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Climate drivers of directional wave power on the Mexican coast

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Abstract
Ocean waves are the main driver of sediment transport on open sandy coastlines, and inter-annual to multi-decadal variability in the wave climate significantly impacts year-on-year coastal risk. As such, the integration of large-scale climatic variability into local-scale coastal management studies is pertinent but seldom implemented in practice, mainly due to the lack of knowledge in this subject as is the case of Mexico. This knowledge gap is addressed here by quantifying the seasonal to long-term variability of the wave climate along the coasts of Mexico. The influence of large-scale climate drivers on this variability is also characterized. To do this, we identify monthly-averaged directional wave power signatures of the Mexican coast at a 0.5° resolution pertaining to a range of climate indices, using a newly available climate reanalysis product (ERA5) and a statistical-based global wave climate classification method. The wave climate of the Mexican Pacific coast is strongly bi-directional with considerable seasonal variability and high sensitivity to pan-hemispheric climate variability in the Pacific. Conversely, the wave climate of the Mexican Caribbean coast is more homogenous year-round, having its origins in the tropical Atlantic. Results show that El Niño effects break down the bi-directionality of the Mexican Pacific wave climate, leading to a more uni-directional, shore-normal, and more energetic nearshore wave power climate, compared with ENSO-neutral periods. Additionally, the wave power response to individual ENSO events can be either amplified or dampened depending on the underlying phase of the multi-decadal PDO.

Keywords Wave climate · ENSO · PDO · AMO · Mexico

List of acronyms

ENSO	El Niño Southern Oscillation
ETW	Extratropical westerlies
ITCZ	Inter-Tropical Convergence Zone
NAO	North Atlantic Oscillation
ONI	Oceanic Niño Index
PDO	Pacific Decadal Oscillation
SLP	Sea-level pressure
SST	Sea surface temperature
STS	Subtropical southerlies
TE	Tropical easterlies

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1 Introduction

The characteristics of onshore-propagating ocean waves are important determinants for the design of coastal structures, sustainable coastal management, and renewable energy consumption. In order to distinguish the effects of local anthropic causes from those of large-scale climate on ocean wave variability, it is necessary to study the offshore wave climate. For example, coastal erosion associated with storm waves is a worldwide problem (Silva et al. 2014; Luijendijk et al. 2018; Mentaschi et al. 2018) and Mexico is no exception (Valderrama-Landeros et al. 2019). While there has been a large number of studies on coastal erosion carried out at local level in Mexico

(Odériz et al. 2014; Gonzalez-Vazquez et al. 2014; Mendoza et al. 2015; Escudero-Castillo et al. 2018; or Escudero et al. 2019), none has considered the long-term and basin-wide climatic variability impacts on wave climate.

It is well known that inter-annual and multi-decadal changes in wave fields can increase or decrease the seasonal risk of erosion-flooding at the coast (Wahl and Plant 2015). Recent work has focused on how atmospheric teleconnection patterns modulate wave climate on these timescales. These works have shown that wave power in the North Pacific—relevant for the Mexican west coast—has a tendency to increase during El Niño (Shimura et al. 2013a) and during the warm phases of the Pacific Decadal Oscillation (PDO) (Méndez et al. 2006; Bromirski et al. 2013). Similarly, waves in the Northeast Atlantic show a correlation with the North Atlantic Oscillation (NAO) (Bauer 2001). An extension of this work in Latin America was carried out by Reguero et al. (2013). However, in Mexico, the long-term variability of the wave climate has not been analyzed in detail, and further work is required for it to be integrated into coastal hazard assessments.

The aim of this paper is to quantify the seasonal to long-term variability of the wave climate along the Pacific and Atlantic (Caribbean Sea and Gulf of Mexico) coasts of Mexico. The study is based on the global-scale wave climate classification, comprising, at the highest level, dominant wave climate types classed as the extratropical westerlies (ETW), the subtropical southerlies (STS), and the tropical easterlies (TE). This statistical-planetary wave climate classification allows a link to be drawn between directional wave power at any location in the world and atmospheric climate variability. In this study, we undertake a statistical seasonal analysis for all the wave climate types identified for the east and west coasts of Mexico. The long-term variability is analyzed by calculating the correlation of the wave power (P_w) and the mean wave direction (Dir_m) with the Oceanic Niño Index (ONI; a measure of El Niño Southern Oscillation (ENSO)), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) climate indices.

This paper is structured as follows. Section 2 describes the data and methods used to quantify the seasonal and long-term variability of the Mexican wave climate. Section 3 describes the wave climate variability and significant synchronicity between the climate types on the Mexican coast. The ENSO appears to be the main driver of inter-annual variability of wave climate, whereas the PDO and AMO have significant impacts on directional wave power at multi-decadal timescales. Section 4 discusses the findings obtained in Section 3. And finally, Section 5 shows the main conclusions, and implications of them, for coastal hazard planning at a national scale, in Mexico. This may be of relevance for coastal climate planning on other mid- to low-latitude coasts, in the northern hemisphere, with limited observational data.

2 Data and methods

2.1 Data

For this analysis, the wave power and mean wave direction of the ERA5 reanalysis were used as indicators of coastal hazards. ERA5 (Copernicus Climate Change Service (C3S) 2017) is the latest wave reanalysis dataset from the ECMWF (European Centre for Medium-Range Weather Forecasts). The dataset (1979–2018) is computed with the WAM model, with a spatial resolution of 0.5° and an hourly temporal resolution. The wave power was calculated for irregular waves ($P_w = \frac{\rho g^2}{64\pi} {H_{m0}}^2 T_e, W/m$), where H_{m0} (m) is the zero-moment wave height, and the energy period (T_e, s) was approximated by T_{01} following the next ratio $T_e = \alpha T_{01}$; $\alpha = 1.08$ (Webb and Fox-Kemper 2011). The values of P_w and Dir_m were monthly averaged.

The long-term analysis requires an extended temporal range of data and ERA5 reanalyses have more temporal extended range, especially in Mexico, unlike others, such as NOAA-WWIII, which covers from 1990 in the global mesh. The dataset was validated for some buoys of the NDBC meteorological/ocean program of National Oceanographic and Atmosphere Administration of USA (46072, 46067, 41040, 61000) with a good performance, as shown later. To evaluate the ERA5 performance, four estimators were used, the bias, the Root Mean Square Error (RMSE), the Pearson correlation coefficient (R), and R-squared.

