

A large-scale Atlantic-European circulation dipole amplifies western Mediterranean wave climate and intensifies under climate change

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Research Article

Keywords:

Posted Date: May 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9359064/v1>

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Version of Record: A version of this preprint was published at Climatic Change on September 21st, 2026.
See the published version at <https://doi.org/10.1007/s10584-026-04301-6>.

Abstract

The Mediterranean basin is highly sensitive to large-scale atmospheric circulation, where small shifts in hemispheric climate drivers can amplify coastal marine hazards. Yet, the circulation mechanisms governing Mediterranean wind and wave interannual variability remain poorly constrained. Here, we analyse 75 years of ERA5 reanalysis data to identify dominant circulation modes influencing Mediterranean wind and wave conditions. Principal component analysis of sea-level pressure over Europe (20–65°N, 25°W–20°E) reveals a previously unrecognized dipolar structure linking the north-eastern Atlantic and Central Europe. This circulation mode, termed the Atlantic-Europe Dipole (AED), strengthens meridional pressure gradients across western Europe and favours northerly circulation patterns conducive to Mistral-Tramontane-type winds over the Gulf of Lion. Positive phases of the AED explain up to 40% of winter significant wave height variability in the north-western Mediterranean. Climate model projections from more than 230 CMIP6 simulations, indicate that this circulation mode might intensify under greenhouse warming, increasing the frequency of extreme dipole phases by up to 50% by the end of the twenty-first century. Our results reveal a dynamical pathway linking large-scale atmospheric circulation variability to regional marine hazards in the Mediterranean basin and highlight the importance of regional circulation modes for climate-risk assessments.

Introduction

The Mediterranean Sea exhibits a complex and highly heterogeneous wave climate, shaped by the interplay of regional wind systems, basin geometry, and large-scale atmospheric circulation. Unlike open-ocean basins, Mediterranean waves are predominantly fetch-limited and strongly controlled by localized wind regimes, resulting in pronounced spatial variability between sub-basins such as the western, Adriatic, and eastern Mediterranean (Lionello and Sanna 2005; Barbariol et al. 2021; De Leo et al. 2024). Extreme wave conditions therefore arise from distinct atmospheric drivers depending on the region, including Mistral and Tramontane winds in the western basin, Bora events in the Adriatic, and Etesian winds in the eastern Mediterranean (Zacharioudaki et al. 2015; Pomaro et al. 2017).

Over the past decade, increasing attention has been devoted to understanding the links between large-scale climate variability and Mediterranean wave conditions. Pioneering work by (Martínez-Asensio et al. 2014) demonstrated that Mediterranean wave climate variability is closely tied to large-scale atmospheric pressure patterns over the North Atlantic-European sector. This framework was further developed in (Morales-Márquez et al. 2020), who highlighted the strong influence of regional atmospheric circulation on wave energy variability and emphasized the spatially heterogeneous response of the Mediterranean basin. These studies established that basin-wide analyses may obscure regionally coherent signals, and that wave-climate relationships must be investigated at appropriate spatial scales.

Subsequent work has reinforced this view, showing that Mediterranean wave climate is strongly modulated by large-scale circulation patterns but with region-dependent responses (Amarouche et al.

2022; De Leo et al. 2024). While indices such as the North Atlantic Oscillation (NAO) influence Mediterranean conditions, they do not fully explain regional wind forcing and associated wave variability (Lionello and Sanna 2005; Martínez-Asensio et al. 2014; Morales-Márquez et al. 2020). This limitation highlights the need to identify circulation patterns that directly control the pressure gradients responsible for key regional wind systems.

In parallel, projections of future wave climate under anthropogenic climate change suggest relatively modest changes at the global scale but potentially significant regional variations driven by shifts in atmospheric circulation (Hemer et al. 2013; Morim et al. 2019, 2021; Casas-Prat et al. 2024). In the Mediterranean, uncertainties remain large, but several studies indicate that changes in wind regimes and storm characteristics may substantially affect regional wave conditions. These results further emphasize the importance of understanding the dynamical links between large-scale circulation and regional wave generation.

Within this context, the western Mediterranean basin represents a key hotspot of wave activity, where strong northerly wind regimes such as the Mistral and Tramontane frequently generate extreme waves (Drobinski et al. 2005; Obermann-Hellhund et al. 2018; Obermann et al. 2018). Although the synoptic mechanisms driving these winds are well documented, their modulation by large-scale atmospheric variability at seasonal to interannual timescales remains insufficiently characterized.

Atmospheric variability across the North Atlantic-European sector is commonly described using a limited number of large-scale teleconnection patterns, such as the North Atlantic Oscillation (NAO), the East Atlantic pattern, or Scandinavian blocking (Barnston and Livezey 1987; Hurrell 2003; Hatzaki et al. 2023). These indices have been widely used to investigate links between climate variability and Mediterranean wave conditions (Lionello and Sanna 2005; Martínez-Asensio et al. 2014; Morales-Márquez et al. 2020). However, their relationship with regional wave height is often moderate and spatially inconsistent, reflecting the fact that these large-scale modes do not explicitly resolve the atmospheric structures driving regional wind systems. In particular, the pressure gradients across western Europe that control northerly wind regimes such as the Mistral and Tramontane are not directly captured by these basin-scale indices. As a result, a significant fraction of the variability in Mediterranean wind forcing and wave climate remains unexplained when using standard teleconnection frameworks.

To address this limitation, a more regionalized approach is needed to better isolate the atmospheric variability relevant to the western Mediterranean. In this study, we restrict the spatial domain used to characterize large-scale circulation to the North Atlantic-European sector surrounding the western Mediterranean, and recompute dominant modes of variability using empirical orthogonal function (EOF) analysis. This approach allows the identification of circulation patterns that are more directly linked to regional pressure gradients and wind forcing. We then investigate how these circulation modes influence both the seasonal variability of significant wave height and the occurrence of extreme wave conditions, characterized here using daily 90th, 95th and 99th percentile thresholds. By bridging large-scale atmospheric variability and regional wind-wave generation, this framework aims to provide new insight

into the mechanisms controlling wave climate in the western Mediterranean and their potential sensitivity to climate variability and change.

