Coastal erosion in central Chile: A new hazard?

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A B S T R A C T
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 Rincón 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, experienced an accretion 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...
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; Bagdanaviciut 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 (Isda 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 Curauamilia Point in the south (33°05’S) (Munoz-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 semi-diurnal (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-km² 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-km² 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 Cabreríta 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
extended to 2015 and compared to the buoy record.

2.2.2. Storm frequency

To characterize storm frequency, statistical data were gathered from previous studies and hindcasts. The main source of qualitative information was found in Campos-Caba et al. (2015) and Campos-Caba (2016), in which events between 1924 and 2015 were characterized from historical records, newspapers and instrumental data. Recent storm statistics were provided by INGEMAT through the SIPROL® wave modeling tool. Wave parameters at a virtual buoy located in deep waters off Valparaíso Bay between January 1st and December 31st, 2016 were considered. The position of this buoy is shown in Fig. 1. In addition, field data collected after the storm of August 8th, 2015 (Winckler et al., 2017), which included observations of damage on the affected coast, were used.

The Peak Over Threshold method was used to estimate the quantity of extreme wave events per year (Goda, 1988). The threshold was set at a value in which the significant wave height surpassed twice the standard deviation of the arithmetic mean (i.e., waves over 3.71 m). The least squares method was used to calculate the trend and the uncertainty of the slope was calculated at 95% confidence. The slope of the linear trend was calculated using the equation:

\[ m = \frac{\sum_{i=1}^{N} (t_i - \bar{t})(y_i - \bar{y})}{\sum_{i=1}^{N} (t_i - \bar{t})^2} \]

where \( t_i \) is the year in which \( y_i \) storms were recorded and the overbar denotes the mean value. The uncertainty \( U \) of the slope was calculated as the product of the standard error \( SE \) and the critical value \( CV \) obtained from the t-Student distribution with \( N-2 \) degrees of freedom, where \( N \) is the number of years with observations:

\[ U = SE \times CV \]

The standard error was calculated using the equation:

\[ SE = \sqrt{\frac{\sum_{i=1}^{N} (y_i - \bar{y}_{\hat{y}})^2}{(N-2) \sum_{i=1}^{N} (t_i - \bar{t})^2}} \]

2.2.3. Sea level and ENSO events

Hourly tide gauge series obtained by SHOA at the port of
Valparaíso (33°01'38"S, 71°37'33"W) were used. This record covers a 75-year period between 1944 and 2016, with significant gaps between 1971 and 1982. Monthly averages representing the mean sea level (MSL) were calculated, the anomaly of which was compared with the Oceanic Niño Index series (ONI), available at www.cpc.noaa.gov. The linear trend and uncertainty were estimated in the same way as the number of extreme wave events.

2.2.4. Coastal evolution

Coastal evolution on three urban beaches on Valparaíso Bay (Reñaca, Las Salinas and Los Marineros) were estimated for a 52-year period covering 1964 to 2016. Due to the lack of long-term
shoreline data, Caleta Portales Beach was analyzed for a period of only 12 years. Aerial photographs used to create a geospatial database in ArcGIS 10.4 were georeferenced and processed in accordance with the criteria proposed by Martínez et al. (2013b), ensuring root mean square errors (RMSE) lower than 1 m. The sources of data are included in Table 1. The shoreline was digitized following the high tide line, as visually detected from the photographs. The historical series were complemented with a topographic survey of the shoreline carried out in May 2017 using dual-frequency GPS and geodetic referencing. To determine changes in the relative shoreline position, the DSAS 4.3 (USGS) extension for ArcGIS was used (Himmelstoss, 2009; Thieler et al., 2009). The mean change rate in m/yr was determined using an End Point Rate algorithm (EPR). Erosion/accretion processes for each beach were classified according to the criteria of Rangel-Buitrago et al. (2015), in which four levels are considered: high erosion (≥−1.5 m/yr), erosion (−0.2 to −1.5 m/yr), stability (−0.2 to +0.2 m/yr) and accretion (≥+0.2 m/yr). In order to determine if coastal erosion has accelerated in the last decade compared to previous periods, two time periods were compared for each beach as a function of the EPR result, following the criteria of Rangel-Buitrago et al. (2015).

