

EXTREME WAVES AND CLIMATE CHANGE IN THE GULF OF MEXICO

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Abstract

The characterization of extreme ocean waves allows for better planning of maritime operations, regulation of coastal activities, and the design of coastal and offshore structures and facilities. In the Gulf of Mexico, extreme ocean waves are a consequence of tropical cyclones and anticyclone cold front systems known as *Nortes*. Waves derived from tropical cyclones have devastating consequences but have a low probability of occurrence, whereas *Nortes* are a frequent phenomenon producing disruptions of maritime activities during autumn/winter. While current planning of maritime operations and the design of structures is based on historical data, global warming will likely affect such conditions during the coming years and into the 22nd century. In this study, we analyze the expected waves induced from tropical cyclones and *Nortes*, considering the influence that climate change has on their frequency and intensity.

Key words: ocean waves, climate change, tropical cyclones, cold fronts, *Nortes*

1. Introduction

The Gulf of Mexico (GoM) is one of the world's main oil and gas production areas (Kaiser, 2015), besides being an important asset for fisheries, shipping and tourism (Adams et al., 2004). Extreme ocean waves affect all of these economical activities, mainly those associated to the passage of Central American Cold Surges (*Nortes*) during fall-winter, and to tropical cyclones (TC) during summer-fall (Appendini et al., 2014). While the *Nortes*-derived waves are more frequent, TC generated waves are more energetic and usually have catastrophic consequences. For instance, mean annual losses due to hurricanes in the US have been estimated to be 10 billion USD, and with single events being able to generate losses up to 157 billion USD (Pielke et al. 2008). Nevertheless, *Nortes* more frequently disrupt the maritime activities, with approximately 22 events per year (Ramírez-Elías, 2007), and have an important impact over downtimes in the GoM. In addition, *Nortes* can still generate significant damage, for instance in 2007 the cold front crossing the GoM at the end of November damaged oil rigs in the Campeche Bank by an estimated amount of \$2.5 billion USD (López-Méndez, 2009). It is then important to consider both *Nortes* and TCs derived waves for design and planning of operations in the GoM.

The increase in greenhouse gas concentration in the atmosphere and the subsequent global warming is expected to generate changes in the climate, modifying existing risks differently among regions (IPCC, 2014). Considering the impacts of global warming in the climate system, the winds and consequent ocean waves are likely to suffer changes. There are several studies assessing wave tendencies based on observations (e.g. Gulev et al. 2003; Gulev and Grigorieva 2004), buoy data (e.g. Allan and Komar 2006; Menéndez et al. 2008; Ruggiero et al. 2010), satellite data (e.g. Woolf et al. 2002; Young et al. 2011), model results for the present climate (e.g. Sterl and Caires 2005; Semedo et al. 2011; Dodet et al. 2010; Appendini et al. 2014; Weisse et al. 2009), and model results under different climate change scenarios (Caires et al., 2006; Fan et al., 2014, 2013; Hemer et al., 2013; Lionello et al., 2008; Mori et al., 2010; Semedo et al., 2013; Wang et al., 2004). While the studies based on historical data cannot provide accurate projection by the end of the 21st century, the studies based on Global Circulation Models (GCMs) are too

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coarse to accurately resolve the GoM and wind fields of tropical cyclones. Thus, the available information of wave conditions in the GoM by the end of the century is limited and likely inaccurate.

Considering that TC derived waves are the largest generated waves in the GoM, their assessment is crucial in the structural design of maritime structures and facilities. On the other hand, Norte derived waves have a higher frequency and thus are fundamental for the operative design of maritime facilities. This study is then divided in two parts. First we present the assessment of climate change over tropical cyclone derived waves and hence over the design of structures. Secondly, we present an assessment of the different types of Norte derived waves according to their generated wave power in the GoM, and the effect of climate change over their frequency, hence their effect over the operations planning of maritime terminals.

