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Variability of multivariate wave climate in Latin America and the Caribbean

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ABSTRACT

Wave climate is highly variable on the world's coast and its temporal changes and extremes usually imply consequences like erosion or impacts to infrastructures. Alterations in wave climate were little addressed in the four IPCC reports although variations in wave climate may cause extensive coastal impacts. Changes are also often related to climate pattern variability. This variability as well as long-term trends has been an issue of research in recent years. In the region of Latin America and the Caribbean (LAC) an understanding of wave climate and its variability is scant. In this paper we use an extensively calibrated and validated wave reanalysis to describe the wave climatology in the region at different time scales and for scalar and directional wave parameters. Long-term changes are identified in the wave heights and mean direction of the energy flux shows high spatial variability. Correlation patterns of the mean significant wave height and direction of mean energy flux lead to the detection of prominent modes of influence of several climate indices. A wave climate type approach is also used to identify wave variability along the region that allows an identification of different wave climate types in terms of wave parameters and occurrence frequency. In line with the results, the influence of El Niño events shows a higher frequency of occurrence of certain sea-states with respect to non ENSO years. We also explore how climate change affecting storm patterns may be translated into a modification of sea-state occurrence and therefore implying different consequences for coastal zones depending on local wave propagation.

1. Introduction

The marine climate on the world's coasts is highly changeable, its changes generally implying consequences for the coasts in terms of sediment transport, erosion or impacts to the activities of ports. Impacts in coastal zones from changes induced by global warming (Nicholls, 2011) include rising sea levels and other, less studied, climatic factors such as possible changes to the wave climate (e.g., Wang et al., 2004; Caires et al., 2006; Wang and Swail, 2006). Alterations in the global wave climate were little addressed in the fourth IPCC report (Solomon et al., 2007), even though not just variations in intensity or in average conditions but also its direction may affect coasts at the global level. It has been confirmed that erosion on the beaches of Southeast Australia is intimately related to interannual changes in swell direction (Harley et al., 2010). In turn, possible long-term changes in storm patterns have made study of the trends in the wave climate a matter for current research (e.g., Izaguirre et al., 2011; Semedo et al., 2011a; Young et al., 2011).

The available wave data come from visual observations (voluntary observing ships, VOS), buoys, satellite altimetry or hindcasts. Visual data provide global information over several decades, which has long made them an important complementary source of information on the wave climate. These data have been used to study sea climatology and for other purposes (Gulev and Hasse, 1999; Gulev and Grigorieva, 2004). Buoys provide reliable data and continuous time series in general, covering approximately the last two to three decades, but with the main drawback being that their spatial location is discontinuous and most are installed in the Northern Hemisphere (NH). In general, there are few long-term data sets of this type from the Southern Hemisphere (SH), particularly along the coast of South America. On the other hand, satellite data offers global cover and have been available since 1985, although they are unfortunately discontinuous in time (with gaps between successive sweeps). A fourth source of information on the wave climate comes from numerical reanalysis, solving the problem of space–time cover. Forcing numerical wave generation models (Cavaleri et al., 2007) with atmospheric reanalysis can produce homogenous time series for various decades. A number of global studies based mainly on altimetry data (Young, 1999; Izaguirre et al., 2011; Young et al., 2011) or numerical reanalysis (e.g., WASA-Group, 1998; Sterl and Caires, 2005; Alves, 2006; Semedo et al., 2011a; Reguero et al., 2012) have described the global climatology of wind waves, particularly in the NH. However, the wave climate in the SH has been less researched, limited to a small number of some regional

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studies (Short and Trenaman, 1992; Laing, 2000; Scott et al., 2002; Gorman et al., 2003; Hemer et al., 2008; Dragani et al., 2010).

In the study of wave climate trends and climatic variability, the NH has also been more broadly examined, especially the North Atlantic and North Pacific (Allan and Komar, 2000; Woolf et al., 2002; Gulev and Grigorieva, 2004; Allan and Komar, 2006; Gulev and Grigorieva, 2006; Menéndez et al., 2008; Dodet et al., 2010; Ruggiero et al., 2010), although there are also some studies on a global scale (Sterl and Caires, 2005; Komar et al., 2009; Semedo et al., 2011a; Young et al., 2011). Hemer et al. (2010) studied trends for the SH and possible links with the Southern Oscillation Index and the Southern Annular Mode.

Some studies have also developed future climate projections (Hemer et al., 2006; Mori et al., 2010; Semedo et al., 2011b) that show an increase in wave heights due to increasing wind speeds that are associated with storms in many regions of the mid-latitude oceans. Some efforts have also been made at regional scales (Lionello et al., 2008; Weisse et al., 2009).

In the Latin American and the Caribbean (LAC) region, however, an understanding of the wave climate, in terms of both available data and of studies done, is scant, despite having one of the most diverse coasts and maritime climates of the planet. The LAC region is also affected by various climatic patterns since it constitutes a physical separation between two oceans and borders with the Southern Ocean at the south of the continent, one of the world's most intense areas of swell generation (Young, 1999).

As far as we know, the climatic pattern most influencing wave climate throughout the LAC coastal zone is not understood at this scale. Moreover, past changes in wave intensities and shifts in their directionality are not known homogenously for the region as a whole.

