



Interannual variability of wave climate in the Caribbean Sea

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Abstract

Low-frequency interannual climatic oscillations have been reported to influence the precipitation regimes, river discharges, winds, and sea level in the Caribbean Sea. Here, we analyzed the presence and relevance of low-frequency oscillations in the waves' climate of the Caribbean Sea using data from WAVEWATCH III (NOAA) reanalysis and applying frequency domain wavelet transform technique. Results show a clear sectorization of the Caribbean Sea according to the presence and relevance of interannual oscillations in wave climate, where the southwestern region (Colombian basin) exhibits a larger number of statistically significant oscillations (at 95% confidence levels) with recurrence periods of 2–4, 4–8, and 8–12 years. Only some of these frequencies are observed in the rest of Caribbean basin. Two climatic events occurring in the periods 1997–1998 and 2010–2011 stand out in the study zone for their high energy in wavelet analysis. These events have been associated with the occurrence of the warm and cold phases of the El Niño Southern Oscillation (ENSO), respectively, and are well known due to their strong global effects on hydroclimatology. Thus, an additional analysis was performed in the time domain to investigate the effect of the two events on Caribbean Sea waves. The results revealed an influence of ENSO on significant wave height and peak period comparing with multi-year average conditions, producing highly variable spatial and temporal wave patterns, with more evident effects during the cold phase of ENSO (La Niña). These results confirm the sectorization of the Caribbean Sea regarding the energy and interannual variability of waves.

Keywords Waves · Caribbean Sea · Interannual variability · ENSO

1 Introduction

The Caribbean Sea is the third largest sea of the planet, its basin covers an area of approximately 2,753,000 km², and is located between latitudes 9° N–22° N and longitudes 89° W–60° W, has about 7000 islands among 25 countries, owns the 14% of coral reef in the world, and its blue beaches are one of the most popular tourist destinations worldwide. Its basin is divided into four sub-basins: Venezuela, Colombia, Yucatan, and Cayman. The Caribbean Sea presents four marked

seasons (Poveda 2004): a main dry season between December–February (DJF), followed by a secondary rainy season in March–May (MAM), a secondary dry season between June–August (JJA) when the Caribbean low-level jet (CLLJ) intensifies (Amador 1998), and a main rainy season (Gamble and Curtis 2008) in September–November (SON). This climatological variability is caused by latitudinal oscillation of the intertropical convergence zone (ITCZ) (Schneider et al. 2014).

Previous studies have identified a relationship between interannual climatic oscillations and the hydrology and oceanography of the Caribbean Sea. In particular, a strong influence of El Niño/Southern Oscillation (ENSO), the most energetic interannual climate signal at global level (Neelin et al. 1998), has been reported on many climatic variables such as precipitation, humidity, and temperature, for which a spatial differentiation has been identified between the southwest and northeast regions during ENSO (Bernal et al. 2006). It was also shown that the flow of major rivers into the Caribbean Sea basin increases during the cold phase of ENSO (La Niña) and decreases during the warm phase (El Niño) (Restrepo and Kjerfve 2000). Additionally, ENSO is the main responsible for the interannual variability of water levels in the

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Caribbean Sea (Torres and Tsimplis 2012). On the other hand, there is an apparent decrease in the frequency of tropical storms in the warm phase, due to increased wind speed during the Caribbean hurricane season (Ortiz-Royero et al. 2013). Finally, an inverse behavior of winds was found between the first (June–November) and second semesters (December–May) of ENSO, with direct consequences for currents and waves in the basin (Ruiz-Ochoa et al. 2012), (Ruiz-Ochoa and Bernal 2009).

Meanwhile, the effect of interannual climatic oscillations in wave climate has been scarcely investigated. Osorio et al. (2016) identified a weak and variable influence of ENSO on the waves of southwestern Caribbean Sea analyzing four locations. Additionally, Reguero et al. (2013) investigated the variability of wave climate at Latin American scale and found that The North Tropical Atlantic and The Tropical South Atlantic indices, the south Annular Mode and El Niño Southern Oscillation are some of the most important features for wave climate variability in the region. They also found that during El Niño events there is a higher frequency of occurrence on the most representative sea-states with respect to non ENSO years. We did not identify other studies analyzing long-period oscillations in wave climate and covering the whole Caribbean basin. Here we present a new characterization of the interannual variability of the wave climate of the Caribbean Sea, based on analyzing the frequency and time domains, and with special emphasis on two highly-energetic interannual events. Finally, we present a sectorization of the Caribbean Sea regarding the presence of distinct interannual oscillations in wave climate.

2 Methodology

Since in situ oceanographic and climatological information on the Caribbean basin is scarce, studies often rely on reanalysis databases (Ortiz-Royero et al. 2013; Andrés Fernando Osorio et al. 2017). This study was based on the NOAA wave reanalysis database generated with the WAVEWATCH III model (Tolman 2007), covering 38 years of information (1980–2017) of main wave parameters: significant wave height (SWH), peak period (TP), and mean wave direction (MWD). The temporal resolution of the model is 3 h and the spatial resolution for the Caribbean Sea is 0.16° by 0.16° . This database has been calibrated and validated against altimetry (Ray and Beckley 2003) and in situ oceanographic data (Bitner-Gregersen and Guedes Soares 2007).

Twenty uniformly distributed nodes of the model—virtual buoys (VB)—spaced by 1.8° in latitude and 4° in longitude were selected for frequency domain analysis throughout the Caribbean basin (Fig. 1). SWH series were pre-processed into daily SWH anomalies, by extracting the long-term daily mean wave cycle and detrending and normalizing the data. Wavelet

spectral analysis was applied to the processed series following the methodology described by Torrence and Compo (1998). The wavelet transform represents a time series through transposed and expanded versions of a finite wave, thereby identifying oscillations whose energy varies in time and frequency, in contrast to the Fourier transform that assigns a fixed energy at each frequency (Addison 2017). Wavelet analysis thus allowed the identification of relevant interannual frequencies in data at each VB and the time intervals where these dominant frequencies produced significant variations in SWH.

Given the substantial influence of ENSO on the climatology of the Caribbean, special interest was given to oscillations in the interval of 2–8 years' characteristic of ENSO (Neelin et al. 1998). These recurrence periods, the sum of the energy by frequencies (or scale-average time series) was calculated for two subgroups in order to analyze separately the effects of the two phases of ENSO on SWH; the first subgroup including the energy within the shortest recurrence period in the interval from 2 to 4 years (related to El Niño or warm phase of the ENSO), and the second including the energy within the longest period from 4 to 8 years (related to La Niña or cold phase of ENSO) (Osorio et al. 2017). On this way, it was possible to identify the most energetic El Niño and La Niña events in the last decades and the spatial patterns of their influence in the Caribbean Sea. To investigate in more detail, the temporal and spatial behavior of waves during these most energetic events identified with the wavelet analysis, a time domain analysis was performed for the SWH and TP including all VB in the reanalysis database for the Caribbean Sea. This analysis consisted on identifying absolute and relative differences in SWH and TP in a quarterly basis, during the occurrence of these events, comparing with the long-term climatology. The same analysis but on a monthly basis was performed in four observation points of interest (red boxes in Fig. 1), located in the southwest Caribbean. The time domain analysis for these selected two events started in June of the first year of the event and ended in May of the following year, corresponding to the start of ENSO events (spring in the northern hemisphere) (Poveda 2004).

