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LETTER

Future changes and seasonal variability of the directional wave spectra in the Mediterranean Sea for the 21st century

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Supplementary material for this article is available online

Abstract

A state-of-the-art regional assessment of future directional wave spectra in the Mediterranean Sea and the projected changes with respect to hindcast is presented. A multi-model EURO-CORDEX regional ensemble of bias-adjusted wave climate projections in eleven locations of the Mediterranean are used for the assessment of future seasonal changes in the directional wave spectra under the high-emission scenario RCP8.5. This analysis allows us to identify climate change effects on the spectral energy of the swell and wind-sea systems and their seasonal variability which cannot be captured with the standard integrated wave parameters, such as significant wave height and mean wave direction. The results show an overall robust decrease in the predominant wave systems, resulting in a likely decrease in the significant wave height that is in agreement with previous studies. However, the results depict a robust increase in other less energetic frequencies and directions leading to a projected behavioral change from unimodal to bimodal/multimodal wave climate in many locations which has strong repercussions on the vulnerability of coastal assets and ports operability.

1. Introduction

Projected changes in wave climate arising from changes in atmospheric circulation vary on a regional and local scale and can enlarge or alleviate coastal hazards. Therefore, the main starting point for designing adaptation and mitigation strategies for coastal planning is obtaining an accurate representation on current and future wave climate including the multimodal characteristics of waves (IPCC 2019, Oppenheimer *et al* 2019). Studies of wave climate variability traditionally focus on integrated bulk parameters (such as the significant wave height, mean wave period, and mean wave direction). Nevertheless, in detail analysis of wave climate and its relation to climate circulation patterns needs to include information on its multimodal behavior, i.e. the wave spectral density distribution over different frequencies (inverse of periods) and directions which can be achieved by means of 2D directional wave spectrum (Shimura and Mori 2019). Echevarria *et al* (2019) analyzed the seasonal variability of wave climate on a coarse global grid by resolving the directional wave spectra and found that a more complete depiction of the complexity of ocean waves, allowing to identify different wave systems, is given by the description of wave spectral density which can not be properly captured with the traditional integrated parameters analysis. Additional directional wave spectra analysis at regional or local scales Mortlock and Goodwin (2015), Portilla-Yandún *et al* (2016), Villas Bôas *et al* (2017), Shimura and Mori (2019), i.e. agree on the advantages to understand the behavior of multimodal and multivariate wave climate and their seasonal and regional variability and more so when multiple swell and wind-sea wave systems are present.

Future changes of global wave climate under climate change scenarios are usually based on the simulations of wave generation and propagation models forced by surface winds from Global Climate Models Morim *et al* (2018), Oppenheimer *et al* (2019), GCMs,. On a regional scale, wave models driven by high-resolution dynamically-downscaled surface winds from Regional Climate Models (RCM) allow

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an enhanced characterization of wave climate which is fundamental for coastal impact and adaptation assessments. In Europe, the EURO-CORDEX (Jacob *et al* 2014, 2020) initiative provides a large ensemble of GCM–RCMs atmospheric simulations with up to 0.11° (≈ 12.5 km) and 6 h spatial and temporal resolution, respectively.

Many studies in the recent decades have focused on understanding the projected future changes in mean and extreme values of integrated parameters, mainly significant wave height, and some include information on mean wave period and wave direction Hemer *et al* (2013), Mentaschi *et al* (2017), Morim *et al* (2019), De Leo *et al* (2021), Lira-Loarca *et al* (2021a), e.g.. Although there is a general agreement regarding projections of annual and seasonal mean changes in wave climate there is still a limited knowledge regarding changes in temporal variability and in-depth analysis of changes in wave direction and period (Collins *et al* 2019, Morim *et al* 2019, Lira-Loarca *et al* 2021a).

Therefore, the analysis of projections of directional spectra could provide information on future changes in the energy spread over frequency and direction therefore allowing to analyze the wave systems, their development and evolution, crucial for longshore sediment transport and shoreline stability assessment in a changing climate. Recently, Lobeto *et al* (2021) presented an analysis of wave spectra on different locations of the world based on future and base-period simulations for a wave climate ensemble forced by GCMs surface winds highlighting the need for spectral analysis in order to properly characterize the propagation of swell projected changes. Given that the wave projections were forced using GCMs, the analysis does not include a location in the Mediterranean Sea where, due to the characteristic regional wind and wave climate circulation, high-resolution regional wave climate projections are needed to accurately represent its behavior. Additionally, accurate assessments of future changes in wave climate should be done with respect to validated historical conditions and taking into account and adjusting the systematic bias inherent in GCM and RCM simulations using bias-correction techniques. The use of bias-adjustment methods for GCM/RCM outputs is extended in climate and hydrological impact studies but their application to wave climate still remains an open and challenging issue due to the multivariate behavior, the spatial correlation and diverse temporal variability of wave climate (Lemos *et al* 2020). Additionally, the use of bias-correction techniques to wave spectra has not been addressed given the 2D characteristics of the wave density spectra (Lobeto *et al* 2021). To the authors knowledge, a detailed assessment of projected changes in wave directional spectra with respect to hindcast using high-resolution RCMs in the Mediterranean Sea has not been previously studied.

To address the need for understanding of the multimodal and multivariate characteristics of future wave climate, this study presents an assessment on the projected changes in wave directional spectra in the Mediterranean Sea using high-resolution GCM–RCM wave climate simulations for mid-century (2034–2060) and end-of-century (2074–2100) under a high-emission scenario. Additionally, it tackles the bias-correction of 2D energy density spectra applying the widespread delta method to seasonal averages of the projections of a multi-model ensemble with respect to historical conditions. Therefore, this study provides a broader understanding of the effects of climate change, in the Mediterranean Sea, on wave energy, the projected changes in period and direction as well as the seasonal variability of the wave field accounting for the different observed wave systems in the spectra and their temporal variability.

This paper is organized as follows. Section 2 provides a description of GCM–RCMs ensemble of surface wind data, the wave generation and propagation model and the methodology employed for correcting the bias of the projections as well as the analysis of future seasonal changes. Section 3 presents the results for the performance of the multi-model GCM–RCM ensemble for the historical baseline period (1979–2005), the bias-adjustment of GCM–RCM wave spectra simulations and the projected changes in wave climate focusing on the spatial and seasonal variability observed in the Mediterranean Sea for mid-century (2034–2060) and end-of-century (2074–2100), each period covering 27 years as in the baseline historical period. Finally, section 4 presents the discussion and the main conclusions from this work.

2. Methods and data

This section provides a description of the hindcast simulations using the numerical model Wavewatch III and the multi-model ensemble wave climate projections of directional wave spectra under climate change scenario RCP8.5 developed with the same setup. Additionally, the bias-adjustment method used to correct for systematic biases in GCM–RCM simulations is presented, as well as the methodology followed to evaluate projected changes under a climate change scenario and their uncertainty.

2.1. Wave hindcast and projections in the Mediterranean Sea

The wind-wave hindcast in the Mediterranean Sea developed by the Meteocean research group[1] of the University of Genoa (Italy) provides high-resolution wave climate data from 1979 to 2020 with a regular

[1] www3.dicca.unige.it/meteocean/hindcast.html.

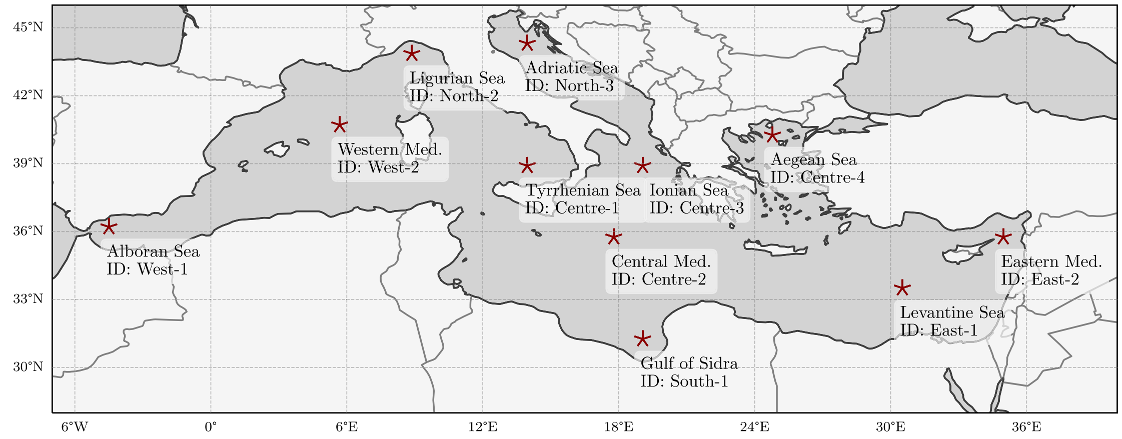

Figure 1. Location and ID of the analyzed points.

