

# Tropical Cyclone Wind Waves in the Gulf of Mexico under a Changing Climate

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## Key Points:

- The use of physics-based synthetic tropical cyclones allows projections of extreme wave climate in tropical cyclone-prone regions
- Extreme ocean waves in the Gulf of Mexico are expected to increase by the end of the century
- As the climate warms, the use of non-stationary wave climates for design reduces failure probability

## **Abstract**

The expected rise in major tropical cyclones due to climate change will increase their associated hazards, including ocean waves which are the main design parameter for maritime structures. To assess how climate change will affect tropical cyclone waves in the Gulf of Mexico we use physics-based synthetic tropical cyclones derived for present and future climates, overcoming the limitations imposed by insufficiently long records and inadequate resolution in General Circulation Models. Using events derived from six Coupled Model Intercomparison Project Phase 5 models, we estimate the probability of extreme waves for the present climate, and global warming under the Representative Concentration Pathway 8.5 scenario. The results show the importance of non-stationary wave climates for planning and design of maritime structures to reduce structure failure probability as we transit into a future climate with an increased probability of extreme waves.

## **Plain Language Summary**

Climate change studies on tropical cyclones predict that the most intense events will be more likely by the end of the century, increasing exposure to their hazards. Ocean waves from tropical cyclones are a destructive force acting directly on maritime structures and are one of the main design parameters for structures. As such, the question of how climate change will affect the extreme waves by the end of the century is paramount for adequate planning. We use physics-based synthetic tropical cyclones to overcome inadequate data and study wind waves in the Gulf of Mexico under present and future climates, finding that extremes waves will be larger by the end of this century. The design of maritime structures should account for a changing climate to correctly estimate the probability of damage and failure during their lifetime.

## **1 Introduction**

Tropical cyclone (TC) derived wind waves determine structural design conditions for maritime structures in TC prone regions, such as in the Gulf of Mexico (GoM) where offshore oil and gas extraction activities started in 1937 (Horowitz, 2020), with continuous extraction since 1948 (Dunn, 1994). Despite the importance of waves, no guidance for design wave parameters was issued for designing structures during the first decades of oil and gas activities (Dunn, 1994; Wisch et al., 2004). Hurricanes Hilda (1964) and Betsy (1965) forced the industry

to recognize the importance of understanding extreme events so that the American Petroleum Institute (API) created its Offshore Committee, and in 1969 the API released its first standard (Wisch et al., 2004). Nevertheless, design wave recommendations appeared until the 7th edition of RP 2A in 1976, where the 100-year return period was recommended as the design wave (Mangiavacchi et al., 2005). Since then, a series of hurricanes have struck the GoM oil and gas extraction areas, generating severe damages and operational down-time (Austin et al., 2008; Cruz & Krausmann, 2008; Kaiser & Yu, 2010), leading the API to update the recommended wave design parameters. After hurricane Ivan (2004) and the highly active 2005 hurricane season, the API release updated design recommendations by dividing the GoM into different regions and providing wave design parameters for each of them (API, 2007). Acknowledging the intensity of hurricanes Ivan (2004), Katrina (2005), Rita (2005), and Ike (2008), and that a particular intense hurricane or hurricane season can modify the extreme wave statistics (Panchang et al., 2013), API recommendations were updated again in 2014 (API, 2014). API recommendations are based on historical data (Supplementary Information Text S1), so that updates are required as new extreme events are incorporated. The fact that wave statistics change by incorporating recent extreme events is evidence that the observation record is too short to provide robust statistics and/or that climate change is affecting extreme waves. In either case, the need for constant update of design recommendations based on historical events leads to uncertainties on structures stability.