2. Extreme waves from tropical cyclones

Tropical cyclones derived waves are the main structural design parameter for maritime structures in the GoM. Their assessment has been part of several studies, including the American Petroleum Institute (API) guidance for winds, waves, current and storm surge (American Petroleum Institute 2007), and the work from (Panchang et al., 2013) based on a 51-year hindcast done to revise the values from the API. Both works are based on historical events, which pose two important limitations. First, the historical database is composed by a limited number of events to provide robust statistical estimates, particularly if we consider accurate data since the satellite era in the mid sixties (Landsea, 2007). Second, because they do not allow for the assessment of climate change influence, besides limited trend analysis.

Several authors have used the GCMs data from the Coupled Model Intercomparison Project (CMIP) phases 3 (CMIP3) and 5 (CMIP5) to perform assessments of climate change over the wave climate, including tropical cyclone derived waves (Fan et al., 2013; Mori et al., 2010). Unfortunately, GCMs underestimate TC activity (Camargo, 2013), as well as the maximum wind speeds for TCs (Emanuel 2010; Hill and Lackmann 2011).

Synthetic TC events allow overcoming the drawbacks of the short-term record of historical events and underestimation of events by GCMs. Here we used the synthetic events as derived by Emanuel et al., (2008, 2006), which have been successfully used to determine hurricane parameters for different return periods, such as wind speeds (Emanuel and Jagger, 2010), storm surge (Lin et al., 2010) and waves (Meza-Padilla et al., 2015). Such events have also being used to assess TC damage under climate change scenarios (Emanuel, 2011; Hallegatte, 2007; Mendelsohn et al., 2012), and to assess the effect of climate change on TCs (Emanuel, 2013).

2.1. Methods

To determine the effect of climate change on TC derived waves we used synthetic events based on Emanuel et al. (2008, 2006). These events are generated by randomly seeding warm core vortices with peak wind speeds of 17 m/s that can develop or decay according to the large-scale oceanic and atmospheric conditions. If they develop, then a beta-advection model driven by the large-scale wind fields stirs them. In this study the synthetic events were derived using the NCEP reanalysis (Kalnay et al., 1996) as reference for the present climate, and the NOAA/GFDL CM3 (GFDL) and the UK Met Office HADGEM2-ES (HADGEM), for the present climate and under the Representative Concentration Pathways (RCP) 8.5. Each database is composed by 1550 events for the present climate, while 1612 and 1560 events respectively for GFDL and HADGEM under RCP 8.5. The present climate events are based on the atmospheric and oceanic climate between 1975 and 2005, while the future climate between 2070 and 2100.

The synthetic events are composed by two hourly information including date, position, maximum wind speed, radius of maximum wind speed and minimum central atmospheric pressure. These data were introduced into the parametric wind model from Emanuel and Rotunno (2011) to generate the wind fields for each synthetic event.

To determine the TC derived waves we used the third-generation wave model MIKE 21 SW (Sørensen et al., 2004), forced with the generated wind fields over the computational domain, encompassing the GoM and western Caribbean Sea (CS). From the model results, we generated maximum envelope maps of significant wave heights (SWHs) to perform statistical analysis including the SWH for a 100 years return

period.

2.2. Results

2.2.1. Assessment of synthetic events

To assess the accuracy of synthetic events to reproduce the TCs climatology, we compared the NCEP derived events to the historical data. Figure 1 shows the relative histograms for maximum wind speed (Fig.1a) and minimum pressure (Fig.1b), where there is a good agreement between historical events (HURDAT2) and NCEP derived events. A good agreement is obtained between NCEP events and GFDL and HADGEM when looking at the basin wide statistics, but a kernel density analysis (Figure1c) shows that the HADGEM derived events are concentrated towards the northeast of the GoM. The HADGEM bias is most likely a result of a lower genesis potential index (Emanuel and Nolan, 2004) in the main development region, as shown by (Camargo, 2013). The GFDL events show a more accurate representation of the distribution of the events, such that these events were used in the assessment of the wave climate.

