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## Coastal erosion in central Chile: A new hazard?

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## ABSTRACT

The coasts of central Chile are increasingly affected by human activity. To date, there are no clear symptoms of shoreline change in the area; however, the incidence of recent extreme storms, in conjunction with an increase in urban area, may have created a new coastal hazard in addition to earthquakes and tsunamis. In this context, coastal erosion on four urban beaches on Valparaíso Bay was analyzed on a decadal scale. Satellite images and topographic surveys were used in order to determine spatio-temporal changes in the shoreline. These changes were linked to the long-term behavior of oceanographic variables such as wave climate and mean sea level. The analysis shows that Reñaca Beach experienced an accretion of 12.6 m between 1964 and 2006, while Los Marineros and Las Salinas proved to be in stable conditions in the same period. Caleta Portales, in contrast, was significantly affected by a shoreline retreat of 12.6 m between 2004 and 2016. In all cases, erosion rates increased due to i) the sea level rise of up to 30 cm observed during ENSO warm phases and ii) an increase in the frequency of extreme storms, which shifted from nearly 5 events per year in the 1960s to more than 20 in recent years. The erosive trend found in the last decade suggests that this coast could deteriorate if such factors are maintained or intensified. A set of preliminary engineering measures, in conjunction with sediment managing schemes, are proposed for the sustainable development of the coastal zone.

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## 1. Introduction

Coastal erosion is responsible for negative impacts on urban coasts, affecting economic activities and sustainable development. Various environmental factors determine the geomorphology of open beaches, among which wind waves, storm surges, crustal changes caused by earthquakes and tsunamis, sea level changes and sediment supply are of major concern. The analysis of these variables is complicated as these phenomena occur at different spatio-temporal scales (Farris and List, 2007; Rodríguez et al., 2012). In recent years, coastal erosion has been exacerbated by

the occurrence of extreme events, the frequency and intensity of which have been associated with climate variability and global environmental change (Zhang and Sheng, 2015). Coastal erosion has been much greater in places affected by abnormal storms responsible for a transitory sea level increase and complex responses on the coast (Masselink et al., 2016). The potential for damage due to short-term mean sea level changes is related to atmospheric perturbations at different spatial scales, the nearshore bathymetry and the geomorphological characteristics of the coast (Morton, 2002; Masselink and Hughes, 2003; Stockdon et al., 2007; Del Río et al., 2012; Jiménez et al., 2012). The magnitude of these phenomena can cause violent changes on the coast, affecting lives and coastal infrastructure.

The impact of storms on erosion processes may be increased due to the generalized urbanization in the coastal zone (Barragán and De Andrés, 2015; Gibbs, 2015). The consequences of anthropization on numerous coasts have been described for several decades and its adverse effects have been associated with unsuitable use of

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the coastal zone (Bird, 1996; Schnack et al., 1998). On the Catalan coast, for example, damage to infrastructure has increased by 40% in the last 50 years due to both coastal erosion and explosive urban growth (Jiménez et al., 2012). The impact of climate change on extreme events has raised concerns over coastal vulnerability, adaptation and resilience (Chust et al., 2010; Mulder et al., 2011; Bagdanavičius et al., 2015; Luo et al., 2015). The magnitude of coastal erosion on urbanized coasts is also associated with a greater intensity and recurrence of extreme events, the cause of which could be associated with inter-decadal phenomena (ENSO phases), climate variability and global environmental change (e.g., Jiménez et al., 2012; Masselink et al., 2016).

Emerging efforts have been made to establish the current state and future projections of coastal erosion in Latin America (Silva et al., 2014, 2017); however, there is no detailed analysis of erosion processes in central Chile, where unique conditions associated with tectonic processes, climate change and human pressure combine. Studies addressing the past and future behavior of oceanographic variables that affect erosion are scarce or provide little information at high resolution on the Pacific coasts of South America. Masselink et al. (2016), for example, argue that an intensification of ENSO warm phases would increase the frequency and intensity of storms during the 21st century, thus increasing erosion and extreme flooding of populated coastal areas along the Pacific Ocean. Tectonic activity also plays a significant role in erosion processes since the coast presents different behavior due to seismic cycles (Isla et al., 2012; Martínez et al., 2015).