2.2 Wave climate types and seasonal variability

First, a wave climate classification was made based on a clustering technique, which allows a multivariate exploratory data mining analysis (Camus et al. 2011; Mortlock and Goodwin 2015). This classification will be deeply analyzed in a future manuscript. In this research, k-means (MacQueen 1967) was used to identify spatial-temporal patterns in the wave climate. Therefore, the results show climatic systems with similar directional wave power. The method optimizes the object function, the Euclidian distance to the centroid (Eq. 1), and the variance is a measurement of the dispersion, where x_k is the variable, C_k is the centroid, d is the distance, k is the number of the cluster, and n is the total number of clusters. Each centroid is the average of all the variables of each cluster (Berkhin 2006).

$$d(x, C) = \sqrt{\sum_{k=1}^{n} (x_k, C_k)^2} \quad (1)$$

The direction is a circular variable and it was decomposed into sine and cosine to avoid false clustering. Standardization of scales was performed following the indications of (Camus et al. 2011) of the variables (cos(Dir), sin(Dir), P_w), where cos(Dir), sin(Dir), and P_w are the variable values, $\cos(\mathrm{Dir})_{min}$, $\sin(\mathrm{Dir})_{min}$, and P_{wmin} are the minimum values of the variable, and $\cos(\mathrm{Dir})_{max}$, $\sin(\mathrm{Dir})_{max}$, and P_{wmax} are the maximum values. To choose the optimal number of clusters, the elbow method was used.

$$\cos(\mathrm{Dir})_n = \frac{\cos(\mathrm{Dir}) - \cos(\mathrm{Dir})_{min}}{\cos(\mathrm{Dir})_{max} - \cos(\mathrm{Dir})_{min}}; \sin(\mathrm{Dir})_n = \frac{\sin(\mathrm{Dir}) - \sin(\mathrm{Dir})_{min}}{\sin(\mathrm{Dir})_{max} - \sin(\mathrm{Dir})_{min}}; P_{wn} = \frac{P_w - P_{wmin}}{P_{wmax} - P_{wmin}} \quad (2)$$

A wave climate type, identified by clustering the directional wave power, was assigned to each month/cell. The monthly time series of P_w and Dir_m associated with each wave climate type for the period 1979 to 2018 around the Mexican coasts were extracted, and their seasonal variability analyzed. For each season, the average and standard deviations of P_w and Dir_m for each wave climate type were calculated. The wave direction was divided by the number of months that each climate type was presented, and the wave power and component of each climate type by the total months (480). The boreal seasons were grouped as winter: December, January, February (DJF); spring: March, April, May (MAM); summer: June, July, August (JJA); and autumn: September, October, November (SON). Although this was done for all seasons, only the results for winter and summer are examined here as they show the largest seasonal variation.

2.3 Inter-annual to multi-decadal variability

Inter-annual to multi-decadal variability in the wave climate was investigated in the context of the principal large-scale climate patterns influencing the Pacific and Atlantic basins, namely El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multi-decadal Oscillation (AMO). El Niño (La Niña) events are manifest in anomalous warm (cool) sea surface temperatures (SST), low (high) SLP, and storminess (calm conditions) in the eastern tropical Pacific. ENSO events persist, on average, for between 6 to 18 months (Mantua and Hare 2002). Previous work indicates that inter-annual variations of coastal vulnerability around the Pacific basin (Barnard et al. 2015) and the Mexican Pacific coast (Ruiz de Alegría-Arzaburu and Vidal-Ruiz 2018) are dominated by ENSO. ENSO phases were detected using the ONI (Ocean Niño Index), calculated as a 3-month moving average of SST anomalies in the central equatorial Pacific. Values greater than 0.5 are El Niño events, values less than − 0.5 are La Niña, and values between − 0.5 and 0.5 correspond to an ENSO-neutral phase.

The PDO also exerts a strong influence on the wave climate of the North Pacific on multi-decadal timescales, particularly when coupled with ENSO (He et al. 2005). The PDO is a pattern that extends outside the equatorial Pacific and persists, on average, for periods of 20 to 30 years. PDO positive (warm phase) is an El Niño–like pattern that reinforces an underlying low SLP anomaly and storminess in the eastern Pacific (Bromirski et al. 2013).

The AMO is the primary multi-decadal climate modulator in the North Atlantic and can also impact climate patterns in the Pacific, including ENSO (Zanchettin et al. 2016; Levine et al. 2017). The warm phase represents a positive SST and low SLP anomaly in the North Atlantic and a negative SST and high SLP anomaly in the North Pacific.

The relationship between the monthly wave power and wave direction and large-scale climate drivers (ENSO, PDO, and AMO) was investigated using Pearson's correlation coefficient (*R*). To avoid low correlation and short perturbation associated with annual variability (Bauer 2001), the data were de-trended using the least square error approach and the annual component was removed using a 12-month moving average. Then, the residual series of the additive model (data minus trend and annual component) were correlated with each climate index (ONI, PDO, and AMO). The Pearson correlation coefficient was calculated at the 95% confidence level for statistical significance.

The range of values for the correlation coefficient was denoted as follows: 0 indicates no relationship between the variables; values between 0 and 0.25 (− 0.25 and 0) indicate a weak positive (negative) correlation; values between 0.25 and 0.5 (− 0.5 and − 0.25) have a moderate positive (negative) correlation; values between 0.5 and 0.75 (− 0.75 and − 0.5) show a strong positive (negative) correlation; and values between 0.75 and 1.0 (− 1.0 and − 0.75) indicate a very strong positive (negative) correlation.

For the analysis of longer-term wave climate (i.e., inter-annual to multi-decadal), we do not use the wave climate types used in the seasonal analysis. This is because a monthly analysis of 40 years of reanalysis data renders a 480-point time series for each ERA5 grid cell. The dominant wave climate type is assigned to each month/cell according to the *k*-means analysis. At almost all locations, the dominant wave climate type assigned to each grid cell is not the same throughout the monthly 40-year time series due to seasonal variations. As a result, there was not enough data to calculate an *R* value between each climate type and the climate index on an inter-annual to multi-decadal basis. Therefore, the correlation was undertaken with monthly P_w and Dir rather than indices of wave climate type.

3 Results

3.1 ERA5 validation

The ERA5 wave hindcast (H_s) was validated against wave buoy observations from the NOAA deepwater array (buoys 46072 (2002–2018), 51000 (2009–2018), 46047 (1991–2018), and 41040 (2005–2017)). The validation shows a good performance in the H_s parameter. The buoys selected, shown in Fig. 1, were chosen as they cover different points in the Atlantic and Pacific Ocean and are affected by different wave climate types identified in this analysis (ETW and TE).

Results of the validation for each buoy location are shown in Table 1. Results show that H_s is generally well represented by ERA5, although there is a general negative bias (under-prediction) for high wave heights. This is a common feature in wave hindcasts that are driven by reanalysis winds (Mortlock et al. 2020). This is because reanalyses have a tendency to under-predict extreme wind speeds. However, since our study focuses on the bulk wave climate and not extremes, and averages of these over monthly periods, these discrepancies in the tail are unlikely to impact our analysis.

3.2 Seasonal variability of the wave climate types on the Mexican coast

The three global-scale wave climate types identified are the extratropical westerly (ETW), subtropical southerly (STS), and tropical easterly (TE). Averaged over time, the ETW produces the highest mean wave power (~ 60 kW/m), followed by the STS (~ 27 kW/m) and then the TE (~ 18 kW/m). This provides a monthly index for each grid cell of the variability of each dominant wave climate type (ETW, STS, TE) over a ~ 40-year period. The results show that these three global wave climate types directly influence the coast of Mexico. Figure 2 shows the mean winter (a–c) and summer (d–f) P_w for each wave climate type (ETW, TE, STS) at 0.5° resolution along the Mexican coast. Figure 3 and Fig. 4 show the contribution of each wave climate type to the total wave power along the coast and the mean direction of each wave climate type, respectively. Overall, the results show that the Mexican Pacific coast is impacted by both ETW and STS wave conditions, with considerable seasonal variation, while the Atlantic coast is influenced by the TE wave climate, year-round.