### 3. Results

#### 3.1. Wave climate

The time evolution of the monthly mean deep water wave

Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Scale</th>
<th>PR</th>
<th>RMSE</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td>1:30.000</td>
<td>0.635</td>
<td>0.371</td>
<td>SAF aerial photography</td>
</tr>
<tr>
<td>1970 (Jul)</td>
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<td>0.482</td>
<td>FONDEF aerial photography</td>
</tr>
<tr>
<td>1986 (Jul)</td>
<td>1:4.000</td>
<td>0.085</td>
<td>0.891</td>
<td>SAF aerial photography</td>
</tr>
<tr>
<td>2003 (Jul)</td>
<td>1:15.000</td>
<td>0.318</td>
<td>0.713</td>
<td>Google Earth Pro</td>
</tr>
<tr>
<td>2004 (Dec)</td>
<td>1:15.000</td>
<td>0.318</td>
<td>0.412</td>
<td>Google Earth Pro</td>
</tr>
<tr>
<td>2009 (Apr)</td>
<td>1:15.000</td>
<td>0.318</td>
<td>0.327</td>
<td>Google Earth Pro</td>
</tr>
<tr>
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<td>0.318</td>
<td>0.195</td>
<td>Google Earth Pro</td>
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<tr>
<td>2016 (Jan)</td>
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<td>0.318</td>
<td>0.222</td>
<td>Google Earth Pro</td>
</tr>
<tr>
<td>2016 (Sep)</td>
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<td>0.318</td>
<td>0.256</td>
<td>Google Earth Pro</td>
</tr>
<tr>
<td>2016 (Nov)</td>
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<td>0.318</td>
<td>0.443</td>
<td>Google Earth Pro</td>
</tr>
<tr>
<td>2017 (May)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Topographic survey</td>
</tr>
</tbody>
</table>

Fig. 3. Shoreline planform changes, Portales (a) and Las Salinas (b) beaches. These pocket beaches show the highest erosion rates, which is observed in their planforms. Figures B and C were made considering the criteria of Rangel-Buitrago et al. (2015).
direction off Valparaíso Bay is shown in Fig. 4A. A change in direction from WSW to SW is observed in recent decades, which could be attributed to the southward shift of the Pacific Anticyclone (Schneider et al., 2017) and the decrease in extreme events generated in the Northern Hemisphere (Webster et al., 2005) that propagate toward the coast of central Chile. This change in direction could have consequences for the erosion/accretion equilibriums and dynamics of sand beaches, especially relatively long and open beaches such as Los Marineros, where a counterclockwise rotation on the shoreline is evidenced (Fig. 2B). The existence of mean direction anomalies above the estimated trend in the years 1977, 1982/83, 1987, 1997/98, 2007 and 2015, all of which correspond to ENSO warm phases (El Niño events), is noteworthy.

Fig. 4B depicts the time evolution of the minimum, maximum and monthly mean significant wave height between 1957 and 2016 off Valparaíso. While no change in behavior is observed in the monthly mean ($-4 \times 10^{-8} \text{ m/yr}$), an astounding increase in the range is noted as time elapses. Indeed, a positive maximum height trend ($+1.4 \times 10^{-3} \text{ m/yr}$) is a manifestation of a greater extreme event frequency. At the same time, the negative minimum value trend ($-8 \times 10^{-4} \text{ m/yr}$) indicates an increase in the number of calms in the analyzed period.

### 3.2. Frequency and effects of storm or extreme wave events

Fig. 4C shows the number of extreme events per year between 1957 and 2015, estimated by selecting storms in which the significant wave height surpassed the average by two standard deviations above the mean. The positive trend shows that extreme events have increased from an average of 3 per year in the middle of last century to roughly 20 per year in the 21st century. As shown by Campos-Caba (2016), the storms that have caused the greatest damage in the area (1965, 1968, 1986 and 1987) were locally generated and occurred mainly during the austral winter (June to September). Since 2014, the frequency of these events has not exhibited seasonal distinction, with events occurring even in summer (December to March). These events are caused by both frontal systems travelling northeastward at high latitudes off Chile or long swells generated in the North Pacific.