Table 1. Analyzed locations for the different representative regions of the Mediterranean Sea.

Point ID	Longitude	Latitude	Region
West-1	−4.5	36.21	Alboran Sea
West-2	5.69	40.71	Western Mediterranean
North-1	8.87	43.86	Ligurian Sea
Centre-1	13.96	38.91	Tyrrhenian Sea
North-2	13.96	44.31	Adriatic Sea
Centre-2	17.78	35.76	Central Mediterranean
Centre-3	19.06	38.91	Ionian Sea
South-1	19.06	31.26	Gulf of Sidra
Centre-4	24.79	40.26	Aegean Sea
East-1	30.52	33.51	Levantine Sea
East-2	34.97	35.76	Eastern Mediterranean

grid of 0.127° in longitude and 0.09° in latitude, corresponding to ≈10 km (Mentaschi *et al* 2013, 2015). It uses the third-generation wave model Wavewatch III version 5.16; The WAVEWATCH III:® Development Group (2019), hereinafter WW3 with the source terms of growth/dissipation ST4 (Ardhuin *et al* 2010, Rascle and Ardhuin 2013). The hindcast has been validated against buoy observations providing data of integrated wave parameters in different locations in the Mediterranean Sea. For further details on the setup and validation, the reader is referred to Mentaschi *et al* (2013, 2015), Besio *et al* (2016).

Hindcast wave directional spectra time series from 1979 until 2020 with hourly resolution are obtained for eleven locations of the Mediterranean Sea as depicted in figure 1 and table 1. For each location, the energy spectra is discretized into 24 directional bins of 15° and 25 frequency bins ranging from ≈0.07 to 0.66 Hz (conversely ≈1.5–15 s in period). The Mediterranean Sea is characterized by a complex morphology and spatial heterogeneity and wave climate driven by regional and local winds. The selection of the analyzed locations was done according to different sub-basins characteristic of regional and local dynamics and the spatial correlation of integrated wave parameters (Lazzari *et al* 2012, Besio *et al* 2016, Di Biagio *et al* 2020, Barbariol *et al* 2021).

The wave climate future projections were obtained using the same WW3 configuration as the hindcast, forced by surface wind fields of seventeen different EURO-CORDEX (Jacob *et al* 2014, 2020) models (GCM–RCM combinations) with 6 h temporal resolution and 0.11° (≈12.5 km) spatial resolution (Lira-Loarca *et al* 2021b). Wave climate simulations for each model were obtained for the base-period from 1970 until 2005 and for the RCP8.5 high-emission scenario extending from 2006 until 2100. The information regarding the GCM–RCM combinations used in this study is presented on table 2. Additional details of the definition and performance of the different RCMs used in this work can be found on Strandberg *et al* (2014) for the Rossby Centre regional climate model RCA4, (Will *et al* 2017) for the CLM-Community CCLM4-8-17 model, Christensen *et al* (2007) for the Danish Climate Centre regional climate model HIRHAM5 and Leutwyler *et al* (2017) for the COSMO-CLM accelerated version COSMO-crCLIM-v1-1.

2.2. Bias-correction of wave directional spectra

GCMs and RCMs outputs exhibit varying levels of systematic errors or biases when compared to observations or hindcast data. Said biases are derived from simplified physics and discretization, coarse spatial

Table 2. EURO-CORDEX RCM and driving GCM combinations and notation used.

Institution	RCM	GCM	Notation
CLMcom	CCLM4-8-17	CCCma-CanESM2	CCLM4-CanESM2
CLMcom	CCLM4-8-17	MIROC-MIROC5	CCLM4-MIROC5
SMHI	RCA4	MPI-M-MPI-ESM-LR	RCA4-MPI-ESM-LR
SMHI	RCA4	NCC-NorESM1-M	RCA4-NorESM1-M
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5	RCA4-CNRM-CM5
SMHI	RCA4	IPSL-IPSL-CM5A-MR	RCA4-IPSL-CM5A-MR
SMHI	RCA4	MOHC-HadGEM2-ES	RCA4-HadGEM2-ES
SMHI	RCA4	ICHEC-EC-EARTH	RCA4-EC-EARTH
DMI	HIRHAM5	ICHEC-EC-EARTH	HIRHAM5-EC-EARTH
DMI	HIRHAM5	NCC-NorESM1-M	HIRHAM5-NorESM1-M
DMI	HIRHAM5	MOHC-HadGEM2-ES	HIRHAM5-HadGEM2-ES
DMI	HIRHAM5	MPI-M-MPI-ESM-LR	HIRHAM5-MPI-ESM-LR
DMI	HIRHAM5	CNRM-CERFACS-CNRM-CM5	HIRHAM5-CNRM-CM5
DMI	HIRHAM5	IPSL-IPSL-CM5A-MR	HIRHAM5-IPSL-CM5A-MR
CLMcom-ETH	COSMO-crCLIM-v1-1	ICHEC-EC-EARTH	COSMO-crCLIM1-EC-EARTH
CLMcom-ETH	COSMO-crCLIM-v1-1	NCC-NorESM1-M	COSMO-crCLIM1-NorESM1-M
CLMcom-ETH	COSMO-crCLIM-v1-1	MOHC-HadGEM2-ES	COSMO-crCLIM1-HadGEM2-ES

resolution, internal variability, numerical parameterizations, among others (Christensen *et al* 2008, Teutschbein and Seibert 2012), which can be inherited in dowscaling processes i.e, when using wind surface fields to force numerical wave models. Bias-correction techniques are widespread in climate and hydrological impact studies dealing with variables such as precipitation and temperature but their application to wave and wind variables still remains an open and challenging issue due to the multivariate behavior and the spatial and temporal variability of wave climate (Lemos *et al* 2020). More specifically, the bias-adjustment of 2D directional wave spectra data is yet to be addressed and further research is required to allow a better understanding of biases of the different wave systems taking into account their frequency and direction (Lobeto *et al* 2021).

To correct for biases in the GCM–RCM wave climate projections, this study uses the widespread simple '*delta method*' (Hay *et al* 2000) which consists on homogeneously correcting the simulated variable by removing the error between the observed and simulated values in the present day or base period simulations (Lemos *et al* 2020). Given that the wave energy density spectrum is bounded below by zero and presents a varied order of magnitude over frequency and direction, a multiplicative rather than additive delta bias-correction method will be applied, which corresponds to applying the projected relative change with respect to hindcast values. In addition, given the seasonal temporal variability present in wave climate (Lira-Loarca *et al* 2021a), the bias-correction will be done per season for the baseline period 1979–2005 (27 years) for both the hindcast and GCM-RCMs simulations. Hence, the bias-correction method applied to the seasonal mean energy density spectra $S(f,\theta)$ for each frequency, f, and direction, θ, in an individual location is as follows,

$$\overline{S^*(f,\theta)_m} = \overline{S(f,\theta)_m} \cdot \frac{\overline{S(f,\theta)_{\mathrm{hind}}}}{\overline{S(f,\theta)_{m_{\mathrm{hist}}}}}, \quad (1)$$

where $\overline{S(f,\theta)_m}$ and $\overline{S^*(f,\theta)_m}$ are the raw and bias-adjusted seasonal mean energy density values of a given GCM–RCM simulation, $\overline{S(f,\theta)_{m_{\mathrm{hist}}}}$ is the seasonal mean of the GCM–RCM simulation in the historical base period (1979–2005) and $\overline{S(f,\theta)_{\mathrm{hind}}}$ corresponds to the hindcast seasonal mean, also for the period 1979–2005.

2.3. Projected change in directional wave spectra for a multi-model ensemble

The assessment of future directional wave spectra under RCP8.5 is done by means of the multi-model ensemble mean per seasons. Given that the ensemble is comprised of a combination of eight forcing GCMs and four different RCMs and that the projected changes in wave climate depend on the GCM-forcing (Morim *et al* 2021), a weighted ensemble mean approach has been used as,

$$WE[S(f,\theta)] = \frac{\sum_{m=1}^{N_m} w_m \cdot \overline{S^*(f,\theta)_m}}{\sum_{m=1}^{N_m} w_m}, \quad (2)$$

where $WE[S(f,\theta)]$ is the weightened multi-model ensemble seasonal average, N_m is the number of GCM–RCMs included the ensemble, w_m is the corresponding weight for each GCM–RCM, calculated as the number of GCM–RCMs ensemble members forced with the same GCM with respect to N_m and $\overline{S^*(f,\theta)_m}$ is the bias-adjusted seasonal mean energy density. Additionally, the ordinary arithmetic ensemble mean was calculated and obtained similar results as the weighted mean approach.