3 Results

3.1 Frequency domain analysis

As an example of the results of wavelet analysis performed for the twenty VB, Fig. 2 shows the wavelet power spectrum, global wavelet spectrum and scale-average time series for the VB9 located southwest of the study area. This analysis allowed to identify the variability of energy as a function of time and frequencies based on the power spectrum (Fig. 2b), the recurrence periods (or frequencies) with highest energy based on the global spectrum (Fig. 2c), and the time intervals

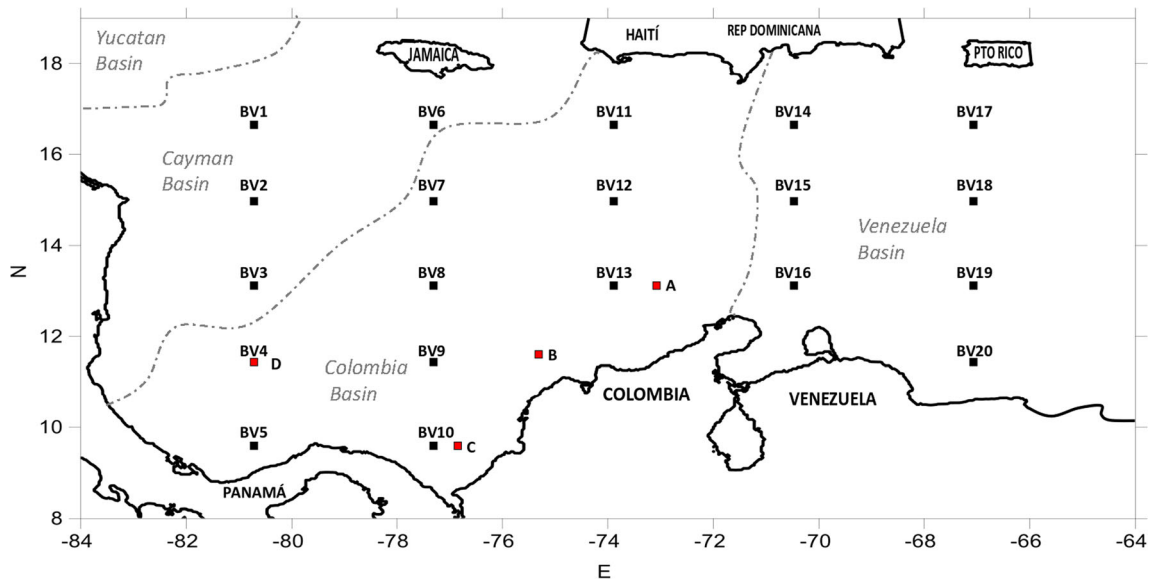


Fig. 1 Study area. Black boxes indicate location of virtual buoys (VBs) selected for Wavelet analysis. Red dots show location of VBs selected for the analysis of temporal anomalies

where a frequency range presents higher energies based on scale-average series. Red lines in all sub-plots in Fig. 2 represent a level of statistical confidence of 95%. The trend toward zero at the beginning and ending of the scale-average time series (Fig. 2d) is due to the reduced observation windows at the start and end of the finite series. In the case of the scale-average time series with a recurrence period of 4–8 years, a growing trend after 2010 can be inferred, but there is not yet a long enough wave record available to confirm it because wavelet method limits the signal frequencies that can be described with statistical significance to those $\geq \frac{2}{T-t_i}$ where T is

the length of the time series and t_i is the moment in time that wants to be analyzed (Torrence and Compo 1998). For 2010, $T - t_i = 8$ years; therefore, only oscillations with period lower than 4 years can be analyzed with significance. A 16-year record after 2010 would be necessary to analyze low-frequency ENSO oscillation (4–8 years).

Figure 3 shows the global wavelet spectrum of SWH anomalies from all 20 VB. It can be seen that wave energy increases from east to west and from north to south of the Caribbean Sea, due to the prevailing direction of winds from northeast to southwest (Amador 1998). Overall, there are four

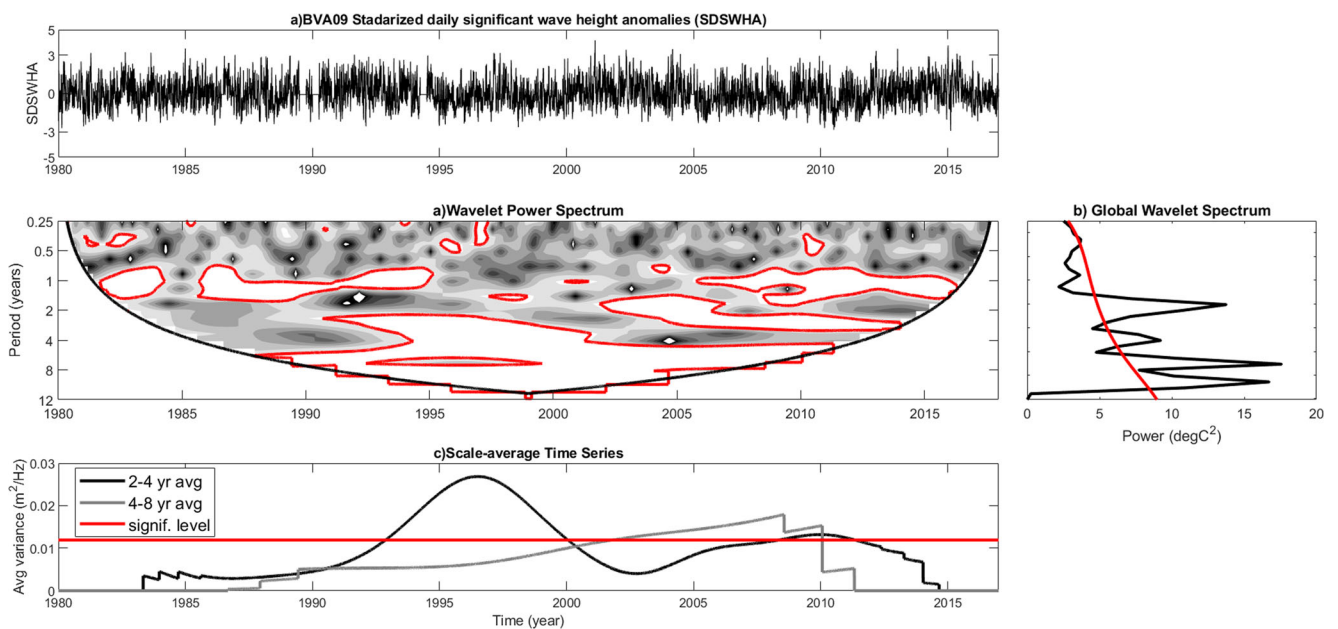


Fig. 2 Wavelet frequency analysis for point VB9. **a** Standardized significant daily wave height anomalies. **b** Wavelet power spectrum. **c** Global Wavelet spectrum. **d** Scale-average time series. Red lines represent confidence interval of 95%

