, they break with great intensity, and as a result, a large volume of water is released on to the beach (Van Rijn, 2009).

It is understood then that besides the rise in sea level due to the presence of a long wave on the platform (tide), there is water on the shore resulting from the wave breaking process (Marone and Camargo, 1994), where the gradient of atmospheric pressure causes the formation of winds, which in turn are responsible for

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generating waves and increasing the sea level. When the air pressure gradient is very intense, there is the possibility that tropical cyclones will form, leading to the generation of tall waves that propagate as swells over long distances to the shore. Water stacking by these waves associated with astronomical spring tides accentuates the erosive power active on the coast to cause super elevation above the tidal prism (Parise, 2007).

The combination of positive meteorological tides with wave set-up can result in extreme values of wave run-up (maximum vertical excursion of swash on the beach face), which can result in the overtopping of dunes as well as structures of coastal protection, especially when these storms coincide with astronomical spring tides. Thus, flooding and erosion can occur in areas where they do not normally occur (Benavente et al., 2006). According to Ferreira et al. (2006), the storms associated with storm surges are the most important factor controlling shoreline movement in the short term.

Thus, the effects of storm surges on the coast may result in many losses for coastal communities, such as by depositing fluid mud on the beach (Calliari and Faria, 2003), the loss of land, the destruction of property and natural habitats, estate depreciation and tourism, the reduction in tax collection and the loss of lives (Teixeira, 2007). However, the distribution of the effects of a storm on a coast depends on many variables, such as subaqueous morphology, refraction and diffraction patterns of waves, sediment budgets, morphodynamic behavior of beaches, dune development and also human interventions and coast line uses (Balsillie, 1986; Lawrence, 1994 *apud* Benavente et al., 2002; Toldo et al., 2010).

The potential consequences of these storm simply the need for tools that recognize vulnerable areas at risk of flooding. This factor has been modeled, and the resulting information forms the basis for mappings of coastal risk (Benavente et al., 2006), as noted in Van Cooten et al. (2011), that coupled hydrodynamic, hydrological and atmospheric models aiming to measure sea level rises during storms and hurricanes in the American coast. Also on the American continent, a great effort has been made in order to study the effect of storm surges on the coast through the Economic Comission for Latin America (CEPAL, 2011), under the project Effects of Climate Change in Latin America and Caribbean coasts. This project uses wave and tidal reanalysis data from the SMC-Brazil model developed by the Hydraulic Institute of Cantabria, Spain. Also on the Brazilian coast, several studies have been developed on this theme, as in Machado and Calliari (2016) that studied the cyclone lifecycle to identify the trajectory of them aiming to predict potential impacts on the southern Brazilian coast. For this same stretch of the coast of Brazil, Guimarães et al., (2014, 2015) combined many different wave models, Wave Watch III, SWAN and SWASH to provided the information on risk conditions during storm events, by simulating the highly dynamic zones during extreme hydrodynamic events over natural and urban structures.

In coastal areas that include an urban settlement, it is prudent to take precautions against sudden and frequent sea level rises that are potentially dangerous (Ferreira et al., 2006). The consequent retreat of coastal erosion from storms is one of the most important phenomena, and it needs to be precisely quantified to facilitate effective management strategies for coastal areas (Callaghan et al., 2009).

In this context, the present study aims to assess the risks related to coastal flooding during the passage of cyclones in Hermenegildo Beach in Brazilian southern coast (Fig. 1). For this an analytical model was developed to calculate the sea level rises using wave, wind, pressure and tide data, and in additional, was also developed a Digital Terrain Model (DTM) with the topography of the area in question. Thus, identifying the contribution of each forcing in elevations and calculating the total lift on sea level quota, with overlapping of the DTM was possible to identify the most vulnerable areas to flooding during storms.

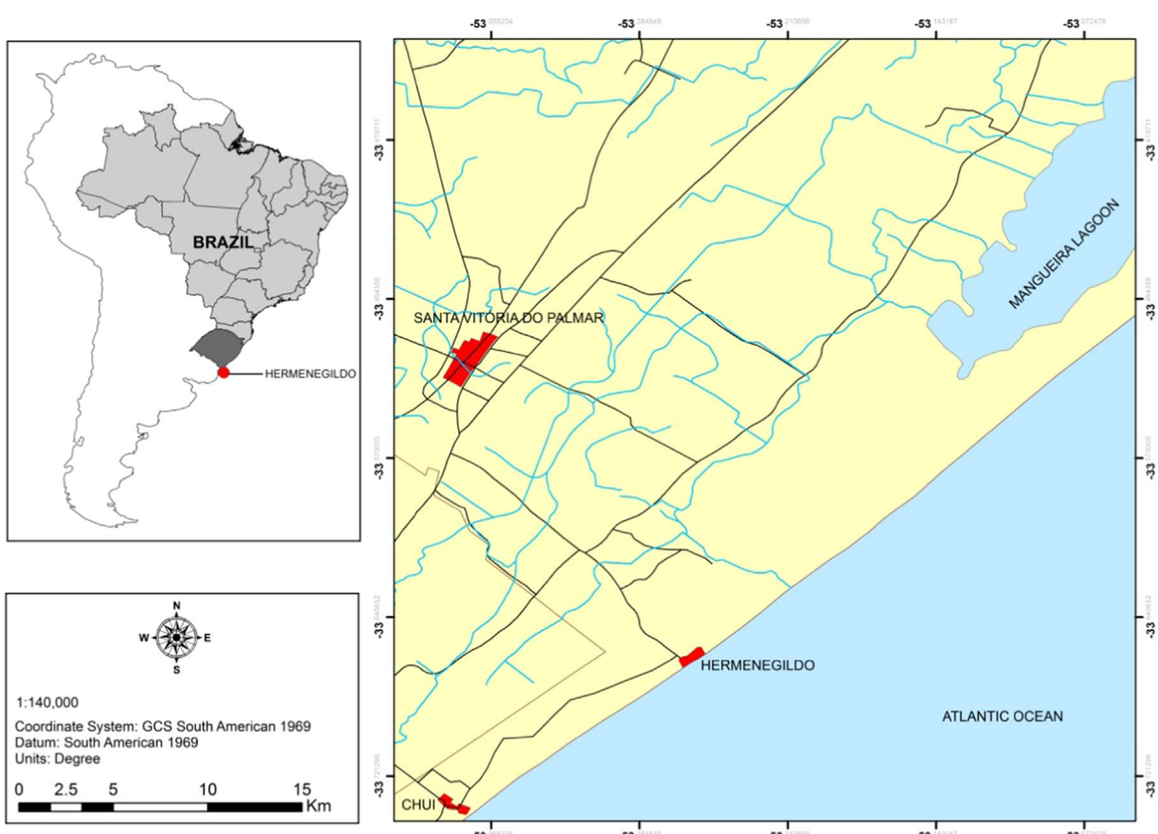

Fig. 1. Hermenegildo Beach, southern coast of Brazil.