A closer look at the statistics in the region for 2015 and 2016 (Fig. 5) is achieved by means of a wave hindcast provided by SIPROL®. According to these data, in 2015, there were 45 extreme events, of which 37 originated in the southwest, 6 in the west, 1 in the northwest and 1 in the north. The difference in the number of storms between the SIPROL® statistics and Fig. 8 is due to the different methods used to determine the occurrence of a storm: in Fig. 8, only extreme events, in which significant height $H_{\text{m0}}$ surpassed the average by $2 \sigma$, are reported. The greatest number of identified events occurred during the autumn (13), winter (13) and summer (12). Of these events, 53% presented peak periods greater than 15 s, of which only 25% surpassed 4.5 m in height. Similarly, in 2016, there were 38 extreme events, 31 of which were formed in the southwest, 4 in the west, 2 in the northwest and 1 in the north. The greatest number of identified events occurred during the summer (12) and winter (11). Approximately 50% presented peak periods greater than 15 s, of which only four surpassed 4.5 m. The combination of relatively high peak periods and significant wave heights implies highly energetic sea states, which were responsible for significant beach erosion in 2015. These results emphasize that in recent years, and with only a few exceptions, extreme wave events formed south of Valparaíso Bay have occurred throughout the year, with a slight seasonal preference toward winter.

To illustrate the effects of extreme sea states on Valparaíso Bay, we further analyzed a series of storms that occurred in August 2015, including the extraordinary event of August 8th, which caused severe damage to coastal infrastructure on the bay. The sea state at the peak of the storm was characterized by a significant wave height of $H_{\text{m0}} = 7.23 \text{ m}$, a peak period of $T_p = 13.3 \text{ s}$ and a peak wave direction of $310°$, which, in conjunction with northwestern winds of up to 110 km/h and the lowest atmospheric pressure ever recorded in the area, resulted in unusually high water levels. This combination of meteocceanographic factors caused damage to coastal highways, railways and coastal defenses, the economic losses from which were estimated at US$ 8 million. This event removed more than 100,000 m$^3$ of sand from three of the affected beaches on Valparaíso Bay (Winckler et al., 2017).

Agredano et al. (2015) reported that Reñaca Beach was struck by three consecutive events on August 2nd, 6th and 8th, with
maximum significant wave heights of $H_{m0} = 4.8, 4.1$ and 6.4 m, respectively. The beach face retreated 30 m, causing a net sediment loss of 13,902 m$^3$ in the northern portion of the beach. A beach scarp of 1.5 m was formed in this part of the beach (Fig. 6) and the preexisting cusps were removed. Despite the loss of volume caused by these extreme storms, the beach apparently recovered fast (Agredano et al., 2015).

As a consequence of the August 8th storm, large volumes of sand buried the first floor of tourism infrastructure on Las Salinas Beach (Fig. 7a). The main damage on the bay occurred at the southern end of Los Marineros Beach (Fig. 7b) and on El Sol Beach (Fig. 7c), where the promenade was undermined and previously buried structures were exposed by the waves. On Peru Avenue, a few hundred meters south of Los Marineros Beach, flooding from overtopping extended nearly two blocks from the shoreline, causing damage to buildings (Fig. 7d).

Based on a 3-year beach monitoring plan, Molina et al. (2015) found that Caleta Portales Beach retreated 20 m, while the total sediment loss in the emerged portion of the beach was nearly 38,500 m$^3$ (Fig. 8). The railway connecting Viña del Mar and Valparaíso, located at the back of the beach, suffered damage due to overtopping. Service was suspended for 10 days, affecting local transit. A fishing port located in the upper strand of Caleta Portales Beach was severely affected.

### 3.3. Sea level and ENSO events

Mean sea level data from between 1944 and 2016 in Valparaíso were marked by significant gaps between 1971 and 1982; therefore, in reality, there are two sections with different slopes. The period covering between 1944 and 1971 showed an estimated change rate of 8 mm/yr ± 4 mm, while between 1982 and 2016, the rate was 5 mm/yr ± 1 mm. Significant variations of up to ±400 mm and ±300 mm above and below the trend associated with ENSO events, which could be explained by the passage of Kelvin waves, were also observed. Fig. 9 presents the monthly mean sea level evolution for the port of Valparaíso between 1944 and 2016, compared with the Oceanic Niño Index (ONI). The El Niño phenomena of 1982–83 and 1997–1998, which caused an increase of 15–20 cm in the mean sea level, stand out.

