STORMS OR COLD FRONTS? WHICH ONE IS REALLY RESPONSIBLE FOR THE EXTREME WAVES REGIME IN THE COLOMBIAN CARIBBEAN COAST?

L. J. Otero[1], J. C. Ortiz-Royero[1], Julie K. Ruiz-Merchan[1], A. E. Higgins[1] and S. A. Henriquez[1]

[1] Applied Physics Group – Ocean and Atmosphere Area – Physics Department, Universidad del Norte, Barranquilla, Colombia.

Correspondence to: L. J. Otero (ljotero@uninorte.edu.co)

Abstract

On Friday, March 7, 2009, a 200-meter-long section of the tourist pier in Puerto Colombia collapsed under the impact of the waves generated by a cold front in the area. The aim of this study is to determine the contribution and importance of cold fronts and storms on extreme waves in different areas of the Colombian Caribbean to determine the degree of the threat posed by the flood processes to which these coastal populations are exposed, and the actions to which coastal engineering constructions should be subject. In the calculation of maritime constructions, the most important parameter is the wave's height; therefore, it is necessary to definitively know the design wave height to which a coastal engineering structure should be resistant. This wave height varies according to the return period considered. Using Gumbel's extreme value methodology, the significant height values for the study area were calculated. The methodology was evaluated using data from the reanalysis of the spectral NOAA Wavewatch III (WW3) model for 15 points along the 1,600 km of the Colombia Caribbean coast (continental and insular) for the years 1979 to 2009. The results demonstrated that the extreme waves caused by tropical cyclones and cold fronts have different effects along the Colombian Caribbean coast. Storms and hurricanes are of greater importance in the Guajira Peninsula (Alta Guajira). In the central area formed by Baja Guajira, Santa Marta, Barranquilla, and Cartagena, the strong influence of cold fronts on extreme waves is evident. On the other hand, in the southern region of the Colombian Caribbean coast, from the Gulf of Morrosquillo to the Gulf of Urabá, even though extreme values of wave heights are lower than in the latter regions, they are dominated mainly by the passage of cold fronts. Extreme waves in the San Andrés and Providencia insular region present a different dynamic from that in the continental area due to its geographic location. The wave heights in the extreme regime are similar in magnitude to those found in Alta Guajira, but the extreme waves associated with the passage of cold fronts in this region have lower return periods than the extreme waves associated with hurricane season.

These results are of great importance when evaluating the threat of extreme wave height in the coastal and port infrastructure. Both for purposes of the design of new constructions, and in the coastal flood processes, due to run-up because, according to the site of interest in the coast, the forces that shape extreme wave heights are not the same.

Key words: Gumbel’s distribution function, hurricanes, extreme waves, Caribbean Sea, cold fronts

1 Introduction

The principal source of coastal energy and responsible for sediment dynamics are waves. The waves generated by ‘sea’-type local winds and those generated offshore by atmospheric disturbances known as swells determine the average and extreme maritime climate of a region. The activities that develop in coastal or maritime areas, such as fishing, maritime transport and transit, oil exploitation, structure design, and even surfing, demand knowledge of waves. The maritime climate, particularly winds, is a dynamic phenomenon that presents short-period cyclic variations (daily, weekly), seasonal variations, and long-term variations. Considering that winds are the main wave-generating agent, the wave climate also varies based on this pattern. Given the incidence of the wave climate in the operation and construction costs of maritime infrastructures, it is important to design these constructions taking into account the temporal variation of this phenomenon at an oceanic and local scale.

Cold fronts occur when two air masses at different temperatures and densities come into proximity. The cold air mass with higher density pushes the hot air, making it ascend. The rising hot air cools down, producing clouds, the pressure gradient in the area, strong winds, storms, and increases in the wave height or swell through its passage along the Colombian Caribbean coast, (Ortiz et al., 2013).

The incidence of cold fronts in the Colombian Caribbean coast has not been widely studied. Cold fronts are noted in the marine-meteorological monthly reports of the Center of Oceanographic and Hydrographic Research (Centro de Investigaciones Oceanográficas e Hidrográficas, CIOH) of the General Maritime Direction (Dirección General Marítima, DIMAR). Their potential incidence in the events of extreme waves in the region under study has been described by Ortiz et al. (2014a), where the most important marine-meteorological event of the last 10 years in the Colombian Caribbean was reconstructed, namely the passage of a cold front on March 2009 whose associated waves caused 200 meters of the pier at Puerto Colombia to collapse.

Ortiz et al. (2013) performed the characterization of cold fronts in the central region of the Colombian Caribbean and their relation with extreme waves, finding that cold fronts have been the cause of the major waves in this region over the last 15 years.

On the other hand, Ortiz (2012) and Ortiz et al. (2014b) described the threat of hurricanes in the Colombian Caribbean. Joan in 1988 and Lenny in 1999 were two of the most important events in the continental Caribbean coast, while for San Andrés Island, the list is longer: Hattie in 1961, Alma in 1970, Joan in 1988, Cesar in 1996, Katrina in 1999, and Beta in 2005 are hurricanes that have affected the island over the last 50 years. This is why the San Andrés y Providencia Archipelago is the zone in the Colombian Caribbean that is most vulnerable to hurricane threats.

In this context, the traditional method of constructing the extreme wave regime has consisted of performing predictions of waves based on historical information for a period of no less than 10 years (Martínez and Coria, 1993; Naveau et al., 2005). Based on this information, the most unfavorable extreme values of each year are selected, and the results are then extrapolated to different return periods.

Although there is no physical, theoretical, or empirical evidence of which should be the selection or adjustment of a probability distribution function for the calculation of the design wave height, the Gumbel or Fisher Tippett I and Weibull distribution functions are widely used for such purposes, as reported by Martínez and Coria (1993), Katz et al. (2002), García et al. (2004), and Naveau et al. (2005).

In response to the lack of information on the variability of extreme waves in coasts of the Colombia Caribbean, the main objective of this study is to determine the importance and contribution of cold fronts and storms for extreme waves to ascertain the actions to which coastal and port structures in different regions of the Colombian Caribbean should be subjected and, similarly, to assess the degree of the threat to which coastal populations are exposed due to flood processes caused by wave run-up.

2 DESCRIPTION OF THE STUDY AREA

The coastline of the Colombian Caribbean has a wide territory that extends from 8ºN to 13ºN and from the country's border with Panamá in the southwest (SW) at longitude 79ºW to the Guajira Peninsula on the northeast (NE) at longitude 71ºW. The Colombian coastal area is approximately 1,600 km in length and includes important cities from the economic and touristic perspective: Riohacha, Santa Marta, Barranquilla, and Cartagena. The total area of the Colombian Caribbean is approximately 590,000 km^2. These cities are home to maritime and river ports of great importance for the economy of the country. Of the four cities, the most populated one is Barranquilla (2,400,000 inhabitants), followed by Cartagena (1,200,000 inhabitants), Santa Marta (415,000 inhabitants), and Riohacha (150,000 inhabitants).

The insular Colombian Caribbean in formed by the Archipelago of San Andrés, Providencia, Santa Catalina, the Roncador, Quitasueño, Serranía, and other cays, adjacent islets, and deep-water coral reefs.

San Andrés Island is located in the Caribbean Sea, at 180 km east of Nicaragua and northeast of Costa Rica and 480 km northwest of the Colombian coast (Parsons, 1954). The island of San Andrés is the largest of the islands that form part of the Archipelago of San Andrés, Providencia, and Santa Catalina, with a total extension of 26 km^2. It is surrounded on its northwestern side by a small coral reef and several cays that are home to marine flora and fauna (Geister, 1973).

It is interesting to review and analyze the phenomenon responsible for the extreme wave regime in this area because the entire region of the Colombian Caribbean is not located at the same latitude.