Results

1. Dominant modes of atmospheric circulation

Empirical Orthogonal Function (EOF) analysis of seasonal mean sea-level pressure (MSLP) anomalies from the ERA5 reanalysis (Hersbach et al. 2020; Bell et al. 2021) over 1950–2024 reveals three dominant modes of atmospheric variability across the North Atlantic–European sector (Fig. 1). The leading two modes closely resemble well-known large-scale teleconnection patterns. The first mode (EOF1), explaining between $\sim 38\%$ and 43% of the seasonal variance depending on the season, is characterized by a pressure gradient extending from the North Atlantic toward western Europe and is consistent with the Western European Pressure Anomaly (WEPA; (Castelle et al. 2017)) that leads during its positive phase to an increase in wave height around the Bay of Biscay. The second mode (EOF2), accounting for roughly $21\text{--}37\%$ of the variance, displays a meridional pressure dipole over the North Atlantic and Europe that closely matches the canonical North Atlantic Oscillation (NAO) and leads during its positive phase to an increase of wave height on the western coast of the British Isles and a decrease in southern Spain.

The third mode (EOF3), explaining approximately $13\text{--}17\%$ of the seasonal variance, exhibits a distinct spatial structure consisting of a pressure dipole between the north-eastern Atlantic and western–central Europe. This pattern appears consistently across all seasons, indicating that it represents a robust mode of variability rather than a transient statistical feature. We refer to this circulation structure as the Atlantic-Europe Dipole (AED). In its positive phase, the AED is characterized by positive pressure anomalies over the north-eastern Atlantic and negative anomalies over western and central Europe, resulting in an enhanced meridional pressure gradient across western Europe. The associated geostrophic wind anomalies indicate strengthened northerly to north-westerly flow directed toward the western Mediterranean basin. Although this seasonal-scale circulation pattern does not represent individual synoptic wind events, it favors atmospheric configurations conducive to the occurrence and persistence of northerly wind regimes over southern France and the Gulf of Lion, conditions typically associated with the Mistral and Tramontane wind systems.

2. Coupling between the AED and Mediterranean wave climate

The influence of these large-scale circulation modes on regional wave conditions can be assessed by looking at spatial correlations between the principal components (PCs) of the three EOF modes and seasonal significant wave heights (H_s) across the western Mediterranean basin (Fig. 2). The three modes exhibit distinct wave responses. EOF1 (associated with the WEPA pattern) produces predominantly positive correlations across large parts of the basin, particularly during winter and spring, indicating that enhanced WEPA conditions tend to coincide with higher wave activity. In contrast, EOF2

(NAO-like variability) is associated with mostly negative correlations over the western Mediterranean, suggesting that its positive phase generally corresponds to reduced wave heights in the region.

The most pronounced and spatially coherent signal emerges for EOF3, corresponding to the AED. Across all seasons, PC3 shows strong positive correlations with Hs throughout much of the western Mediterranean, with maxima in the Gulf of Lion and around Corsica. This relationship is particularly evident in winter, when correlations locally exceed 0.7. The spatial structure of these correlations is consistent with the circulation anomalies identified in Fig. 1: during the positive phase of the AED, the enhanced meridional pressure gradient between the north-eastern Atlantic and western Europe favors northerly flow directed toward the north-western Mediterranean. Although the seasonal-scale analysis does not resolve individual wind events, this circulation configuration is conducive to atmospheric conditions that favor the development and persistence of strong northerly wind regimes over the Gulf of Lion, thereby promoting increased wave generation in the region. The location of maximum correlation in winter is marked near Corsica and is used in the following analysis to investigate the temporal relationship between AED variability and regional wave conditions.

To further assess the robustness of the relationship between large-scale circulation and extreme wave conditions, supplementary analyses are presented in Figures S1–S3. These figures display spatial correlations between the leading principal components and extreme significant wave height, defined using the 90th, 95th, and 99th percentiles, respectively. The results reveal a consistent and spatially coherent pattern across all thresholds, with the strongest correlations systematically located in the north-western Mediterranean, particularly in the Gulf of Lion region. The similarity of these spatial structures across different percentile definitions indicates that the identified circulation–wave relationship is largely insensitive to the specific choice of extreme metric in terms of statistical significance. This consistency supports the existence of a robust dynamical link between large-scale atmospheric variability and the occurrence of high-energy wave conditions. However, the magnitude of the correlations decreases for more extreme thresholds (e.g., P99), likely reflecting increased variability and reduced sample size associated with rarer events.

3. Dynamical structure of the AED

The “surface expression” of the AED can be characterized by examining the relationship between PC3 and key atmospheric variables, including near-surface temperature, precipitation, and wind speed. The spatial correlations reveal a coherent set of anomalies associated with the positive phase of the AED across all seasons. In winter in particular, PC3 is associated with enhanced surface wind speeds across France and the north-western Mediterranean, with maxima over the Gulf of Lion and surrounding regions (Fig. 3). This pattern is consistent with the circulation anomalies identified in Fig. 1 and with the strong correlations between PC3 and wave height shown in Fig. 2, indicating that the AED exerts a direct influence on regional wind forcing over the western Mediterranean.

In addition to the wind signal, the positive phase of the AED is associated with widespread negative temperature anomalies over southern and western Europe, particularly during winter and summer

(Fig. 3), suggesting enhanced advection of colder continental air masses toward the Mediterranean basin. Precipitation responses are more heterogeneous but generally indicate reduced precipitation over parts of the western Mediterranean and southern Europe during positive AED conditions. Together, these anomalies point to a circulation configuration favoring cold and dry northerly airflow from continental Europe toward the Mediterranean.

Although the present analysis is based on seasonal variability rather than individual synoptic events, the spatial structure of the wind anomalies is consistent with atmospheric conditions known to favor the development of strong northerly wind regimes over southern France described in the Introduction. In particular, the large-scale pressure gradient associated with the AED can interact with regional topography to channel airflow through major orographic corridors such as the Rhône Valley and the Pyrenean gaps, enhancing wind acceleration toward the Gulf of Lion (Flamant 2003; Drobinski et al. 2005). Such configurations are conducive to the occurrence of Mistral and Tramontane wind systems and therefore provide a dynamical mechanism linking large-scale atmospheric variability to enhanced wind forcing and wave generation in the north-western Mediterranean.