### 3.4. Coastal evolution

Based on the relative position of the shoreline, conditions of accretion, stability and erosion were determined for the four beaches. Renaca presented the highest accretion rates, with an average shoreline change of +0.24 m/yr in a 52-year period between 1964 and 2016 (Table 2). The average shoreline change ranged from −0.02–0.67 m/yr, evidencing conditions of stability and accretion. A total mean spatial accretion of 12.6 m was recorded throughout the period. As shown in Fig. 2A, stable areas were observed along the central and northern portions of beach, while the relatively large accretion rates found on its southern extreme are probably associated with the construction of the coastal road at the outlet of Renaca Stream circa 1984. Between 1964 and 2004, the beach showed evenly distributed accretion rates of nearly +1 m/yr, while between 2004 and 2016 it presented a high erosion rate of nearly −2 m/yr. From this analysis, we conclude that Renaca Beach is generally stable, with the exception of its southern end, in which accretion was triggered by the construction of a coastal road.

Los Marineros beach showed an average shoreline change of −0.03 m/yr and a range between −0.19 and 0.31 m/yr in the same
period, displaying stable and accreting conditions (Table 2). A total mean spatial retreat of $-1.6$ m was recorded throughout the period. As shown in Fig. 2B, the beach presented a significant rotation, with accretion at its northern end and erosion toward the south. Between 1964 and 2004, the beach exhibited evenly distributed accretion rates of nearly $+0.5$ m/yr, while between the 2004 event and 2016, it showed a high erosion rate of approximately $-1.5$ m/yr.

In the same period, Las Salinas showed an average shoreline change of $-0.06$ m/yr and a range between $-0.26$–$0.41$ m/yr, with conditions of erosion, stability and accretion (Table 2). A mean retreat of $-3.3$ m was recorded throughout the period. The beach presented an erosion pattern toward the southern end and stable conditions on its northern end (Fig. 3B). Between 1964 and 2004, the beach showed unevenly distributed small accretion rates below $+0.5$ m/yr, while between 2003 and 2016, it exhibited an erosion rate of up to $+1.0$ m/yr in its northern portion.

Fig. 6. Changes in the northern part of Renaca Beach. The images were taken on (A) August 4th, 2015, (B) August 7th and (C) August 10th; the dates among which storm events occurred. The evolution of the vertical cut and the shoreline retreat are can be observed.
Caleta Portales was the beach most affected by erosion processes, registering an erosion rate of \(-1.05\) m/yr and a range between \(-0.76\) and \(-1.33\) m/yr in the period between 2004 and 2016. A total mean spatial retreat of \(-12.6\) m was recorded throughout the period. As shown in Fig. 3A, a highly erosional pattern was observed on the entire beach, with especially high erosion toward its northern extreme. Between 2009 and 2013, the beach showed spatially variable accretion rates of up to \(+7\) m/yr, while between 2013 and 2016, it exhibited high erosion of up to \(-4\) m/yr. These results may not be conclusive due to the short range of analysis, in which decadal cycles are not captured.

4. Discussion

4.1. Storm frequency and seasonality

The analysis shows an increase in the frequency of extreme events in the last 57 years. Between 2015 and 2016 alone, there
were 83 events with significant wave heights above 3.0 m. The most destructive events of August 2015 and July 2016 were characterized by locally generated storms with wave heights above 6.0 m occurring in conjunction with frontal systems during the (austral) winter. Though most of these storms originated in the SW, other destructive events generated in the North Pacific during (austral) summer had relatively low heights but longer wave periods.