The Colombian climate is characterized by two seasons in the year that are marked according to precipitation: a dry season and a wet season. The main dry season in the region occurs from December to May; in this season, swells produced by cold fronts can occur. The wet season occurs the rest of the year, interrupted by a relative minimum in June and July known as Indian summer (Andrade and Barton, 2001). The dry season and Indian summer are associated with the jet stream winds of San Andrés and the northeastern (NE) trade winds. When the jet stream of San Andrés is stronger, the dry season occurs in the entire Caribbean coast, coinciding with very intense NE trade winds; the same occurs with Indian summer (Andrade and Barton, 2001). By contrast, the wet season, which ranges from August to November, coincides with the time of most intense jet stream winds from Chocó and less intense jet stream winds from San Andrés (Poveda, 2004).

Along this entire region, the rainiest month of the year is October, and the driest months are February and March. From December to March, the intertropical convergence zone (ITCZ) is located over South America, the high pressure centers are strong in the Caribbean, and the northeast trade winds are maximal, which is consistent with the main dry season in the Caribbean region. From July to September, the location of the ITCZ shifts towards the center of the Caribbean, trade winds weaken, and southwest (SW) winds, which are weaker but can bring strong storms to the Caribbean region, dominate. These annual periods coincide with maximums in the jet streams from San Andrés and Chocó, respectively. However, the second maximum jet stream from San Andrés, which occurs from July to August and is associated with Indian summer, is not directly related to the ITCZ but instead to a temporal intensification of the high pressure system from the North Atlantic (Andrade and Barton, 2001).

Wiedeman (1973) and Kjerfve (1981) established that Caribbean tides are weak, with a tidal range oscillating from 20 to 30 cm, and occasionally surpassing 50 cm; therefore, it was classified as microtidal (range <2 m). Using information from different tide stations in the Caribbean, Morales (2004) concluded that, in Cartagena and Islas Del Rosario, which are located in the central Colombian Caribbean, the tide classification is mixed and mainly diurnal.

Similarly, the zone of the Santa Marta bay also located in central Colombian Caribbean has a mixed tidal classification that is mainly diurnal and with a tidal range of 48 cm (García et al., 2011), while the insular region of San Andrés is found within the mixed tidal classification and is mainly semidiurnal.

The annual wave cycle presents a bi-modal behavior influenced by the NE trade winds, showing 2 wind periods, intense waves, and low precipitation in the dry season and 2 wind periods, weak waves, and high precipitation during the wet season (Mesa, 2010).

3 METHODOLOGY

In the area under study, there are no extensive historical records of waves of an experimental nature (Meza, 2010). Buoys of the National Oceanic and Atmospheric Administration (NOAA) are very far from the coastal zone of the Colombian Caribbean. The DIMAR controls several directional buoys near the Colombian coasts in the Caribbean and the Pacific. For the Caribbean, the DIMAR has 2 buoys, 41193 and 41194, located near the coasts of Barranquilla and Riohacha, respectively, and in the central Caribbean, the NOAA controls scalar buoy 42058, as shown in Fig. 1.

The National Data Buoy Center (NDBC) database has records for 2008, 2009, and 2010. Directional buoy 41194, which began operation in 2007, is located near Bocas de Ceniza, which is the mouth of the Magdalena River in the Caribbean Sea, located near the city of Barranquilla. Directional buoy 41193 is near Puerto Bolívar (Guajira Department) and has records since 2010, and buoy 42058 has been collecting data since 2005. Therefore, in order to characterize the wave climate, it is necessary to resort to data obtained from models, visual waves, or satellites (Agudelo et al., 2005). According to Martínez and Coria (1993), for an analysis of extreme waves, it is necessary to have at least 10 years of wave data in the area of interest. For this purpose, a historic database of 30 years (1979-2009) from 15 reanalysis virtual buoys distributed along the Caribbean coastline from the NCEP Climate Forecast System Reanalysis Winds (CFSRR), was initially analyzed (Chawla et al., 2011). The Data was downloaded from web site: http://polar.ncep.noaa.gov/waves/CFSR_hindcast.shtml. The spatial resolution of wave data for the Caribbean Sea is 1/6° x 1/6°. The wave model used at NCEP is a third generation wind wave model WAVEWATCH III (Tolman, 2009). The wind fields with which the model was forced originate from a new reanalysis of the atmospheric, oceanic, sea-ice and land data from 1979 through 2010, and a reforecast run with this reanalysis (Saha et al., 2010). The detailed description of the data is carried out in Chawla et al., (2013).

The locations of these virtual buoys (Bv) are shown in Fig. 2. Similarly, this figure shows the segmentation of the continental and insular Colombian Caribbean coast into 4 zones, as proposed by Ortiz (2012), in accordance with their level of vulnerability to the threat of hurricanes.

Given the limited information of oceanographic buoys in the area of study, detailed parametric calibration and validation were applied to the re-analysis wave series for data coinciding with the significant wave heights (H_s) in undefined depths for a zone in the Caribbean where data from oceanographic buoys existed. In this study, the data from buoy 42058 was used for the calibration of the database, and the data from buoy 41194 was used for validation. Buoy 42058 was selected to perform the calibration process for two main reasons: first, due to the higher extension of continuous data available and, second, due to its location in undefined depths.

From the data on significant wave heights (H_s) from the WW3 model for the point 14.9ºN-75ºW and the data collected by oceanographic buoy 42058, a detailed parametric calibration method was applied for coinciding data using power and linear regression models (Tomas, 2009). With the coefficients obtained in each regression model, the data from the series corresponding to buoy Bv05 were corrected. These data were validated with the values of significant wave heights (H_s) measured by oceanographic buoy 41194 of Barranquilla, Colombia.

With the aim of verifying the degree of adjustment of the measured and calculated time series, the *D* adjustment index and the Average Deviation *P* described by Willmott (1981) were applied.,in order to determine the adjustment degree of the regression models, the r^2 correlation coefficient was used.

In accordance with Wornon and Welsh (2002a, 2002b), the *D* index is very sensitive to errors in the mean square root of the difference between predictive and observed values. A $D = 0$ shows total dissociation, while $D = 1$ shows a perfect association between the measured and calculated data. Willmott's *D* index is defined as:

$$D = 1 - \frac{\sum_{n=1}^{N}(Pn - On)^2}{\sum_{n=1}^{N}(|Pn - O| + |On - O|)^2} \quad (1)$$

where *Pn* is the prediction performed, *On* are the measurements, and *O* is the mean of the measurements performed.

The Average Deviation P is defined as:

$$bias(P) = \frac{\sum_{n=1}^{N}(Pn - On)^2}{\sum_{n=1}^{N} On} \quad (2)$$

For example, a deviation of -0.05 shows mean underestimations of the order of 5%.

To differentiate the influence of cold fronts on hurricanes, calculations of extreme values were performed for 2 seasons of the year: the hurricane season of the Caribbean from June to November and the cold front season from December to May.

For the calculation of extreme values, Gumbel's maximum distribution or Fisher-Tippet type I distribution were selected. This distribution is suitable for random, identically distributed, and independent variables and is widely used to characterize extreme regimes of oceanographic geophysical variables. Gumbel's maximum distribution is a bi-parametric function with a location parameter λ and a scale parameter δ, (García et al., 2004).

$$F(x) = e^{-e^{-b}} \quad (3)$$

where

$$b = \frac{x - u}{\alpha} \quad (4)$$

$$\alpha = \frac{S_x}{\lambda} \quad (5)$$

$$u = \bar{x} - \delta\alpha \quad (6)$$

x is the data series, S_x is the standard deviation, and $\bar{x}$ the arithmetic mean of the data series. The values of λ and δ are selected according to the number of data, in this case, λ = 0.53622 and δ = 1.11237.