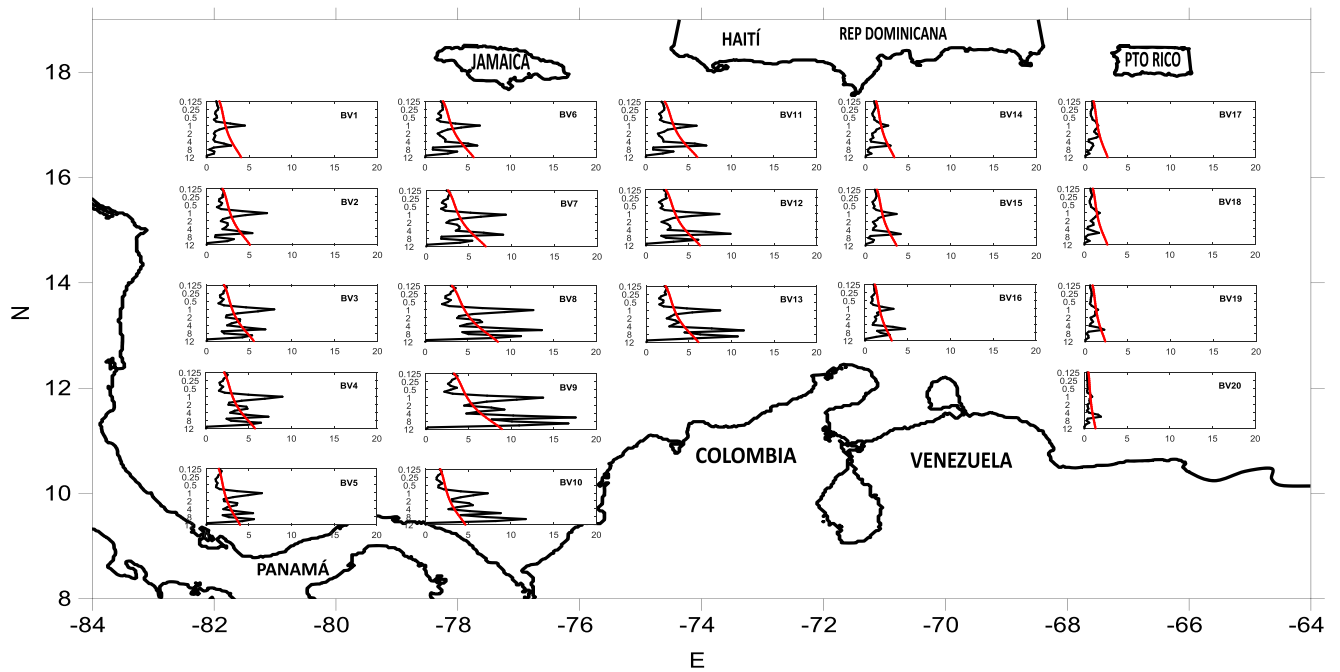


Fig. 3 Global wavelet spectrum for the analyzed VBs. Vertical axis represents period (in years) and horizontal axis represents density of variance (m^2/Hz). Red lines represent confidence level 95%

periods of interannual oscillation whose energy is statistically significant in some or all VB, which allows the segmentation of the Caribbean Sea according to the presence of a significant oscillation frequency. The periods are:

- (i) One year, related to the annual cycle and found in all VB.
- (ii) Two to 4 years, found in the southwest Caribbean (Colombia basin), at points VB3, VB4, VB5, VB8, VB9, VB10, and VB13.

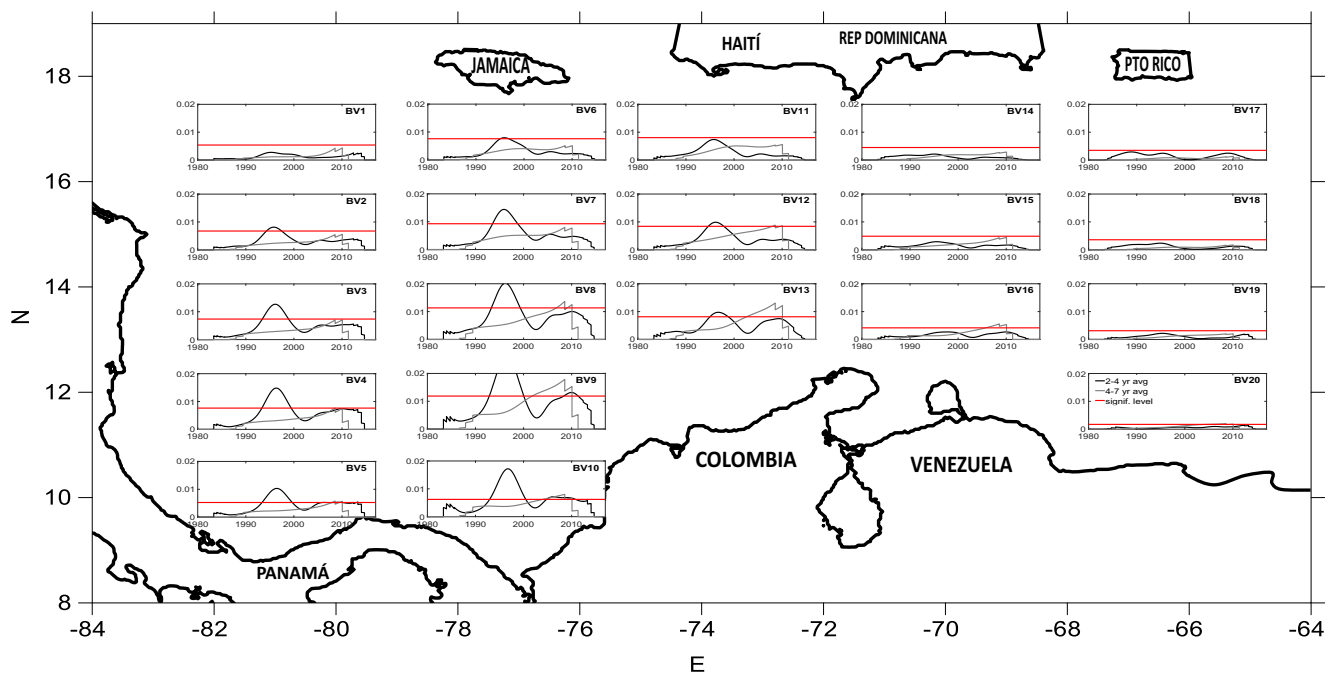


Fig. 4 Scale-average time series for the selected VBs. Vertical axis represents average variance of energy (m^2/Hz) and horizontal axis represents time (years) in the observation window (1980–2017). Red lines represent level of confidence of 95%. Black lines represent energy in the recurrence periods of 2–4 years, and gray lines represent energy in the periods of 4–8 years