Through an analysis of global models, Sierra and Casas-Prat (2014) pointed out that alterations in statistical wave parameters due to climate change may modify the equilibrium of beach profiles. Additionally, Thomas et al. (2016) found that storm wave direction is as a relevant factor in subaerial rotation on open coast beaches. On a historical level, changes in offshore wave conditions have been identified by various authors in Central Chile. Molina et al. (2011), for example, computed an increase of 10 cm in significant wave height and a deviation of 12° southward in offshore wave direction based on 20 years of hindcast data for central Chile; their results proved to be sensitive to ENSO events. As for future predictions, CEPAL (2011) found an increasing trend in monthly mean significant wave heights by 2070, ranging from 30 mm in the north to 60 mm in the far south of the country. In the same line, Church et al. (2013, AR5) estimated an increase on the order of 5% in significant wave height for the majority of Chilean territory, with the exception of the extreme south. The change in offshore direction and slow increase in wave height for extreme events identified within the analyzed period (Fig. 4) is consistent with such studies and could partially explain the counterclockwise rotation of the shoreline undergone by the relatively long Los Marineros Beach. The shift in directions was found to have negligible consequences on the other beaches, probably due to the topobathymetric constraints of these pocket-type beaches. These results, however, require further research to be conclusive.

Recent changes in seasonal storm frequency are another matter of concern that has not been deeply explored in the region. Vergara and Hickmann (1982), for example, found that Las Salinas presented an unstable equilibrium, shifting annually between winter conditions characterized by high storm frequency and calm periods in summer. Even though the most violent storms usually take place in winter (e.g., 1924, 1929, 1968, 1987 and 2013), recent years affected by ENSO warm phases (e.g., 2015—2016) were characterized by extreme events occurring throughout the year. In addition to their relatively large wave height, the newly observed events in summer are characterized by long periods, which tend to generate
severe overtopping and cross-shore sediment transport on beaches. However, the contribution of these distantly formed events to sediment dynamics in Valparaíso Bay remains unknown. For warning and forecast purposes, it proves highly necessary to delve into the generation mechanisms, development and incidence of these storms upon reaching the coast.

4.2. Sea level and ENSO events

The increase in global MSL triggered in both geological scales and recent years has been thoroughly studied in the Northern Hemisphere (e.g., Anderson et al., 2014). In the Southern Pacific, however, studies are scarce. INVEMAR, for example, found out that the Pacific coasts of Colombia are very sensitive to MSL changes.

In Chile, the MSL is conditioned by the seismic activity in the subduction zone between the Nazca plate and the South American plate. Vertical coseismic subsidence may cause sudden decreases on the order of meters in MSL, which are equivalent to centuries of rising associated with climate change. Various studies (Martínez et al., 2015; Contreras-López et al., 2012) have found no evidence of a significant increase in MSL in recent decades. These results could be overshadowed by the uplift of the earth's crust as a consequence of tectonic activity (Wyss, 1976; Albrecht and Shaffer, 2016). Within the seismic cycle, coseismic and interseismic movements (occurring during and between earthquakes, respectively) translate into coastal uplift and/or subsidence, which may contaminate sea level records: A decrease in MSL can indicate that the reference level of the tide gauge, fixed on land, is rising during the interseismic period more rapidly than the increase due to climate change.

Land changes due to earthquake activity and tsunami have been excluded from the analysis since no significant events affected Valparaíso in the period of concern. Indeed, since 1959, Valparaíso has suffered only a Mw 8.0 earthquake in 1985, which generated a negligible uplift (Quezada et al., 2012) and a tsunami of 1.15 m smaller than the tidal range. The recent tsunamis of 2010, 2014 and

Table 2

Relative, average and total shoreline rate on urban beaches of Valparaíso and Viña del Mar. The time period considered in the erosion rate calculation is indicated in parentheses.