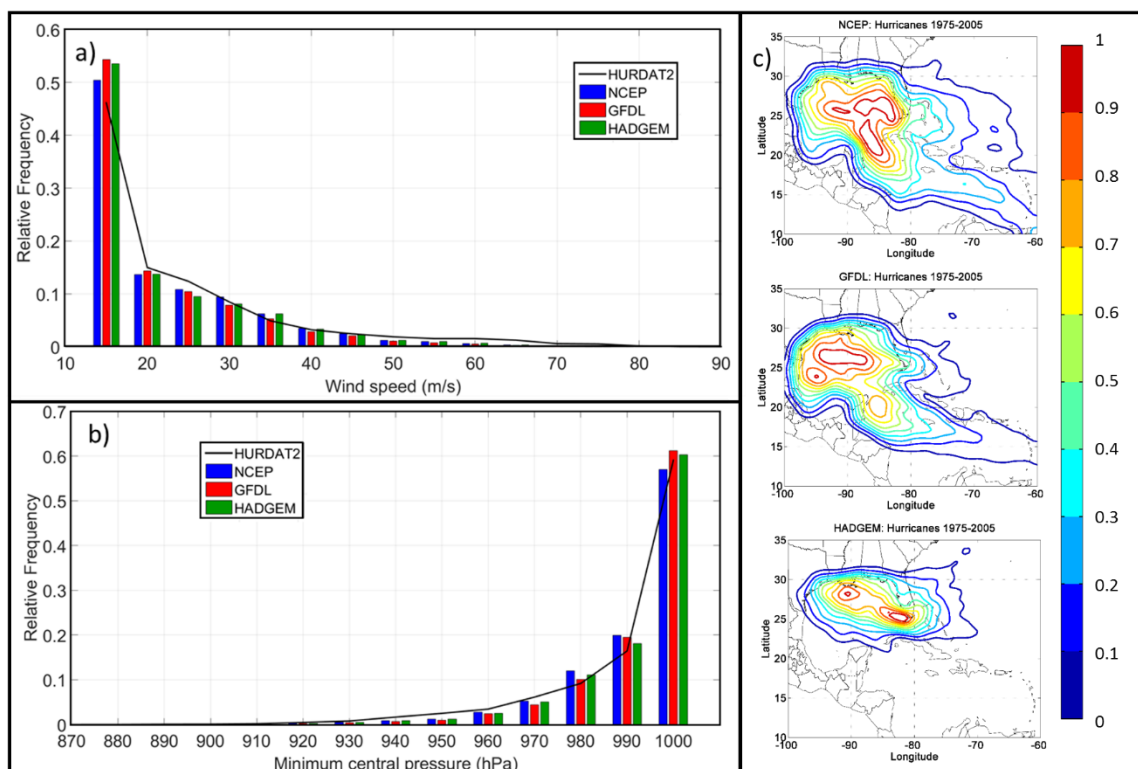


Figure 1. Relative frequency histograms for a) maximum wind speed and b) minimum central pressure; and c) normalized kernel density (each event scaled to have the unit maximum) for synthetic hurricanes in the present climate 1975-2005 for NCEP (top), GFDL (middle) and HADGEM (bottom).

2.2.2. Wave climate from tropical cyclones

Despite the assessment of the GFDL to reproduce the TC climatology, we run the model for the present climate to assess the bias of the GFDL events derived wave climate in relation to NCEP. As shown in Figure 2a, the GFDL events produce a positive bias for the 99th percentile of the maximum SWHs in the western CS and southern GoM, while we found a negative bias in the eastern part of the GoM. Figure 2b show the difference in the 99th percentile maximum SWH between the future and present climates. The extreme waves in the future climate show increases up to six meters in most areas of the GoM and western CS, with a decrease in the southernmost part of the GoM in the Campeche Bank.