Further insight into the physical mechanisms underlying this relationship is provided by Figure S4, which shows the correlation between the leading principal components (PC1-PC3) and 10 m wind speed. The results indicate that PC1 (WEPA-like) exhibits stronger correlations over the North Atlantic and western European sector, consistent with its influence on large-scale westerly flow (Castelle et al. 2017; Jalón-Rojas et al. 2021; Masselink et al. 2023). In contrast, PC2 (NAO-like) shows a more pronounced correlation over northern Europe, reflecting a different spatial structure of atmospheric variability (Castelle et al. 2017; Masselink et al. 2023; Granger et al. 2025). Both modes display comparatively weaker correlations with wind speed over the western Mediterranean, suggesting that they primarily represent large-scale atmospheric variability patterns rather than directly controlling the regional wind forcing responsible for wave generation.

4. Temporal variability of the AED

Figure 4 provides a physically interpretable view of the seasonal and interannual variability of the circulation mode by comparing the EOF-derived PC3 with a pressure-gradient index (ΔSLP) and significant wave height (H_s) observed near Corsica over the period 1950–2024. The ΔSLP index is defined as the sea-level pressure difference between the two regions identified in Fig. 1, representing the main centers of action of the circulation pattern.

The correlation between PC3 and ΔSLP is consistently strong across all seasons ($r = 0.86\text{--}0.95$), demonstrating that the variability of the EOF mode can be accurately captured by a simple and physically based pressure-gradient index. This result provides a practical framework for reconstructing this mode in climate model simulations using sea-level pressure fields alone, which is particularly relevant for CMIP6 analyses.

We also estimated the relationship between the PC3 and regional wave conditions. Significant correlations with H_s near Corsica indicate that fluctuations in the large-scale pressure gradient directly translate into changes in Mediterranean wave generation. The coupling is strongest in winter ($r = 0.76$), when enhanced meridional pressure gradients intensify northerly wind regimes and promote wave growth in the north-western Mediterranean. Moderate but still significant correlations during the other seasons ($r \approx 0.57\text{--}0.68$) suggest that this mechanism operates year-round, with a maximum influence during the winter storm season.

These temporal relationships are consistent with the spatial patterns shown in Fig. 2, where positive phases of the circulation mode correspond to coherent increases in wave height across the Gulf of Lion and Ligurian Sea. The stability of these relationships over the full 75-year record supports the use of the ΔSLP index as a robust proxy for investigating past variability and future changes in wave climate.

5. Future evolution of the AED

To investigate potential future changes in the AED, the circulation index was computed from Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations using historical and scenario integrations extending to the end of the twenty-first century. Figure 5 presents the multi-model ensemble statistics for the high-emission scenario SSP5-8.5. The ensemble mean time series reveals a gradual increase in the AED index during the twenty-first century, indicating a strengthening of the pressure gradient between the north-eastern Atlantic and central Europe (Fig. 5a). Although individual models display substantial variability, the multi-model mean exhibits a clear upward tendency after the mid-twenty-first century. This behaviour suggests that future climate conditions may favour more frequent atmospheric configurations associated with positive phases of the dipole.

Changes in the statistical distribution of the AED index further support this tendency. Probability density functions computed for successive time periods show a progressive shift of the distribution toward higher values relative to the 1980–2010 reference period (Fig. 5b). While the overall shape of the distribution remains approximately symmetric, the increasing probability of positive anomalies indicates a systematic modification of the large-scale circulation regime.

The evolution of extreme dipole events was analysed using a fixed 90th percentile threshold defined from the historical reference period. The distribution of extreme AED values shows a gradual intensification through the twenty-first century, with slightly higher median and upper-range values in future periods (Fig. 5c). Consistent with this behaviour, the frequency of extreme events increases from approximately 10% during the reference period to nearly 15% by the end of the century (Fig. 5d). This result indicates that strong positive phases of the dipole may become more common under strong greenhouse-gas forcing.

The robustness of these changes was evaluated using additional emission scenarios. Supplementary Figures S5 and S6 show equivalent diagnostics for the intermediate scenarios SSP3-7.0 and SSP2-4.5. Both scenarios exhibit a similar qualitative behaviour, with modest increases in the mean AED index and

a gradual rise in the occurrence of extreme positive phases. However, the magnitude of the changes is smaller than in the high-emission scenario, indicating a clear dependence of the AED index on the level of radiative forcing. Taken together, these results suggest that anthropogenic climate change may promote atmospheric circulation patterns characterized by stronger pressure gradients between the North Atlantic and continental Europe, potentially increasing the frequency of large-scale configurations associated with enhanced northerly wind regimes over western Europe.

Discussion and conclusions

The relationship between large-scale atmospheric variability and wave climate has been extensively investigated using a limited set of dominant teleconnection patterns, primarily the North Atlantic Oscillation (NAO), the East Atlantic Pattern (EAP), and the Scandinavian pattern (SCAND). These modes are known to structure atmospheric variability over the North Atlantic-European sector and have been used to interpret wave climate variability, particularly in the North Atlantic and, to a lesser extent, in the Mediterranean basin (Barnston and Livezey 1987; Hurrell 2003; Martínez-Asensio et al. 2014; Morales-Márquez et al. 2020). Previous studies have shown that these large-scale indices can exhibit statistically significant relationships with wave height in certain regions. However, these correlations are generally moderate and spatially heterogeneous, especially in semi-enclosed basins such as the Mediterranean (Lionello and Sanna 2005; Martínez-Asensio et al. 2014; Morales-Márquez et al. 2020). This limitation reflects the fact that such indices describe broad hemispheric-scale variability and do not explicitly resolve the regional pressure gradients that control the wind systems responsible for wave generation. As a result, a substantial fraction of Mediterranean wave variability remains unexplained within these traditional frameworks.