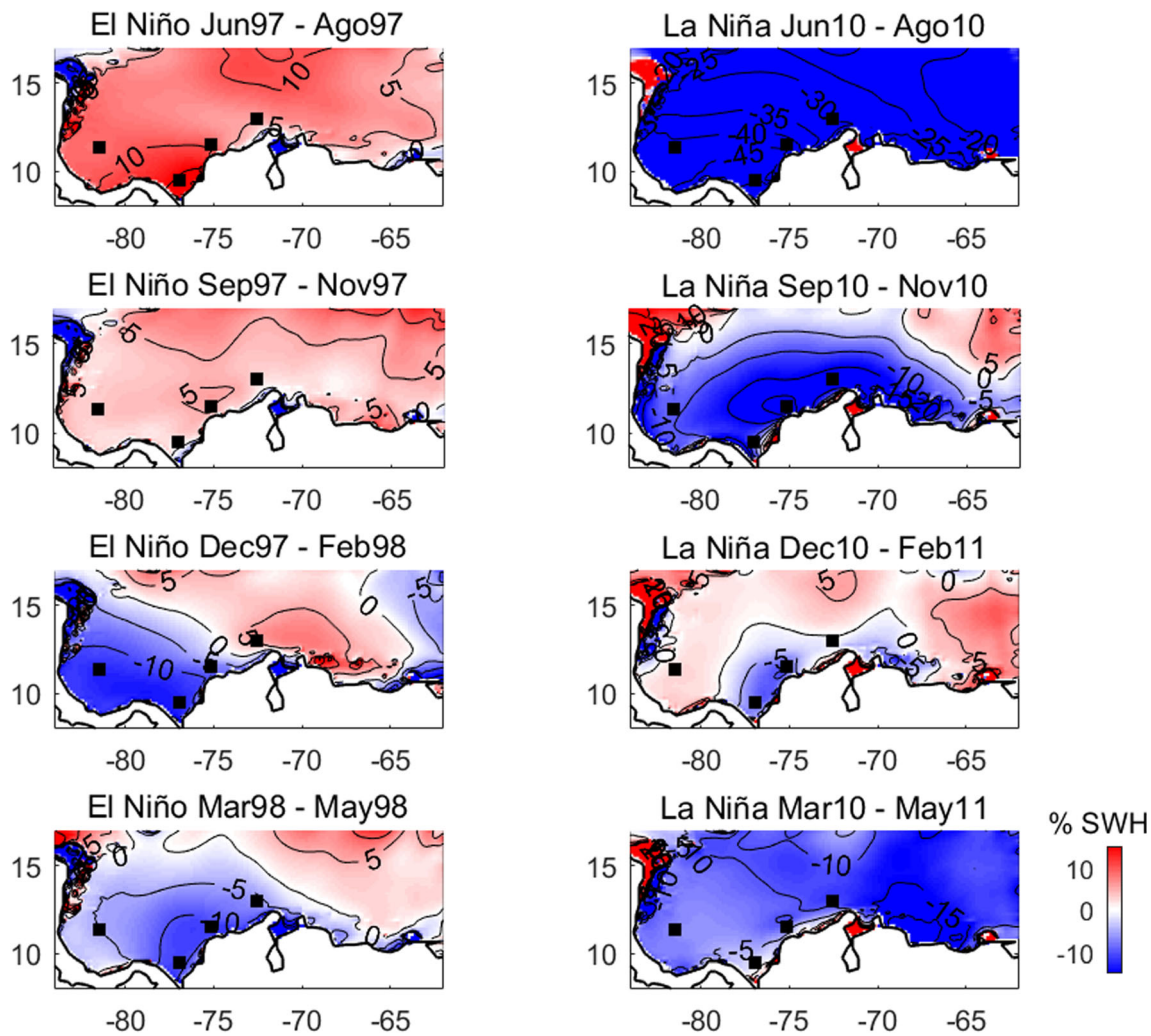


Fig. 5 Mean quarterly SWH relative differences with respect to climatology during El Niño (1998–1999) and La Niña (2010–2011) events. Blue color indicates decreases and red color increases with

respect to the climatology. Squares represent location of VBs selected for the analysis of monthly anomalies

- (iii) Four to 8 years, found in all VB except for VB17 and VB18.
- (iv) Eight to 12 years, found in the Colombia basin, at points VB3, VB4, VB5, VB8, VB9, VB10, VB12, VB13, and VB16.

The first significant period, the annual cycle is an expected signal detectable even in anomalies series since it is a strong factor of climate variability. This recurrence period was excluded from our study as it has been broadly analyzed in previous studies (Calverley et al. 2002; Appendini et al. 2014; Osorio et al. 2016).

The second and third significant periods respectively coincide with the two dominant frequencies of ENSO (Barnett 1991), the quasi-biennial (QB)-type ENSO with a period of 2–3 years, and the low-frequency (LF)-type ENSO (or quasi-quadrennial-type) with a typical period of 4–7 years. Additional

evidence of its relation with ENSO is provided by the scale-average time series for the periods of 2–4 years and 4–8 years (Fig. 4), which show maximum energy values respectively in the time ranges of 1993–1999 and 2003–2010. The latter range seems to extend beyond 2010, but this inference cannot be confirmed with the available observation window.

The previous time ranges can be related with the two dominant frequencies of ENSO, since during the period between 1993 and 1999, characterized by high QB-type ENSO energy according to the scale-average time series, an abrupt decaying of El Niño and a fast transition to La Niña occurred, as shown by the Multivariate ENSO Index (MEI) (<https://www.esrl.noaa.gov/psd/ens/mei/>), this behavior is expected to occur when the QB-type ENSO is dominant (Kim and Kim 2002). On the other hand, in the period 2003–2010, characterized by high LF-type ENSO energy this abrupt decaying of El Niño and transition to La Niña did not took place; on the contrary, two prolonged La Niña events occurred consecutively with a