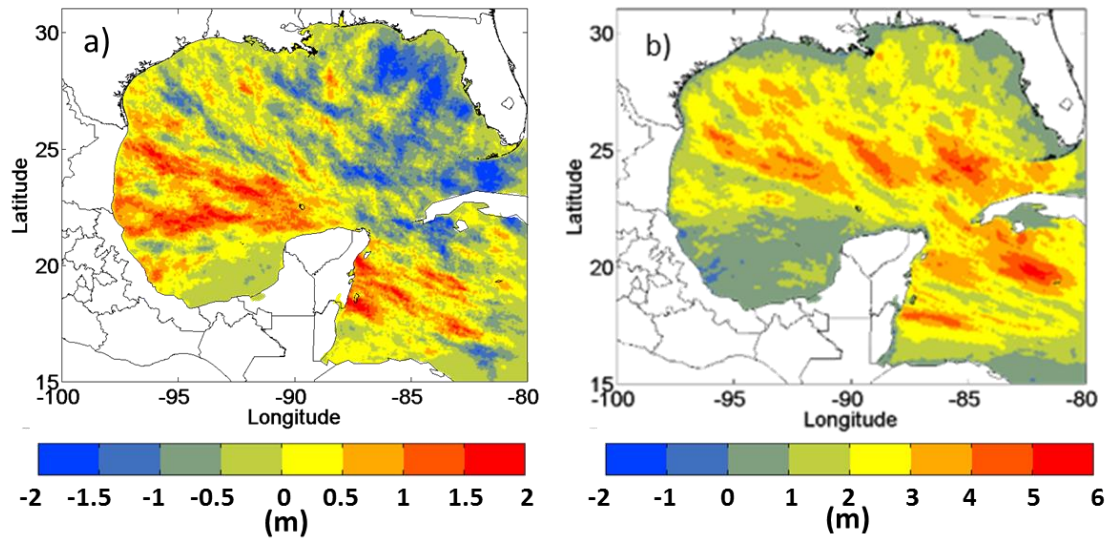


Figure 2. a) GFDL model bias for 99th percentile maximum SWH; b) 99th percentile of maximum SWH increase for the future climate (2070-2100) in relation to the present climate (1975-2005) based on GFDL events.

To illustrate the effect of climate change on the design waves for maritime structures, we calculated the SWH for a 100 years return period. Figure 3a show the results for the present climate based on the GFDL model, while figure 3b shows the difference between the 100 years SWH of the future and present climates.