Considering the short historical record hindering a robust wave climate characterization, and that climate change is expected to modify the future climate where the most extreme TC (i.e. categories 4 and 5 in the Saffir-Simpson scale) are expected to increase in proportion by the end of the century (Knutson et al., 2020), synthetic TC can be used to obtain robust statistics for the present climate and to generate wave climate projections towards the end of the century. The limitation and advantages of using TC directly or dynamically downscaled from Global Circulation Models (GCM) versus synthetic TC, to characterize future TC climates, are highlighted in Emanuel (2021); the main disadvantage for synthetic events is the lack of feedback between the large-scale environment and the downscaled events which may lead to an overestimation of events. Considering the advantages of synthetic events, Appendini et al. (2017) presented an assessment of the extreme wave climate in the GoM considering global warming using synthetic TC derived from RCP 4.5 and 8.5 scenarios and two different GCM, finding that

the 100-year design wave can be up to 5 m higher when considering global warming instead of the present climate. This study showed the relevance of including climate change into the design parameters, as the coastal and offshore structures that we design in this decade, will be operating during future climate conditions. Nevertheless, there is large uncertainty in their study as it only consider two GCM.

Efforts done by the scientific community under the COWCLIP framework (Hemer et al., 2012), have already produced wave projection ensembles to identify robust changes in the wave climate by the end of the century (Morim et al., 2019). Nevertheless, the challenges to resolve extreme waves in TC-affected areas have been acknowledged, due to the low GCM resolution used to force the wave models (Morim et al., 2019) and the small number of TC in the GCM (Mori et al., 2010). Both issues have been reported in studies related to TC projections in a future climate (Camargo, 2013; Emanuel, 2010; Hill & Lackmann, 2011; Knutson et al., 2020). As such, it becomes relevant to employ techniques that can address both issues, as is the use of synthetic TC. The use of synthetic events allows robust characterization of extreme events by overcoming the short observational record, and it also allows sampling extreme-wave conditions under projected future climate in TC-prone areas. This work aims to provide an alternative method to determine extreme wave conditions in the GoM following Appendini et al. (2017), aiming to highlight the importance of using non-stationary wave climates for planning and design of offshore structures.

## 2 Materials and Methods

To assess the extreme wave climate in the GoM we followed the methodology used by Appendini et al. (2017), as summarized in Figure S1. The extreme wave climate was obtained by using synthetic TC derived from reanalysis and global circulation models (GCM) as described in section 2.1, from which we created wind fields using a parametric wind model to force a third-generation wave model. The following subsections summarize each of the methodological steps.

### 2.1 Synthetic tropical cyclones database

The synthetic events datasets were derived following Emanuel et al. (2006, 2008) and Emanuel (2013). As summarized by Appendini et al. (2017), the generation of the synthetic events consists of the random seeding of warm-core vortices across the ocean with peak wind

speeds of 12 m/s that can either develop (by reaching an intensity of at least 21 m/s) or decay according to the large-scale oceanic and atmospheric conditions. The events are stirred by a beta-advection model (Marks, 1992), and the intensity of the events is calculated along each track position using the model by Emanuel (2004). Both models use synthetic wind time series at 250 and 850 hPa, represented as Fourier series of random phase, constrained to have the monthly means, variances, and covariances calculated using daily data from reanalyses or GCM, and to have a geostrophic turbulence power-law distribution of kinetic energy (Emanuel et al., 2008). The intensity model also considers the monthly mean potential intensity and 600 hPa temperature and specific humidity derived from the reanalysis or GCM (Emanuel, 2013).

The synthetic TC databases for the present and future climates encompass the events derived using six different GCM from the Coupled Model Intercomparison Project Phase 5 (CMIP5): GFDL, HADGEM, IPSL, MIROC, MPI, and CCSM (refer to table S1 for the complete name of each model, version, and reference). For a future climate, we used Representative Concentration Pathway 8.5 (RCP 8.5) scenario (Moss et al., 2010). The present climate is considered for the years from 1975 through 2005 and a future climate from 2070 through 2100 (except for HADGEM which goes from 2069 through 2099). The synthetic events on each database consist of 3000 events for the reanalysis and GCM derived events for the North-Atlantic basin. Nevertheless, we followed Appendini et al. (2017) and only used the synthetic TC entering the GoM and the western Caribbean Sea, which encompass the numerical domain of the wave model. The number of events entering the wave model domain is a reduced subset of each database (Table S2) and were used to force the wave model. The validation of the synthetic database is presented in Appendini et al. (2019), where the NCEP/NCAR (NCEP) wind reanalysis (Kalnay et al., 1996) derived events were validated using the Hurricane Database (HURDAT2) dataset (Landsea & Franklin, 2013).