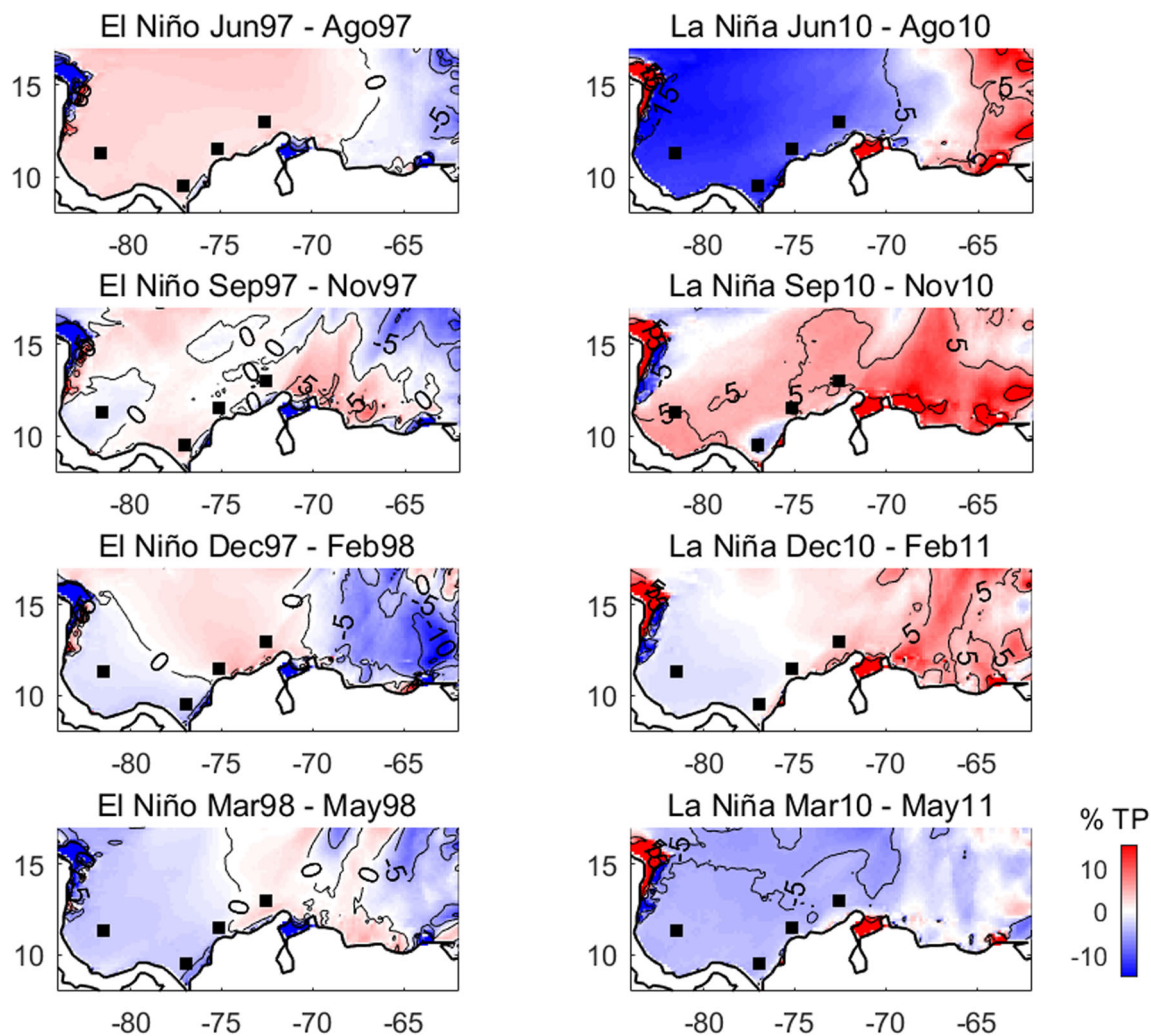


Fig. 6 Comparative differences in quarterly TP with respect to climatology during El Niño (1998–1999) and La Niña (2010–2011) events. Blue color indicates decrease and red color indicates increases

with respect to the climatology. Squares represent location of VBs selected for the analysis of monthly anomalies

year of weak positive anomalies in between. The first time range (1993–1999) coincided with the occurrence of the strong El Niño event of 1997–1998 (Wolter and Timlin 1998), while the second (2003–2010) coincided with the strong La Niña event of 2010–2011 (Euscátegui and Hurtado 2011). The climatological and hydrological effects of these two ENSO events have been previously reported in the Caribbean Sea (Cadena et al. 2006; Hoyos et al. 2013; Ruiz et al. 2002). The influence of these events on SWH changes across the basin area, exhibiting higher energy in the southwest Caribbean.

Regarding the fourth predominant quasi-decadal period of 8–12 years, there is little reported evidence about this frequency in climatological and oceanographic studies of the Caribbean Sea, possibly due to the lack of sufficiently long records. We postulate a hypothesis about the nature of this recurrence period in the discussion section.

3.2 Temporal domain analysis

This analysis evidenced the spatial and temporal effects of the events El Niño 1997–1998 and La Niña 2010–2011 (the most energetic interannual signals in the studied time frame) in the SWH and TP of Caribbean Sea, comparing with the long-term wave climatology. Figure 5 shows results of the quarterly analysis of SWH for the whole basin, with positive values indicating an increase of SWH with respect to climatology and vice versa. It can be claimed from Fig. 5 that (i) there is mainly an increase in SWH during El Niño and a decrease during La Niña comparing with the climatology, (ii) wave height reduction during La Niña is stronger than wave height increase during El Niño, and (iii) the first quarter of the hydrological year (JJA) exhibits the strongest and most widespread effects of ENSO in the Caribbean Sea.

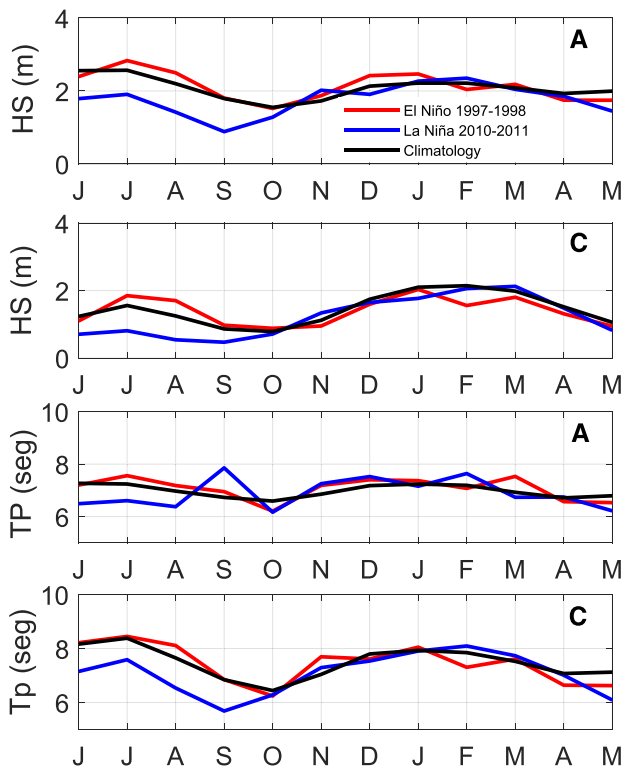
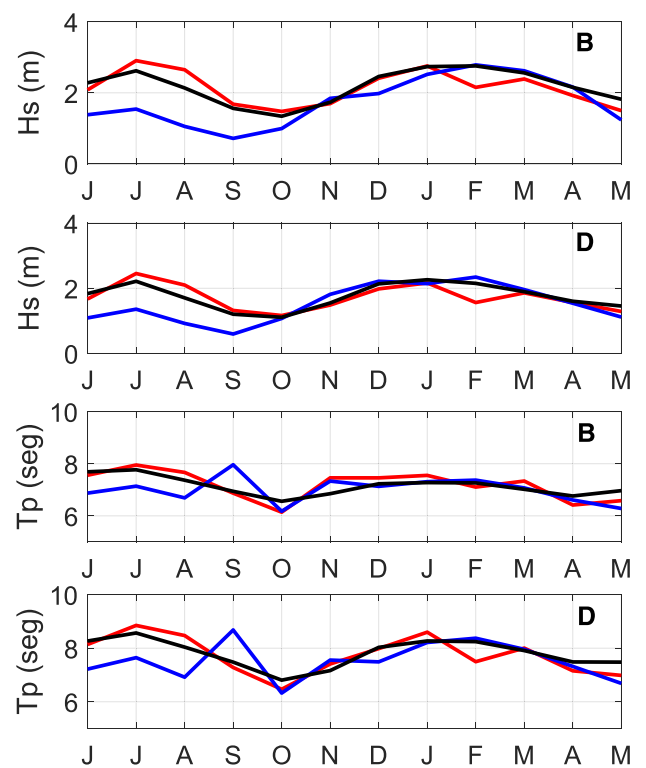