In this study, we adopt a regionalized approach to large-scale atmospheric variability by restricting the analysis domain to the North Atlantic-European sector surrounding the western Mediterranean and recomputing the dominant modes of variability. This approach allows the identification of a circulation pattern that differs from the canonical NAO, EAP, and SCAND modes and is more directly linked to pressure gradients across western Europe. As a consequence, this mode exhibits substantially stronger correlations with significant wave height than classical teleconnection indices, both at seasonal timescales and for extreme conditions. In particular, the strong relationship observed with seasonal mean wave height indicates that this circulation pattern captures a key component of the atmospheric forcing controlling wave variability in the western Mediterranean. Furthermore, its ability to explain variability in extreme wave conditions, as quantified by daily 90th, 95th and 99th percentile thresholds, suggests that it also modulates the occurrence and persistence of high-impact events. This dual relevance for both mean and extreme conditions highlights the importance of considering regionally adapted representations of atmospheric variability when investigating wave climate.

These results provide a new perspective on the interpretation of Mediterranean wave-climate trends. As highlighted by recent reviews, observed changes in wave conditions across the Mediterranean remain uncertain and sometimes contradictory, with studies reporting increasing, decreasing, or non-significant

trends depending on the region, dataset, and methodology (Martucci et al. 2010; Caloiero et al. 2022; De Leo et al. 2024). Such inconsistencies likely arise from the strong spatial heterogeneity of atmospheric forcing and the limitations of basin-wide analyses that aggregate distinct regional signals. Within this context, the circulation pattern identified here offers a physically consistent framework to interpret regional wave variability and its evolution. By directly linking large-scale pressure gradients to the wind systems that drive wave generation, it provides a mechanism through which changes in atmospheric circulation can translate into regionally coherent wave responses. In particular, the projected increase in the frequency and intensity of this circulation pattern in climate model simulations suggests a tendency toward enhanced wave activity in the western Mediterranean under future climate conditions.

This result is consistent with broader findings indicating that changes in wave climate are primarily driven by modifications in atmospheric circulation and wind patterns rather than uniform thermodynamic effects (Hemer et al. 2013; Morim et al. 2019, 2020, 2021; Casas-Prat et al. 2024). While global projections often indicate modest changes in mean wave height, regional responses can be substantial where circulation changes reinforce dominant wind systems. The mechanism identified here therefore provides a plausible explanation for how relatively weak large-scale climate signals may lead to significant regional impacts in the Mediterranean. The implications of these findings are particularly relevant for coastal risk assessment. The western Mediterranean includes densely populated coastlines that are highly sensitive to wave forcing, which plays a central role in coastal erosion and flooding processes (Callaghan et al. 2008; Alexandrakakis et al. 2015; Chataigner et al. 2022). An increase in the frequency of atmospheric conditions conducive to extreme waves could therefore amplify coastal hazards, even in the absence of strong trends in mean wave climate.

Several limitations should nevertheless be acknowledged. The analysis is based on reanalysis datasets and climate model simulations, both of which are subject to uncertainties, particularly in representing regional atmospheric circulation. In addition, the focus on the western Mediterranean implies that the identified mechanism may not be directly applicable to other sub-basins influenced by different wind systems. Extending this framework to the entire Mediterranean would require identifying additional region-specific circulation modes. Overall, this study demonstrates that a regionalized characterization of atmospheric variability can substantially improve our understanding of Mediterranean wave climate. By identifying a circulation mode that is more directly connected to the physical drivers of wave generation than traditional large-scale indices, it provides a clearer framework for interpreting both present-day variability and future changes in marine hazards.

Methods and data

We used the ERA5 (Hersbach et al. 2020; Bell et al. 2021) reanalysis monthly dataset (1950–2024) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Table 1). Variables included mean sea-level pressure (MSLP), 10 m wind speed, precipitation, surface temperature and the significant wave height (H_s).

Table 1
List of climate variables used in this study and their spatial resolution.

Variable	Units	Purpose	Spatial resolution
Sea Level Pressure (SLP)	hPa	EOF	0.25°
Precipitation	mm/day	Correlation with PC1	0.25°
Temperature	°Celsius	Correlation with PC1	0.25°
Wind speed	m/s	Correlation with PC1	0.25°
Significant height of wave and swell (Hs)	m	Correlation with PC1	0.5°

Hourly Hs from ERA5 is additionally analysed to quantify the relationship between extreme wave conditions, defined using the daily 90th, 95th and 99th percentile, and the seasonal circulation index.

Empirical Orthogonal Function (EOF) analysis.

The analysis domain spans 20–65°N, 25°W–20°E, encompassing both the North Atlantic and Mediterranean sectors. The analysis was conducted separately for each climatological season: DJF (winter), MAM (spring), JJA (summer), and SON (autumn). For each season, monthly climatological means were computed over the 1950–2024 period, and anomalies were calculated as deviations from these seasonal climatologies. Long-term linear trends were removed gridpoint-wise using least-squares detrending to isolate internal variability.

To ensure equal area representation, anomalies were multiplied by the square root of the cosine of latitude, prior to decomposition (North et al. 1982). This weighting corrects for the convergence of meridians at high latitudes, avoiding spurious dominance of polar regions in the covariance matrix.

The main modes of atmospheric variability were extracted by performing a Singular Value Decomposition (SVD) of the covariance matrix of weighted SLP anomalies for each season:

$$\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^T$$

where $\mathbf{A}$ (time $\times$ space) represents the anomaly matrix, $\mathbf{U}$ contains the temporal principal components (PCs), $\mathbf{V}^T$ contains the spatial EOFs, and $\mathbf{S}$ is the diagonal matrix of singular values s_i .

The percentage of variance explained by each EOF mode i was computed from the singular values s_i of the SVD decomposition as:

$$\lambda_i = \frac{s_i^2}{\sum_{j=1}^r s_j^2} 100$$

where r is the rank of the anomaly matrix A . This quantity represents the relative contribution of each mode to the total variance of sea-level pressure anomalies.

EOF spatial patterns were scaled by their corresponding singular values and expressed in hPa, representing typical pressure anomalies associated with one standard deviation of the corresponding PC. The PCs were likewise expressed in hPa, preserving physical meaning and allowing direct interpretation as amplitude variations of basin-scale pressure anomalies.

Correlation with wave and surface fields

Spatial correlations between AED principal components and anomalies in Hs, surface wind, temperature, and precipitation were computed using Pearson coefficients, with significance assessed at $p < 0.05$. Linear regressions were used to estimate fractional contributions to local wave variance.