## 2.2 Wave modeling

To obtain the wave conditions for each of the TC in the synthetic databases, we first obtained the wind fields for each event, as described in Text S2. The resulting wind fields were used to force the MIKE 21 SW wave model (Sørensen et al., 2004), which is a flexible mesh, finite volume model based on the wave action equation to simulate the growth, decay, and transformation of wind-generated waves. The wave model domain encompassed the GoM and

the western Caribbean Sea, with boundaries along the 80°W longitude and 15°N latitude. A computational mesh based on triangular elements was created using ETOPO1 bathymetric data (Amante & Eakins, 2009) and available local surveys for the Mexican coastal areas. For details on the wave model, setup and validation please refer to Appendini et al. (2017). Nevertheless, for this study, we used 32 bins for the directional discretization instead of 17 to mitigate the garden sprinkler effect (Tolman, 2002) over the wave period. While Appendini et al. (2017) mentioned that the garden sprinkler effect is mitigated when analyzing the maximum value maps for significant wave height (SWH), it is not the case for wave period, thus we decided to increase the directional spectral resolution. We validated the wave model by simulating historical events from 1975 to 2020 and comparing the model results to NDBC buoys as represented by their inverse cumulative distributions or quantile function (Text S3). The resulting statistics are shown in Table S3. Correlation analysis resulted in correlation coefficient values larger than 0.95 for Hs.

### 2.3 Wave analysis

For each synthetic event, we calculated the wave fields such as SWH, peak wave period (PWP), and mean wave direction (MWD), thus having the same number of maps for each variable as the number of synthetic events (Table S2). Using the individual maps of maximum values, we characterized the extreme wave climate by taking mean values or specific percentiles. In this article, we are only presenting the results related to SWH. Furthermore, we characterize the extreme wave probability using the return period, which is commonly used to define the design wave criteria. As such, we characterized the SWH for different return periods both for each mesh element in the wave model and for the API (2014) regions defined for the northern GoM, as described in Text S4.

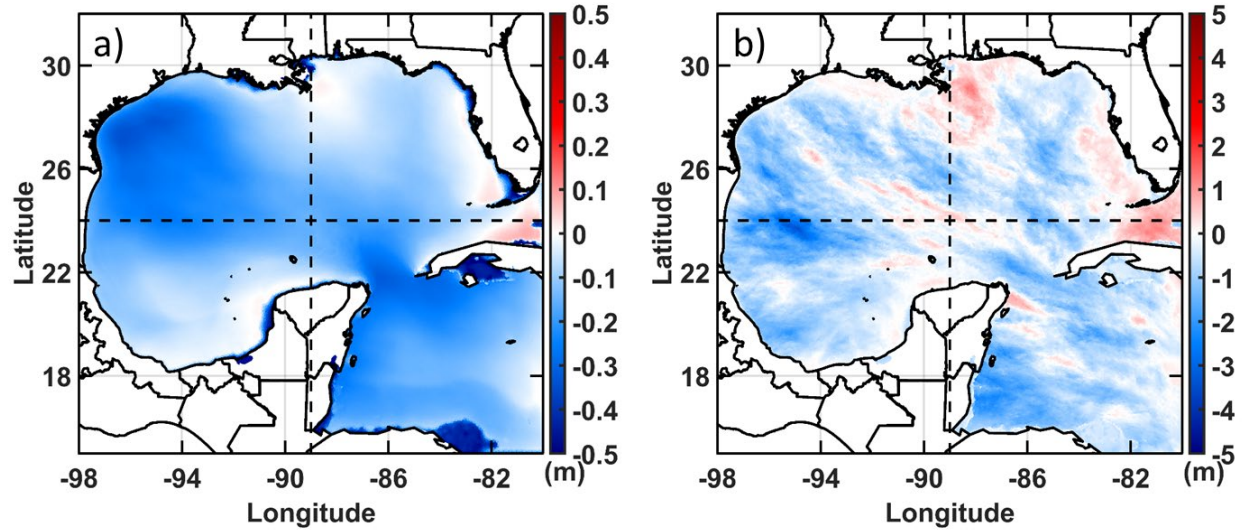
## 3 Results and discussion

### 3.1. Bias assessment for waves derived from GCM derived synthetic events

The validated wave model was forced with the NCEP derived synthetic events to obtain a reference wave climate for present conditions. This wave climate was then used as the baseline to assess the wave climate bias as obtained from the GCM-derived events, and as a reference to assess the API recommended values. For each synthetic event, we created a map with the resulting maximum SWH field, and using all the maxima fields we computed the mean, 90%,