The assessment of the projected changes of directional wave spectra under RCP8.5 is done by evaluating the relative change between the multi-model ensemble seasonal mean and hindcast seasonal mean with respect to the maximum value, in frequency and direction (f, θ), of the corresponding hindcast seasonal mean,

$$\Delta S(f,\theta) = \frac{WE[S(f,\theta)] - \overline{S(f,\theta)}_{\mathrm{hind}}}{\max_{(f,\theta)}\left\{\overline{S(f,\theta)}_{\mathrm{hind}}\right\}} \cdot 100 \quad [\%], \quad (3)$$

where $\Delta S(f,\theta)$ is the seasonal projected relative change in percentage and $\overline{S(f,\theta)}_{\mathrm{hind}}$ corresponds to the hindcast seasonal mean.

The analysis of the uncertainty of the results across the different GCM-RCMs, follows a methodology proposed by the IPCC reports considering model agreement according to the number of models that agree on the sign of the change (Collins *et al* 2013). Therefore, for all results presented henceforward relating projected changes in the directional energy density spectra, the areas where at least 80% of the GCM-RCMs agree on the sign of the change are stippled and interpreted as results depicting 'model agreement'. On the other hand, regions where the models do not agree on the sign of the change are left without any pattern.

3. Results

This section presents the results of the projected seasonal changes in wave directional spectra in the Mediterranean Sea. The results are presented in terms of the prevailing incoming wave directions and systems, highlighting the difference in future behavior of the wind-sea waves comprising waves with periods between 3-6 seconds and swell waves for waves with periods higher than 7 s. Additionally, where possible, the results will be compared to projected changes in integrated wave parameters: significant wave height, H_s, peak period, T_p, and mean wave direction, θ_m presented in the supplementary information and referencing previous studies (e.g. Mentaschi *et al* 2017, Morim *et al* 2019, De Leo *et al* 2021, Lira-Loarca *et al* 2021a, 2021b). This section is organized as follows. First, an assessment of the performance of the raw multi-model GCM–RCM ensemble during the base period (1979–2005) against hindcast is presented. Second, we present the analysis of the bias correction of the 2D spectra. Next, the general spatial characteristics of the projected changes in wave spectra in the Mediterranean Sea under are addressed. For clarity and brevity, we present only the spatial variability during spring. Finally, an in-depth analysis of the seasonal variability focusing on the points located in the Alboran sea, Central Mediterranean and Eastern Sea is depicted. The remaining results are included in the supplementary information.

3.1. Performance of the multi-model GCM–RCM ensemble

In order to accurately assess the confidence in the projection of the directional wave spectra for the multi-model GCM–RCM ensemble, we must first analyse its performance for the baseline period (1979–2005) against the validated hindcast dataset (Bricheno and Wolf 2018). Then, figures 2 and 3 present the seasonal mean hindcast 2D spectra, the ensemble mean and standard deviation for the raw GCM–RCM simulations for the points West-1 (Alboran Sea) and Centre-2 (Central Mediterranean), respectively. The remaining locations are included in the supplementary information.

Regarding the performance of the GCM–RCM ensemble at the Point West-1 (Alboran Sea), it can be observed in figure 2 the ensemble mean presents a similar distribution of wave systems as the hindcast spectra, with a more energetic swell system ($T = 5$–10 s) from the ENE–ESE direction and a less energetic system in the WSW–WNW directions. The latter is more noticeable in the hindcast spectra with energy values depicted for both swell and wind sea condition in all seasons, whereas the ensemble mean presents lower values and does not accurately captures the western swell system. The highest energy values are observed during winter ($S \approx 0.015$ $\mathrm{m^2\,s\,deg^{-1}}$) and spring ($S \approx 0.01$ $\mathrm{m^2\,s\,deg^{-1}}$) for the hindcast. For winter, the ensemble presents an underestimation of $\Delta S \approx 0.003$ $\mathrm{m^2\,s\,deg^{-1}}$ but with a higher spread with standard deviations of ≈ 0.005 $\mathrm{m^2\,s\,deg^{-1}}$, encompassing the hindcast values. For spring, the ensemble presents an overestimation of $\Delta S \approx 0.0025\,\mathrm{m^2\,s\,deg^{-1}}$ in the mean values and standard deviation values of $\approx 0.004\,\mathrm{m^2\,s\,deg^{-1}}$. Likewise for summer and fall the ensemble mean presents overestimated values of density spectra in the main East swell system with larger spreads encompassing the hindcast values.

Regarding the performance of the GCM–RCM ensemble for the Centre-2 (Central Mediterranean) location, it can be observed that the ensemble mean captures the multimodal system present in the hindcast energy spectra. It can be highlighted that in this case, the ensemble mean presents overestimated energy values with respect to hindcast for the more energetic systems. The highest differences are obtained for winter with a maximum difference of $\Delta S \approx 0.007\,\mathrm{m^2\,s\,deg^{-1}}$ between the ensemble mean and the hindcast with low values of spread. The highest values of ensemble spread are obtained for summer where the ensemble standard deviation presents values of the same order of magnitude as the ensemble mean.

The analysis of the performance and the spread of the GCM–RCM ensemble during the baseline period allows to better understand the reliability of the future projected changes. It can be observed that

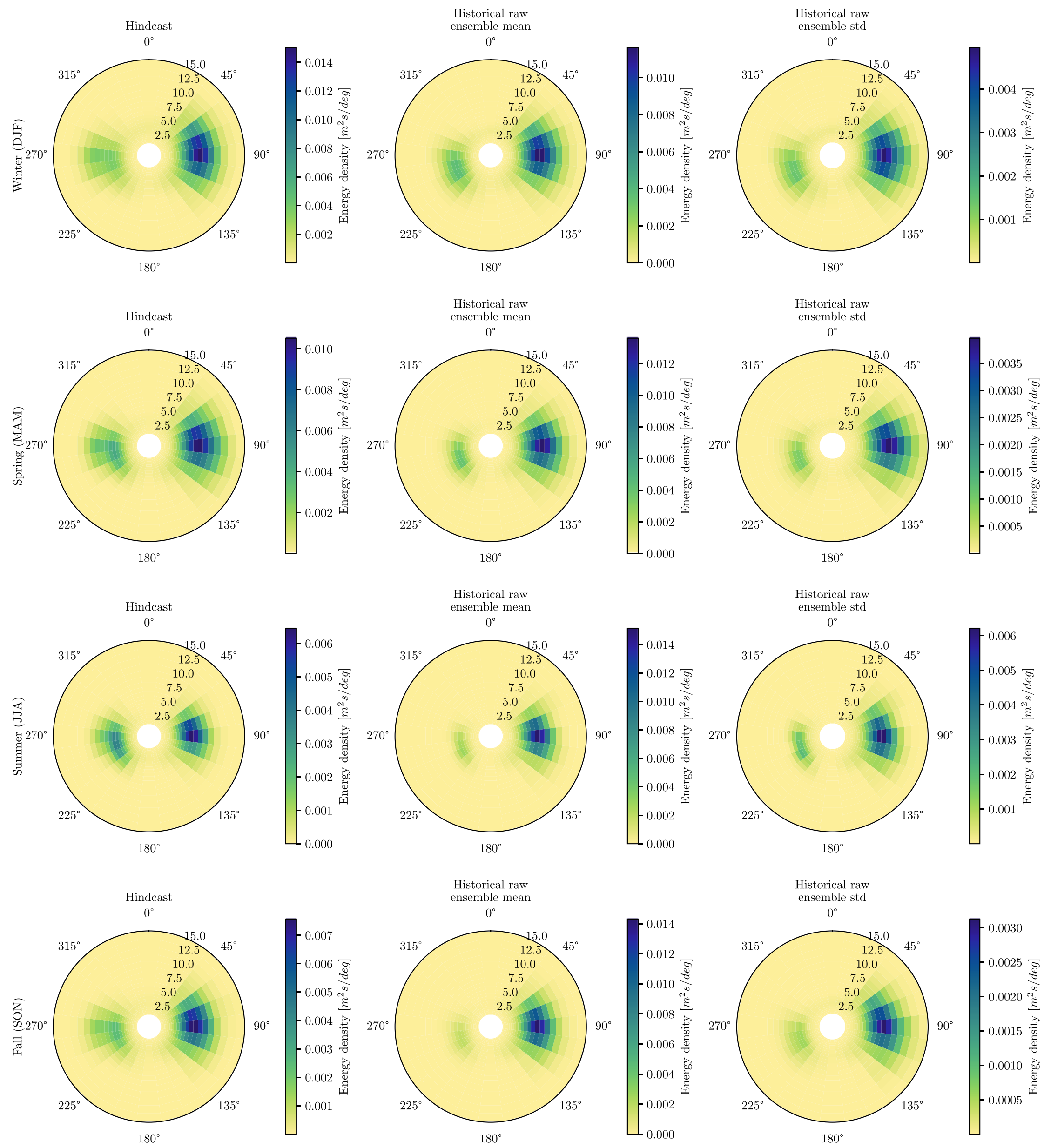

Figure 2. Seasonal mean directional spectra at the location West-1 (Alboran Sea) for the base period (1979–2005): hindcast (left), ensemble mean (center) and standard deviation (right) of the raw GCM–RCM simulations.

although the spread of the multi-model historical simulations encompass the hindcast values, the different GCM–RCM models present inherent biases that can be corrected using different bias-adjustment techniques.