From the series of annual maximums, the characteristic waves for return periods of 5, 10, 25, 50, and 100 years were calculated using Gumbel's maximum distribution.

4 ANALYSIS AND RESULTS

Fig.3 Shows the results of the calibration of the H_s WW3 re-analysis data and the data from the Central Caribbean oceanographic buoy (42058). The lines represent the linear regression Eq. (7) and power regression Eq. (8) models. The dispersion diagram shows that both models present a good correlation with the data, with r^2 values of 0.92 and 0.93 for the power and linear regression models, respectively. The calibration equations obtained were the following:

$$H_{scal} = \alpha H_{sbuoys} + \beta \quad (\alpha = 1.047 \pm 0.024;\ \beta = 0.07619 \pm 0.047) \tag{7}$$

$$H_{scal} = aH_{sbuoys}{}^{b} \quad (a = 1.096 \pm 0.0265;\ b = 0.9847 \pm 0.0284) \tag{8}$$

Based on the previous calibration relations, the H_s data from the WW3 model in the coordinate point 11.25ºN-74.75ºW, coinciding with the location of buoy 41194, were corrected.

Fig. 4(a) compares the uncorrected H_s values of the WW3 model and the data from buoy 41194, with a D = 0.97 and a *bias(P)* = -0.06. Figures 4(b) and 4(c) compare the H_s series from buoy 41194 with the H_s series corrected using a linear and power regression model, respectively. Based on the adjustment index D and Willmott's Average Deviation P, the improvement in the adjustment degree in the H_s time series are shown in Table 1. As shown in the table, the indices show improvements of equal proportion for both models. In this sense, the linear regression model was selected for the correction of the WW3 H_s series of the 15 points selected for the analysis.

Once the information of the data for each of the 15 buoys was calibrated and validated, we proceeded to perform a detailed analysis from which a total of 8 buoys were selected as representative samples of each of the zones of interest based on the H_s value and the location of the cities and ports of interest.

As noted above, tropical cyclones occur in the season from June to November, and cold fronts occur from December to May. Therefore, the H_s time series of the 8 buoys were divided for these 2 seasons with the aim of independently performing extreme wave analysis. That is, the extreme regime was calculated considering only the H_s information for the months between June and November, and the extreme regime was also calculated taking into account only the months from December to May. Additionally, the extreme regime was calculated considering the complete series to identify which seasons of the year contributed the most to this regime. This method of presenting the results allows a comparative analysis to identify in which seasons of the year the most extreme waves for the area occur and also to establish which atmospheric phenomenon is responsible for generating these extreme waves.

The results of the application of Gumbel's theory for the significant height H_s on each of the 8 buoys are shown in Figures 5, 8, 10, and 11 in the order in which the previous results were presented.

Virtual buoys Bv01-Bv05 are located in the arid zone of the Alta Guajira, north of the Colombian Caribbean (Zone 01 in Fig. 2.). The bar diagrams in Fig. 5 explicitly show that the height of extreme waves is clearly influenced by tropical cyclones. During this period, the extreme waves associated with return periods of 5 and 10 years, oscillate between 3.2 m and 4.5 m. For return periods of 25, 50, and 100 years varying 5.5 m and 6.6 m in height. The highest waves for this region occur because Alta Guajira is the closest zone to the trajectory of tropical cyclones passing through the Colombian Caribbean (Ortiz, 2012). According to Rodríguez (2011), during this time of the year, there is a higher probability of the passage of tropical waves from the east (known as such due to their movement from east to west) that can evolve into tropical depressions, tropical storms, and hurricanes.

On the other hand, the dry season of the year, from December to May, is influenced by the increase of trade winds from the northeast (Bernal et al., 2006; Paramo et al., 2011) and the passage of cold fronts coming from the northern hemisphere, producing strong tides (Ortiz et al., 2013). Extreme wave heights for return periods of 5 and 10 years show significant heights that oscillate between 3.0 m and 4.2 m. Meanwhile, the extreme waves for return periods of 25, 50, and 100 years take significant height values that vary between 3.6 m and 4.8 m.

Regarding the waves' direction, it is considered that it is likely from E and ENE with heights mainly between 1 m and 3 m.

When comparing the extreme regime for virtual buoys Bv01 and Bv03 located in the Alta Guajira area, it can be observed that the significant heights, for return periods of 5 and 10 years that take the complete series of annual maximums, show values greater than the significant heights obtained when dividing the series by season. However, for a return period of more than 50 years, the significant height extrapolated from the cyclone season data surpasses the significant height obtained with the annual maximums. This occurs because, over the 30 years of the registry, there were 16 years in which the maximum significant height was presented in hurricane season. These values were the highest of the record (between 4.9 m and 5.2 m). In the remaining 14 years, the maximum significant height in cyclone season is lower in comparison to the wave height registered in the cold front season. This difference in the significant height for each period generates a greater dispersion in the maximums of the season from June to November. The difference in the standard deviation of data causes an increase in the slope of the line *Hs* against the return period in the semi-logarithmic space (Fig. 6) of the model for the cyclone season. In the remaining virtual buoys, there is no variation in the extreme regime when increasing the return period because all of the extreme wave events are found to be related to 1 of the 2 seasons is shown in Fig. 7.

The diagrams of Fig. 8, correspond to the central zone of the Colombian Caribbean formed by Baja Guajira, Santa Marta, Barranquilla, and Cartagena (Zone 02 in Fig. 2). Because of the geographic location of this zone in Colombia, it is important to highlight that the dry and wet climate seasons present a significant variability in the duration and intensity of the winds and the rain regime due to the influence of different events, such as the El Niño-South Oscillation event (ENSO) on its warm phase (Niño) and on its cold phase (Niña), trade winds, the passage of waves from the east, and cold fronts, among others (Nystuen et al., 1993; Andrade and Barton, 2001).

It can be seen that in Bv06, for both the cyclone season (June-November) and the cold front season (December-May), there are similar magnitudes in the extreme waves, but they present slightly higher values in the dry season, especially in the return periods of 5 and 25 years. From Bv09, it can be seen that the most energetic waves in the coastal zone of this region are influenced clearly by cold fronts. While the less energetic waves are dominated by tropical cyclones. Therefore, the extreme waves for return periods of 5 and 10 years register significant heights between 3.5 m and 4.5 m, and the extreme waves for return periods of 25, 50, and 100 years present values that vary between 4.0 m and 5.5 m in height,.

In this transition region, the behavior of extreme waves is modified because a clearer and stronger preponderance of cold fronts begins, decreasing the influence of tropical storms on this regime. This modification can clearly be seen in Fig. 8, where the extreme regime calculated considering the complete series is influenced by the maximum wave heights that occur in the cold front season.

It is important to highlight that the extreme wave height regime in an area of the central zone of the Caribbean is higher than in Alta Guajira (i.e Buoy 09). This zone of the Colombian coast ceases to be directly influenced by tropical cyclones and the extreme regime starts to prevail due to the passage of cold fronts.

In relation to the direction of the waves, it is reported that, in this sector of the central Colombia Caribbean, the NE direction is predominant with heights mainly between 1 m and 3 m. With respect to zone 01, the energy in the average regime is similar, and the direction of the wave trains is affected by the orientation of the coastline, which goes from NE to SW.

The data shown in Fig. 9, correspond to the zone known as the western Caribbean, which is formed by the area between the Morrosquillo Gulf and the Urabá Gulf (Zone 03 in Fig. 2). In this zone, regardless of the season, the wave energy is lower in comparison to the other zones of the Colombian Caribbean because the Morrosquillo Gulf is protected from winds by Boquerón Island and the other islands of San Bernardo, the Urabá Gulf is protected from waves in the eastern zone, and the Colombia bay is protected by its closed-U shape. The northwestern coast of the gulf directly receives waves originating from the open sea (Escobar, 2011). In this zone of the Colombian Caribbean, few studies have been conducted on waves, especially on waves in the Urabá Gulf.