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<thead>
<tr>
<th>Beach</th>
<th>Relative shoreline change (m/yr)</th>
<th>Average change (m/yr)</th>
<th>Total change (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refiaca (1964-2016)</td>
<td>0.06</td>
<td>0.67</td>
<td>0.23</td>
</tr>
<tr>
<td>Los Marineros (1964-2016)</td>
<td>0.31</td>
<td>0.05</td>
<td>-0.19</td>
</tr>
<tr>
<td>Las Salinas (1964-2017)</td>
<td>0.41</td>
<td>-0.09</td>
<td>-0.10</td>
</tr>
<tr>
<td>Caleta Portales (1964-2016)</td>
<td>-0.76</td>
<td>-0.91</td>
<td>-1.19</td>
</tr>
</tbody>
</table>

Fig. 9. Mean sea level, port of Valparaíso (1944–2016) and ONI. The El Niño phenomena of 1982–83 and 1997–1998, which caused an increase of 15–20 cm in the mean sea level, stand out.
2015, on the other hand, generated no significant erosion on Valparaíso Bay. Nevertheless, the occurrence of future earthquakes and tsunamis in the area is imminent as the area has been struck by locally generated earthquakes of magnitudes above 8 in 1575, 1647, 1730, 1822, 1906 and 1985 (Lomnitz, 2004) and by a major tsunami in 1730 (Carvajal et al., 2017). Coastal uplift or subsidence could be on the order of meters. For instance, earthquakes of similar magnitude triggered in southern Chile caused coastal uplift of nearly 3 m in the Gulf of Arauco in 2010 (Farias et al., 2010) and land changes between –2 and 3 m in Valdivia in 1960 (Barrientos and Ward, 1990). Although earthquakes and tsunamis have been shown to affect morphodynamic processes (Cienfuegos et al., 2014; Villagrán et al., 2011; Martínez et al., 2015), their impact on MSL remains as a novel topic for the scientific community.

In addition to climate change, seismic and tsunami effects, MSL is affected by large-scale irregular cyclical oscillations such as ENSO. Based on statistical analysis of hourly series, various authors have observed that monthly MSL averages may increase by up to 30 cm during the El Niño phase and decrease by the same order during the La Niña phase (Fonseca, 1985; Martínez et al., 2011; Contreras-López et al., 2012). The results presented herein are consistent with these findings. The increase in MSL during an El Niño year is therefore comparable to the expected increase associated with climate change by the end of the 21st century (Church et al., 2013).

4.3. Improvement of monitoring schemes and modeling tools

Shoreline modeling combined with long-term monitoring schemes has proven to be an excellent tool for determining erosion rates at various time scales, thereby providing valuable information for land-use planning in the coastal zone. The prediction of shoreline changes can be achieved by the combined use of shoreline analysis systems (Thieler et al., 2009; Klein et al., 2010), physically based numerical models for storm-induced beach change (e.g., Seymour et al., 2005), optical remote sensing (Holman and Stanley, 2007), aerial or satellite imagery (Blain et al., 2013), methods relating wave heights and storm duration to eroded volumes of sand (Carley and Cox, 2003) and/or statistical schemes, with which success is possible in areas with data series over 10 years in length (Callaghan et al., 2009).

However, the lack of long-term beach profile time series in Valparaíso, or elsewhere in Chile, implies a significant limitation to the use of these tools. Monitoring schemes of both nearshore processes and beach morphodynamics are nonexistent in the country since coastal municipalities, which are responsible for land uses in the coastal zone, have little understanding of or concern for how these environments function. Fortunately, a few efforts to evaluate morphological changes caused by extreme events have recently been initiated (e.g., Agredano et al., 2015; Molina et al., 2015) and a growing number of specialists are working on coast-related matters. The local scientific community should raise awareness among decision makers of how coastal dynamics shape the physical space upon which economic activities take place, and propose long-term monitoring schemes for the most in-demand beaches.

Another limitation to the study of coastal phenomena is the lack of long-term oceanographic records in Chile. There is an immense disparity between the availability of data on land and in the ocean. For example, in the fields of climatology and hydrology, the Chilean network has 1145 pluviometers, 295 temperature stations and 788 river stream gauges (DGF, 2017) while the seismic network is composed of 467 instruments of different types (Sergio Barrientos, personal communication, 2016). In the ocean, however, there are only 40 tide gauges and there is no permanent offshore wave buoy network in Chile such as those that have long existed in the United States (e.g., Hamilton, 1980), Spain (Clemente, 2001) or Italy (Arena et al., 2001). Only a few short-term wave records with uneven spatio-temporal coverage are publicly available. To cope with this impediment, an open-access wave database entitled the Chilean Wave Atlas was recently introduced (Beya et al., 2016). This fully calibrated database represents a milestone in coastal research in Chile, as it will provide comprehensive deep water wave data and in the vicinity of the main ports, which may be used, among other purposes, for the study of coastal morphodynamics. Systematic data acquisition of oceanographic variables, in conjunction with this type of hindcast model, could provide evidence to i) assess the relative importance of ENSO events in storm frequency and intensity, ii) improve climate change forecasts and iii) assess the natural variability of such factors on seasonal, interannual and decadal scales.