3.2. Bias-correction of wave directional spectra

The bias-correction of the GCM–RCMs projections was done seasonally following the 'delta method' for each frequency and direction as presented in section 2.2. Figure 4 presents the seasonal mean directional spectra for the base period (1979–2005) in the location West-1 (Alboran Sea): (a) the hindcast data in the top row, (b) raw CCLM4–MIROC5 projections in the second row, (c) Mean Absolute Error (MAE) between the raw CCLM4–MIROC5 model and Hindcast in the third row, and (d) bias-adjusted CCLM4–MIROC5. The results for the remaining GCM–RCMs are included in the supplementary information. It can be observed that the model overestimates the energy spectra with MAE up to 0.01 $m^2\,s\,deg^{-1}$ during winter and ≈0.004 $m^2\,s\,deg^{-1}$ for the remaining seasons in the principal directions (East) while shows an underestimation for the secondary directions (West and SouthWest).

3.3. Spatial variability of wave directional spectra in the Mediterranean Sea

The mean directional wave spectra for spring (March, April and May) for hindcast and the projected changes under RCP8.5 for mid-century (2034–2060) and end-of-century (2074–2100) in the Mediterranean Sea are presented in figure 5 for all the locations included in figure 1 and table 1.

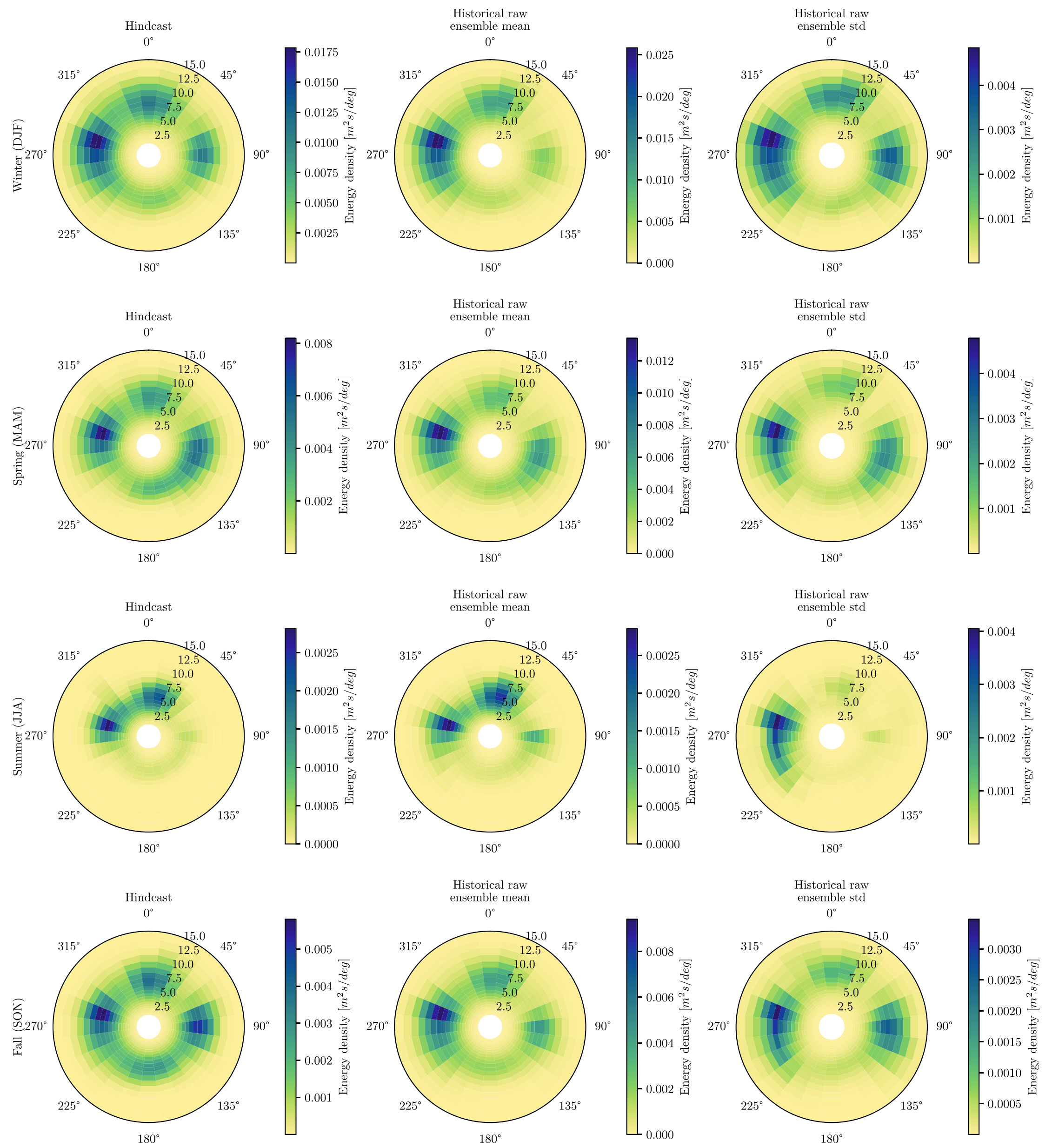

Figure 3. Seasonal mean directional spectra at the location Centre-2 (Central Mediterranean) for the base period (1979–2005): hindcast (left), ensemble mean (center) and standard deviation (right) of the raw GCM–RCM simulations.

Recent studies on projected changes of annual and seasonal mean significant wave height agree on a projected decrease over the Mediterranean Sea of significant wave height and mean period (Morim *et al* 2018, 2019, De Leo *et al* 2021). It can be observed that Centre-3 (Ionian Sea), Centre-2 (Central Mediterranean), Centre-1 (Tyrrhenian Sea), South-1 (Gulf of Sidra), East-1 (Levantine Sea) and East-2 (Eastern Mediterranean) present a robust decrease for the predominant wave systems in agreement with the cited studies. Nonetheless, it can be highlighted that all locations present robust increases on other directions and frequencies. Therefore, the directional wave spectra allows to understand the future changes in the multimodal directional behavior of waves crucial for coastal engineering adaptation and mitigation strategies. In the case of West-1 (Alboran Sea) and North-2 (Adriatic Sea), a robust increase is observed for both analyzed periods whereas West-2 (Western Mediterranean) and Centre-4 (Aegean Sea) present low model agreement with varying conditions.

More specifically, it can be observed on the top panel of figure 5 that the location West-1 (Alboran Sea) presents a clear bimodal hindcast system with incoming swell waves from the E, with wave periods, T, between 5–10 s and a wind-sea WSW system. Robust projected increases of up to $\approx$25% and $\approx$40% for mid-century and end-of-century