The winds of this region also present bimodal characteristics with a predominance of strong winds from the north and northeast in the dry season. In the wet season, winds from the south and southeast predominate (Roldán, 2007). Oceanic-atmospheric factors such as winds and waves present significant differences between the dry season (December-April) and wet season (the remaining months), which in turn is in accordance with the displacement of the ITCZ (Meza et al., 1997).

The bar diagrams on Fig 9 show that the least energetic waves of the entire Colombian coast, which are mainly influenced by the passage of cold fronts, can be found in this area. The significant height for return periods of 5 and 10 years show values oscillating between 4.0 m and 4.5 m, and the extreme waves for return periods of 25, 50, and 100 years take values that vary between 4.5 m and 5.0 m in height. On the other hand, the least energetic extreme waves are dominated by tropical cyclones. In these graphics, it is evident that the extreme wave height is clearly influenced by cold fronts, which is confirmed when the values of the extreme wave heights are calculated taking into account the complete series of maximum heights. Regarding the waves' direction in the southwestern Colombian Caribbean sector, NE and NNE are predominant, with heights mainly between 1 m and 2 m. Regarding zones 01 and 02, the energy in the average regime is lower.

Bv15 is located in the insular region of San Andrés and Providencia (Zone 04 in Fig. 2). In Fig. 10 shows that extreme waves for return periods of 5 and 10 years have significant height values between 5.0 m and 5.5 m for the wet season influenced by hurricanes, while for the dry season influenced by cold fronts, the values oscillate between 4.5 m and 4.7 m. The extreme waves for return periods of 25, 50, and 100 years take values that vary between 5.1 m and 5.7 m in height for the dry season influences by cold fronts, while for the wet season, the values for extreme values oscillate between 6.2 m and 7.0 m. Because of its geographic location out over the Colombian Caribbean Sea, the islands of San Andrés and Providencia exhibit high vulnerability to tropical storms and the passage of cold fronts (Ortiz et al., 2014b). Regardless of the analyzed series, it is clearly evident that the waves generated by tropical storms are the waves that govern the extreme regime. This is because the San Andrés and Providencia islands are located in a zone where hurricanes pass.

Previous studies have revealed that, according to historical records for the years 1900 to 2013, a total of 17 hurricanes have affected San Andrés and Providencia, and in 7 of these phenomena, the eye of the storm was located less than 150 km from the islands. Of these 7 hurricanes, Joan in 1988 generated the highest wave heights, with significant height values of 5.0 m SE of the island of San Andrés in the 50-meter isobath (Ortiz et al., 2014b). The position of Bv15 coincides with the outline of the intermediate calculation grid employed by Ortiz et al. (2014b) (Fig. 11). It can be seen that the maximal significant wave height generated by the passage of Joan in the outline of the grid is 5.0 m. This value of *Hs*, according to Fig. 10, is associated with a return period of 25 years. It is important to highlight that, over the last 50 years, of all the hurricanes that have affected the island of San Andrés, only Joan has generated wave heights of 7.8 m (Ortiz et al., 2014b). Nevertheless, values higher than 5 m. have been registered during that season, due to the passage of hurricanes. In the 30-year analysis of the dry season for Bv-15 heights superior than 5 m. were not found. This finding means that wave heights in the extreme regime associated with the passage of tropical storms in Zone 04 have lower return periods than the wave heights associated with the cold fronts season.

The wind speed patterns in the San Andrés and Providencia islands are influenced by fluctuations in the Azores anticyclone, the latitudinal fluctuations of the ITCZ, the entrance of cold fronts, and the passage of hurricanes in the zone.

The wide insular platform and coral reefs located along the northeast coast act as a natural defense that dissipates the energy of waves before they reach the coast. The southwest coast is completely exposed to the extreme waves’ energy due to its narrow insular platform and scarce coral reefs (Ortiz et al., 2014b).

5 Conclusions

The present study has permitted to conclude that extreme waves along the Colombian Caribbean coasts (continental and insular) are not generated by the same forces. The geomorphology of the 1,600 kilometers of coastline of the Colombian Caribbean and its geographical position ensure that the waves generated by extreme events do not have the same magnitude of influence in all areas. There is a clear difference for the north zones (Alta Guajira), central zones (Baja Guajira, Santa Marta, Barranquilla, and Cartagena), west zone (Morrosquillo Gulf and Urabá Gulf), and the Archipelago of San Andrés because the waves’ extreme regime is influenced by the spatial and temporal changes of the atmospheric phenomena that develop over a particular zone in the Colombian Caribbean coast, depending on the dry and wet climatic seasons.

Based on the analysis of the variability of extreme waves in the continental coast of the Colombian Caribbean, it can be concluded that, in the higher part of the Guajira (Zone 01), there are higher extreme wave heights caused by tropical cyclones, which is consistent with the findings reported in Ortiz (2012), followed by the central zone (Zone 02), where the influence of extreme waves is associated with the passage of cold fronts, while less energetic extreme waves occur in the western part of the Caribbean (Zone 03), where they are mainly forced by the passage of cold fronts.

The extreme waves in the insular region of San Andrés and Providencia (Zone 04) show a dynamic different from the continental region due to its geographic location. Although the waves' heights in the extreme regime are similar in magnitude to those found for Zone 01 (Alta Guajira), the extreme waves associated with the passage of tropical storms in this zone have lower return periods than the extreme waves associated with the cold fronts season.

The previous results make a valuable contribution to the moment of determining the extreme regime and the design waves for the construction of coastal infrastructure. Furthermore, they provide an important component for the planning of alert and mitigation strategies against marine-meteorological threats. In addition, because different zones of the Colombian Caribbean are affected by coastal erosion, this study constitutes a source of data for the further analysis of how and how much these events are related to erosion.

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Table 1. Adjustment index D and Willmott's Average Deviation P, data from buoy 41194 and WW3 model.

Significant Height H_S *(m)*	*D*	*Bias(P)*
WW3 vs Buoy (41194)	0.97	-0.06
WW3 corrected with linear regression vs Buoy (41194)	0.99	0.02
WW3 corrected with power regression vs Buoy (41194)	0.99	0.02