Future projections

Future changes in the AED were assessed using simulations from more than 230 CMIP6 experiments for the three different future scenarios (see supplementary table S1). Monthly SLP were extracted from historical and scenario simulations extending from 1970 to 2100. Three emission scenarios were analysed: SSP2-4.5, SSP3-7.0, and SSP5-8.5. The AED index was defined as the spatially averaged sea-level pressure difference between two regions representing the dipole structure identified in the observational analysis. The western pole corresponds to the northeastern Atlantic sector (45° – 62° N, 25° – 20° W), while the eastern pole is located over central Europe (45° – 62° N, 10° – 15° E).

To remove model biases and ensure consistency across simulations, the index was normalized relative to the mean value of the 1980–2010 reference period for each model. Ensemble statistics were then calculated by combining all available members from the CMIP6 archive. To assess changes in extreme circulation states, a fixed 90th percentile threshold (P90) was computed for each model using the 1980–2010 reference period. Extreme events were defined as time steps where the AED index exceeded this threshold. Changes in the distribution of the index were further analysed using probability density functions and boxplot statistics for four time periods: 1980–2010, 2010–2040, 2040–2070, and 2070–2100.

Declarations

Ethics approval and consent to participate

This study does not involve human participants or animals. Therefore, ethics approval and consent to participate are not applicable.

Consent for publication

All authors have reviewed and approved the final version of the manuscript for publication.

Competing Interests

The authors declare that they have no competing interests.

Author contributions

RA conceived the study, performed the analysis, and drafted the manuscript. DS, BC and JO contributed to the interpretation of the results and provided critical revisions. JC and TR contributed to the discussion and manuscript editing. All authors reviewed and approved the final manuscript.

Funding

This study received financial support from project IRICOT (PEPR IRIMA), managed by Agence National de la Recherche (ANR), France 2030, ANR-22-EXIR-0004, and by Région Nouvelle-Aquitaine (PSGAR CORALi). Additional funding was provided by the Government of France under the framework of the University of Bordeaux's Investments for the Future (IdEx) programme/RRI Tackling Global Change and PSGAR GRIFON. The author acknowledges ECMWF for providing the ERA5 reanalysis dataset and thanks the IPSL-ESPRI high-performance computing center for computational support.

Availability of data and materials

All reanalysis data used in this study are publicly available from the **Copernicus Climate Data Store (ERA5)** at <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>. **CMIP6 data from historical simulations and SSP's projections are accessible through the Earth System Grid Federation (ESGF) archive as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset** at <https://esgf-index1.ceda.ac.uk/projects/esgf-ceda/>.

The Python analysis scripts developed for this study are available upon request and will be released via Zenodo upon publication.

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Figures

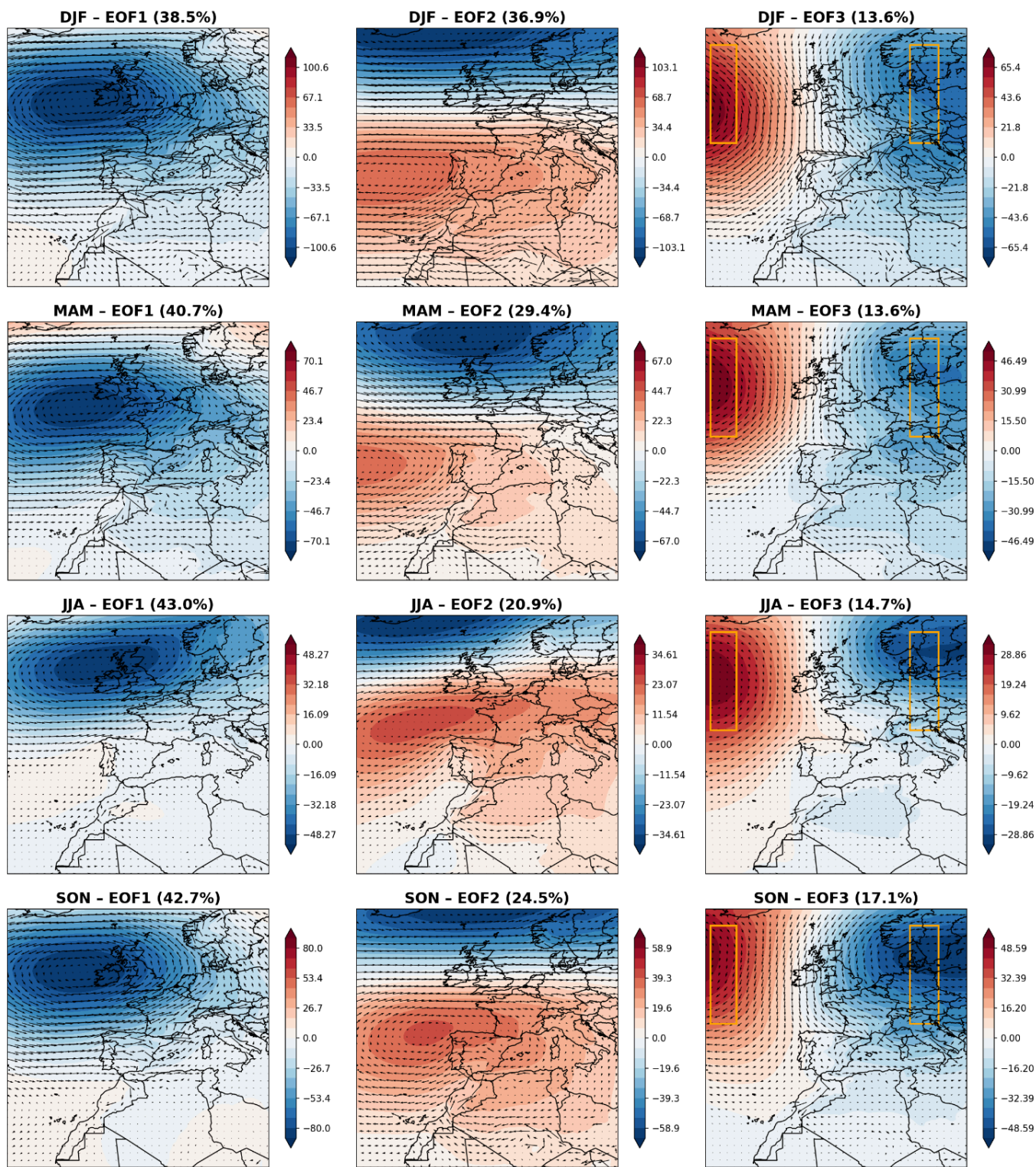


Figure 1

Maps of the first three EOF modes of sea-level pressure (SLP) for each season (DJF, MAM, JJA, SON). Colors represent the normalized amplitude of each EOF mode ($\pm$ max), while arrows indicate the associated geostrophic wind vectors. Orange rectangles show regions of maximum and minimum pressure used to compute Δ SLP. The percentage of variance explained by each mode is indicated in each panel title.