Fig. 7 Monthly average of SWH and TP for different phases of ENSO in four points of the most energetic zone of the basin. **a** North, **b** center, **c** south of the Colombian continental coast, and **d** archipelago of San



Andrés and Providencia. Red lines show wave averages for the 1997–1998 period, blue lines represent the 2010–2011 period, and black lines correspond to the climatology

More specifically, during El Niño, there is an increase between 5 and 10% in SWH during JJA and SON, while in DJF and MMA, a bipolar behavior is observed, with decrease in

SWH of up to 10% in the southwest area, and a slight increase below 5% elsewhere in the basin. On the other hand, during La Niña there were strong reductions in SWH during all quarters

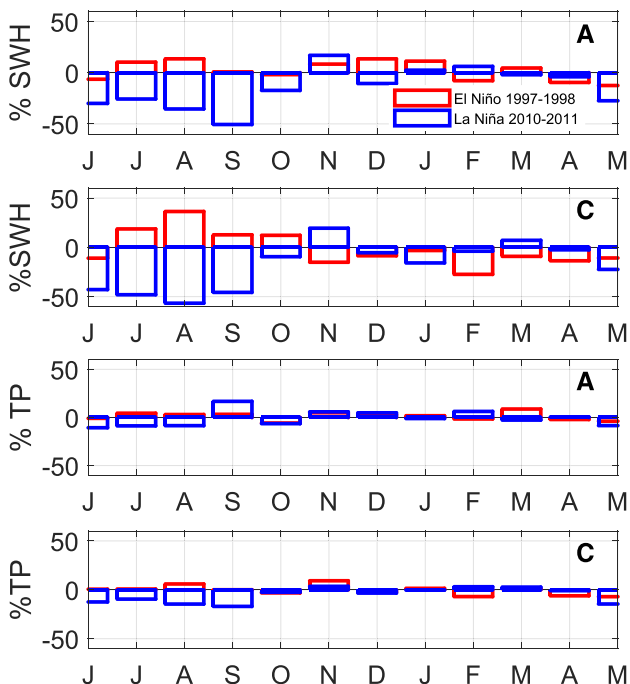
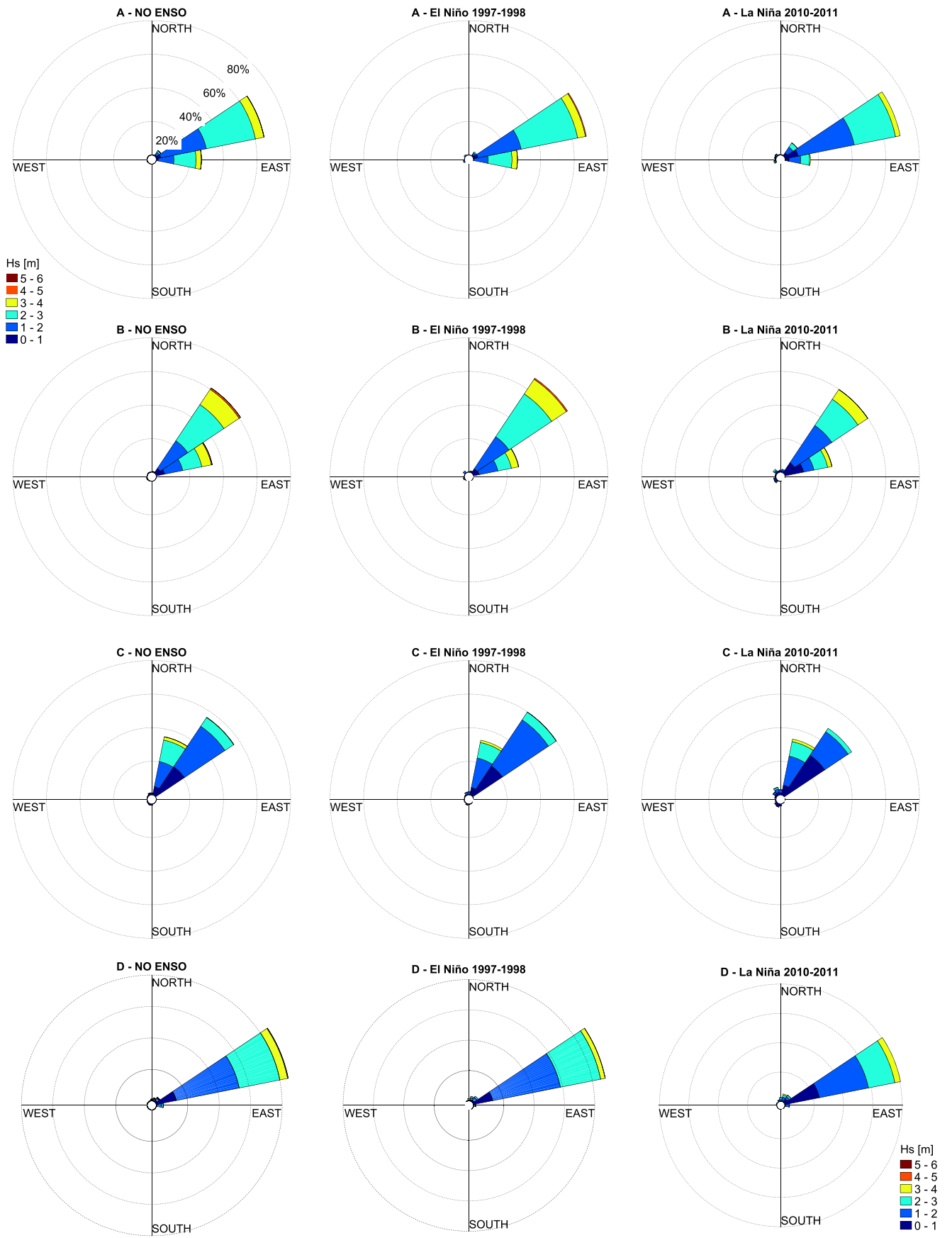


Fig. 8 Percentage changes in SWH and TP monthly mean for both phases of ENSO. **a** North, **b** center, **c** south of the Colombian continental coast, and **d** archipelago of San Andrés and Providencia. Red lines represent the 1997–1998 period. Blue lines represent the 2010–2011 period



◀ **Fig. 9** Quarterly wave displays of climatology (right column), El Niño 1997–1998 (center column) and La Niña 2010–2011 (left column) for quarters: **a** JJA, **b** SON, **c** DEF, and **d** MAM

but DJF, when effects were negligible and under 5% in most of the basin. During JJA, wave reduction reached 45%, with the southwest area showing again the greatest changes. Meanwhile, Fig. 6 shows the results of the quarterly time domain analysis for TP, revealing smoother variations and more complex patterns than in the case of SWH. In general, increases and decreases of TP are lower than 10% comparing with the climatology. Additionally, for most cases, there is a direct correlation between the variability patterns of SWH and TP.