To date, coastal erosion has not been identified as a recurring hazard in Chile, perhaps because it is overshadowed by other natural phenomena such as earthquakes, tsunamis and El Niño–Southern Oscillation (Castillo, 2003; Bello et al., 2004). Research in this field is not systematic and knowledge is therefore scarce and fragmented. Martínez et al. (2011), for example, showed that some headland-bay beaches in central Chile present moderate erosion rates, while other researchers have showed that beaches are very sensitive to tectonic uplift and/or subsidence associated with earthquakes (Cienfuegos et al., 2014; Villagrán et al., 2011; Martínez et al., 2015). Unfortunately, there are no accounts of erosion/accretion processes on urban beaches in Chilean metropolitan areas. The purpose of this investigation is therefore to determine, at a decadal time-scale, the magnitude of coastal erosion on urban beaches on Valparaíso Bay, which have been affected by intense storms in recent years. The beaches under scrutiny are Reñaca, Las Salinas, Los Marineros and Caleta Portales (Fig. 1). On this basis, mitigation and control measures are proposed for the future development of the area.

## 2. Materials and methods

### 2.1. Study area

The coast of central Chile (33°–35°S) is located on an active continental margin in which tectonic processes and changes associated with the sea level have influenced coastal geomorphology. The region is characterized by bays open to the north in which cliffs, small pocket beaches and headland-bay beaches are interspersed (Fig. 1). The area is formed by a Paleozoic granodiorite complex that extends from the mouth of the Aconcagua River (32°55'S) to Curaumilla Point in the south (33°05'S) (Muñoz-Cristi, 1971). The sediments of most of the beaches are therefore formed by granitic quartz-feldspar sands (Vergara and Hickmann, 1982).

The wave regime in central Chile is influenced by the South Pacific anticyclone, which generates prevailing S-SW winds during the year. In winter, the northward shift of the Pacific anticyclone

enhances the growth of low pressure systems, triggering strong winter storms. The area is also affected by the almost continuous impact of distantly generated swells from the SW-WSW, which constitute a permanent source of energy for coastal dynamics (Beya et al., 2016). The tide regime is mixed semidiurnal (SHOA, 1994).

The main coastal metropolitan area of the country, Greater Valparaíso, is inhabited by roughly 1 million people. This conurbation is made up of six coastal cities, the built surface area of which tripled between 1975 and 2004, causing a series of environmental impacts such as loss of natural heritage, ecosystem services and natural landscape quality and plant cover reduction. This area is one of the most attractive sites for beach tourism in the country, receiving between 100,000 and 200,000 visitors a month during summer (INE, 2017).

Reñaca (Fig. 2A) is a 1.3-km-long straight beach, showing a northward net sediment transport, the influx of which is provided by Reñaca Stream, at its southern end. The 35.4-km<sup>2</sup> basin that contributes to the flow of this stream has been subjected to a considerable increase in population density during the period of analysis (Ojeda, 2013). Los Marineros (Fig. 2B) and Las Salinas (Fig. 3B) are part of a single sedimentological unit fed by Marga-Marga Stream (Pozo, 2008), a pluvial stream connected to a 425-km<sup>2</sup> coastal basin. Los Marineros is a 3.3-km-long beach, while Las Salinas is a 200-m-long pocket beach, which is sedimentologically connected to the former via a strong northward littoral drift (Vergara and Hickmann, 1982). Caleta Portales (Fig. 3A) is a relatively open beach, the sediment of which comes from Cabritería Stream. The small basin has been severely modified by urban expansion in recent decades.

### 2.2. Methods

In this paper, we intend to establish the role of storm wave intensity and frequency, sea level changes and ENSO effects in the erosion/accretion patterns of four beaches on Valparaíso Bay. Land changes due to earthquake activity and tsunami are excluded from the study since no significant event impacted the area in the period under scrutiny. The analysis of each of these variables is presented as follows.

#### 2.2.1. Wave climate

To study the evolution undergone by the wave climate in recent decades, three long time series were used:

- A deep water wave hindcast off Valparaíso extracted from the Chilean Wave Atlas, which comprises sea states every 3 h over 35 years, between 1980 and 2015 (Beya et al., 2016).
- A series of reconstructed deep water waves from the INAE + SENESCYT “Physical relationships resulting from climate change between Antarctica and Ecuador” project (referred to as the ULEAM series hereafter). The dataset comprises sea states every 6 h over 56 years, between 1957 and 2013.
- A record of sea states from a Watchkeeper buoy in intermediate waters (32.99°S; 71.82°W), managed by the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA). The record comprises data every 3 h over 6 years, between 2011 and 2016, and was used only to corroborate the coherence of the reconstructed sea states.

The Chilean Wave Atlas and ULEAM series were compared for the overlapping period covering between 1980 and 2013. The correlations showed a coefficient of determination of  $R^2 = 0.786$  for the significant wave height and of  $R^2 = 0.790$  for mean direction. By means of regression lines for these variables, the ULEAM series was

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