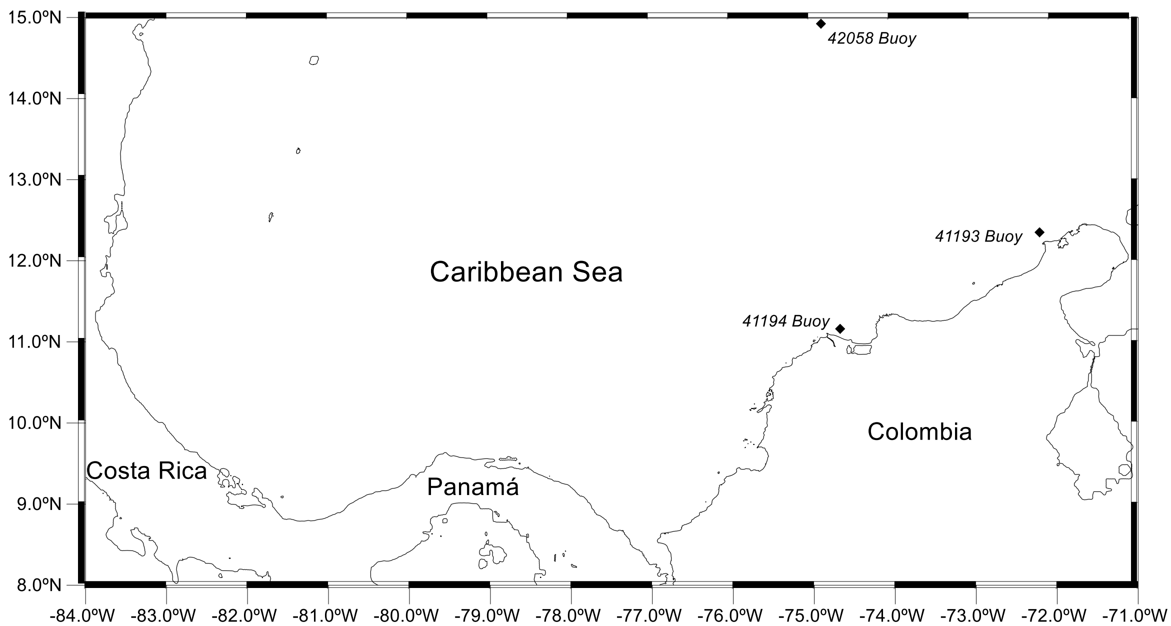


Figure 1. Location of the DIMAR and NOAA buoys on the Colombian Caribbean coast.

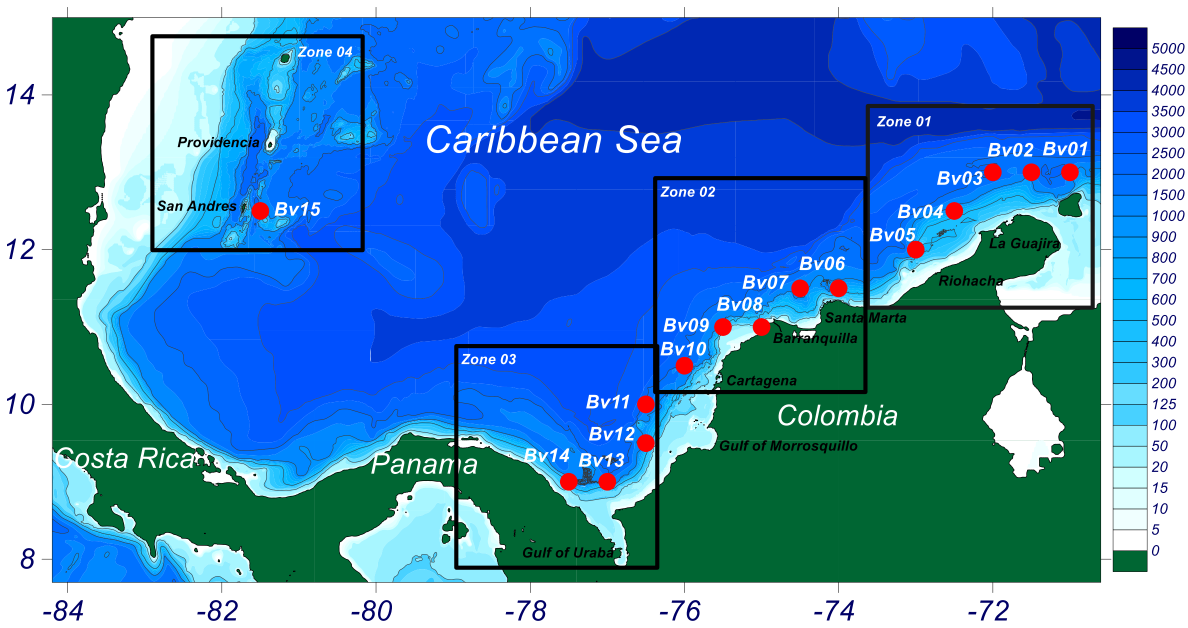


Figure 2. Location of the 15 virtual buoys generated using WW3 and the zoning proposed by Ortiz (2012) based on the threat degree of hurricanes.

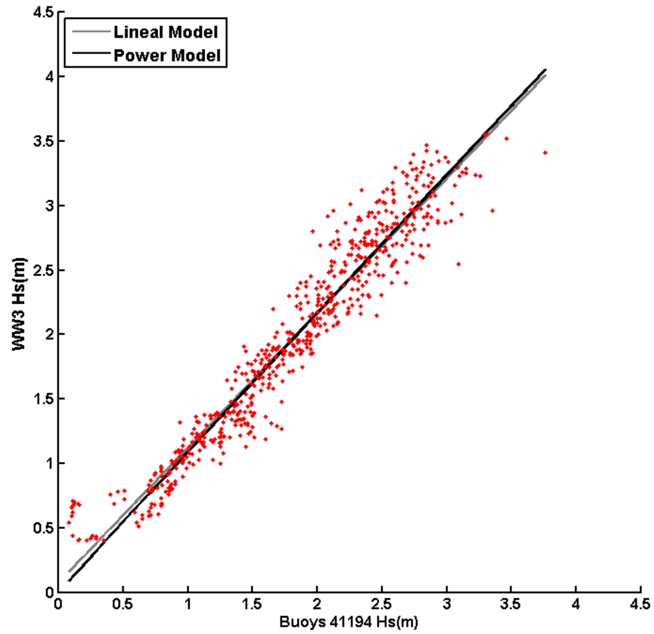


Figure 3. Scalar calibration using power and linear regression models of Hs WW3 with coinciding data from the Central Caribbean buoy (n = 594).

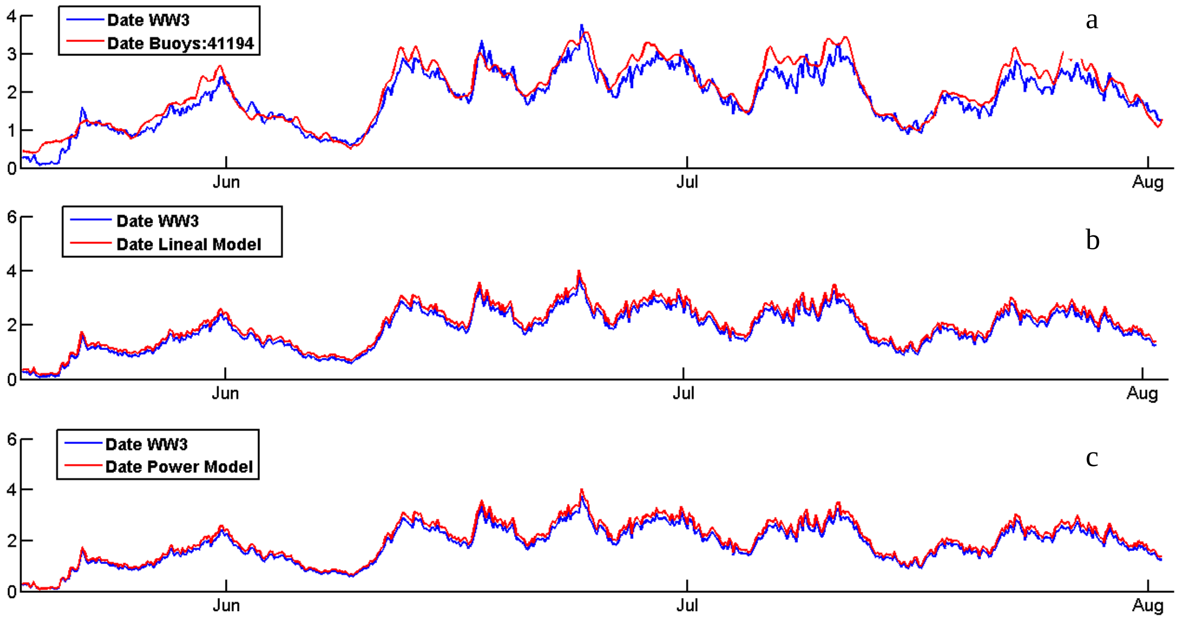


Figure 4. Validation of the *Hs* time series (m) corresponding to the year 2009 (n = 767). (4a) Buoy 41194 and WW3 data without calibration. (4b) Buoy 41194 and data corrected with the linear model. (4c) Buoy 41194 and data corrected with the power model.