This work analyzes the wave climate in the region of LAC, analyzing the climatology on various time scales, differentiating: (i) the monthly and seasonal scale, gathering average variations in months and seasons along a 61-year time span; (ii) the annual scale, as a mean description of annual conditions; (iii) inter-annual variability, or changes over several years, and (iv) long-term trends, analyzing changes on the scale of decades. The following were the variables used in the study: significant wave height (H_s; i.e. the average of a third of the largest waves in each sea-state), the average wave period (T_m), the peak wave period (T_p) and the mean wave direction (θ_m). The statistical parameters used to characterize and analyze wave climate on the different time scales are: (1) average significant wave height ($\overline{H}_s$), (2) the significant wave height exceeded on average 12 h every year (H_{s12}), (3) direction of the mean energy flux (θ_{EF}), and (4) the probability of occurrence of triads of significant wave height, peak period and mean direction: Prob(H_s,T_p,θ_m).

This introduction is followed by Section 2 which describes the regional setting of the study. Subsequently, Section 3 deals with the data explaining the sources of information used and describes the wave climate in the region, with a brief discussion of the sea-types on its coasts. Section 4 analyzes the results for the long-term trends in the different wave statistics. The influence of climatic variability and particularly the effects of El Niño events are discussed in Section 5. Next, Section 6 also includes a discussion of how propagation and the change in the frequency of occurrence of various sea-types may have different effects in the impacts on the coasts. Finally, the main findings from this study are set out in Section 7.

2. Regional setting

The area of study is the region of the Atlantic and Pacific Ocean basins that wash the coasts of Latin America and the Caribbean (LAC). With a total coastline length of about 72,182 km this region is highly variable in terms of coastal dynamics and geomorphological features. From the varying conditions in the Atlantic and Pacific, the Caribbean Sea is a third area with particular characteristics. Covering from high latitudes in the Southern Ocean to equatorial areas, the range of wave climate types in the region is greatly diverse. Generally, little knowledge is available on wave climate and its temporal past changes in the region.

3. Data

3.1. Data sources

Based on the fields of wind and ice cover of NCEP–NCAR reanalysis (Kalnay et al., 1996), global simulations of wave climate since 1948 were made using the Wavewatch III model (Tolman, 2002a,b) with a resolution of 1.5° longitude and 1° latitude. A global wave reanalysis, named as GOW data set (Reguero et al., 2012), was developed as an initial step towards the regionalized characterization. Higher spatial-resolution domains on the coasts studied were nested (see Fig. 1) within the global grid domain design along with three more detailed grids, two with a spatial resolution of 0.5°×0.5° (longitude×latitude) covering the Atlantic and the Pacific coasts, and one with a spatial resolution of 0.25°×0.25° for the Caribbean region. The results of the reanalysis were hourly time series of various statistical wave parameters. Despite the spatial resolution, hurricane influenced events are not adequately modeled in peak intensity due to lack of spatial resolution in the input wind fields. Consequently, results for extremes in hurricane prone areas must be taken with caution in the following.

The numerical data were corrected with satellite data using the method proposed in Mínguez et al. (2011), in a similar manner to the global reanalysis (Reguero et al., 2012). The altimetry wave height measurements used covered the period from 1992 to 2008 with variable spatial and time resolution, from the missions: Jason-2 (since the end of 2008), Jason-1, Topex/Poseidon, ERS-2, Envisat and GFO, which were corrected according to Hemer et al. (2010). Validation of the global implementation and the results of correction can be further consulted in Reguero et al. (2012), where a validation of the correction procedure was also addressed.

To compare the wave reanalysis data performance in the LAC region in particular, several diagnostic statistics were computed for comparing the numerical data with altimetry derived data. Specifically, Fig. 2 shows the results for the systematic deviation between the mean value of altimetry data minus the mean value of numerical data (BIAS; panel a) and the root mean square error (RMSE; panel b). In any case, the BIAS remains below 0.1 m although the highest values are found in the NH area. Conversely, the RMSE is low in that particular region with the highest values of about 0.65 m found at the southern part of the region, where the largest wave heights of the region occur. The results for the correlation coefficients, the residual scatter index and the quantile distribution comparison of each data set (not shown) confirm an adequate representation of the wave climate along the region of study. Further validation and information of the wave reanalysis can be found in Reguero et al. (2012).

3.2. Offshore wave climate in the region

Because of the limited understanding of wave climate in the LAC region, this section includes a description of the main wave statistics, and a comparison of the climate types existing in the region. Wave characterization was obtained by numerical simulation nested within the global GOW wave reanalysis (Reguero et al., 2012). The annual mean significant wave height ($\overline{H}_s$) and the percentage of seasonal variation are described as indicators of the mean monthly conditions (Fig. 3). The significant wave height likely to exceed 12 h every year (H_{s12}), is also used as a descriptor of wave climate (Fig. 4) owing to its relationship with the closure depth for simple models of beach profiles (Birkemeier, 1985) and being associated with the 99.86% exceedance percentile. It also represents a quantile of the high range of wave height conditions during the year. Finally, the direction of the