Table 1 Estimators (RMSE, bias, *R*, *R*-squared) of ERA5 for H_s

Buoy ID	H_s–RMSE (−)	H_s–bias (−)	H_s–R (−)	H_s–*R*-squared (−)
51000	0.50	0.06	0.80	0.63
46072	0.66	− 0.39	0.95	0.91
46047	0.27	− 0.08	0.96	0.92
41040	0.24	− 0.07	0.91	0.83

During winter, the ETW wave climate type impacts the whole of the Mexican Pacific coast, with a north to south wave power gradient of approximately 15 kW/m in the north (influencing the northern section of coast between 90 and 100% of the time during winter) to 7.5 kW/m (10 to 50% of the time) in the south. Only the coasts of Guerrero and Oaxaca, in the south, are influenced by the STS wave climate type, generated in the Southern Hemisphere, at this time of year, with a contribution of between 10 and 100% during this season. In summer, the ETW wave climate is confined to the Baja California peninsula, Nayarit, and Jalisco (P_w ~ 10 kW/m), in the north, (occurring 20–100% of the time along this section of coast in summer), while the STS wave climate becomes more dominant, affecting almost all of the Pacific coast (~ 15 kW/m), with the exception of Baja California State, at this time of the year. Both the STS and ETW exhibit a clockwise rotation of around 10 and 25 degrees in winter, respectively.

The Atlantic-generated TE wave climate is the dominant system (100% of the time) in the Gulf of Mexico and the Mexican Caribbean coast year-round. Most wave power is delivered to the Gulf of Mexico, with less reaching the Yucatan Peninsula because of the effects of wave refraction across the shallow gulf. TE wave power on the east coast is significantly less than ETW and STS wave power on the west

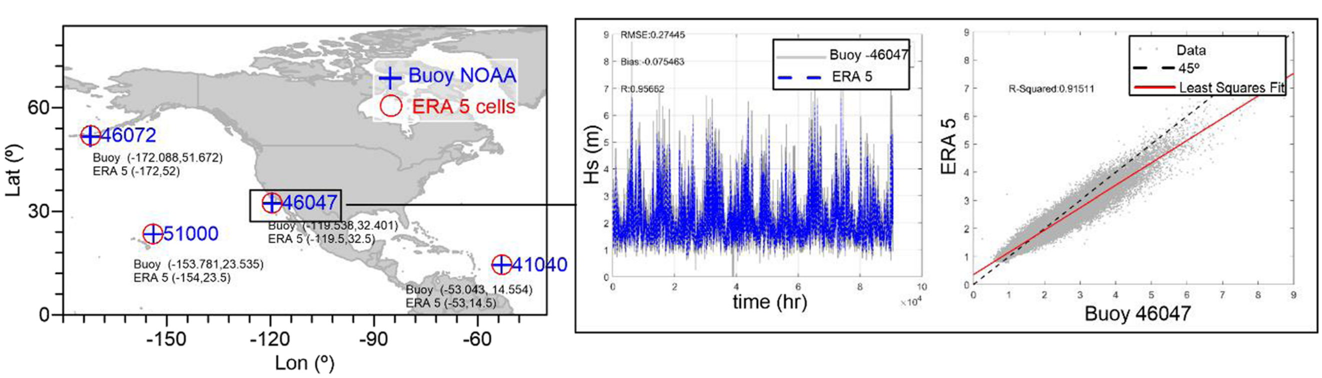

Fig. 1 Locations of the buoys used in the validation of ERA5 and the results for buoy 46047

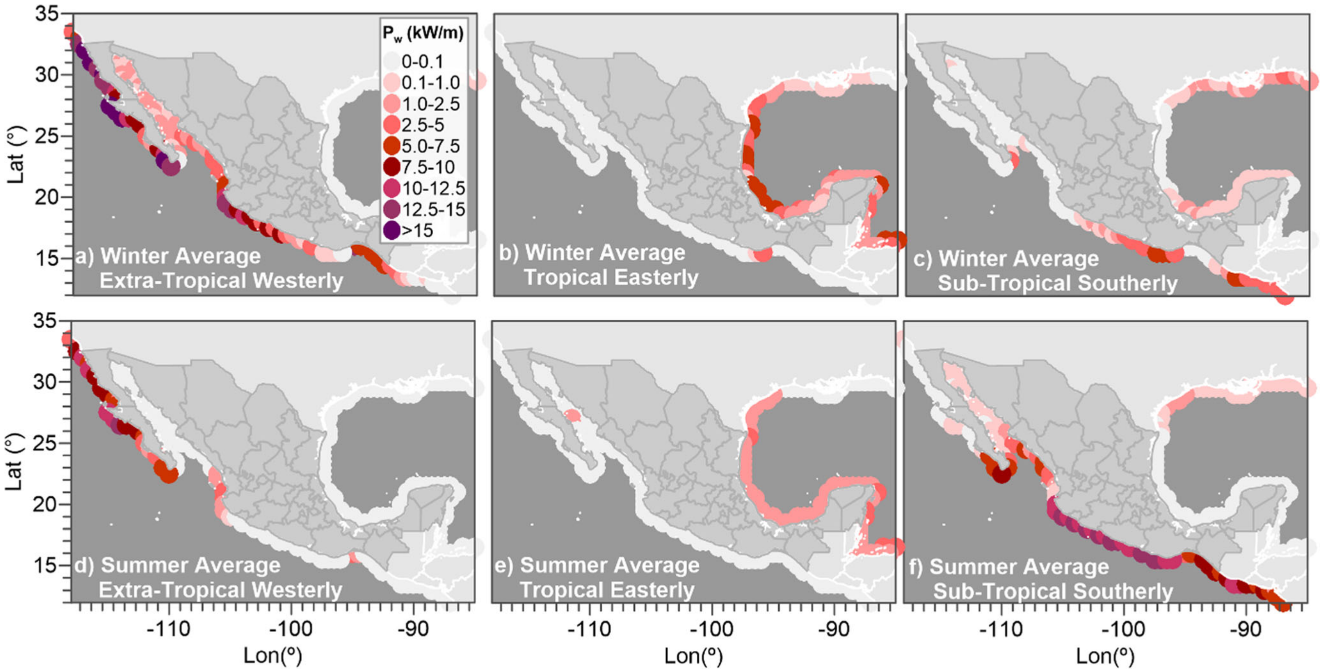

Fig. 2 Wave power averages by season for each wave climate type. **a** ETW P_w average for winter. **b** TE P_w average for winter. **c** STS P_w average for winter. **d** ETW P_w average for summer. **e** TE P_w average for summer. **f** STS P_w average for summer

coast (~ 7.5 kW/m) because it is a more proximal wave generation source derived from the relatively weak tropical trade winds in the Atlantic. An anticlockwise rotation in the wave field of approximately 20 degrees is evident during the summer.