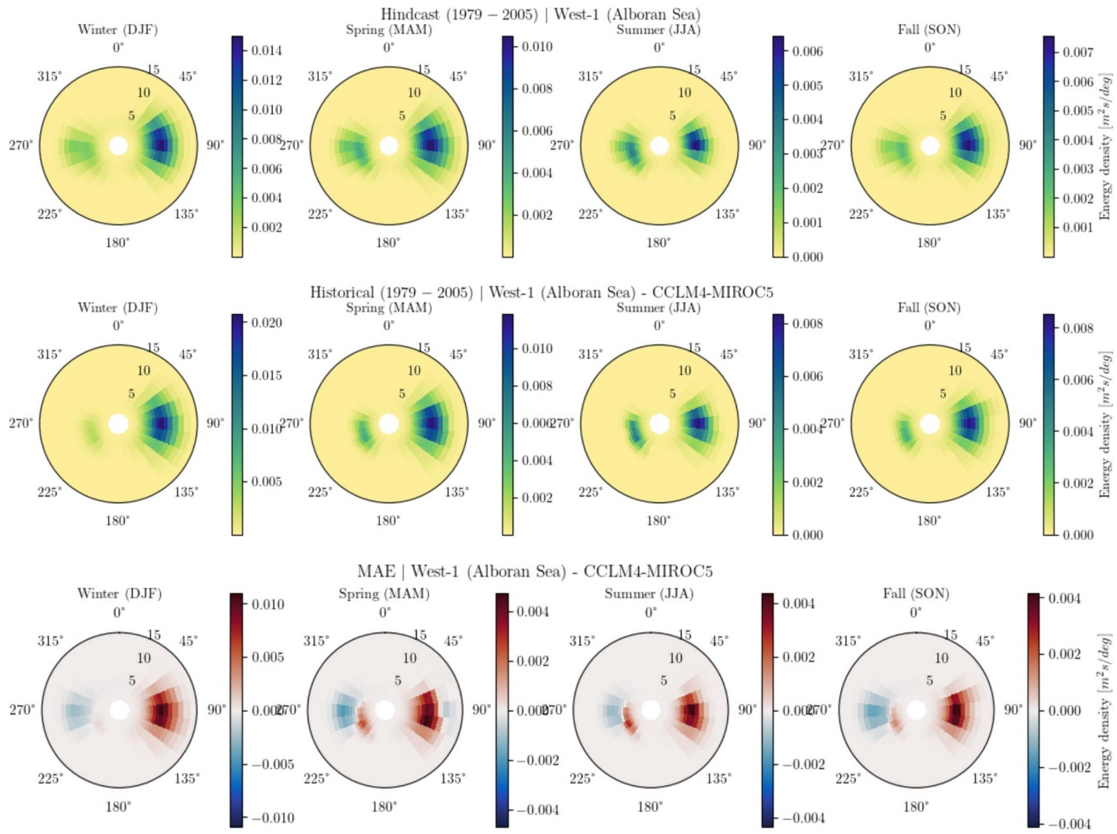

Figure 4. Seasonal mean directional spectra at the location West-1 (Alboran Sea) for the base period (1979–2005): Hindcast (top), raw CCLM4–MIROC5 data (middle row) and mean absolute error (MAE) between the raw CCLM4–MIROC5 and hindcast (bottom). The results for the remaining GCM–RCMs are included in the supplementary information.

conditions, respectively for the easterly swell whereas slight decreases are observed on the WSW wind-sea system. The increase in the dominant easterly waves during spring is in agreement with previous where an increase of ≈5% and 10% is expected for H_s for mid- and end-of-century conditions and ≈3% and 5% for T_p due to the increase in longer swells. Therefore wave climate is projected to become less bimodal under climate change conditions with a dominant easterly swell system. The results on the point North-1 (Ligurian Sea) show a hindcast wave climate dominated by the SW swell system and lower energy dispersed in the remaining directions and wind-sea frequencies. It can be highlighted that the results for mid-century present a increase for the dominant SW swell of 5% with low model agreement and a robust increase of 10% for NE-SE low-energy waves. This projected increase on the SW swell is no longer visible for end-of-century conditions, instead an increase for the NW-NE systems for higher wave periods is depicted, therefore, leading to a northerly swell system at the end of the 21st century. Finally, the location Centre-3 (Ionian Sea) presents energy on a large range of directions from SE to N for wind-sea waves ($T < 5$ s) and presents the highest energy values from SE to SW for a combination of wind and swell waves. The multi-model ensemble presents a projected robust decrease of ≈10% for mid-century and end-of-century conditions for the SW wind-sea system and projected increases of ≈10% for the more energetic SE swell. With respect to integrated wave parameters, H_s presents decreases of 2% and 4% for mid and end of century conditions whereas T_p presents decreases of less than 1% due to the uncertainties in the changes of the longer swells.

Regarding the middle panel of figure 5, the location West-2 (Western Mediterranean) presents the higher hindcast energy values from all the analyzed points with values up to ≈0.03 $m^2\,s\,deg^{-1}$ for the predominant NW swell and lower energy distributed on the remaining directions, as expected given the central position of this point. Likewise, the projections present varying behavior with lower model agreement but in general, lower projected changes (±3% for mid-century and ±15% for end-of-century conditions). It can be highlighted that the predominant NW swell presents increases for mid-century in all frequencies but these can only be observed for the lower periods at the end of the century. On the other hand, the NE swell system presents contrary behavior with increases (decreases) for mid-century (end-of-century). The point North-2 (Adriatic Sea) presents a

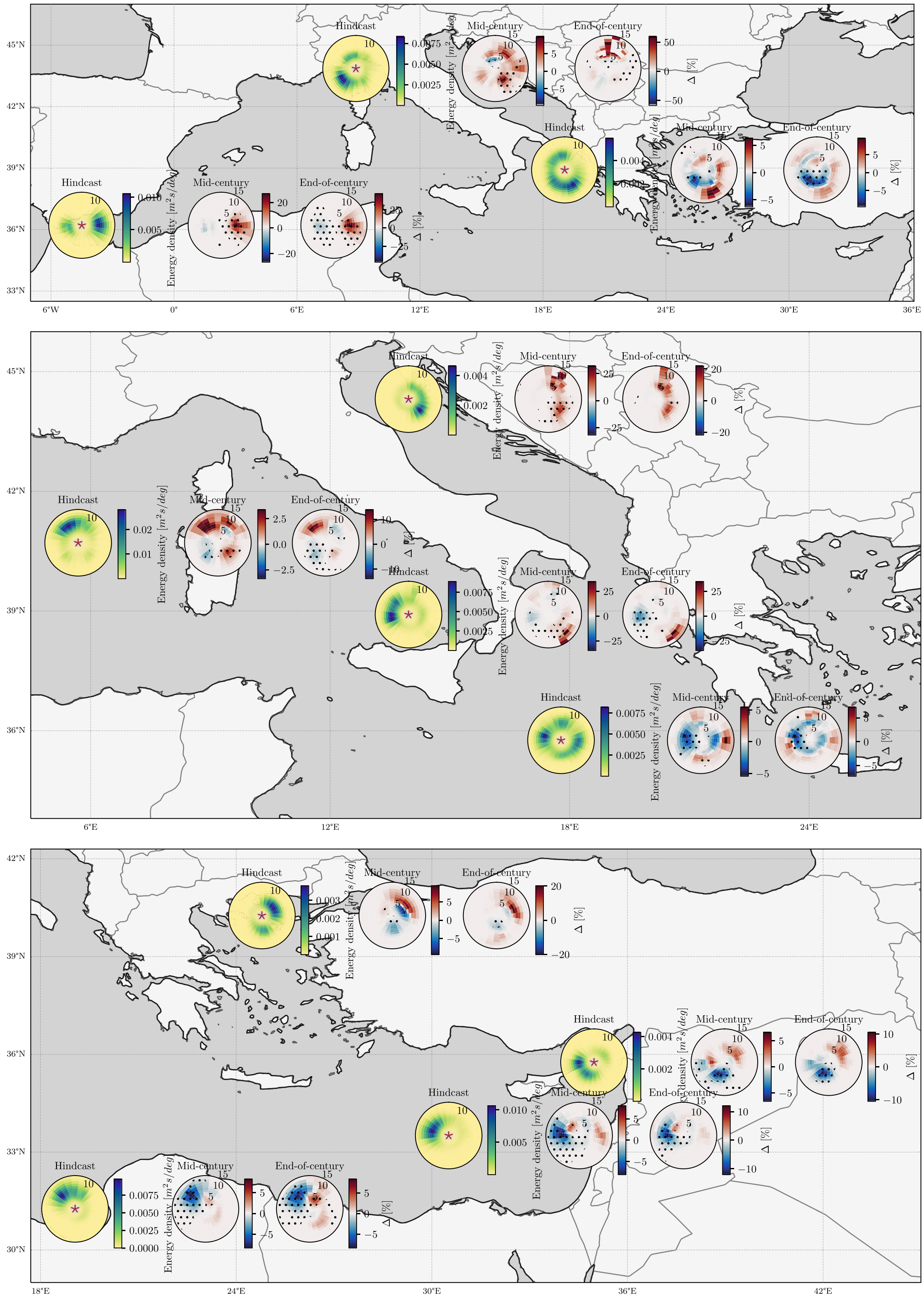

Figure 5. Mean directional spectra for spring (March, April and May) for hindcast data (1979–2005) and projected percent change for the multi-model ensemble under RCP8.5 for mid-century (2034–2060) and end-of-century (2074–2100) for the different locations in the Mediterranean Sea. Stippling indicates regions where at least 80% of models agree on the sign of change. Lack of stippling indicates low model agreement (less than 80%). The star in the hindcast panels presents the location of the points corresponding to figure 1.

wave climate dominated by southeasterly swell waves which present robust increases of $\leqslant 15\%$ for both mid and end-of-century conditions reflected as well in the projected changes of integrated wave parameters with an increase of 3% for H_s for mid-century conditions. A projected increase of ≈20%–30% is observed for the less energetic NNE direction for swell waves that were not depicted for the hindcast although without model agreement. The location Centre-1 (Tyrrhenian Sea) presents a wave climate dominated by the W-NW swell with robust decreases of ≈10% and ≈20% for mid-century and end-of-century, respectively. It can be highlighted that the results for mid-century present a robust increase of ≈25% for a SE swell not noticeable in the hindcast spectra. Finally the point Centre-2 (Central Mediterranean) presents energy in almost all the directions for a combination of wind and swell waves, with the most energetic ones corresponding to westerly swell waves. Under RCP8.5, this system presents projected decreases of ≈5%–8% for mid- and end-of-century, respectively in agreement with projected decreases of 3%–5% for H_s and 1%–2% for T_p.