95%, and 99%-iles, which are shown in Figure S2, where the model domain is divided into four sectors referred to as northwestern (NW), northeastern (NE), southwestern (SW) and southeastern (SE) regions. The NW events affect the offshore areas of Texas, Louisiana, and northern Mexico, the NE affects offshore areas West Florida and Mississippi, as well as the north part of the loop current, the SW the Campeche sound and the SE the western Caribbean Sea, the Yucatan current and the southern part of the loop current. The results show that the highest events are found in the northern section of the GoM (NW and NE) as well as in the northern part of the SE region, while the SW region is the area with the milder TC-derived waves (Figure S2).

The present wave climate bias was obtained for each of the six GCM derived events using the NCEP derived wave climate. Figure S3 shows the bias when considering the mean values and Figure S4 when considering the 99%-ile. The bias considering mean values (Figure S3) shows high variability between models, where some overestimate in the NE region (HADGEM, IPSL, and MIROC), others in the SW and SE GoM (GFDL and MPI), while CCSM shows a general underestimation and HADGEM a large underestimation in the SE region. Similar bias patterns are obtained for the 99%-ile (Figure S4), although the bias is less smooth and intensified, particularly in locations such as the Mexican GoM in sector SW in HADGEM or the NE sector in IPSL. Nevertheless, the bias is reduced considerably when considering the model ensemble (Figure 1), with a general underestimation of the mean SWH in the entire study area showing higher biases in the NW and SE regions (Figure 1a). The same occurs for the 99%-ile model ensemble, where the bias is reduced, with some overestimations offshore Louisiana, Mississippi, western and southern Florida, and the northwestern Yucatan Peninsula (Figure 1b).

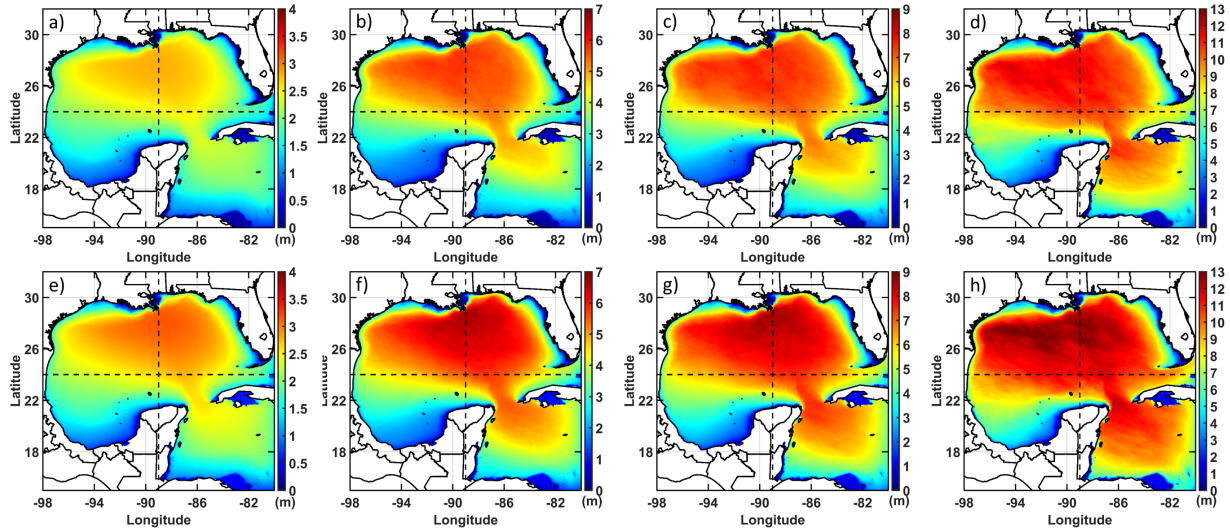


**Figure 1.** Significant wave height bias for the Global Circulation Models ensemble considering a) mean and b) 99%-ile values.