Each wave climate type is generated by surface-level wind patterns, resulting from the variability in sea level pressure (SLP). Those generation mechanisms are the key to understanding present, and indeed future, seasonal to multi-decadal wave climate variability. The prevalence of each wave

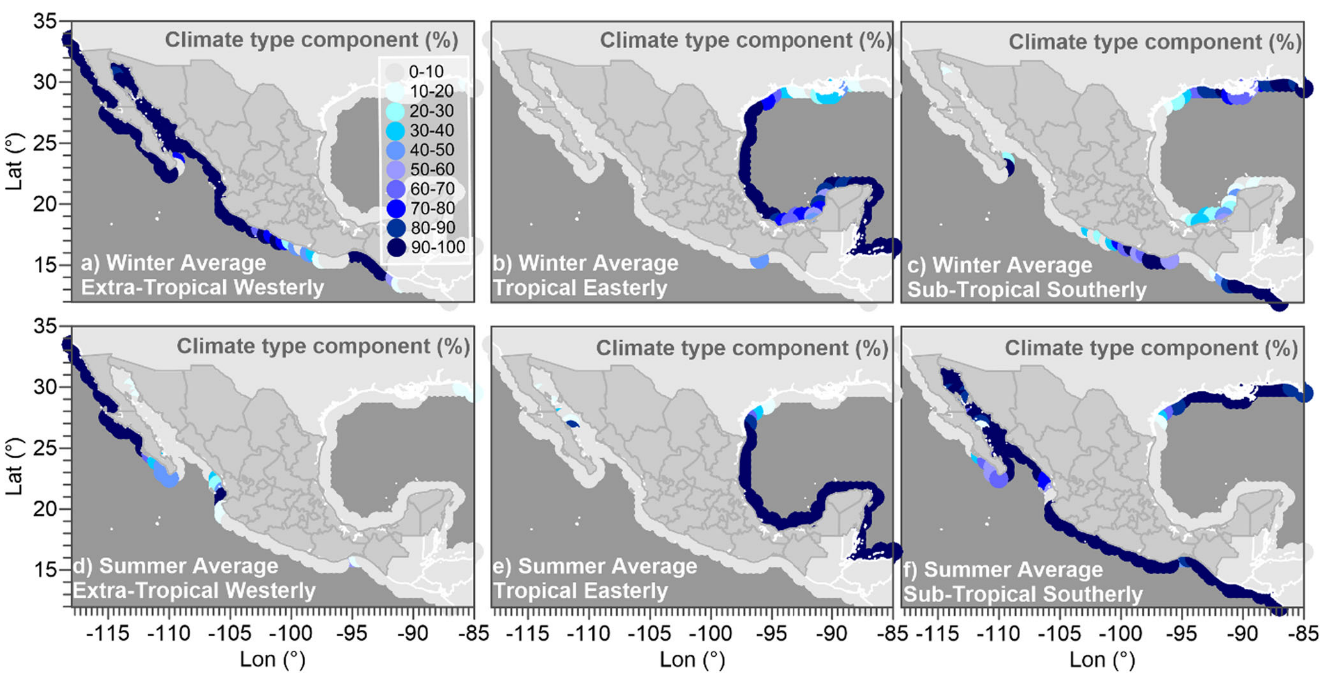

Fig. 3 Wave climate type percentage contribution by season average. **a** ETW percentage contribution for winter average. **b** TE percentage contribution for winter average. **c** STS percentage contribution for winter average. **d** ETW percentage contribution for summer average. **e** TE percentage contribution for summer average. **f** STS percentage contribution for summer average

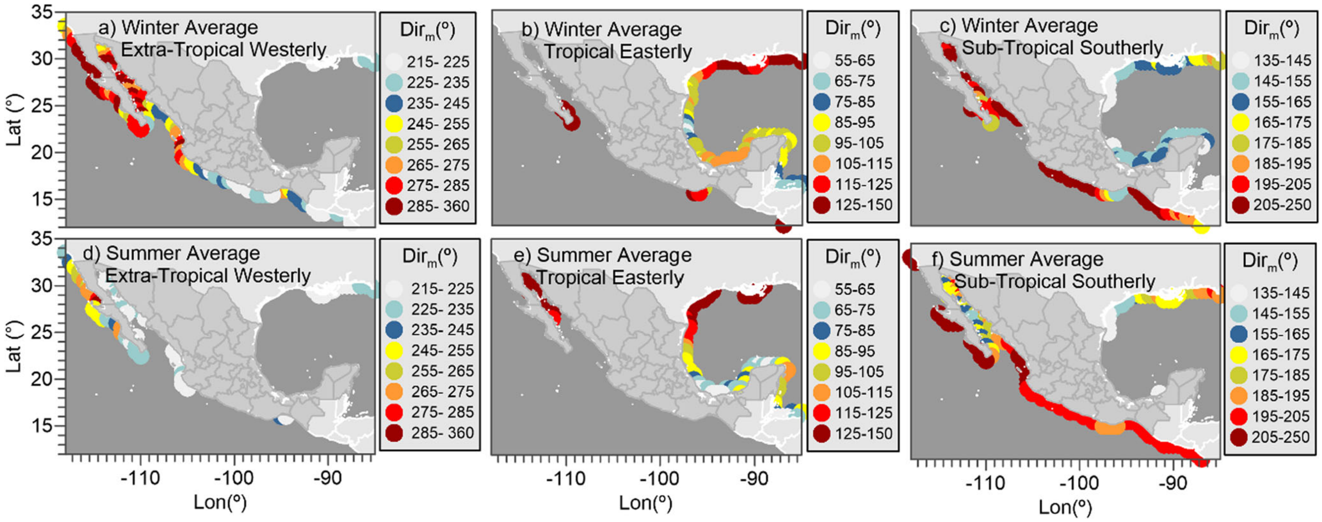

Fig. 4 Wave climate type mean direction by season. **a** ETW mean direction for winter. **b** TE mean direction for winter. **c** STS mean direction for winter (DJF). **d** ETW mean direction for summer (JJA). **e** TE mean direction for summer (JJA). **f** STS mean direction for summer (JJA). The direction follows meteorological convection

climate type (ETW, TE, or STS) is dependent on the relative position of regional low and high atmospheric pressure cells.

The atmospheric configuration responsible for the generation of ETW wave climate in the northern hemisphere mid-latitudes is a quasi-stationary low-pressure system (Aleutian Low) located to the north of a high-pressure system (Pacific High), producing surface-level westerly winds and waves in the North Pacific. This wave climate type leads to high-power north-westerly wave conditions along the Mexican Pacific coast.

The STS wave climate is generated in the southern hemisphere subtropics and propagates towards the Mexican Pacific coast when an anti-cyclonic high-pressure system is located to the east of a cyclonic low-pressure system. This is produced by the interaction of a Southeast Pacific Oceanic High and a South American Continental Low, or a Southeast Australian Continental High and a Southwest Pacific Oceanic Low. This produces moderate-power, south to south-easterly wave conditions along the Mexican Pacific coast.

While both ETW and STS wave climate types are the result of Pacific meridional configurations, the TE wave climate is produced by a zonal configuration in the Atlantic involving the cyclonic Azores and anti-cyclonic St Helena Oceanic Highs in the Northern and Southern Hemisphere, respectively, and the equatorial low-pressure belt over the Atlantic. This configuration produces surface-level, easterly “trade” winds across the tropics, leading to relatively low-power, easterly wave conditions for the Mexican Atlantic coast.

Seasonal to multi-decadal variability in the SLP systems leads to variability in the wave climate types at similar timescales. For example, during the boreal winter, the Aleutian Low and Pacific High form a constant low-/high-pressure belt that covers the North Pacific region (Fig. 5b) and, consequently, the ETW wave climate type is a dominant feature of the Mexican Pacific coast at this time of year. However, during the summer, the Aleutian Low and Siberian High both dispel in the Northern Hemisphere and, instead, an austral-winter continental high and oceanic low become dominant in the Australian-Southwest Pacific region (Fig. 5b), which leads to more STS wave conditions along the Mexican Pacific coast in the boreal summer. Likewise, the seasonal location of zonal TE wave conditions is controlled by the position of the Inter-Tropical Convergence Zone (ITCZ) and thus linked to the location of the tropical Hadley cell. Inter-annual to multi-decadal variations in these basin-scale configurations are then controlled by large-scale climate-ocean feedbacks such as ENSO, the PDO, or the AMO.