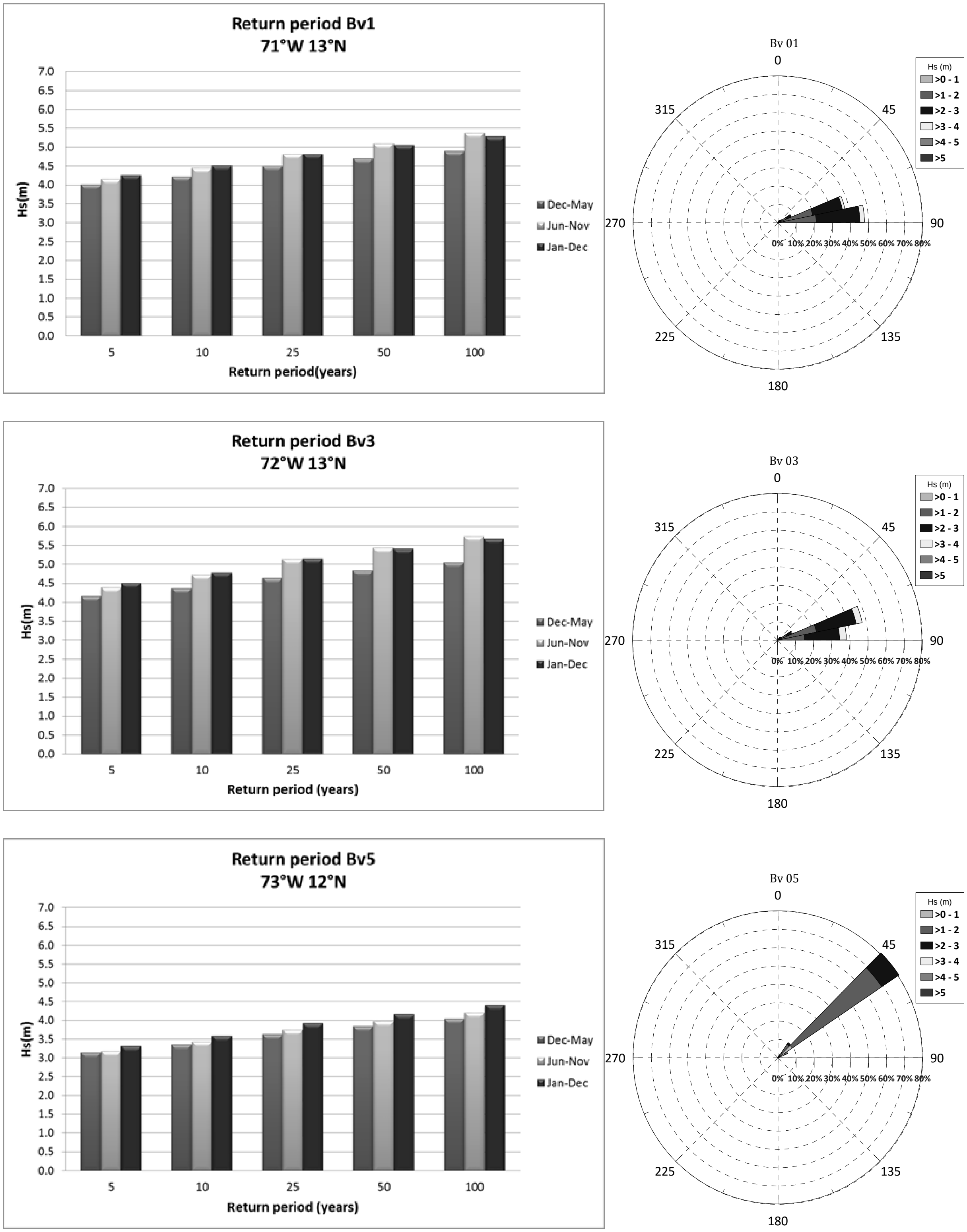


Figure 5. Return periods for H_s of virtual buoys BV01-BV05 (Zone 01).

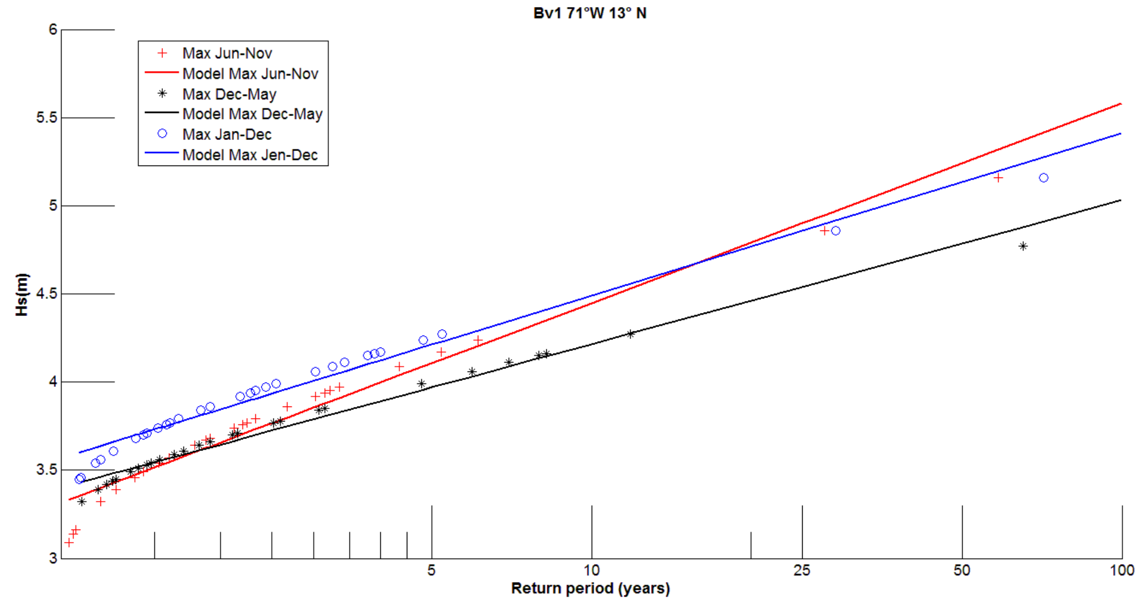


Figure 6. Comparison of the extreme wave regime in Virtual Buoy 01, considering the maximums of the complete series, the maximums of the cold front season, and the maximums of the hurricane season.