Finally, on the lower panel of figure 5, the location South-1 (Gulf of Sidra) presents a hindcast unimodal wind-sea and swell wave climate with a dominant NW direction which presents robust decreases of up to ≈10% under RCP8.5 for mid- and end-of-century conditions in agreement with projected decreases of 2% and 1% for H_s and T_p, respectively. The point Centre-4 (Aegean Sea) presents a hindcast bimodal distribution with predominant wind-sea and swell wave systems from the NE-E and S. It can be observed that the dominant NE-E directions present different behaviors with respect to wave period (inverse of frequency) with the higher periods, corresponding to swell waves, showing a projected increase and the wind-sea waves (lower periods), a decrease (increase) for mid-century (end-of-century) but without model agreement. The location East-1 (Levantine Sea) presents a clear unimodal behavior with predominant W-NW hindcast wind-sea and swell wave systems. The projections present a robust decrease of up to ≈10% for the W swell and an increase, without model agreement, in of ≈5 for the NW wind-sea waves leading to projected decreases of 2%–3% and 1%–2% in H_s and T_p, respectively. Therefore the unimodal behavior is expected to be restricted to shorter range of directions in the future. Finally, the point East-2 (Eastern Mediterranean) presents predominant incoming hindcast wind-sea and swell waves with directions from S to W with the latter being more energetic. It can be highlighted that the multi-model ensemble presents robust decreases of up to ≈5%–10% for mid- and end-of-century conditions for the SSW-W wind-sea and swell waves and lower increases for the not so energetic NE wind-sea waves. Therefore, it is projected that the wave climate will turn into a bimodal system under climate change conditions.

3.4. Seasonal variability of wave directional spectra

The results for three representative locations in the Mediterranean sea; West-1 (Alboran Sea), Centre-2 (Central Mediterranean) and East-2 (Eastern Mediterranean) are presented and their seasonal variability is analyzed. Figure 6 depicts the seasonal mean directional spectra for the hindcast period (1979–2005) and the projected percent changes for mid- (2034–2060) and end-of-century (2074–2100) conditions under RCP8.5 for the Point West-1 (Alboran Sea).

It can be observed that the hindcast wave climate in the Alboran Sea location is mainly bimodal with strong swells coming from the ENE–ESE direction for all four seasons and weaker wind-sea waves from the WSW–WNW direction. The higher energy values are obtained for winter and spring reaching values of ≈0.015 and ⩾0.010 $m^2\,s\,deg^{-1}$, respectively and lower values for fall and summer (⩾0.006 $m^2\,s\,deg^{-1}$). Robust projected decreases in spectra density are observed during winter for the two swell systems up to ≈15% for mid-century and end-of-century although for the latter and the ENE–ESE direction it is only noticeable for a limited range of swell periods (5–10 s) leading to projected decreases of 4%–6% in H_s and 1%–2% in T_p. On the other hand, for spring a robust increase of up to ≈30%–40% for mid-century and end-of-century for the ENE–ESE swell. Slight decreases without (with) model agreement are depicted for the westerly waves for mid-century (end-of-century). In summer, a robust increase is observed for the wind-sea WSW–WNW component of up to ≈45% whereas no significant changes are observed for the remaining frequencies and directions therefore indicating a more clear and energetic bimodal future wave climate leading to projected increases if 3%–4% and 2% for H_s and T_p, respectively. Finally, for fall, robust increases of ≈15%–20% are observed for both mid- and end-of-century for the easterly swell waves whereas for the westerly waves, large robust increases ≈40% are obtained for the swell system at the end of the century. Increases are also observed for mid-century condition but without model agreement. For both periods, the wind-sea westerly waves present slight decreases. It can be highlighted that seasonality is increased in this locations, where the hindcast presented a similar distribution throughout the seasons but different projected behaviors between seasons are expected under climate change conditions which is crucial for coastal and harbor management and risk prevention considering the different the seasonal tourism and transport of the region.

Figure 7 presents the seasonal results for the Point Centre-2 (Central Mediterranean).

The hindcast wave climate presents a combination of wind-sea and swell waves and for almost all directions for winter, spring and fall with the highest energy density values (≈0.0175 $m^2\,s\,deg^{-1}$) during winter whereas predominant W-NE wind-sea waves are obtained for summer. The multi-model ensemble

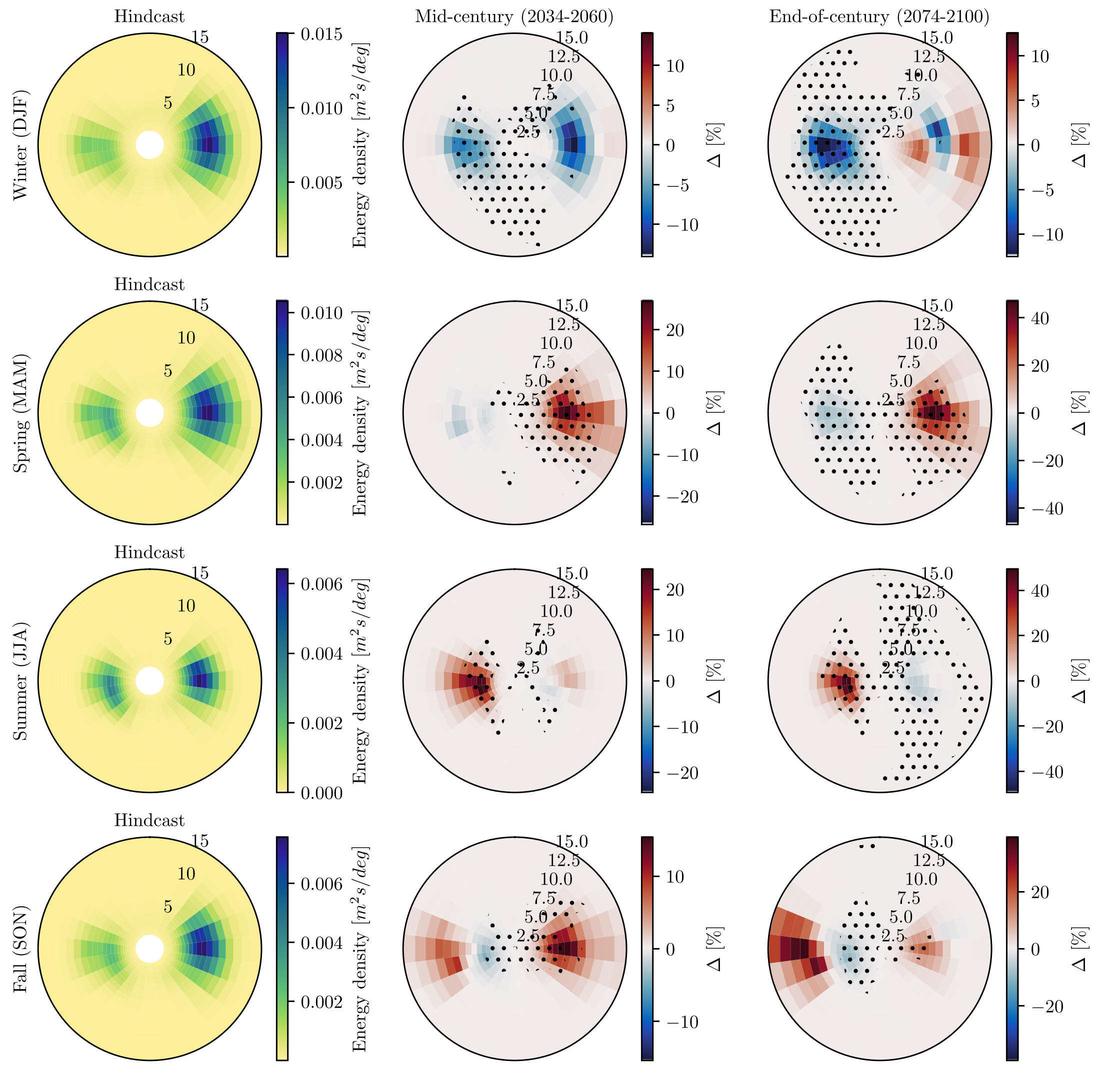

Figure 6. Seasonal mean directional wave spectra for the hindcast period (1979–2005, left) and projected changes in percentage between the multi-model ensemble mean under RCP8.5 with respect to hindcast for mid-century (2034–2060, middle) and end-of-century (2074–2100, right) for the Point West-1 (Alboran Sea). Stippling indicates the frequency-directional bins where at least 80% of the models agree on the sign of the change. Lack of stippling indicates low model agreement (less than 80%).