3.3 Inter-annual variability in wave climate

Inter-annual variability in the wave climate was analyzed in the context of the main driver of sub-decadal regional climate variability, the ONI (ENSO). The correlations between this climate index and the Mexican wave climate was calculated using the monthly wave direction (Dir_m) and wave power (P_w) time series with the trend and annual components removed (see Section 2 for details).

Figure 6 shows the correlation between P_w and Dir_m with the ONI. A positive (negative) correlation for P_w indicates an increase (decrease) in wave power with an increase (decrease) in the ONI. A positive (negative) correlation for Dir_m indicates a clockwise (anticlockwise) rotation in wave direction with an increase (decrease) in the ONI. Section 2.4 explains the range of values for the correlation coefficients.

Figure 6 shows there is a moderate-strong positive correlation between wave power and the ONI along the north and

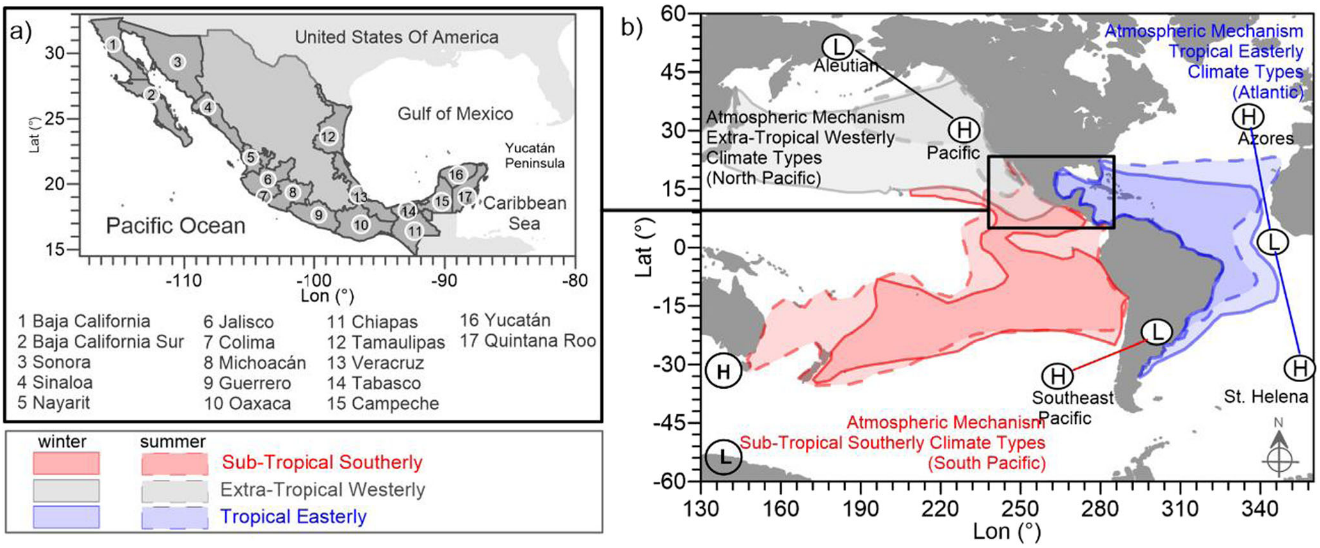

Fig. 5 **a** Geographical regions of Mexico and **b** the average areas of each wave climate type (subtropical southerly, extratropical westerly, and tropical easterly) in winter and summer, and their atmospheric mechanisms

central Mexican Pacific coast, with the highest values seen on the coast of Baja California. This falls to a moderate-strong negative correlation along the south Pacific Mexican coast. This suggests that wave power increases (decreases) during El Niño (La Niña) on the north and central Pacific coast, but this relationship seems to be inverse along the south Mexican and Central American Pacific coast where wave power decreases (increases) during El Niño (La Niña). The wave power response to ENSO on the Caribbean coast is weaker.

Wave direction is negatively moderate-strong correlated with the ONI on the coasts of northern Baja California, Central America, and the Gulf of Mexico, suggesting that an

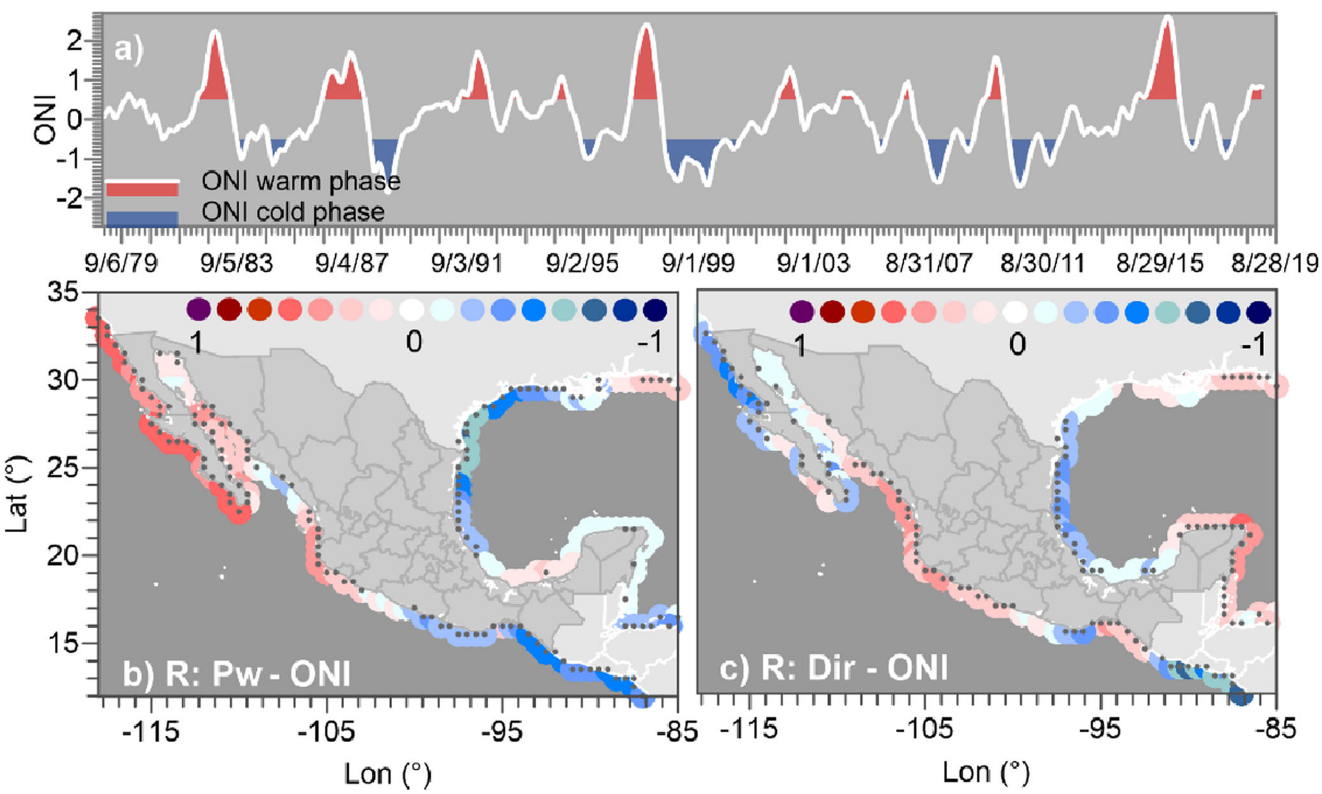

Fig. 6 **a** Time series of ONI climate index, in blue are the cold phases (La Niña) and in red the warm phases (El Niño). **b** Correlation coefficient (*R*) with the ONI and wave power. **c** Correlation coefficient with the ONI and mean wave direction. Points indicate correlation coefficient at 95% confidence level

anticlockwise (clockwise) rotation of the wave field occurs in these areas during El Niño (La Niña). Conversely, wave direction is moderately positively correlated with the ONI on the Yucatan Peninsula and center and south Pacific coast, with the exception of Oaxaca, indicating a significant clockwise (anticlockwise) rotation of the wave field during the El Niño (La Niña).

