Wind energy future projections over Western Europe: results from the BOREAS project

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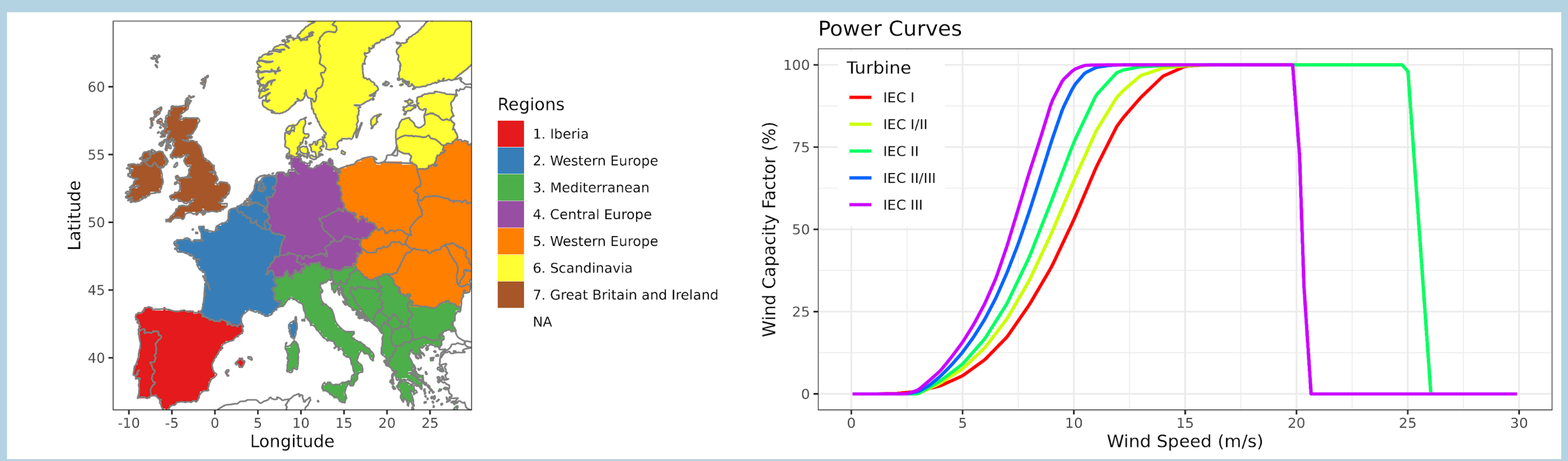
Introduction

The production of renewable energy is critical to replacing a fossil-fuel-based energy system and reaching carbon neutrality. This energy generation is highly dependent on climate conditions and variability, which increases the vulnerability of electricity supply. Climate projections have proven to be key for policy and decision making in a global warming scenario, as they allow for maximizing renewable energy production.

Herein, the BOREAS project aims to improve energy production and demand forecasting, supporting energy transition governance and the development of climate adaptation measures at different levels. In this contribution, we analyse future changes in near-surface winds under multiple radiative and socio-economic scenarios.



Left side: European domain considered in this study. Colors show different **sub-regions** based on the regionalisation by Priestley et al. (2024). Right side: **Power curves of wind capacity factor** (expressed as a percentage) for different types of turbines (colored lines), adapted from Lledó et al. (2019).