presents a robust decrease in the westerly sea and swell waves of approximately 10% (20%) for winter, 8% (10%) during spring and 20% (28%) for fall for mid-century (end-of-century) conditions leading to projected decreases in H_s values of 5%–10% for winter, 4%–6% for spring and 4%–12% for fall and decreases in T_p of 1%–3% for winter, 1%–2% for spring and 1%–3% for fall. For summer, the westerly sea system depicts a robust decrease of ≈10% for mid-century whereas for end-of-century a robust increase of ≈40% − 50% for the swell system is obtained. During winter, the rest of the directions present decreases with the exception of an increase for the easterly waves for mid-century although without model agreement. For fall, a robust decrease is observed in the southerly wind-sea waves for both periods whereas a different behavior between mid- and end-of-century conditions is observed for northerly and easterly waves. During mid-century conditions, an increase in spectral wave density is observed for easterly waves in winter, southerly and easterly waves for spring and northerly waves for fall but without model agreement. Therefore, the location Centre-2 (Central Mediterranean) presents a multi-directional hindcast wave climate during winter, spring and fall and predominant easterly and northerly waves during summer with robust projected decreases for the more energetic westerly waves for all seasons for both mid-century and end-of-century conditions with up to 30% decrease in some cases.

Finally, figure 8 presents the seasonal wave directional spectra for the Point East-2 (Eastern Mediterranean). The hindcast wave climate is dominated by wind-sea and swell waves with periods less than 10 s during winter, mainly wind-sea waves for spring, fall and summer, with the latter depicting the lower

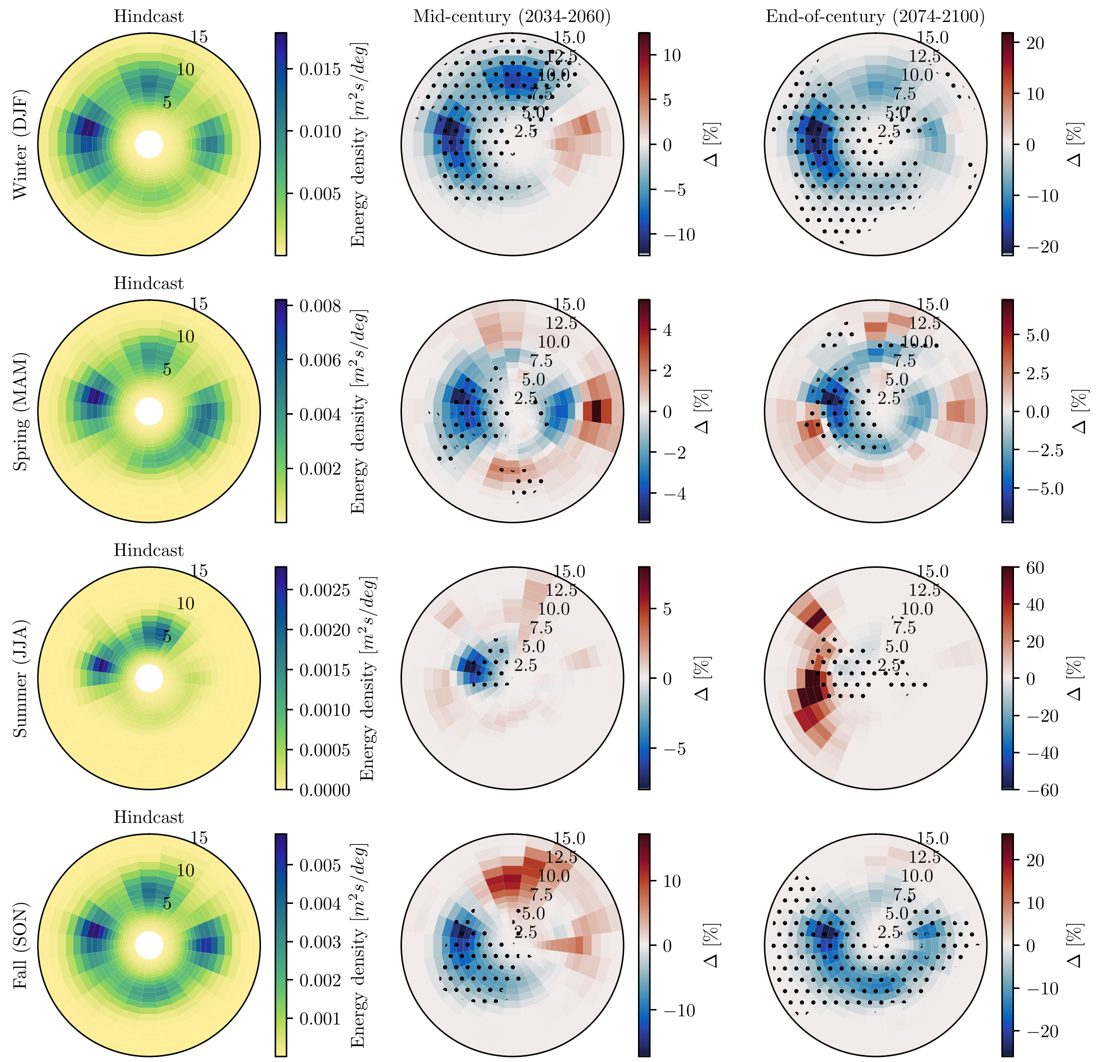

Figure 7. Seasonal mean directional wave spectra for the hindcast period (1979–2005, left) and projected changes in percentage between the multi-model ensemble mean under RCP8.5 with respect to hindcast for mid-century (2034–2060, middle) and end-of-century (2074–2100, right) for the Point Centre-2 (Central Mediterranean). Stippling as in figure 6.

wave periods $\leqslant$5 s. During winter and fall two directional systems are observed, mainly northeasterly short swell and wind waves (NNE-E) and southwesterly swell waves (S-SW). The latter system (S-SW) is also noticeable for spring and summer although with a predominant westerly energetic direction. On the other hand, the northeasterly system is not present for the summer months. Therefore, a bimodal wave climate is present throughout most time of the year except for summer months when a unimodal climate prevails. Regarding the climate projections, a higher degree of model uncertainty is observed with respect to the previous cases. During winter, a robust increase in N-E wind-sea waves is observed for mid-century whereas a lower increase without model agreement for end-of-century conditions is presented. A robust decrease for the less energetic southerly swell system is depicted for both mid- and end-of-century therefore the wave climate is expected to turn almost unimodal at the end of the 21st century during winter. Likewise, fall presents an increase with low model agreement for N-E waves therefore changing the bimodal behavior to unimodal under future conditions. The robust decrease in southerly wind-sea waves is also present during spring and fall for both mid- and end-of-century with decreases up to $\approx$20% at the end of the 21st century during fall. These results are in agreement with projected changes in integrated wave parameters with a decrease of 4%–12% and 1%–5% during winter, 3%–4% and 0.5%–1% during spring and 1%–7% and 0.3%–1% during fall for H_s and T_p, respectively. Regarding the summer behavior, a robust increase of up to $\approx$10% is observed on the unimodal wind-sea southerly system.