4.4. Control and mitigation schemes

The coastal zone is undoubtedly the main economic resource in Valparaíso Bay due to its seaport and the tourism activities that revolve around the sea. In addition, this metropolitan area has become an engine of urban expansion, in which real estate developers use the coastal space in an unrestrained manner, causing significant problems in terms of degradation of beaches, wetlands and dune fields (Arenas et al., 2015; Hidalgo et al., 2016). According to McLachlan et al. (2013), from a mitigation perspective, shoreline retreat can be tackled by different levels of action: namely, doing nothing, managing retreat, beach nourishment or using hard solutions (e.g., seawalls, dikes, groins or detached breakwaters). In the context of this study, the “doing nothing” level is not an option since the beaches analyzed herein are located in urban centers that are constantly threatened by storms and have experienced damage or sand loss in the past.

The use of coastal defenses has been the general response to coastline erosion (Nordstrom, 2000; Charlier et al., 2005). To use them effectively, it is necessary to predict collateral impacts due to the modification of sedimentary dynamics (Kraus and McDougall, 1996; Griggs, 2005), which may increase both the risk to people and erosion downstream of the structure (Dugan et al., 2008, 2011). As Chilean coasts are expected to undergo seismic uplift/subsidence and tsunamis, the use of hard solutions to stabilize the shoreline should ideally be capable of addressing all of these hazards together. This approach is challenging since hard structures may become obsolete when prone to subsidence, even when they were properly designed for storm conditions. Additionally, recent tsunamis in the country have caused massive beach erosion (e.g., Fritz et al., 2011; Villagrán et al., 2011; Contreras-López et al., 2016), which we speculate would have happened even in the presence of hard solutions. The emerging experience gained through the construction of artificial beaches in the country (there are about 10 state-developed artificial beaches in Iquique, Tocopilla, Antofagasta and the lake zone), in conjunction with the relatively deep understanding of coastal geohazards, should be used in the development of future projects on Valparaíso Bay.

Beach nourishment, on the other hand, has traditionally been used in tourist destinations with high erosion rates to regenerate spaces for recreation. Cases on the Mediterranean coasts of Spain, in the State of Florida and in The Netherlands, for example, are abundant in the literature. Unfortunately, there is no experience with such solutions in Chile and their eventual use would require the adaptation of well-established methods and the training of skilled professionals, who are currently scarce.

Finally, retreat management is an interesting option, which could be combined with one of the aforementioned solutions. Understanding the causes of shoreline retreat and its connection
with land use within the basin may allow effective management of the coastal zone, but it alone does not prevent/reverse erosion processes. In order to provide a solution tailored to each case, retreat management would require a deep understanding of coastal processes, the expected morphological response and land-use patterns, which are yet to be defined for each beach. The evidence on Valparaíso Bay, however, shows that these connections have not been understood or taken into account in the past. For example, the erstwhile popular Miramar and Recreo beaches were completely lost due to the construction of coastal roads during the 20th century (Contreras-López et al., 2012).

Any of these levels of action, nevertheless, should be matched with sediment management schemes, which could be propelled by the municipalities of Valparaíso (Caleta Portales) and Viña del Mar (Los Marineros, Las Salinas and Renaca) in conjunction with the Ministry of Public Works, which oversees the agencies responsible for basin management (DGa, DOH) and coastal works (DOP). The urban beaches under analysis are fed by sediment contributions from Marga-Marga and Renaca streams, which have been undergone drastic intervention to consolidate urban processes (e.g., building of coastal highways, transport networks, urban developments and riverine defenses) in recent decades. Complementary sediment management schemes, consequently, should account for the urbanization process.