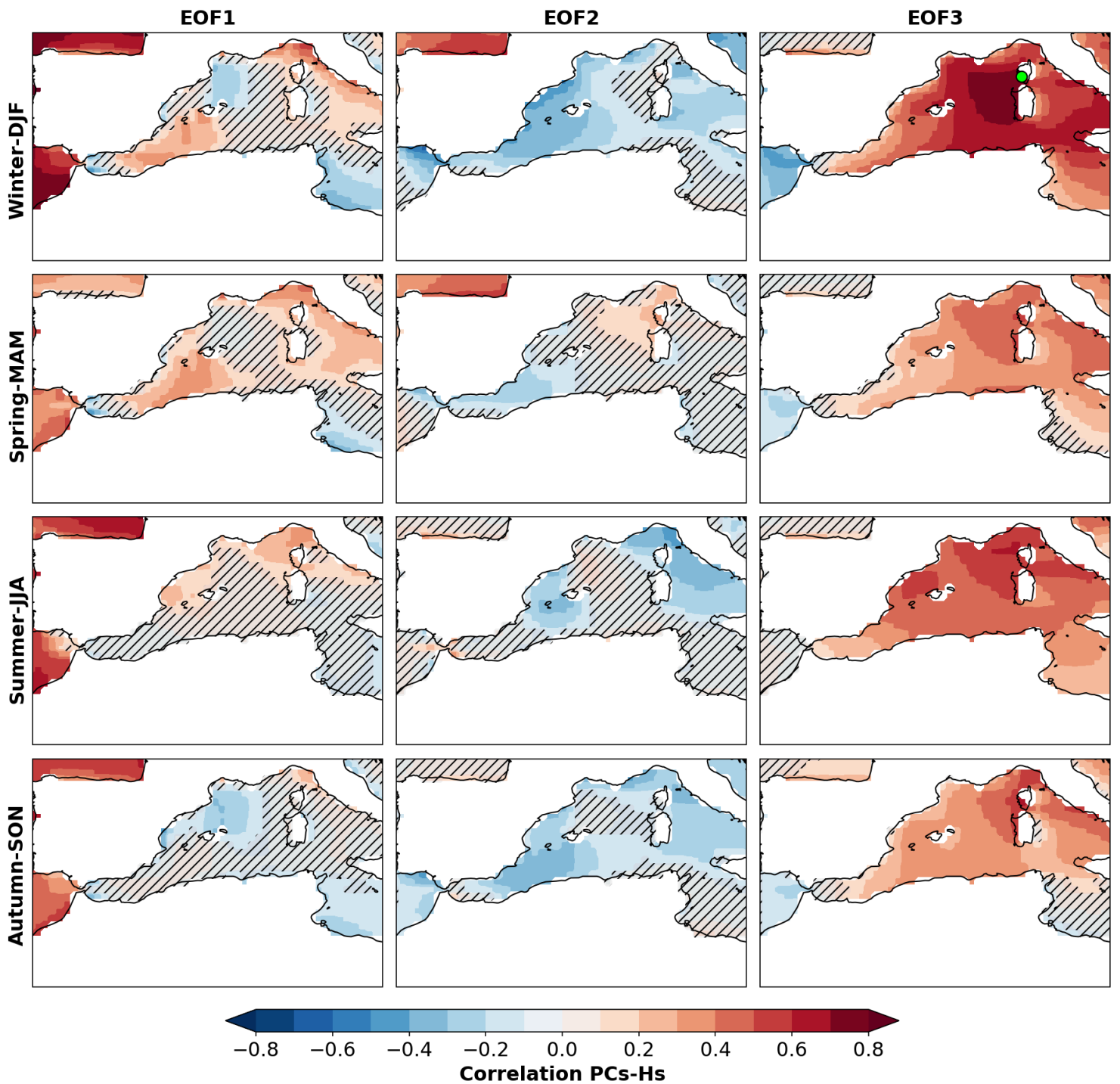


Figure 2

Spatial correlation between the first three principal components (PC1, PC2, PC3) of SLP EOFs and significant wave height (Hs) for each season. Black-hatched areas indicate non-significant regions ($p \geq 0.05$). The green point marks the location of Corsica for PC3 in winter (DJF), corresponding to the maximum local correlation. The color scale reflects both the magnitude and sign of the correlation.