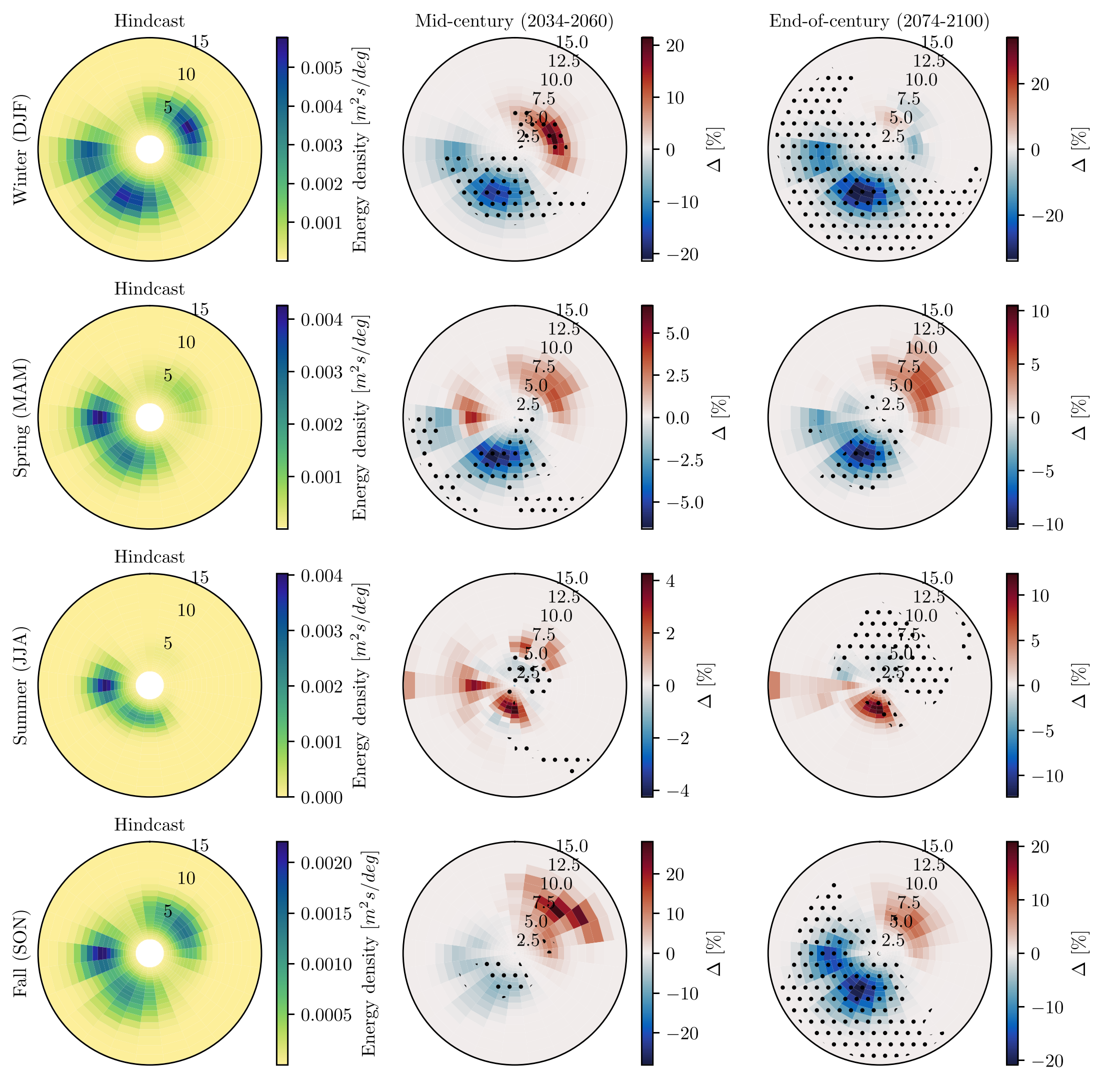

Figure 8. Seasonal mean directional wave spectra for the hindcast period (1979–2005, left) and projected changes in percentage between the multi-model ensemble mean under RCP8.5 with respect to hindcast for mid-century (2034–2060, middle) and end-of-century (2074–2100, right) for the Point East-2 (Eastern Mediterranean). Stippling as in figure 6.

4. Discussion and conclusions

This work presents an assessment of changes, with respect to hindcast 1979–2005, in the 2D directional wave spectra under climate change scenario RCP8.5 for 2034–2060 (mid-century) and 2074–2100 (end-of-century) in the Mediterranean Sea on the basis of an ensemble of seventeen EURO-CORDEX GCM–RCMs bias-adjusted wave projections. The projected changes were estimated against hindcast data of 2D directional wave spectra obtained with the numerical model Wavewatch III. Due to the lack of availability and difficulties in estimating detailed time series of directional wave spectra of wave buoys (Gorman 2018), the direct validation of the wave spectra could not be completed. Nonetheless, the hindcast of the integrated wave parameters, which was performed alongside the wave spectra, has been validated against observations and applied extensively in different studies (Mentaschi *et al* 2013, 2015, Besio *et al* 2016).

The Mediterranean Sea is characterized by a complex morphology and spatial heterogeneity and wave climate driven by regional and local winds. This study presents the characterization of the future changes in the 2D directional spectra for eleven locations selected with the aim to capture different sub-basins representing regional and local dynamics. The number of analyzed points was chosen as a trade-off between capturing the regional and local heterogeneity in the Mediterranean Sea and the limitation in storage and computing infrastructure. An increased number of points would allow the analysis of the spatial correlations and common characteristics of the directional wave spectrums in the different regions and a more in-depth characterization of the future changes in wave systems throughout the Mediterranean basin which is not possible to do in the current work due to the limited number of points in which the spectra was obtained.

The bias-correction in wave projections has been done using the delta method, which, by definition, adjusts the mean value for each directional-frequency bin and was shown to reduce the errors inherent in GCM–RCMs. Nonetheless, the delta method does not take into account the energy distribution and the extreme values and given that the correction is applied to each frequency-directional bin, it does not take into account possible bin-variability (more energetic bins) under future conditions. Therefore, further research is needed to address systematic errors in wave climate projections taking into account the multimodal and extreme characteristics of directional wave spectra. The use of the delta method, although simple, presents a first step for the analysis and correction of projections in 2D wave spectra providing important information to understanding the future changes in complex wave systems in the Mediterranean Sea.

The robustness of the results was analyzed by means of the number of GCM–RCMs that agreed on the sign of the change. An overall model agreement is obtained for the projected changes in many of the locations in the Mediterranean Sea although the Centre-4 (Aegean Sea) and North-2 (Adriatic Sea) locations present low model agreement with varying conditions both in frequency and direction. In the case of the Adriatic sea, wave climate is dominated by short intense events whereas the Aegean Sea is characterized by complex orography, both of which are difficult to capture with 0.1° resolution leading to low model agreement, in accord with previous studies. This highlights the need for the implementation and development of regional and local assessments of future wave climate in the Mediterranean Sea as projected changes are greatly influenced by small-scale orographic features. Additionally, changes in wave climate are directly related to changes in atmospheric and oceanic circulation. Directional wave spectra gives detailed information on the distribution of energy of waves for a single sea state, where its shape is controlled not only wind energy transfer but other wave-related processes such as white-capping dissipation and non-linear interactions. Therefore, an in-depth assessment of the relation of Mediterranean atmospheric dynamics and wave spectra in a future climate change scenario entails a detailed non-stationary and spatial analysis of a multi-model ensemble of Mediterranean atmosphere and ocean dynamic variables such as surface wind, sea level pressure and temperature.

The seasonal variability of three specific locations, Alboran sea, Central and Eastern Mediterranean, was analyzed. For the point West-1 (Alboran Sea), the historical bimodal wave climate is expected to become almost unimodal throughout the different seasons and with more uniform values along the year given the projected decreases (increases) during winter (summer). The location Centre-2 (Central Mediterranean) presents a multi-directional wave climate with robust projected decreases for the more energetic westerly swell waves for all seasons for both mid-century and end-of-century conditions. Therefore, the wave climate is expected to remain multimodal and its analysis by means of 2D directional spectra is crucial as integrated parameters such as significant wave height and mean direction will fail to capture this behavior. Finally, for the East-2 (Eastern Mediterranean) location, an overall decrease in the less energetic wind-sea southerly system is obtained leading to a projected change of the hindcast bimodal behavior into a unimodal system.

The projected changes of wave directional spectra during spring for all the analyzed points in the Mediterranean Sea present an overall robust decrease in the predominant wave systems, in agreement with previous studies depicting a decrease in the integrated parameter, significant wave height. Nonetheless, a robust increase in other less energetic frequencies and directions is observed for both mid-century and end-of-century conditions throughout the Mediterranean basin. Therefore, the analysis of 2D directional wave spectra allows a better understanding of the future changes in wave climate, depicting a projected behavioral change from unimodal to bimodal wave climate in many locations.

For future adaptation and mitigation coastal strategies and engineering planning it is crucial to analyze the changes in the different swell and wind-sea systems in wave climate as integrated parameters fail to capture the overall behavior and changes in waves. More specifically, hard engineering coastal defenses such as dikes and seawalls, which are widespread in many coastal cities and likely to be a cost-efficient response to climate change impacts are designed for a dominant incoming wave direction. A change in incoming wave directions from unimodal to bimodal/multimodal wave climate has strong implications in sediment transport, currents and erosion process therefore leading to increased vulnerability of coastal assets and possible significant damages and economic and personal losses. A clear example of this risk and consequent damages was observed in the extreme event of October 2018 in the Ligurian coast (Italy) with intense bimodal SE and SW systems, deviating from the usual unimodal behavior, which induced significant damages and collapse of coastal defenses, loss of property and infrastructure (Iengo and Del Giudice 2019).

Moreover, in-depth understanding of future changes in wave directions and therefore, in the consequent changes in wave propagation processes and sediment transport, is crucial for port operability. Changes in processes such as shoaling, refraction, diffraction and reflection could hamper the navigability in harbors and agitation in berthing areas whereas changes in the sediment transport processes could lead to increased sedimentation and shoaling forcing continuous dredging operations and hindering port operability (Sierra *et al* 2015, 2017, Sánchez-Arcilla *et al* 2016). This highlights the need to further analyze and understand the future changes in wave climate as a multimodal and multivariate process.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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