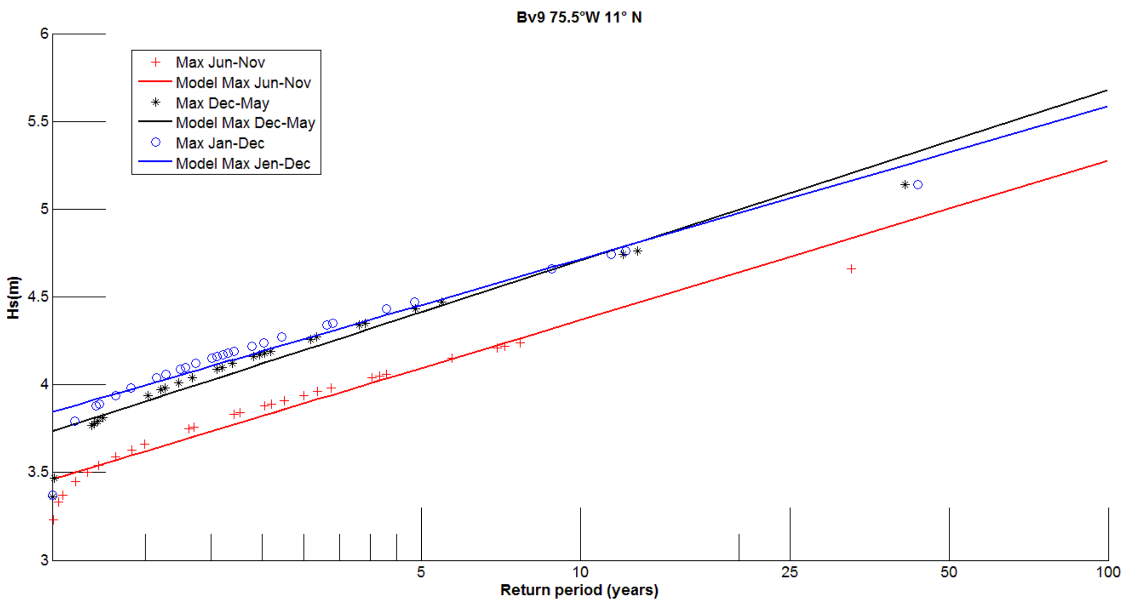
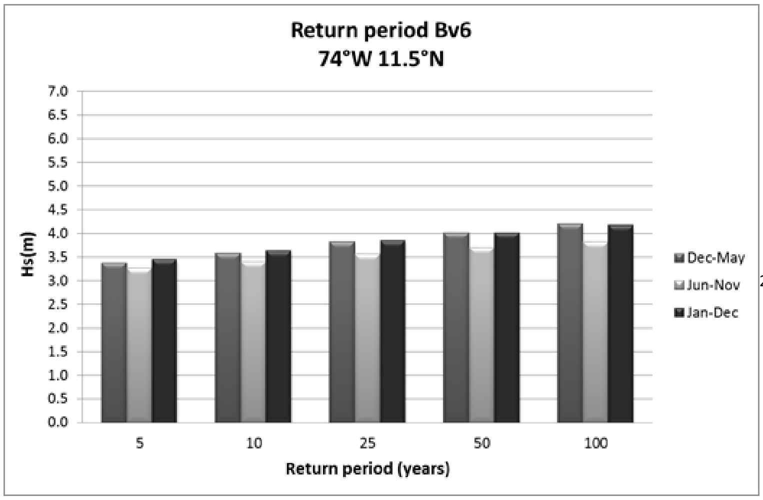
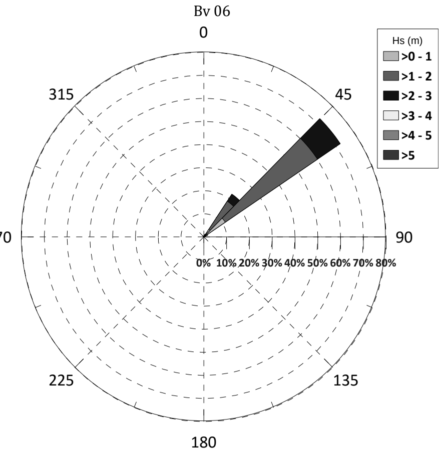
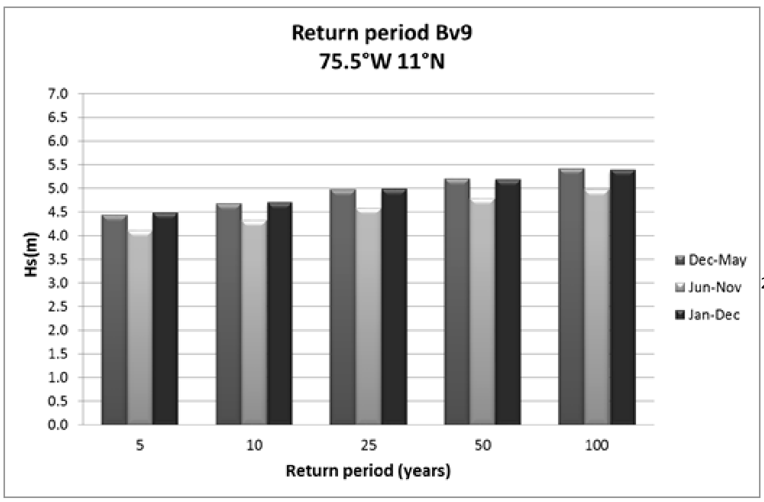
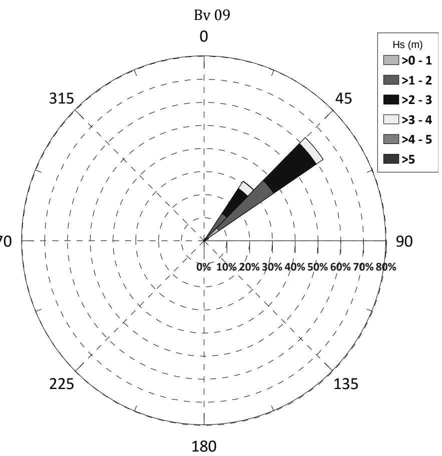


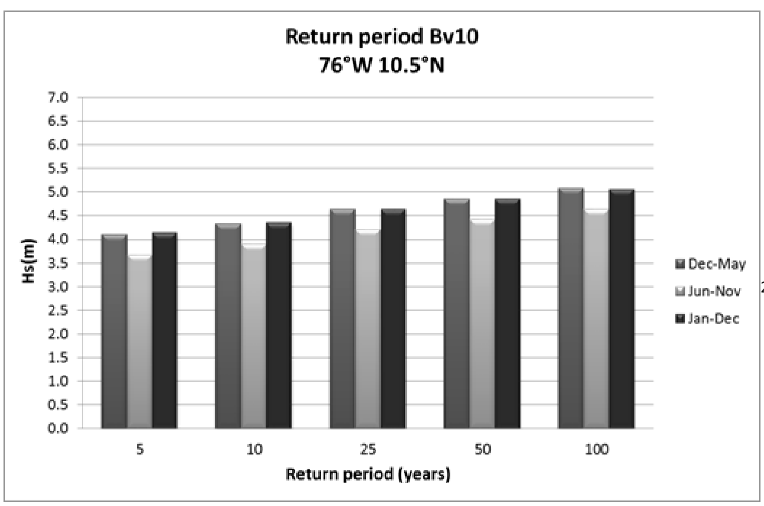
Figure 7. Comparison of the extreme wave regime in Virtual Buoy 09, considering the maximums of the complete series, the maximums of the cold front season, and the maximums of the hurricane season.











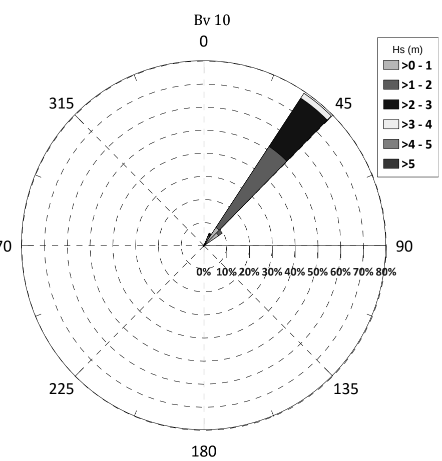


Figure 8. Return periods for Hs of virtual buoys BV6-BV10 (Zone 2).