The above results indicate that the southwestern Caribbean or Colombia basin exhibits the highest interannual wave variability associated with ENSO. For this area, a more detailed monthly time-domain analysis was performed for SWH, TP (Figs. 7 and 8), and MWD (Fig. 9), showing the variations in the mean monthly wave climate during ENSO events at four locations corresponding to (A) north, (B) central, and (C) south Colombian continental coast, and (D) near San Andrés and Providencia archipelago (Fig. 1, boxes highlighted in red). Results from Fig. 7 show that the highest SWH in the Caribbean Sea occur during the DJF dry season, when the intertropical convergence zone (ITCZ) is in its southernmost position in the Amazon basin (Bernal et al. 2006), with strong northeastern winds crossing the Colombian Caribbean Sea. Another increase in SWH occurs in July, as the Caribbean low-level jet intensifies (Andrade and Barton 2000). On the other hand, the lowest waves occur during SON, when the ITCZ is over the Caribbean Sea and winds are reduced.

Figures 7 and 8 shows that the impacts of ENSO on SWH are higher in the first semester of the hydrological year (June–November) than in the second semester (December–May), especially during La Niña, when reductions of up to 50% in SWH across the four points are observed. During the second semester at location A, successive increases and reductions of up to 15% in SWH are observed, while at locations B, C and D, SWH is not

significantly affected by ENSO. Variation in TP matches the pattern observed in SWH although increases and reductions do not exceed 20% with respect to the mean, suggesting a weaker effect of ENSO on this parameter. Finally, MWD showed little variation in response to ENSO across the four points (Fig. 9), in accordance with previous studies that claim that ENSO primarily affects wind speed magnitude rather than wind direction in the Caribbean Sea (Ochoa and Bernal 2009).

4 Discussion

4.1 Caribbean low-level jet and ENSO

According to Figs. 5 and 8, the occurrence of ENSO mostly affects the wave climate of the Caribbean Sea during the quarter JJA; this may be related with alterations of the CLLJ during the occurrence of ENSO (Stensrud 1996). The CLLJ is an increase in the Caribbean wind regime generated by southern gradients of atmospheric pressure in the low troposphere (Muñoz et al. 2008) as a result of differences in sea surface temperature between the tropical Atlantic and Pacific Oceans (Wang 2007). The CLLJ approximately covers the area between 12°–16° N and 71°–76° W (McPhaden et al. 2006), with a core at 15°N, 75°W (Schneider et al. 2014), and exhibits the highest wind speeds (over 11 m/s) during JJA (Stensrud 1996). Appendini 2015 found that the CLLJ modulates the wave climate in the central Caribbean Sea.

The atmospheric pressure gradients that determine CLLJ intensity are modified by heating (during El Niño) or cooling (during La Niña) of the tropical Pacific Ocean during ENSO, especially in JJA, when the CLLJ is most intense (Wang 2007; McPhaden et al. 2006). Warm anomalies in the tropical Pacific temperature during El Niño intensify CLLJ in JJA by increasing the surface temperature gradient between the North Atlantic Ocean and the Pacific Ocean and thus the pressure gradient in the lower troposphere. The