The Pacific coast of Mexico receives a bi-modal wave climate, with northern sections under the influence of prevailing westerly wave conditions, and southern sections of the coast affected more by southerly wave conditions. The rotations identified in Fig. 6 indicate a shift of the mean wave direction on the Baja California coast from west to southwest during El Niño and west to north-west during La Niña. On the southern Pacific coast of Mexico and into Central America, there is an intensification of the predominant southerly wave conditions during El Niño and a rotation towards the southwest during La Niña. On the Caribbean coast, the prevailing wave direction is easterly. During El Niño, an anticlockwise shift means more north-easterly wave conditions in the Gulf of Mexico, and during La Niña, more south-easterly conditions.

3.4 Multi-decadal variability in wave climate

Multi-decadal variability in the wave climate was analyzed using the PDO and AMO. Figure 7 shows the correlation between monthly P_w and Dir_m and the PDO, while Fig. 8 shows the same for the AMO.

On the Pacific coast, the multi-decadal wave climate responses to the PDO (Fig. 7b) is similar to the shorter-term response to ENSO (Fig. 6b); an increase (decrease) in wave power occurs along the north and central Mexican Pacific coast during El Niño–like PDO positive (La Niña–like, negative) periods, while the opposite relationship occurs on the south Mexican and Central American Pacific coast. This suggests that the PDO may amplify the wave power response to individual ENSO events along the Pacific coast. Similarly, the response of wave direction to the PDO (Fig. 7c) is similar to that of ENSO (Fig. 6c). There is a moderate negative correlation on the Pacific coasts of Baja California and Central America and in the Gulf of Mexico, with a positive response along the central Pacific Mexican coast and on the Yucatan Peninsula.

The AMO shows a regionally consistent wave climate response of moderate positive correlation on the entire Pacific coast and Yucatan Peninsula for wave power and direction, and weaker negative correlation in the Gulf of Mexico. This indicates that AMO positive (negative) drives an increase (decrease) in wave power with the opposite occurring on the Gulf coast. Figures 7 and 8 indicate coupling of wave climate response to the PDO and AMO on the north and central Pacific coast of Mexico and the Yucatan Peninsula.

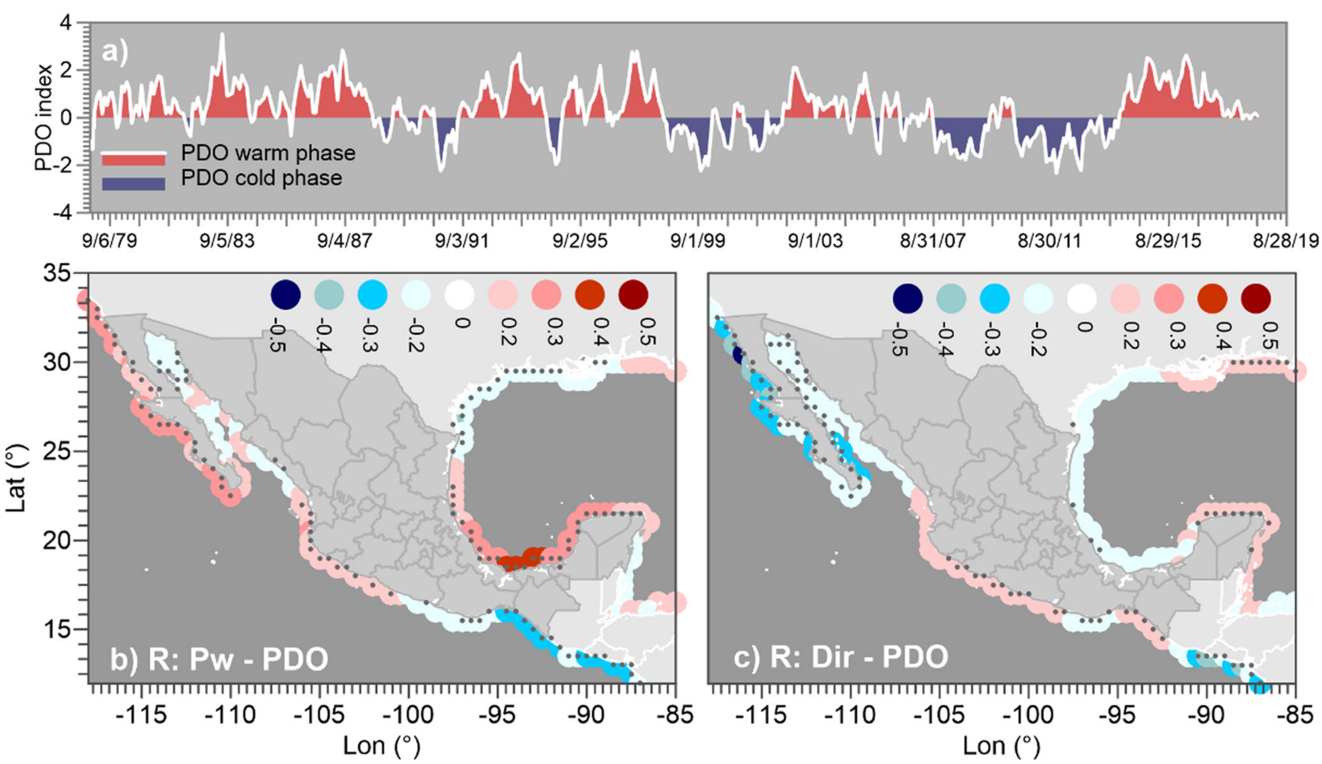

Fig. 7 **a** Time series of PDO climate index, in blue are the cold phases and in red the warm phases. **b**, **c** Correlation coefficient of the PDO phases with wave power (**b**) and wave direction (**c**). Points indicate correlation coefficient at 95% confidence level