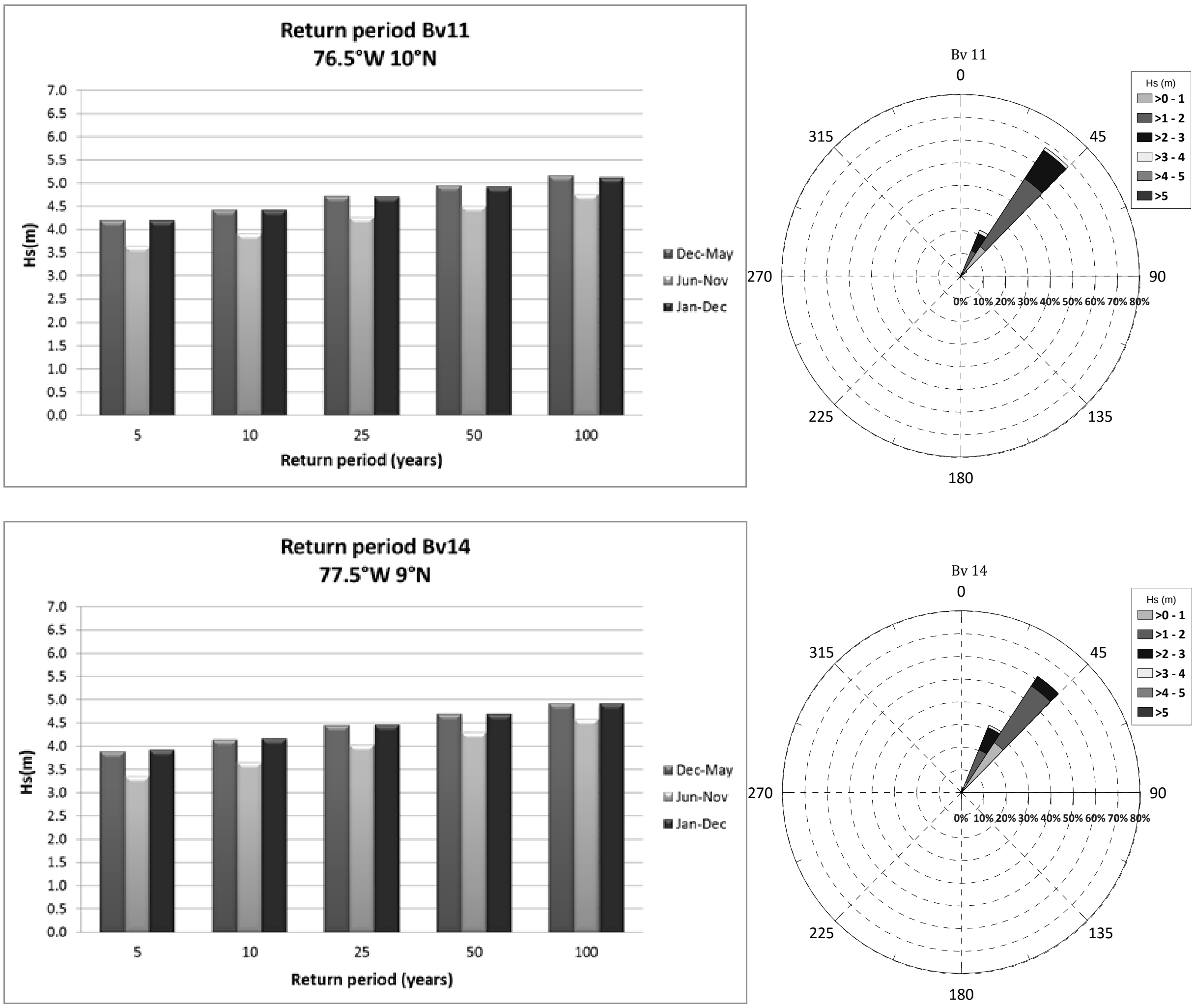


Figure 9. Return period for Hs of virtual buoys BV11-BV14 (Zone 03).

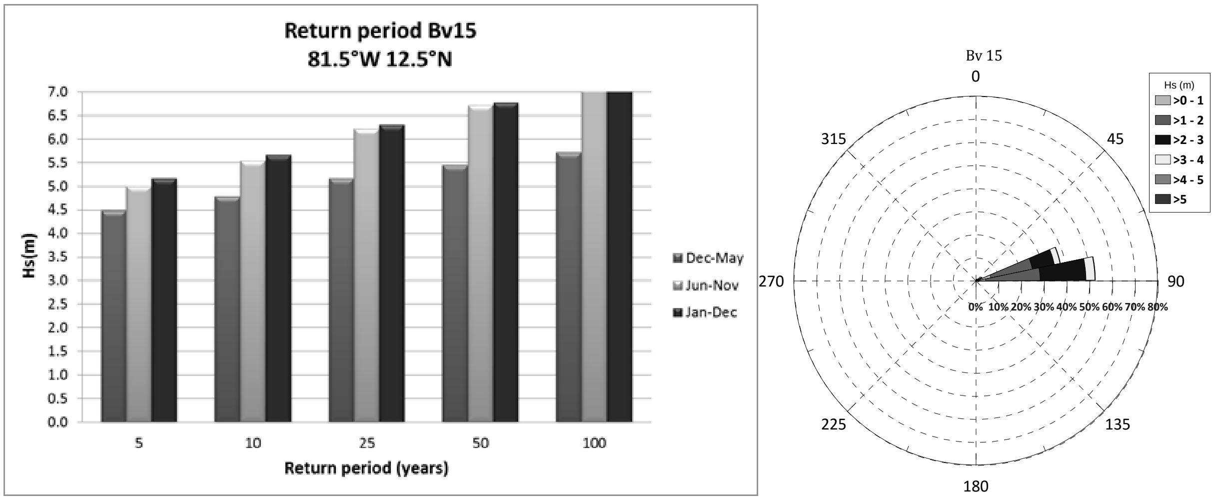


Figure 10. Return periods for Hs of virtual buoys BV15 (Zone 04).

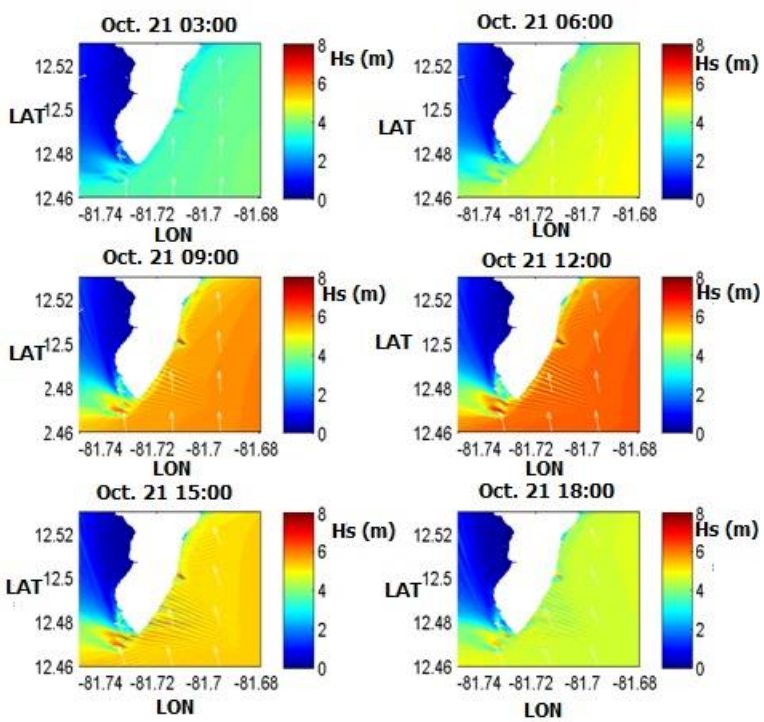


Figure 11. Significant wave height (Hs in m) fields for Hurricane Joan (1988) simulated using the SWAN model for the nested south grid in San Andres. The narrow shelf allows the energy of waves of approximately 5.0 m to affect the coastline. Source: Ortiz et al. (2014b).