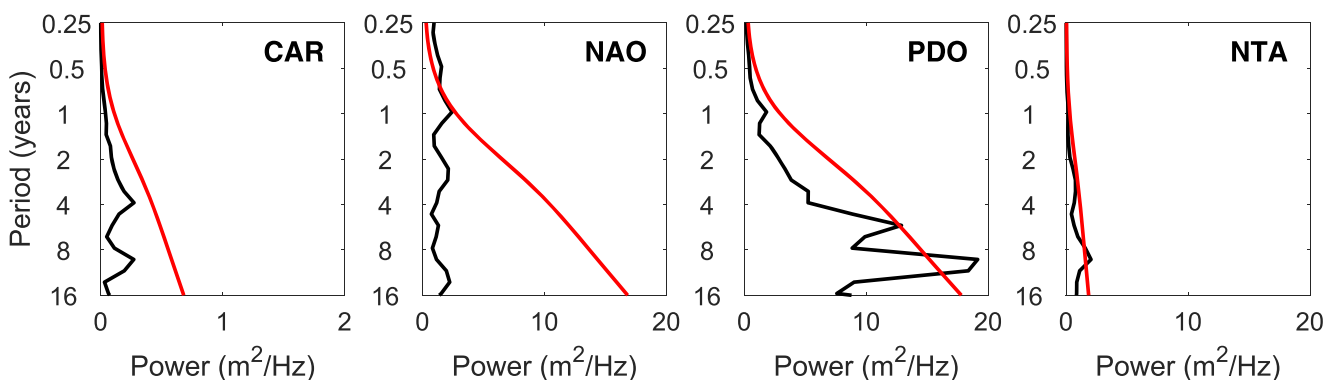


Fig. 10 Global wavelet spectrum for CAR, NAO, PDO, and NTA indexes

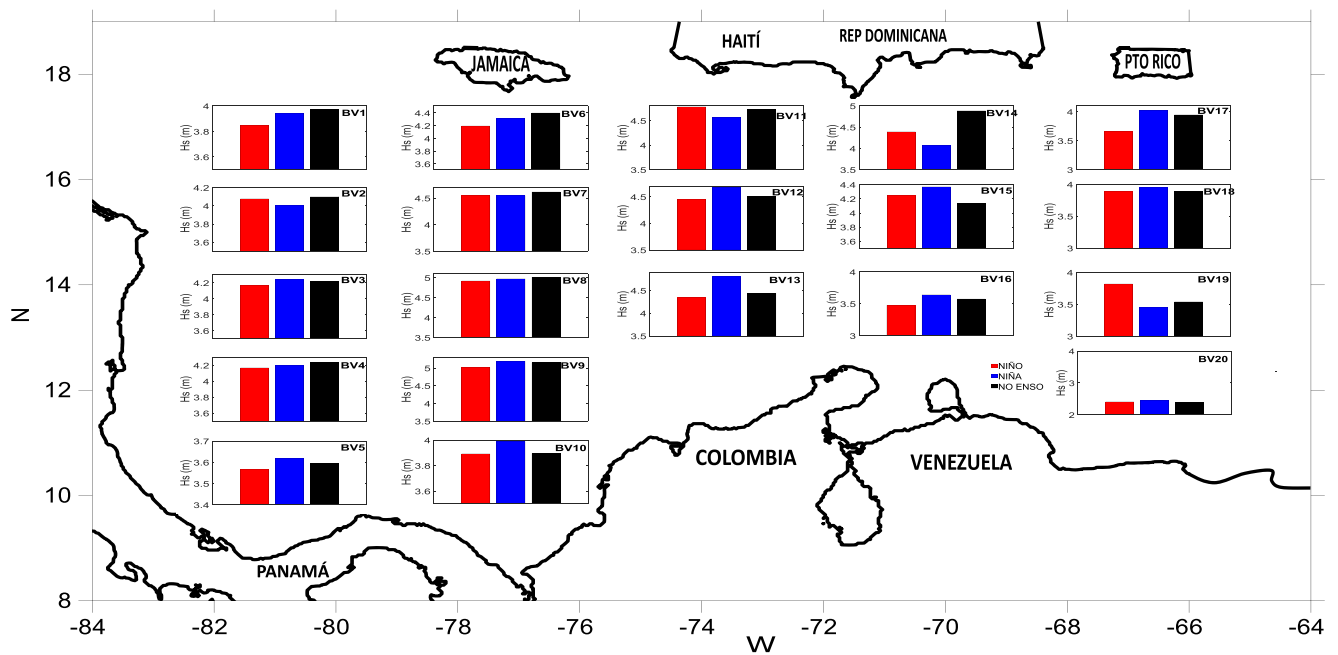


Fig. 11 Average SWH extremes in selected VBs during the warm phase of the ENSO (red bars), cold phase of ENSO (blue bars), and non-ENSO periods (black bars)

opposite effect (weakening of the CLLJ) occurs during La Niña, when the temperature gradient between the two oceans decreases. This explains why the greatest changes in Caribbean Sea waves during ENSO events take place in the June–August period.

4.2 Quasi-decadal oscillation in wave climate

To analyze the possible causes of the quasi-decadal oscillation with recurrence period of 8 to 12 years, revealed to be significant by the wavelet analysis, the global wavelet spectrum was calculated in the period 1950–2017 for the macroclimatic indexes Caribbean (CAR), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and North Tropical Atlantic (NTA); these indices can be found in <https://www.esrl.noaa.gov/psd/data/climateindices/list/>, which provide information on interannual variability patterns in the Atlantic Ocean, Pacific Ocean, and Caribbean Sea. Significant frequencies in those indexes in similar quasi-decadal periods could demonstrate teleconnections or causal relationships with the wave climate of Caribbean Sea.

Figure 10 shows that PDO (Mantua and Hare 2002) and NTA (Handoh et al. 2006) indices show energies that exceed the level of confidence of 95% in the recurrence period of 8–12 years, while the CAR and NAO indices are not significant. PDO and NTA indexes analyze monthly averages of anomalies of sea surface temperature respectively in the Pacific Ocean and in the tropical North Atlantic. This indicates that sea surface temperature anomalies presented by the PDO and

the NTA have a possible relationship with wave variability in the Caribbean Sea, in agreement with the hypothesis proposed by Penland and Matrosova (1998). The analysis performed here cannot demonstrate whether any of the two oscillations mostly influence wave variability in quasi-decadal frequencies. However, our results are consistent with previous studies showing the effect of NTA on the hydro-climatology (Poveda and Mesa 1996) and wave climate (Reguero et al. 2013) in South America, and relationships between PDO and hydrological variables such as rainfall (Espinoza Villar et al. 2009) and river discharges (Restrepo et al. 2014), (Restrepo 2019), or oceanographic variables such as temperature and surface currents (Tootle et al. 2008).

4.3 Effects of ENSO on extreme waves

Extreme waves regime is of fundamental importance for coastal management, ocean engineering applications (Devis-Morales et al. 2017), and conservation of coastal ecosystems (Bernal et al. 2016), among others. To further investigate the relationship between ENSO and extreme wave events in the Caribbean Sea, we selected the extreme events of SWH in the 20 VB showed in Fig. 1 and classified them by date of occurrence as No-ENSO, El Niño, and La Niña, according to the Oceanic Niño Index (ONI) of the NOAA Climate Prediction Center (CPC). The average extreme SWH was calculated for each of the three groups. Extreme events were selected based on the peak-over-threshold (POT) methodology, defining as

threshold the SWH with 1% probability of exceedance in the empirical cumulative distribution function from each VB.

Figure 11 shows that in 55% of the 20 VB, the average of extreme waves is greatest during La Niña, and in 70%, the lowest average of extreme waves occur during El Niño. In the Colombia basin where the strongest ENSO influence was found, in 71% of the VB in this region, the highest averages of extreme waves occur during La Niña, while in 100% of the cases, the lowest averages occur during El Niño. This pattern is opposite to the mean wave regime described in Sect. 3.2, where SWH tended to be smaller during El Niño and higher during La Niña. This finding requires more detailed analysis related with extreme values distributions and recurrence intervals; however, evidence for a causal relationship between ENSO and extreme waves in the Caribbean Sea is provided here.

5 Conclusions

This study investigated the interannual variability of waves climate of the Caribbean Sea. Wavelet spectral analysis performed on 20 virtual buoys uniformly distributed across the basin revealed three predominant interannual oscillation frequencies during the 38-year observation window from the reanalysis dataset. The three oscillation frequencies correspond to recurrence periods of 2–4 years, 4–8 years, and 8–12 years.

The first oscillation period of 2–4 years is associated with the warm phase of ENSO (El Niño) and only significant influence (with 95% confidence) in the southwestern Caribbean. The second oscillation period (4–8 years) is associated with the cold phase of ENSO (La Niña) and has a more generalized influence, with significant energies across the entire study area except for the northeast corner. Finally, the third predominant interannual oscillation period (8–12 years), similarly to the first one, exhibits significant energy only in the southwest Caribbean (Colombia basin), which is the sector with the greatest wave energy and highest number of significant interannual variability frequencies, due to the predominant wind direction and the increasing east-to-west fetch. We found evidence that this lower frequency oscillation may be associated with climate forces represented by the NTA and PDO indexes, while no relationship was found with the NAO and CAR indices.

A time domain analysis revealed a much more substantial impact of ENSO during its first semester of occurrence (June–November), especially in the JJA quarter, in comparison to the second semester (December–May). This is related to variations in the CLLJ during the occurrence of ENSO, especially during this quarter. The intensity of the CLLJ is intensified during El Niño because the positive SST anomalies in the tropical Pacific increase the atmospheric pressure gradient

between the tropical Atlantic and Pacific oceans. The opposite occurs during La Niña, when the intensity of the CLLJ decreases by reduction of the atmospheric pressure gradient between the two ocean basins.

La Niña generates a greater impact than El Niño, causing reductions over 50% in SWH in the southwest Caribbean. During the first semester of El Niño, an increase of up to 36% in SWH occurs with respect to climatology; meanwhile, in the second semester, a dipolar effect is observed in the basin, where SWH decreases in the southwest zone and increases in the rest of the Caribbean basin. It was also found that wave TP and MWD are not largely affected by climatological oscillations in the Caribbean Sea. TP shows a similar behavior to SWH, but its variability around the average is below 10%. MWD does not show relevant changes with respect to climatology.

In the future, longer reanalysis time series will allow more detailed studies of interannual climatology, as well as testing our hypothesis about the causes of the quasi-decadal oscillation in SWH and the possible relationship between magnitude of extreme wave events and ENSO.

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