Ocean Engineering 163 (2018) 126–135

Contents lists available at ScienceDirect

Ocean Engineering

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

Exploring changes in Caribbean hurricane-induced wave heights

Rubén Darío Montoya[a,*], Melisa Menendez[b], Andrés F. Osorio[c]

[a] GICI-GICAMH Research Groups, Civil Engineering Program, Universidad de Medellín, Carrera 87 No 30 – 65, Medellín, Colombia
[b] Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, Calle Isabel Torres 15, PCTCAN, Santander, 39011, Cantabria, Spain
[c] OCEANICOS Research Group, Universidad Nacional de Colombia, Sede Medellín. Cl. 80 #65 - 223, Medellín, Antioquia, Colombia

ARTICLE INFO

Keywords:
Hurricane waves
Extreme values
Caribbean Sea
Non-stationary model
Colombian Caribbean

ABSTRACT

During recent decades there has been open debate about a possible increase in the number and magnitude of more energetic hurricanes in the Atlantic, including their causes and implications. In this work, changes in extreme wave heights induced by hurricanes in the Caribbean Sea are analyzed. A non-stationary model is employed to study possible changes in the frequency of occurrence and magnitude of extreme waves from an hourly time series during the period of 1979–2012. The results indicate an increase in the occurrence of extreme wave events in the eastern and central Caribbean, and consequently, a positive long-term trend for 30yr return values. The zone of the highest trends is observed in the western basin in the middle of the Caribbean Sea towards the Gulf of Mexico. A final rate of approximately 2 events/year for 2012 is found throughout the Yucatan basin.

1. Introduction

In the Caribbean Sea, the climate is strongly influenced by the northeast trade winds which characterize the wave climate for most of the year. However, these dynamics are altered during the last months of the year by the occurrence of the hurricane season in the Atlantic. Despite having a lower intensity than hurricanes in areas such as the United States, the economic impact associated with hurricanes in the Caribbean is significant. The most affected regions are Puerto Rico, Cuba, the Dominican Republic and Haiti.

A considerable amount of research has been dedicated to assessing hurricane behavior in the Atlantic basin as a whole, but there are few studies of the Caribbean Sea as an enclosed basin. Employing a parametric hurricane wind wave model and the spectral SWAN model, Ortiz (2009) researched the maximum wave height generated by the passing of hurricane Lenny in the Colombian Caribbean and analyzed which zones are most vulnerable to a hurricane event. Ortiz (2011) presented an analysis of the storms which have passed through the Colombian Caribbean since 1900. The main objective was to identify the most vulnerable zones along the Colombian continental coast. Rubiera (2005) carried out research for the Caribbean Sea, showing that some of the most active hurricanes were observed during the first half of the twentieth century. Ortiz–Royero et al. (2013) showed that other meteorological phenomena such as cold fronts may induce extreme wave events in the Caribbean Sea. Ortiz–Royero et al. (2015), presented an analysis of the most important hurricane inducing extreme waves thought the coastal areas of the San Andres island in the Colombian Caribbean Sea, results shows that the most vulnerable areas are located toward the southeastern, where the insular shelf is narrow and low presence of coral reefs are observed.

Calverley et al. (2002) researched wave climate variability during hurricane conditions in the Caribbean for a long term period of 79 years. They used a peak-over-threshold extremal analysis of separate populations of hindcast sea state peaks for hurricanes in the "cold" and "warm" years.

In the Caribbean, there is limited availability of buoys with long periods of instrumental records. There is also a high dispersion and lack of availability of wave data recorded by observation ships (VOS) during extreme wave conditions. Furthermore, the length of satellite data is short and extreme events are rarely captured. These problems make the use of wave data obtained from numerical modeling an important alternative for long-term climate analysis (Vinoth and Young, 2011). Bertinelli et al. (2016) used synthetic information from hurricane tracks in the Caribbean Sea and local income proxies to investigate the expected risk and losses associated to prevailing climate behavior for a future period of 30 years.