### 3.2. Future wave climate assessment

A future wave climate was obtained from the models' ensemble and compared to the present wave climate using the mean values and percentiles (Figure 2). The results show a general increase for the mean waves and the percentiles, most of it in the NW, NE, and SE. There are barely any differences in the SW which corresponds to the Campeche sound where most oil and gas activities in Mexico take place. These results coincide with the trends reported by Ojeda et al. (2017) in the Mexican GoM. The regions in the NW and NE are where SWH increases the most in a future climate, and correspond to the oil and gas areas in Texas and Louisiana. Present and future wave conditions for each GCM are shown in Figure S5 and S6 respectively, and the projected wave climate for each GCM is discussed in Text S5.



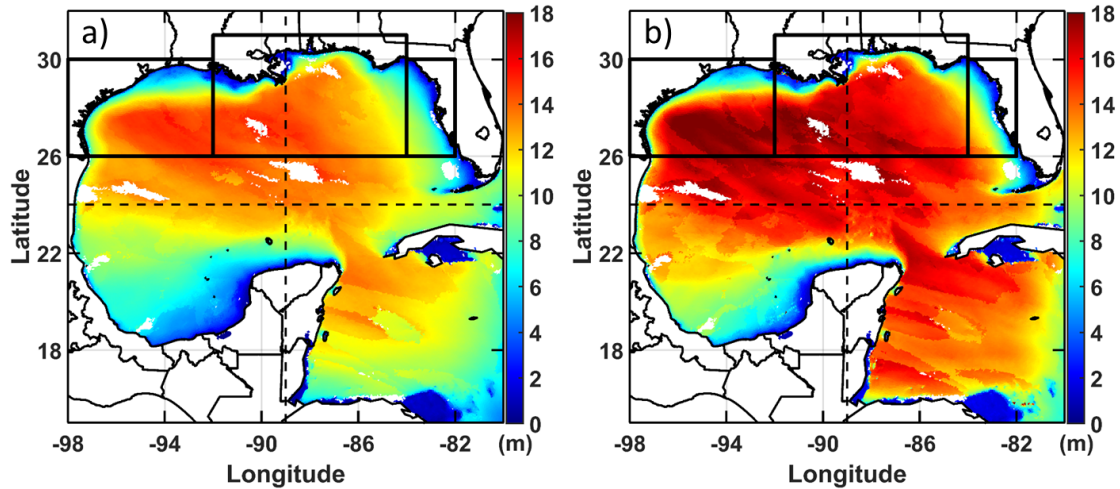


**Figure 2.** Wave conditions for significant wave height for the present (a, b, c, d) and a future (e, f, g, h) wave climate model ensembles, including mean (a, e), 90%-ile (b, f), 95%-ile (c, g) and 99%-ile (d, h).

### 3.3. Wave conditions based on return periods and implications on design

In the previous section we divided the GoM into four regions to describe our results, however, the API recommendations report SWH for different return periods within three regions specific to US GoM waters, as shown in Figure 3 (West, Central, and East US) and defined in Text S4. To determine the wave conditions in a particular area for different return periods, API (2014) recommends grid pooling (Heideman & Mitchell, 2009) due to the low frequency of occurrence and relatively small size of TC, and acknowledging the randomness on storm tracks, which could have varied if slightly different ambient conditions were dominating at a particular time of the storm. As the 100-year return period is commonly used as the design wave parameter (e.g. API recommendations), we use it to represent the probability of a particular wave occurring in the area. Figure 3 shows the 100-year return period wave map for the GoM ensemble under present (Figure 3a) and future (Figure 3b) conditions, showing the regions defined by API (2014) for different return periods (West, Central, and East US). The ensembles were constructed with the GCM that show the same trend, considering at least four models, so that the blank areas indicate those zones where less than four models showed the same trend direction. Considering the 100-year return period for design, most of the GoM will experience an increase in the SWH, except for the southern part of the SW sector. API regions will experience a significant increase

