Global and Planetary Change 104 (2013) 34–50

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Long-term changes in sea-level components in Latin America and the Caribbean

I.J. Losada *, B.G. Reguero, F.J. Méndez, S. Castanedo, A.J. Abascal, R. Mínguez

Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, Spain

ARTICLE INFO

Article history:
Received 19 September 2012
Accepted 19 February 2013
Available online 26 February 2013

Keywords:
inter-annual variability
Latin America and the Caribbean
sea-level components
sea-level rise
storm surge
non-stationary extremes

ABSTRACT

When considering the threat of rising sea-levels, one must take into account not only the changes in the Mean Sea-Level, but also storm surges and changes in extreme events which may also have a bearing on coastal problems. In this study, we combine different components of the total sea-level (astronomical tide, monthly mean sea-level and storm surges) to explain changes detected in the region of Latin America and the Caribbean. Methods based on non-stationary extreme value analysis were applied to storm surge and total sea elevations monthly maxima for the last six decades, while long-term trends in Mean Sea-level were computed from both local regression and a trend-EOF technique. In addition, the relative importance of each factor contributing to the total sea-level is explored by means of defining each statistical distribution. The analysis demonstrates that concerns should be focused on the different components of sea-level in the various areas of the region. For example, changes in the storm surge levels are a key stressor in the Río de la Plata area, while the increase in the extreme total sea-levels in the tropical region and the influence of inter-annual variability on its western coast are the prominent factors. Results show that a clear correspondence between Mean Sea-Level and the Niño3 climate index can be found through a simple regression model, explaining more than 65% of the variance for a representative location on the Peruvian coast.

1. Introduction

Coastal zones are among the most vulnerable areas to climate change and they are likely to be affected by various impacts in the foreseeable future. Among these, rising sea-levels, sometimes combined with land subsidence, have been highlighted as one of the key threats, which may lead to flooding, coastline erosion, impacts on ecosystems and salination of aquifers (Ericson et al., 2006; Syvitski et al., 2009; Nicholls and Cazenave, 2010). As a result, such problems have mandated action being taken for adaptation and integrated coastal management (e.g., Nicholls, 2011). However, the first step is to thoroughly understand the past changes in specific areas where the impacts are to be inferred, and with an adequate spatial scale. For this, a comprehensive understanding of the major factors contributing to total sea-level is required to lead efforts towards further analysis, prevention, and solutions to flooding and erosion. To this end, this work aims to offer a thorough examination of the different sea-level components in Latin America and the Caribbean region (LAC) and to define the long-term trends in the mean and extreme sea-levels.

In this work, time series of Total Sea-Level (TSL) results from the combination of four main components which vary both temporally and spatially:

(1) Monthly mean sea-level (MSL): average height of the sea surface water level (Church et al., 2004), including the seasonal cycle (monthly mean) and the anomalies in time scales from the monthly variations (i.e. anomalies over the seasonal cycle) to the longer-term changes.
(2) Astronomical tide (AT): sea level variation produced by the gravitational interactions of the earth, moon, and sun. In this work, the astronomical tide is calculated as the superposition of harmonic constituents provided by the TPXO database (i.e. eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm) and 3 non-linear (M4, MS4, MN4) harmonic constituents; long period constituents SA and SSA are not included).
(3) Storm Surge (SS): water height above predicted astronomical tide level due to the inverse barometer effect and the wind stress over the sea surface.

Aggregation of the different components forms hourly TSL time series whose analysis may determine the probability of flooding on different time scales. One of the main objectives of this work is explaining the changes observed in the various sea-level components and analyzing the changes in the TSL extremes in the LAC region.

There are however, some additional components of sea level not covered by the former combination of components. For instance,

* Corresponding author at: Environmental Hydraulics Institute, IH Cantabria, Universidad de Cantabria, C/Isabel Torres nº 15, Parque Científico and Tecnológico de Cantabria, 39011, Santander, Spain. Tel.: +34 942 201414.
E-mail address: losadai@unican.es (I.J. Losada).

0921-8181/$ – see front matter
http://dx.doi.org/10.1016/j.gloplacha.2013.02.006

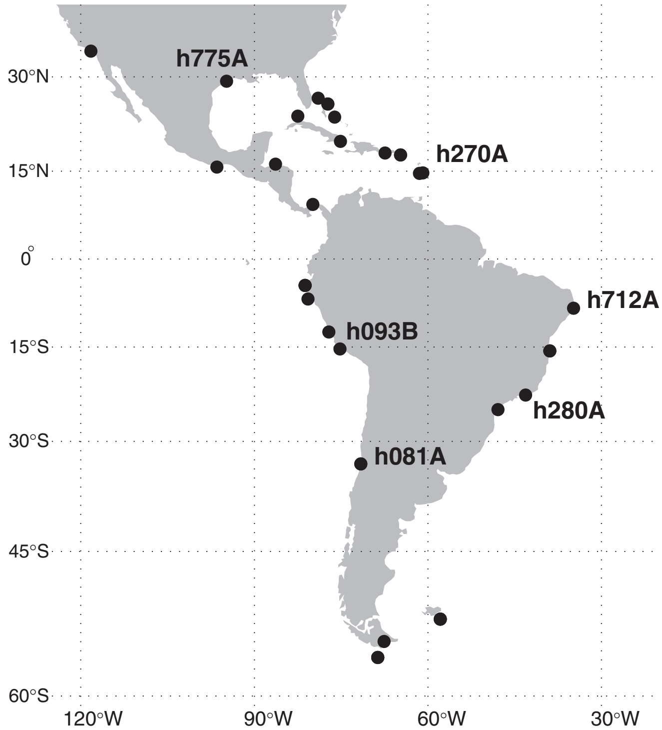

Fig. 1. The region of study, showing the tidal gauges selected for validation purposes.