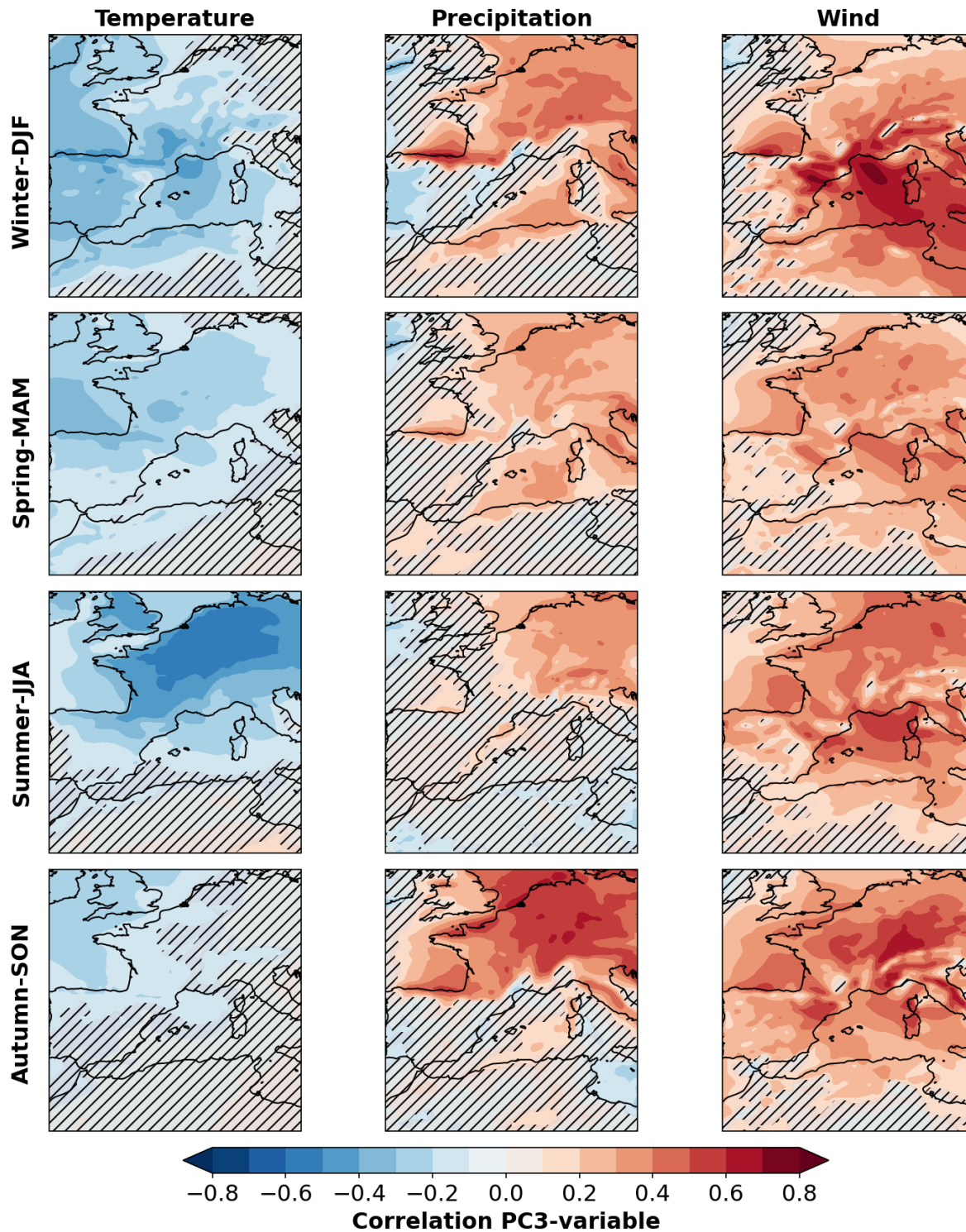


Figure 3

Spatial correlation of the third principal component (PC3) with near-surface temperature, precipitation, and wind speed for each season. Columns correspond to variables, rows to seasons (DJF, MAM, JJA, SON). Black-hatched areas indicate non-significant regions ($p \geq 0.05$). The color scale represents correlation magnitude and sign.