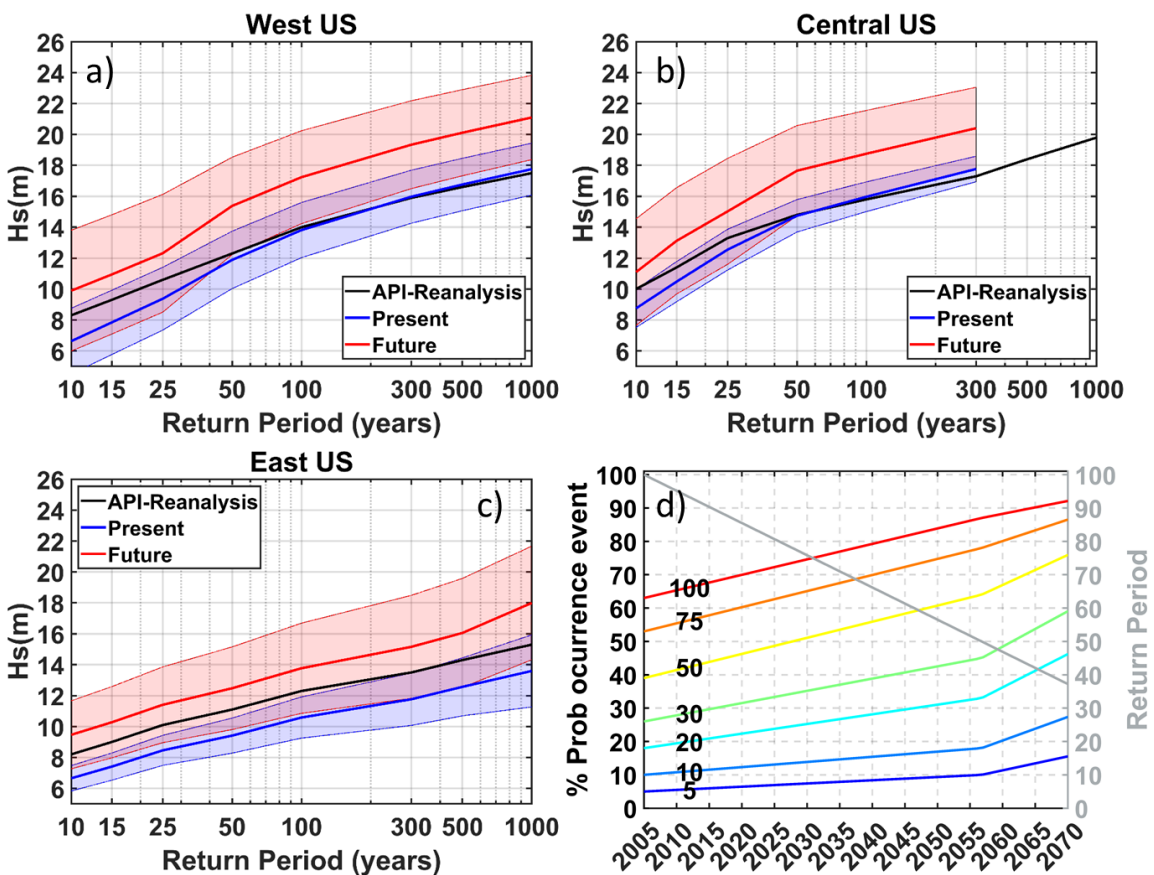
in SWH, including the oil and gas exploitation areas offshore Texas and Louisiana. The individual maps for each GCM are found in figures S7 and S8 for the present and future climates respectively.



**Figure 3.** Significant wave height for the 100-year return period obtained from the GCM derived events ensemble for the (a) present and (b) future wave climates. Blank areas denote regions where less than 4 models show the same trend direction. Solid black boxes represent areas defined by API recommendations.