breaking waves cause sea-level changes in the surf-zone (swell set-up), which depend on local coastal characteristics. This factor is not analyzed here however, since our main focus is on sea-level variations in deep waters and therefore local surf zones are not taken into account.

Sea-Level Rise (SLR) is the name given to changes in the MSL detected over many years. Rising sea-levels have been extensively studied in recent years (e.g., IPCC, 2007; Cazenave et al., 2008; Church and White, 2011; Rignott et al., 2011; or de Santis et al., 2012). Local factors such as land subsidence cause additional displacement to be added to the effect of SLR, the combination of which is known as Relative Sea-Level Rise (rSLR). Land subsidence was not considered in the analysis but it doubtlessly is a factor to consider at a local scale.

There are also variations of the MSL time series that are not represented by the long-term trend. Hereinafter, these sorts of anomalies are referred to as interannual variability. Under this term we analyze variations induced by ENSO events (e.g. Clarke and Van Gorder, 1994; Nerem et al., 1999; Li and Clarke, 2007) or other decadal-scale wind stress curl variability (e.g., Sturges and Hong, 1995; Sturges et al., 1998; Hong et al., 1999). Defining the influence of climatic patterns on different components of the sea-level at a continental scale has not been addressed so far and should be attended to since it may be relevant for coastal areas.

In spite of the great attention to the study of the SLR, the changes in sea-level extremes are the upshot of combinations between SLR, the incidence of storms, local trends and the marine climate, as suggested in Walsh et al. (2012). The combination of rising sea-levels and storm surges has already been dealt with at a global scale in several studies (Dasgupta et al., 2009), and specifically for particular areas of the LAC region (Fiore et al., 2009). Similarly, the effect of SLR on extreme sea-levels has also been addressed at a global scale (Menéndez and Woodworth, 2010). However, identifying specific coastal locations where one or more components (changes in mean sea level, astronomic tide, storm surge, inter-annual change) may be dominant is crucial. For instance, sea-level extremes occur not only under high SS values independently of the AT component, but high rises due to AT and moderate SS values may eventually pose a flooding risk on particular coasts. This is why this study ends with a discussion of the relative importance of each of the contributing factors for the particular region of LAC using homogenous data for the whole of the region.

The structure of the work is as follows. The section following this introduction describes the regional setting of the work. The data sources and the statistical methods used for the extremes analysis and the study of the long-term trends are explained in Section 3. Section 4 deals specifically with the study of sea-level components, their changes, and their relative importance in different parts of the continent. A brief discussion of the climatic patterns with the highest influence on each component is provided in Section 5. Finally, Section 6 highlights the most important conclusions.

2. Regional setting

The area of study is the region of the Atlantic and Pacific Ocean basins that are adjacent to the coasts of LAC (see Fig. 1). With a total coastline length of about 72,182 km, this region is highly variable in terms of coastal dynamics and geomorphological features. In the Atlantic, Pacific and Caribbean shores, the conditions are highly variable and present particular features at each location. Generally, little knowledge is available on the different sea-level components and their past temporal changes over the region extending from the high latitudes in the Southern Ocean to the equatorial areas.

3. Data and methods

3.1. Data

Several sources of instrumental and numerical data were used to evaluate the sea-level components in the LAC region. Table 1 summarizes the variables considered and their original source, as well as their time span and spatial resolution.

MSL data were obtained from the Commonwealth Scientific and Industrial Research Organization (CSIRO) and can be downloaded at: http://www.cmar.csiro.au/sealevel/sl_data_cmar.html.

These data provide monthly MSL series on a 1° × 1° (longitude × latitude) grid of spatial resolution between 65°S and 65°N, from 1950 to 2001, reconstructed from tidal gauges (Church et al., 2004). The seasonal signal is removed from the dataset and it includes the inverse barometer correction and the GIA (Mitrovica) correction made to tidal gauge data. The relative movement between land and

Table 1
Sources of information of the variables considered, their time span and spatial resolution.

Data source	Variables	Time span	Time resolution	Spatial resolution
CSIRO	Mean Sea-level(MSL) Mean Sea-level anomaly	1950–2009	Monthly	Global, 1°
TPXO dataset (v7)	Astronomical Tide (AT)	Harmonic constants	Hourly	Global, 0.25°
Tidal gauges (UHSLC)	Mean Sea-level(MSL) Storm Surge (SS)	Variable	Hourly	Global, variable
Numerical reanalysis (GOS)	Storm Surge (SS)	1948–2008	Hourly	LAC, 0. 25°