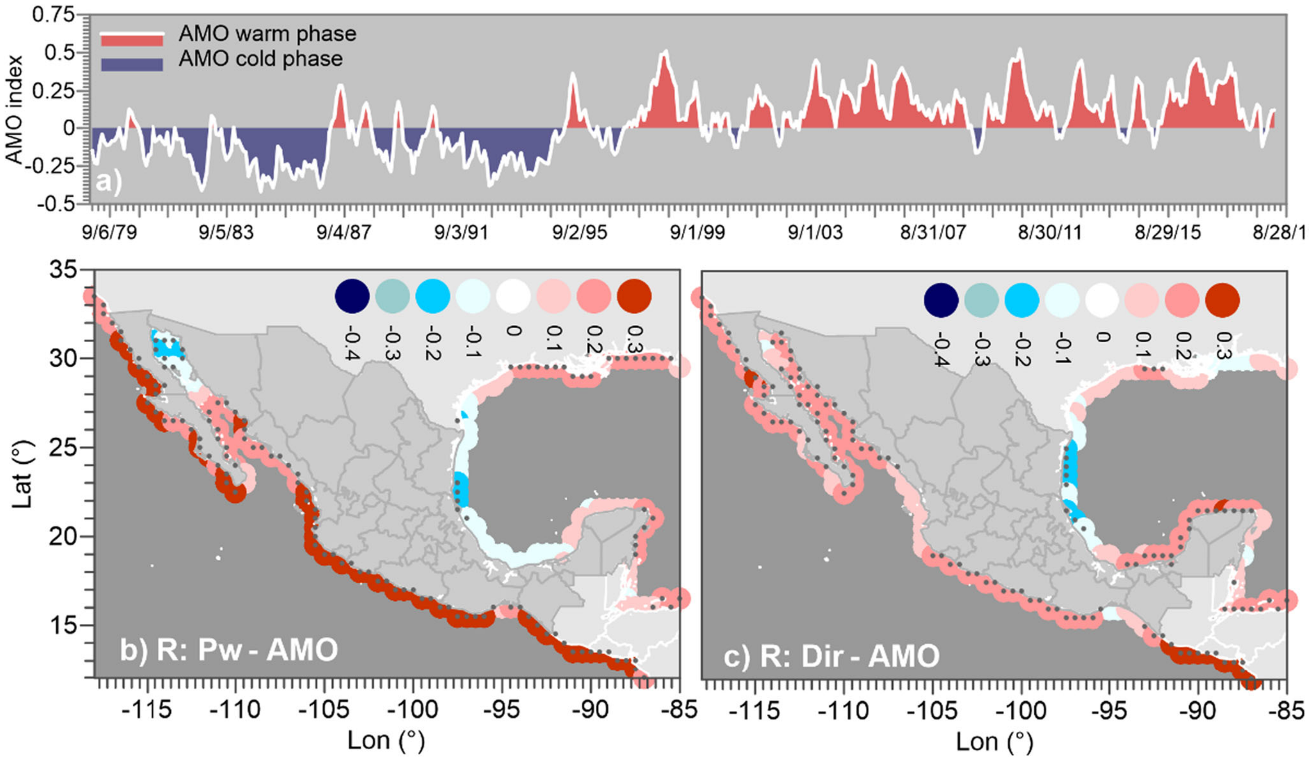

Fig. 8 **a** Time series of AMO climate index, in blue are the cold phases and in red the warm phases. **b**, **c** Correlation coefficient (*R*) with the AMO and wave power. **c** Correlation coefficient with the AMO and mean wave direction. Points indicate correlation coefficient at 95% confidence level

4 Discussion

In this analysis, the monthly averages of wave direction and wave power were used as the key drivers for coastal vulnerability (Muler and Bonetti 2014; Reguero et al. 2019) to study wave climate variability on the coasts of Mexico. The wave power was expressed as the sum of individual events at different time intervals, while the mean wave direction was expressed as the average of the time range studied. For the first time, global ERA5 wave hindcast was used to investigate the large-scale climate drivers of the Mexican wave climate from seasonal to multi-decadal timescales. The results show two distinct wave climate regimes: a highly seasonal, bi-directional wave climate on the Mexican Pacific coast, influenced by the extratropical westerlies (ETW) and subtropical southerlies (STS) global wave climate types, and a uni-directional and broadly seasonally homogenous wave climate on the Mexican Caribbean coast influenced by the tropical easterly (TE) wave climate type.

4.1 Seasonal variability

The Mexican Pacific coast experiences well-defined seasonal variability in wave climate, with the ETW wave climate type more dominant in winter and on the northern section of the coast, and the STS wave climate type more dominant in summer and on the south coast. This is because the ETW wave climate type is generated by the interaction between the Aleutian Low and Pacific High in the North Pacific Ocean producing west to north-westerly waves along the Mexican coast, while the STS wave climate type is generated by the Southeast Pacific Oceanic High and a South American Continental Low in the South Pacific Ocean, producing southerly waves.

These findings mean that the Mexican Pacific coast is sensitive to a broad range of pan-hemispheric climate configurations in the Pacific and experiences a distinctly bi-modal wave climate. Variability and future shifts in these climate systems are therefore likely to affect wave climate along the Mexican Pacific coast with potential implications for longshore sand transport. In contrast, the Mexican Caribbean coast is affected by TE wave conditions year-round, with much less seasonal variation. The TE wave climate type is the result of quasi-stationary low pressure in the tropical Atlantic Ocean and resultant easterly trade winds. As such, wave climate variability in the Gulf of Mexico and Yucatan Peninsula is probably the result of climate variability in a narrow latitudinal band in the tropical Atlantic, in contrast to a much wider area of genesis for waves impacting the Pacific coast.

4.2 Inter-annual variability

Given that ENSO is a primary driver of climate variability in the Pacific, it is not surprising that this analysis shows that it is also a primary driver of inter-annual wave power and wave direction on the Mexican Pacific coast. Results show that wave power increases (decreases) and rotates anticlockwise (clockwise) during El Niño (La Niña) on the north and central Pacific coast. That relationship begins to reverse in a southward direction on the south Mexican and Central American Pacific coast, where wave power decreases (increases) and wave direction rotates clockwise (anticlockwise) during El Niño (La Niña). In the North Pacific, El Niño reinforces the Aleutian Low shifts it eastward, pushing anticlockwise the winds (Niebauer 1988) and waves (Storlazzi and Reid 2010; Barnard et al. 2015). Nonetheless, during the El Niño event of 2015–2016, the waves turned clockwise (Barnard et al. 2017).

In practice, this means that during El Niño, the Mexican Pacific coast experiences a more uni-modal wave climate; both wave climates from the southwest and northwest quadrants increase their power and their opposite rotation trend to make them broadly parallel and coming from the SW (Fig. 9). Meanwhile, La Niña reinforces the bi-modality (high-power westerlies, ETW type, and moderate-power southerlies, STS type) of the prevailing wave climate. A shift towards more SW waves during El Niño means wave conditions are more shore-normal for much of the north and central Pacific coast and therefore less wave energy dissipation occurs with refraction across the shelf. As a result, these coasts experience an increase in nearshore wave power during El Niño. SW waves, however, are more shore-oblique for the southern Mexican Pacific and Central American coasts, which face due south, leading to increased shelf energy dissipation, reflection, and reduced nearshore wave energy during periods of El Niño. In addition, El Niño is associated with more frequent storm wave conditions in the Central East Pacific (e.g., Barnard et al. 2017), meaning an increase in the total monthly wave power (used as the metric in this analysis) towards the tropics (i.e., in a northward direction on the Mexican Pacific coast). In contrast, La Niña reinforces the bi-modality seen in the prevailing wave climate along the Mexican Pacific coast. La Niña is also associated with longer periods of calm wave conditions in the Central Eastern Pacific, which may also be a reason for the reduction seen in the monthly wave power during La Niña on the north and central sections of the coast.

These directional shifts in wave power identified during different phases of ENSO have implications for large-scale sand transport along the Pacific coast. Previous observational and theoretical studies (Rosati et al. 2002; Goodwin et al. 2016) have demonstrated the importance of small shifts in wave obliquity in determining rates of sand transport along the coast. The more shore-normal and higher wave power conditions experienced during El Niño for much of the north and central Pacific coast are likely to switch off, or at least reduce, the southward longshore sand transport that is operational during ENSO-neutral and La Niña periods under prevailing westerly waves (negatively oblique to the coast). Instead, cross-shore transport becomes more important in these periods. Quantification of the impacts of these shifts in directional wave power with ENSO for beach systems on the Mexican Pacific coast requires a high-resolution numerical study, which is the focus of a companion paper to this.