The main topic of this paper is not related to the knowledge of interannual and interdecadal variability of hurricane activity in the Atlantic basin. Instead, modeled wave time series from 1979 to 2012 are employed to analyze changes in extreme waves induced by hurricanes in the Caribbean Sea during recent decades. The corrected NCEP/NCAR reanalysis I winds proposed by Montoya and Osorio (2014) as a

* Corresponding author. Belen, Carrera 87 No 30-65 (Bloque 4), Medellín, Colombia.
E-mail addresses: rmontoya@udem.edu.co (R.D. Montoya), melisa.menendez@unican.es (M. Menendez).

https://doi.org/10.1016/j.oceaneng.2018.05.032
Received 2 July 2017; Received in revised form 24 February 2018; Accepted 16 May 2018

forcing for medium winds and blended winds in hurricane conditions, proposed by Montoya et al. (2013) are used to obtain time series of significant wave height for 278 virtual buoys (hereafter VBs). These VBs correspond to locations defined strategically throughout the domain in some locations where buoys do not operate. This allows a comprehensive spatial analysis to be performed that is not possible using in-situ buoy data. The peak-over-threshold (POT) method is used to investigate the spatial behavior of significant wave height peaks during hurricane conditions.

This paper is organized as follows: Section 2 describes the extreme and average wave data sets employed for the study area and describes the non-stationary model. Section 3 presents the main results for hurricane spatial trends in the Caribbean Sea. The summary and conclusions are given in the last section.

2. Material and methods

2.1. Wave data time series methodology (extreme and average conditions)

There is a significant difference between atmospheric conditions during hurricane occurrence and so-called average conditions in the Caribbean Sea. Hurricane conditions include strong pressure gradients, strong convection between the atmosphere and sea surface, vorticity and vertical wind speed alterations moderated mainly by African easterly waves (AEWs, Agudelo et al., 2011). The strong perturbation of the pressure field produces a zone of strong rotating winds (rotary circulation – counter-clockwise in the northern hemisphere) and a strong debilitation of the wind fields in areas far from the hurricane eye. In contrast, so-called average conditions are mainly affected by the movement of the inter-tropical convergence zone (ITCZ) and the trade winds through the equatorial region.

For ocean wind wave models, the wind speed is the most important forcing. The strong spatial and temporal differences in wind speed during extreme and average conditions requires calibration and validation techniques to be employed separately. For this research, a procedure to obtain the hourly continuous time series of significant wave height for both conditions is presented in the Fig. 1 and summarized as follows:

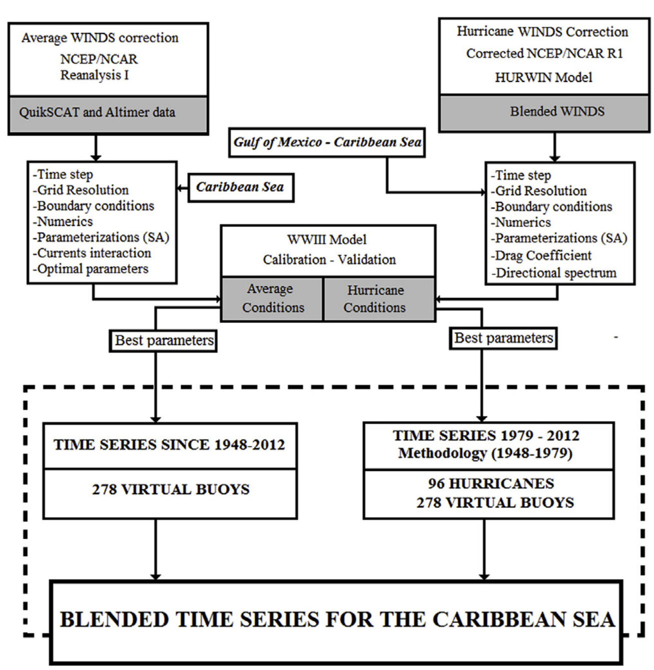

Fig. 1. Schematic procedure to obtain the full time series in the Caribbean Sea.