API (2014) does not specify the procedure to determine SWH return periods, and only refers to Oceanweather Inc., (2015) where no information is provided regarding the analysis for API regions. Thus we are unable to replicate their procedure. We compare the values reported by API (2014) with those we obtained according to the procedure described in Text S4. Figure S9 shows that the API values are smaller than our results using synthetic events, except for the East area where API is enclosed by the uncertainty envelope of the present climate. These results indicate that the use of data derived from historical events can lead to underestimation of extreme waves in a future climate. Here we note that the goal of this study is not to assess API values, but to research changes in wave climate by the end of the century by means of synthetic events, given a changing climate according to GCM. As the API (2014) return-period values are the industry standard, we would like to highlight changes in future wave climate with respect to current API values. To make them directly comparable, we did a bias correction of the resulting waves from synthetic events based on the bias between the reanalysis derived wave estimates

and the API (2014) values. The SWH for different return periods are shown in Figure 4; a good agreement is found for the Western and Central areas between the API-Reanalysis (referred to as API hereafter) values and those from synthetic events derived from the GCM ensemble mean. API values are encompassed inside the present climate uncertainty envelope, the agreement is particularly good for return periods above 50 years where the ensemble mean for the present climate closely follows the API values. The East area shows the API values slightly above the uncertainty of the present climate, except for very large return periods.



**Figure 4.** Corrected values of significant wave height probability in return periods for the different API defined regions in the northern GoM (denoted with the solid black line boxes in a and b of Figure 3), a) West US, b) Central US, and c) East US, showing the return period curves for API and adjusted synthetic events for the present and future climates as derived from the GCM derived events ensemble; d) shows the percentage chance (left ordinate) of a 100-year return period wave in the present climate to occur as we transit into a future climate, where the color lines indicate the projected design life of a structure, and the gray line shows the diminishing return period value (right ordinate) of the present climate 100-year return period wave as we approach a future climate.

Present climate events (API and GCM derived events) show a lower SWH than those for a future climate, while the GCM SWH ensemble mean gives an increase between 2 and 4 m under future conditions. If we use present wave climate conditions to determine the probability of a certain wave height, we will most likely be underestimating such probability as we approach the end of the century, when the simulations used here suggest that the extreme wave climate will be affected by the influence of global warming over TC. Conversely, future wave climate estimates would overestimate the probability of an event early in the century. An alternative approach would be to consider non-stationary wave climates, calculating the change of probability of a certain wave height as climate change affects the extreme wave conditions deriving from TC. This is exemplified with Figure 4d, in which we consider the present wave climate to represent conditions in 2005 and the future wave conditions to represent conditions in 2070, while the wave conditions between 2005 and 2070 are assumed to vary linearly. In Figure 4d we used the 100-year return period in the present climate for the West US area, which equals a SWH of 13.8 m, corresponding to a return period of approximately 37 years in the future climate, where the gray line represents the change of return period linearly interpolated between 2005 and 2070. Each color line in Figure 4d represents a design life for a structure, showing curves for design life between 5 and 100 years, for which the left axis shows the probability of the design wave occurring during the lifetime of the structure, as derived from (CIRIA-CUR-CETMEF, 2007). For instance, a design wave of 100 years using the present climate will have a probability of occurrence of 63% in 2005 for a 100-year design life, and 26% for a 30-year design life, and the probability of occurrence as we approach 2070 will increase to approximately 92% and 58%, respectively. The high probability of occurrence in a future climate indicates that values exceeding the design waves will also increase their probability, leading to an increase in the probability of failure for structures designed using a stationary wave climate based on the present conditions.

## 5 Conclusions

We provided an assessment of the wave climate under climate change using a methodology based on synthetic TC to overcome limitations imposed by GCM regarding the frequency of TC and their underestimation of maximum winds. We find that climate change in

the GoM will impact TC-derived waves, increasing the probability of higher waves in the northern GoM and the western Caribbean Sea. Such an increase in SWH, results in the probability of higher damage for structures designed based on non-stationary wave climates under global warming, as the percentage chance of the design wave occurring increases towards the end of the century. API standards are the oil and gas industry reference for wave design parameters, yet we show how the use of data derived from historical events can lead to the underestimation of extreme waves in a future climate. Thus we show the need to use non-stationary wave climates to reduce the probability of failure. The methodology proposed using physics-based synthetic TC provides an alternative to determine extreme waves climates in TC-prone areas affected by climate change.

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## Data availability

The data used in this study will be available at 10.6084/m9.figshare.16806877 with license CC BY 4.0 upon acceptance of the manuscript.

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