4.3 Multi-decadal variability

On multi-decadal timescales, results indicate that the PDO exhibits a similar response to ENSO on the Pacific coast, suggesting wave power and directional changes during individual ENSO events can be weakened or strengthened by coupling with the PDO in accordance with (Bromirski et al. 2013). The influence of the PDO (and indeed, ENSO) is shown to be weaker on the Caribbean coast.

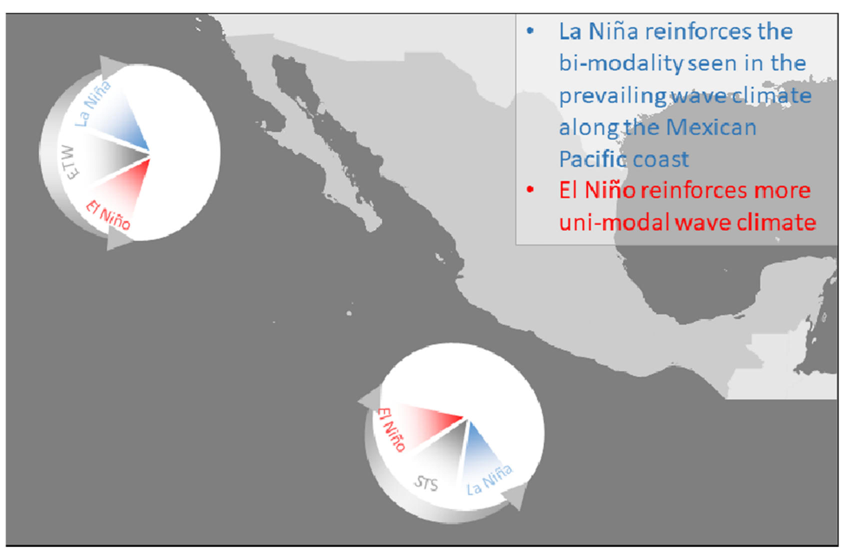

Fig. 9 Sketch of how ENSO, in its different phases (El Niño and La Niña), reinforces the uni- or bi-modality produced by ETW and STS climate types

In contrast, the AMO shows a significant multi-decadal response on both coasts, indicating that the AMO may couple with the PDO and ENSO to reinforce the same directional wave power response on the Pacific coast. Previous work has shown that phases of the AMO can force an anomalous SLP response of the Aleutian Low in the North Pacific (Babolcsai and Hirsch 2019), which suggests that the ETW wave climate type may indeed be influenced by the AMO on multi-decadal timescales. This may indicate that the AMO is the "stronger" of the two multi-decadal signals, and as suggested by previous authors (Steinman et al. 2015), the AMO may in fact be the driver of underlying variability in the Pacific.

4.4 Implications for coastal hazard assessment

Results indicate that for both coasts, wave climates are teleconnected, as they are generated by the structure of the lower atmosphere. The signal of teleconnection patterns is identified in the seasonal and long-term variability. The latter was previously detected by (Shimura et al. 2013b). This classification, under a climate perspective, quantifies the directional wave power associated with the atmospheric origin and presents teleconnection in its seasonal variability along both coasts. This knowledge could be used for understanding of coastal evolution to climate change. For example, the swells generated in the Southern Ocean that impact the center and south of Mexican Pacific are projected to be more energetic (e.g., Young et al. 2011; Babanin et al. 2019).

These wave power signatures can be used either as boundary conditions for coastal morphological models to identify the expected coastal response to these climate oscillations or as nearshore metrics for coastal vulnerability under different climate configurations and scenarios. For example, what might be the expected coastal response to an increased amplitude in ENSO as projected in some climate models (e.g., Cai et al. 2015), and how is the wave and sand transport response amplified or dampened depending on the background climate state in the Pacific (PDO) and Atlantic (AMO)? How can coastal managers mitigate this risk? Given the importance of ENSO, PDO, and AMO on the Mexican nearshore wave climate, and the potential for large-scale ocean-climate oscillations to change with a warming ocean, these should be pertinent questions in coastal hazard assessments, particularly for the design of coastal management plans with an expected life of 20 years or more.

5 Conclusions

A sound understanding of long-term coastal drivers is essential for the development of efficient plans for adaptation to climate change. Ocean waves are the main driver of sediment transport and shoreline change on exposed sandy coasts, with variability in the large-scale climate forcing changes in wave climate and, as a consequence, the shoreline position. Until now, a complete perspective of the seasonal and long-term wave climate variability in Mexico has been lacking. To address this, the present work analyzed the seasonal to long-term variability of the directional wave power of the Mexican coast at a 0.5° resolution using a newly available climate reanalysis product (ERA5) and a global wave climate classification method.

Results indicate that the Mexican Pacific coast has a predominately bi-modal wave climate, consisting of one westerly wave climate type with its origins in the North Pacific extratropics, and another southerly wave climate type generated in the Southern Ocean. This bi-modality exhibits considerable seasonal variability. Conversely, the wave climate of the Caribbean coast exhibits significantly less variability in directional wave power, with the wave field being generated in the Atlantic tropics year-round with much less latitudinal variation.

This work has confirmed ENSO as a key driver of wave climate variability for the coasts of Mexico at inter-annual timescales. Importantly, we showed that the bi-directionality of the Mexican Pacific wave climate is broken down during periods of El Niño leading to a more uni-directional (southwesterly), shore-normal, and higher nearshore wave power climate than during ENSO-neutral periods. Conversely, La Niña reinforces the bi-directionality and obliqueness of the prevailing wave climate and leads to an overall reduction in monthly-averaged nearshore wave power. The identification of these directional wave power signatures during ENSO phases may help understand shoreline fluctuations on inter-annual timescales along the Mexican Pacific coast and is the focus of further research.

Results also suggest that the wave power responses to individual ENSO events along the Mexican Pacific coast can be either amplified or dampened depending on the underlying phase of the multi-decadal PDO. The influence of the PDO appears to be restricted to the Pacific Coast. Conversely, results suggest that the AMO influences directional wave power on both coasts, lending credence to the hypothesis that the AMO governs the PDO and perhaps even wave climate variability in the Pacific.

The wave power signatures identified in this study give further knowledge of the relatively under-studied drivers of the Mexican wave climate. We believe that this information should now be integrated into baseline assessments for individual coastal management plans and hazard assessments. The directional wave power signatures can be used either as boundary conditions for coastal morphological models to identify the expected coastal response to these climate oscillations, or used as nearshore metrics for coastal vulnerability under different climate configurations and scenarios (the data presented in this work have been made available in a Mendeley Data repository: doi:https://doi.org/10.17632/tx3f36mrsm.1). With some studies suggesting the amplitude of ENSO may change in the coming decades with climate change, elucidating the wave power and coastal response to these changes remains imperative for sustainable coastal management in Mexico.

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Authors' contributions Itxaso Odériz: conceptualization and methodology, data acquisition, data analysis, data validation, data interpretation, writing, review, and editing. Rodolfo Silva: conceptualization and methodology, funding acquisition, supervision, data interpretation, writing, review, and editing. Thomas Mortlock: conceptualization and methodology, supervision, data interpretation, writing, review, and editing. Edgar Mendoza: funding acquisition, data interpretation, writing, review, and editing.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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