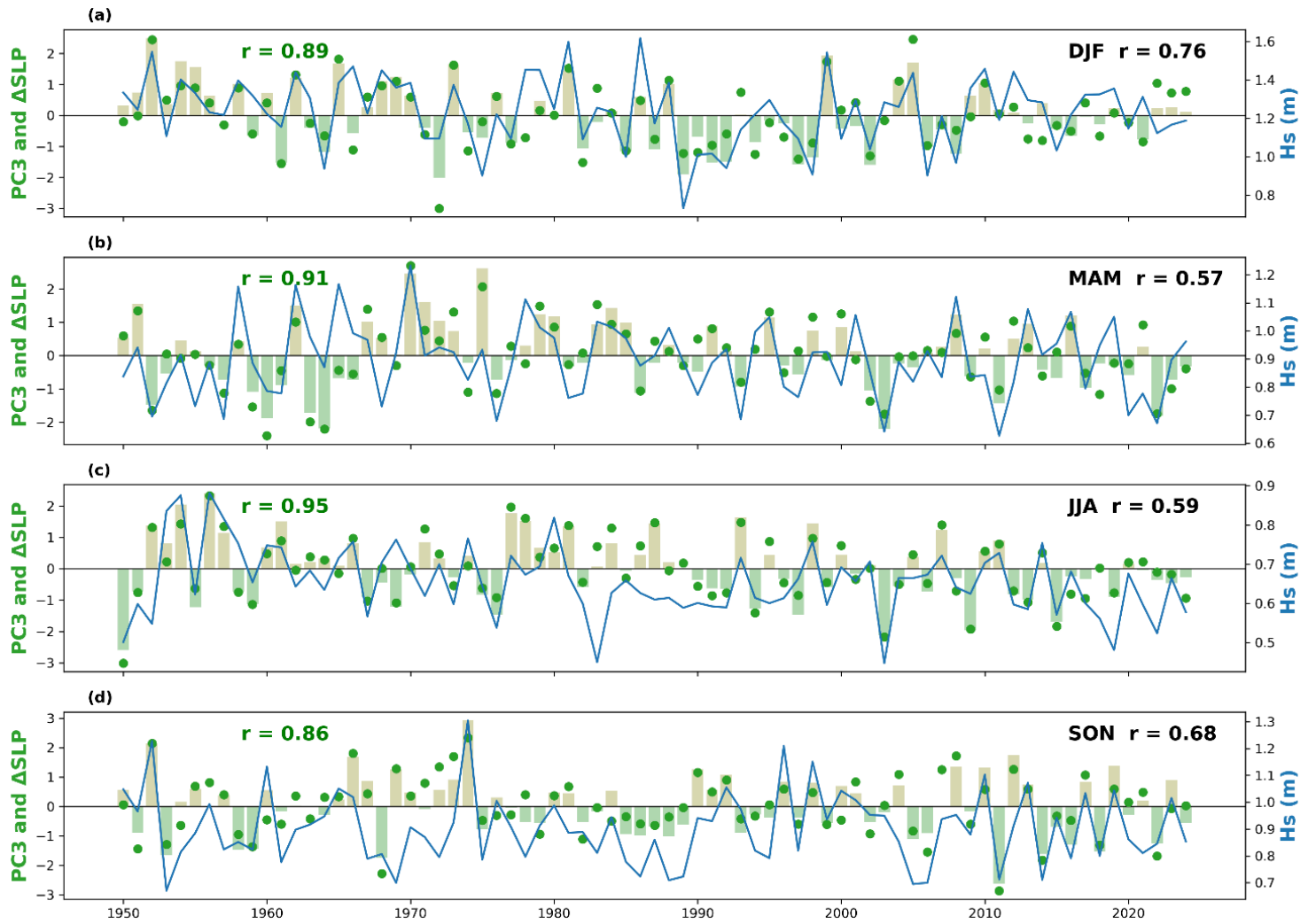


Figure 4

Seasonal time series of the standardized Atlantic-Europe Dipole (AED) index and its relationship with normalized and detrended regional pressure gradients and absolute significant wave height (Hs) near Corsica for the period 1950-2024. Bars represent the standardized principal component of EOF3 (PC3), while green dots indicate the normalized sea-level pressure difference (ΔSLP) between the two dipole centers identified in Fig. 1. The strong correlations between PC3 and ΔSLP (green values) confirm that the EOF-derived mode is well represented by the large-scale pressure gradient across the North Atlantic-European sector. The blue curve shows seasonal mean significant wave height derived from ERA5. Black correlation coefficients indicate the relationship between PC3 and Hs for each season, revealing the strongest coupling during winter (DJF), when enhanced meridional pressure gradients intensify northerly wind regimes and promote wave generation in the northwestern Mediterranean.

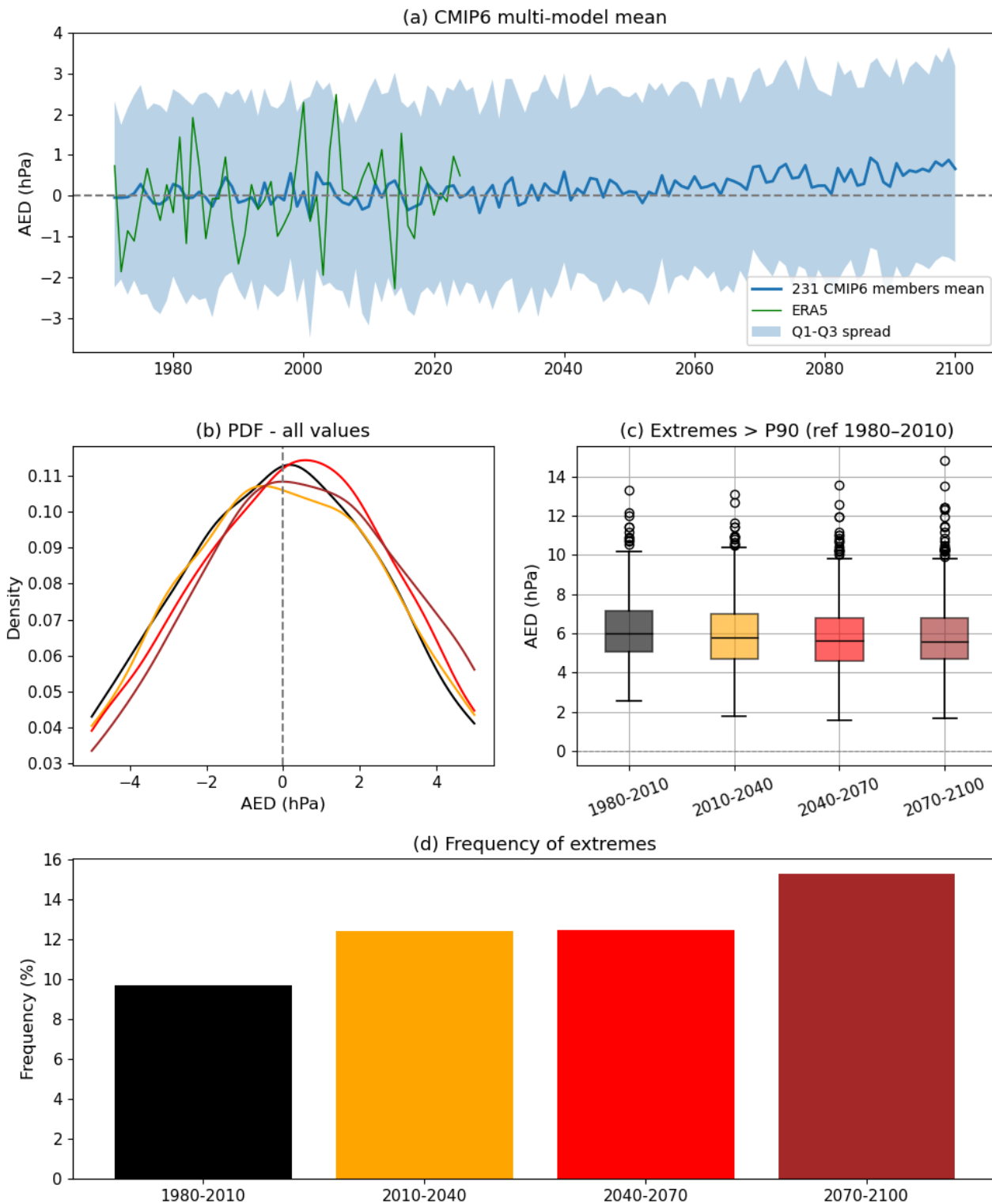


Figure 5

Projected changes in the AED in CMIP6 simulations under the SSP5-8.5 scenario. (a) Multi-model mean evolution of the AED index computed from sea-level pressure differences between the northeastern Atlantic and central Europe. The blue line represents the ensemble mean across 231 CMIP6 members, while the shaded envelope indicates the interquartile spread among models. The index is expressed relative to the 1970-2010 baseline. (b) Probability density functions (PDFs) of AED values for four time

periods (1980-2010, 2010-2040, 2040-2070, and 2070-2100), illustrating changes in the distribution of the circulation index. (c) Distribution of extreme AED events exceeding the 90th percentile threshold defined from the 1980-2010 reference period. Boxplots show the median, interquartile range, and outliers across all model members. (d) Frequency of extreme AED events relative to the reference period.

Supplementary Files

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