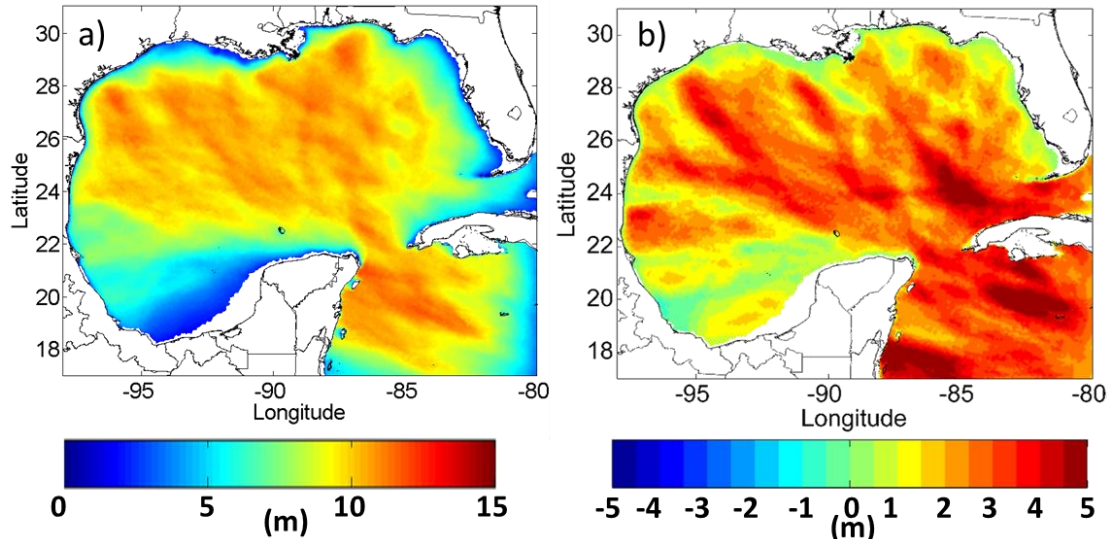


Figure 3. a) 100 years return period SWH based on the tropical cyclone wave climate for the present climate (1975-2005) and b) difference between the future climate (2070-2100) 100 years return period SWH and the present climate (1975-2005).

The results in Figure 3b show increases in excess of 5 m for the future climate. If we consider the construction of a structure in 2020, such structure will only be 50 years old in 2070, so that it could be experiencing the future wave climate during its active years. The design of such a structure under the present climate would considerably increase the damage probability during its lifetime because of a warming climate.

3. Extreme waves from *Nortes*

The high occurrence and regional effect of *Nortes* have yearly consequences for the oil and gas industry, shipping, and fisheries of the GoM. Their presence usually imposes operational downtime so that *Norte*-derived waves are important parameters for the design of onshore and offshore facilities and activities. Despite the yearly economic and social impacts from *Norte*-derived waves, their study is limited and mainly implicit in the characterization of the GoM wave climate, as in the work from (Ramírez-Elías, 2007) and (Appendini et al., 2014).

There are several studies related to *Nortes* but mainly related to the incursion of polar outbreaks as they pass from North America into the GoM and Central America (Dallavalle and Bosart, 1975; Mecikalski and Tilley, 1992; Schultz et al., 1998), as well as their formation of gap winds (Romero-Centeno et al., 2003). In relation to climate change, only the work by Pérez et al. (2014) analyzed the effect of a warming climate on *Nortes* and the associated precipitation along the Mexican coast. The lack of studies related to effect of *Nortes* over the wave climate, as well as the assessment of the effect of climate change, represent an important knowledge gap. In this work, we propose a new method to identify and classify *Nortes* based on the wave energy, as well as to assess the effect of a warming climate on their occurrence.

3.1. Methods

To assess the effect of climate change over the *Norte* derived waves, we use the CFSR reanalysis (Saha et al., 2010) as a reference for the present climate, and the CMIP5 model CNRM-M5.1 (Voldoire et al., 2013) for the future climate. The CFSR data was used as the baseline to assess the CNRM model performance to reproduce the present climate. The selection of the CNRM model was based on the assessment of 15 CMIP5 GCMs where the CNRM showed the best performance for the meridional wind component over the southeastern region of Mexico (Salinas et al., 2016). Considering that a strong meridional wind component is a characteristic of *Nortes*, the CNRM model was then used to assess the present (1970-2005), near future (2026-2045) and far future (2081-2100) climates.

The first step was to identify *Norte* events. Several authors have identified historical *Nortes* or cold surges using satellite imagery and weather charts (Dallavalle and Bosart, 1975; Dimego et al., 1976; Henry, 1979; Mecikalski and Tilley, 1992; Reding, 1992; Schultz et al., 1997). Such a procedure is not applicable to future events, so that we identified events based on the difference of reduced mean sea level pressure between San Antonio, Texas, USA and Merida, Yucatan, Mexico, as well as wind speed in the Campeche Bank and zonal wind component south of Galveston Bay. This allows identifying *Nortes* as they enter and leave the GoM.

After the events were identified, the MIKE 21 SW model was forced by the CFSR and CNRM winds to obtain the wave power generated by each individual *Norte* event. A principal component analysis (PCA) and a *k-means* clustering analysis was done to the resulting wave power maps, in order to classify *Nortes* into different types in relation to their wave power distribution and intensity over the GoM. The identification and classification was done for the present and future climates, in order to assess the effect of climate change over the *Norte* derived waves.