2.1.1. Time series during average conditions (light and moderate winds)

Average time series of the main wave parameters from 1948 to 2012 for 278 virtual buoys (VBs, see Fig. 2) in the space domain were generated employing corrected NCEP/NCAR Reanalysis I (Hereafter NCEPR1), Meridional (v) and zonal (u) winds as forcings of the WAVEWATCH III (hereafter WWIII) (3.14 version) model (Tolman, 2009). The WWIII model is a third-generation spectral wind wave model that solves the spectral action density balance equation for the wave number-direction spectrum F (k,θ). In cases without currents, the variance (energy) of a wave package is a conserved quantity. In cases with currents the energy or variance of a spectral component is no longer conserved due to the work done by the current on the mean momentum transfer of waves (Longuet-Higgins and Stewart, 1961, 1962). However, the wave action density $A \equiv E/\sigma$ is conserved. This creates the wave action density spectrum $N (k\ \theta) \equiv F (k, \theta)/\sigma$, which is the one selected in the model (Tolman, 2009).

These winds were corrected using the methodology proposed by Montoya and Osorio (2014), who showed that the wind speed during light and moderate wind conditions was strongly underestimated for NCEP-R1, near the Cartagena and Barranquilla region of the Colombian Caribbean Sea, when compared with Quick Scatterometer (QuikSCAT) satellite data. This underestimation in NCEP-R1, wind speed near tropical zones has been observed by several authors (McNoldy et al., 2004; Caires et al., 2004; Meissner et al., 2001; Feng et al., 2006; Simionato et al., 2006).

2.1.2. Time series during hurricane conditions

Most of the reanalysis databases do not allow adequate representation of the wind field during hurricane conditions. Their coarse resolution impedes the adequate representation of the high wind variability near the hurricane eye and underestimates winds near the maximum wind speed zone. Even the most accurate scatterometer satellite data presents underestimations for strong winds (above approximately 30 m/s), preventing the possibility of using methodologies based on satellite data such as that proposed by Montoya and Osorio (2014) for light and moderate winds. This problem can be solved using blended winds in which the extremes are well reproduced. Based on this idea, several authors have proposed corrections to wind speed during hurricane occurrence, as mentioned by Montoya et al. (2013) (Swail and Cox (2000); Chao and Tolman (2001); Liu et al. (2007); Stockdon et al. (2007), among others).

The time series of the main wave parameters during hurricane conditions were generated by employing the blended winds suggested by Montoya et al. (2013) as forcings of the WAVEWATCH III (3.14 version) model for all the virtual buoys (278), as proposed for average conditions. However, the corrected NCEPR1 Reanalysis I employed for average conditions was used to calculate environmental winds instead of the North American Regional Reanalysis (NARR) dataset. For the preliminary analysis, approximately 96 hurricanes were modeled from 1979 to 2012.

Montoya et al. (2013) employed (10) buoys and hurricane Katrina in the Gulf of Mexico and compared the main wave parameters such as the significant wave height (Hs), peak direction and the directional spectrum based on the quadrant location for the storm track. They performed a comparison between the available parameterizations included in the multigrid version (3.14) of the WAVEWATCH III model. The available parameterizations employed for comparisons were Tolman and Chalikov (1996) (hereafter TC) with and without limited drag (referred as TCFLX3 and TCFLX2 respectively in the user manual), the BAJ parameterization from Bidlot et al. (2005), the WAM4 parameterization proposed by Gunther et al. (1992) and ACC350 proposed by Ardhuin et al. (2009). For this research the best global performance was obtained by the Tolman and Chalikov (1996) parameterization without limited drag (TCFLX2).

Considering Tolman and Chalikov (1996) as the best parameterization to describe the main wave parameters and directional