Examples of short- to medium-term measures would be i) the definition of sediment extraction quotas for building purposes on Marga-Marga and Renaca streams, ii) the definition of low density areas in the existing zoning plans of Valparaíso and Viña del Mar so as to promote rainfall absorption and sediment supply, iii) the proscription of new developments on coastal dunes such as those that have taken place during recent decades on the northern portion of the bay, iv) the relocation of buildings in coastal areas threatened by storms and erosion, following United Nations guidelines (e.g., UNEP/Map/Pap, 2008) and v) ecological restoration using native species such as Doca (Carpobrotus aequilaterus) or Dicha Grande (Ambrosia chamissonis), which could provide stability to coastal dunes (San Martín et al., 1992) and increase the resilience of beaches during storms (Martínez et al., 2013a). Specifically, nourishment combined with confining groins could be a solution for the pocket beaches of Las Salinas and Caleta Portales. These groins should be defined so as to avoid sediment loss during storms, while nourishment should be planned in advance in order to comply with environmental regulations, which have caused difficulties regarding sand extraction in similar projects elsewhere in the country. For the larger and more exposed Renaca and Los Marineros beaches, no new infrastructure should be allowed so as to encourage their current stable conditions. It is also important to improve the existing coastal zone management policy (Política Nacional de Uso del Borde Costero) enacted in 1994, since it is disconnected from zoning plans and provides no differentiation between the coastal zone and the rest of the territory.

5. Conclusions

A preliminary assessment of morphological changes on a decadal scale was carried out in four urban beaches on Valparaíso Bay, Chile. Shoreline changes were classified according to the criteria of Rangel-Buitrago et al. (2015), in which four levels are considered. The analysis showed that Renaca Beach experienced a mean accretion of 12.6 m, while Los Marineros and Las Salinas proved to be in stable conditions between 1964 and 2016. A slight rotation of the shoreline on Los Marineros and Las Salinas is partly explained by a southward shift in offshore wave direction. Caleta Portales, in contrast, was significantly affected by a shoreline retreat of 12.6 m between 2004 and 2016. On these four beaches, the erosion trend increased in the last decade due to a greater recurrence of extreme storms, which occurred without seasonal distinction during ENSO warm phases. Though no significant historical changes in mean significant wave height were identified, storms have increased in frequency, from an average of 5 per year in the middle of last century to 20 per year in the present. Similarly, the mean sea level showed minor trend changes and fluctuations of up to ±30 cm during ENSO warm phases, in which morphological changes are enhanced.

Despite the preliminary efforts to quantify shoreline change, the relationship between coastal erosion and extreme storm events is still poorly understood on these beaches. This is true partly due to i) the scarcity of long-term wave and sea level records, ii) the lack of high-resolution satellite imagery during the 20th century, iii) the absence of long-term beach profile monitoring schemes, iv) the modest understanding of sediment supply evolution in the basins of Marga-Marga and Renaca streams and v) the lack of knowledge on how urbanization alters sediment supply in such basins. The incidence of other factors, such as ENSO events and seismic cycles, creates additional research challenges, which combine uniquely on the coasts of Chile. The contributions of these variables in long-term, interannual and seasonal beach dynamics constitute another important aspect to consider. Long-term beach monitoring plans on urbanized coasts as well as an improvement in the acquisition of oceanographic data are therefore needed to establish the physical background for future developments.

With the current level of knowledge and the available data gathered for this research, it is not possible to clearly determine if coastal erosion is a new hazard in Central Chile. However, both the erosive trend found in the last decade for these beaches and the increasing urbanization in the contributing basins suggest that this coast could deteriorate if such change factors (e.g., an increase in storm frequency and intensity, southward shift in offshore wave direction and sea level change) are maintained or intensified.

Coastal erosion should be addressed by a combination of engineering solutions and integrated coastal management measures, especially those focused on controlling the intensity of urbanization within the coastal zone. The specific measures proposed herein must be analyzed and understood in relation to physical factors (hydrodynamic, geomorphological and tectonic) as well as current and future land uses in order to promote sustainable development. Contributions from the relatively small scientific community working on coastal dynamics are fundamental in this process.

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