3.2. Results

3.2.1. Identification of *Norte* events

The *Norte* events we identified in the CFSR reanalysis were compared to those identified by Reding (1992), as shown in Table 1. In this work we found more events, which could be explained by the fact that Reding (1992) identified *Norte* events that reach all the way south to Merida and we consider all events passing along the GoM, regardless of their southern reach. It has been shown by Dimego et al. (1976) that not all the events reach all the way to Merida, particularly at the beginning and end of the *Norte* season, when we do register events passing along the GoM.

Table 1. Example of a legible table.

	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
Reding (1992)				1.3	2.5	3.1	3.4	3.3	2.6				16
This work		0.1	0.9	2.2	3.4	3.7	3.9	3.4	2.8	1.7	0.6	0.1	22.8

We also compared the number of events found in the CFSR reanalysis to those obtained from the CNRM model for the present climate (not shown). The monthly distribution of events is similar between datasets, although the CNRM underestimates the total number, with 19.5 events per year. Still, we consider that the CNRM accurately captures the presence of *Nortes* over the GoM.

3.2.2. Classification of Norte events

We applied a PCA to the wave power maps obtained to all the *Norte* events, as obtained from the MIKE 21 SW model. We analyzed 2313 events, including all the CFSR and CNRM events for the present and future climates. Figure 4 shows the mean wave power for all the *Norte* events, with *Nortes* influencing the waves propagating over most parts of the GoM, with more intense waves along the western Mexican Gulf coast. The first three principal component coefficients (not shown) explain 86% of the variance. The first mode explains 63.5% of the variance and is related to how *Nortes* affect most of the GoM, concentrating the wave energy in the southern coast of Veracruz. The second mode explains 15.1% of the variance, which is related to the most intense events, concentrated again in the southern part of Veracruz. While the second mode is also a result of the longest fetch, the intensity of the winds is higher and/or the winds last longer with the same direction, resulting in the most intense events. The third mode explains 7.41% of the variance and is related to the effect of *Nortes* over the northern part of the GoM.

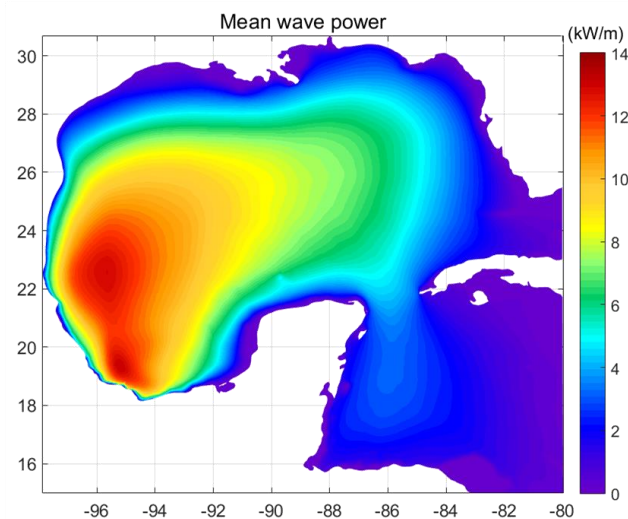


Figure 4. Mean wave power for all *Norte* events.

We based the *k-means* cluster analysis on the principal components (PCs), using a total of 67 PCs which explain 99.86% of the variance. After several tests, a total of 5 clusters provided the most optimal classification for the events. The resulting *Norte* types are shown in Figure 5, together with their relative frequency.