Data and Methodology

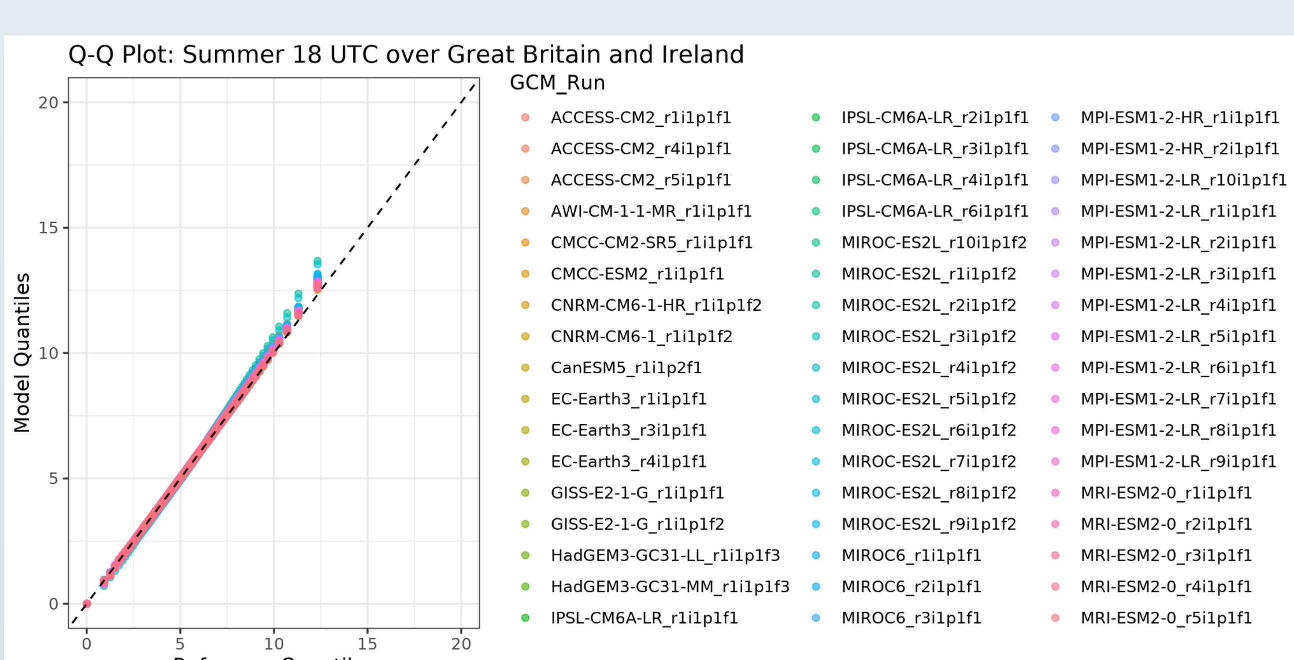
We employ 3-hourly instantaneous surface winds from a large ensemble of 17 CMIP6 models (GCMs) and the ERA5 reanalysis (1979-2014). GCM simulations (multiple members from different models when available, with 1 to 10 realisations in the different models) are considered from their historical, SSP245 and SSP585 scenarios (2040-2100). Surface winds are taken to the 100-m level through vertical interpolation.

BIAS CORRECTION: model fields are bias-corrected taking ERA5 as reference (~25 km), for each 3-hourly output separately, and considering a 30-day moving window. We use a de-trended quantile mapping (DQM), which consists of (i) removing the long-term linear mean trend; (ii) apply empirical quantile mapping to the detrended series; (iii) re-apply the mean trend to the bias-adjusted series. A cross-validation procedure is followed to validate the adjustment.

WIND CHANGES: we estimate relative changes for different seasons and scenarios for the mid and late 21st century. Changes are calculated for each member, separately, and then the model ensemble mean is estimated.

WIND CAPACITY FACTORS: we used the definition by Lledó et al. (2019) as a suitable indicator of wind power generation. WCF measures how efficient the meteorological conditions are for producing energy during a specific period, defined as the ratio between the total produced energy and the maximum production that could be achieved.