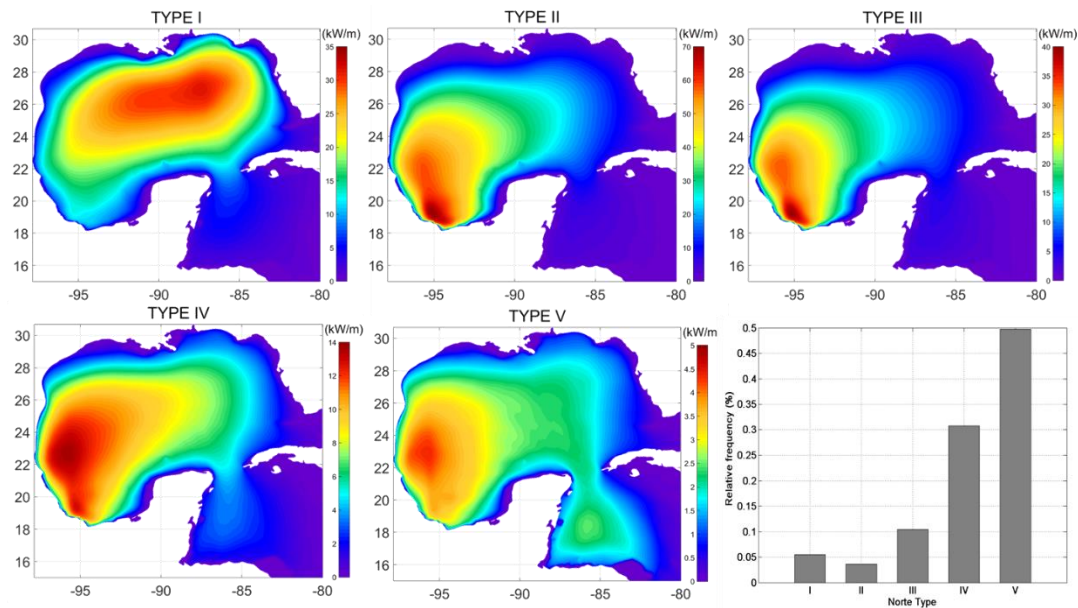


Figure 5. Types of *Nortes* based on *k*-means clustering applied on the wave power principal components, also shown is their relative frequency (bottom right).

The Type I represent *Nortes* that mainly affect the northern GoM, while types II, III, IV and V present a more common pattern for *Nortes* with differences in the highest wave power areas, as well as the wave power intensity. For instance, Type II has a low occurrence but the most extreme events double the wave power of the Type III events and more than 10 times that of the Type V, which is the most common Norte type. The highest wave power in types II and III is located south of Veracruz, an area cited since the end of the 19th century as being “subject to the full force of the northers” (Ruiz 1892).

3.2.3. Climate change influence on Norte derived waves

Based on the *k*-means clustering, we determine the frequency of occurrence of each type of *Norte*, for the present, near future (2026-2045) and far future (2081-2100) climate, as shown in Figure 6. For *Nortes* affecting the northern part of the GoM (Types I, II and III), there is a decrease in frequency in the future climate. There is an exception for the NF climate, where there is an increase on the events with more influence in the eastern side of the GoM (Type I), as well as the second most intense events (Type III). The *Nortes* with the largest influence on the northeastern GoM (Type I) show an increase in the near future but a decrease in the far future, with only one event occurring every 4.8 years. The most intense Norte events (Type II) show a decrease in the future climate. For the far future climate, the frequency indicates the presence of 1 event every 19 years. The least intense events (Type V) show a decrease in the near future, but present the largest increase in the far future from all event types. The Type IV events show a slight increase in near future but large decrease in far future.

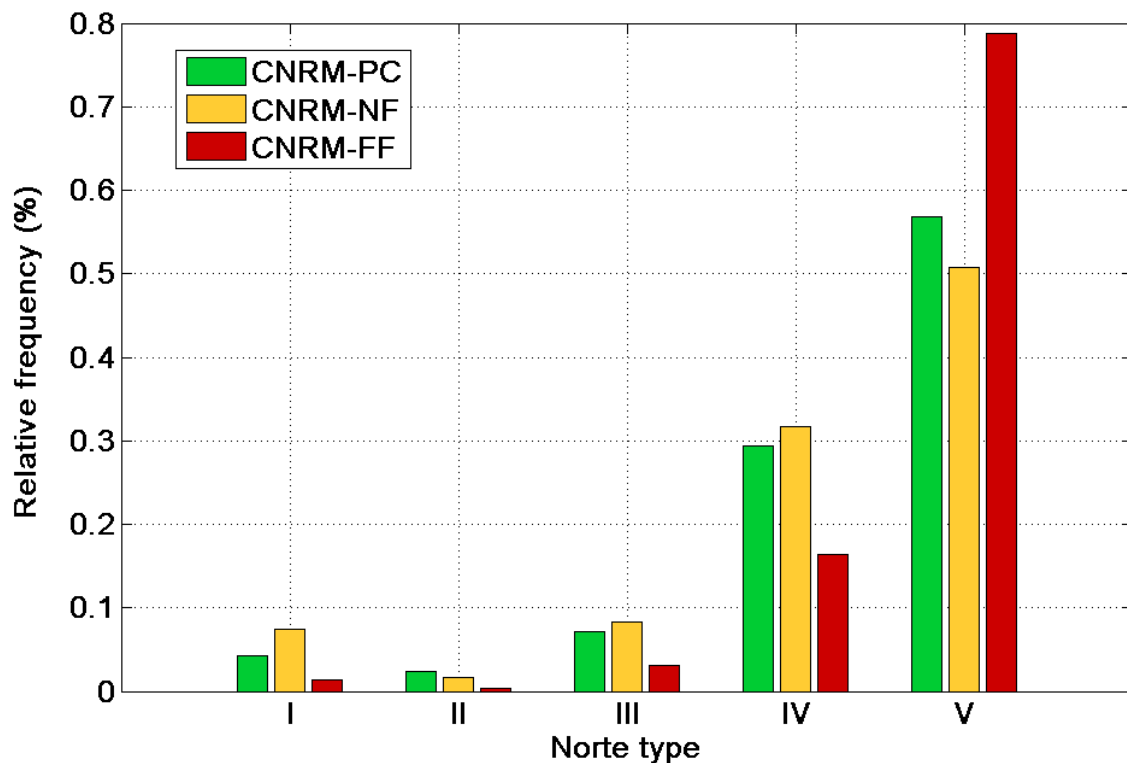


Figure 6. Norte type relative frequency for present (1970-2005), near future (2026-2045) and far future (2081-2100) climate, based on CNRM.

Based on the analysis of Norte types and their frequency under a warming climate, we conclude that the CNRM model indicates that the GoM will present fewer intense events and more mild events in relation to the wave power generated. If we consider that the CNRM provides accurate results, the warming climate will most likely result in less damage to infrastructure and less down-time in marine facilities due to less frequent intense *Nortes* and more frequent mild *Nortes* in the GoM.

4. Conclusions

The main conclusion from the analysis presented in this work is that a warming climate will most likely result in more intense waves derived from TCs but more frequent mild *Norte* events. These results have two important implications. First, the structural design of coastal and marine facilities should be revised to include the effect of increased wave heights for the most extreme events, i.e. from TCs. Secondly, while operational planning maritime facilities should include the effect of the most frequent extreme events, i.e. *Nortes*, it is likely that global warming will reduce the frequency of such events, except for the mildest events which are expected to increase.

The above conclusions are based on a limited set of data derived from the CMIP5 experiments (GFDL and HADGEM for TCs and CNRM for *Nortes*). Considering the uncertainty imposed by the GCMs, the results cannot be considered conclusive, but provide a first approximation in the assessment of the extreme wave conditions in the GoM. It is important to consider also that the uncertainty is not only a result of the GCMs, since there is uncertainty inherent to the wave model, the generation of synthetic events and most important, the climate change scenarios themselves.

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