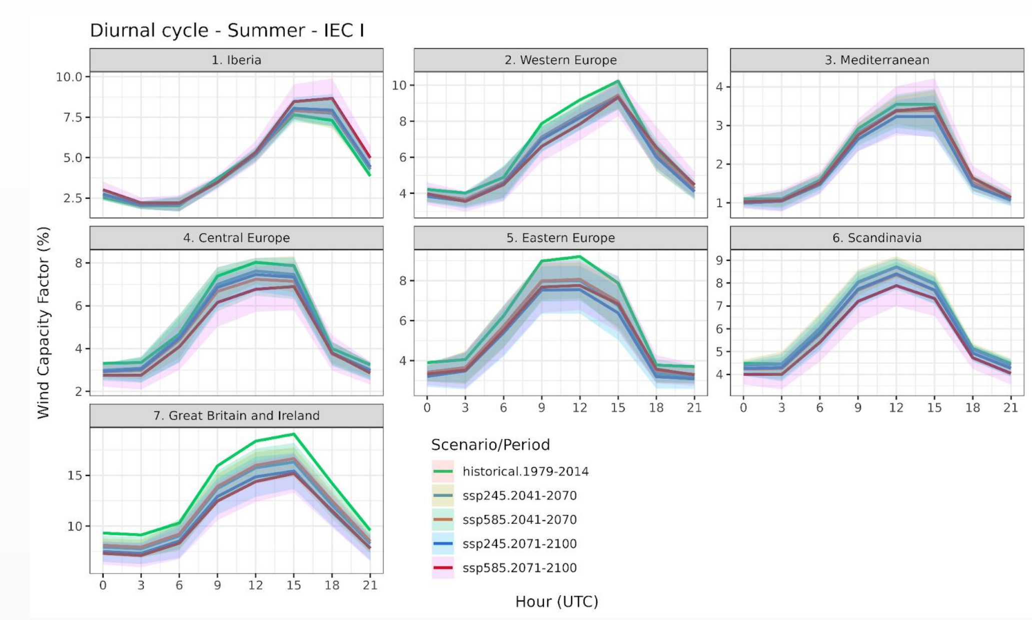
MODELS' CLUSTERING: given the large spread in future wind changes, we propose a selection strategy based on the Ward's cluster method. The spatial patterns of change on daily-mean surface winds for the late 21st century are considered for each model ensemble during the summer and winter seasons, separately. Groups of models with similar spatial patterns of change are obtained.
We selected 3 groups for the summer season and 4 for the winter season, given the larger spread in the latter projections.

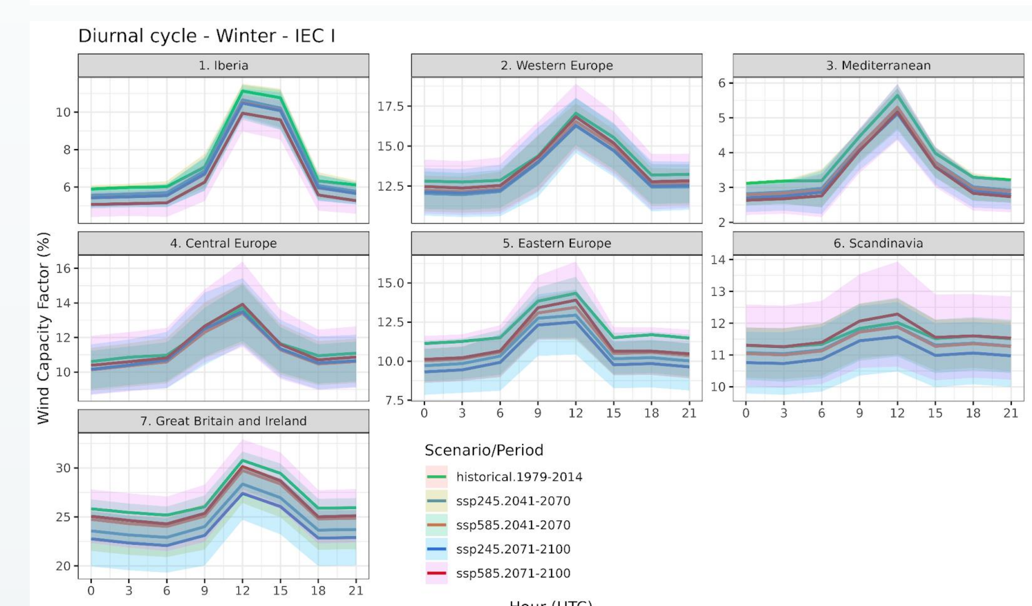


Quantile-Quantile (Q-Q) plots for the different model realisations (colored points, as shown in the list) against the ERA5 reference. Results are shown, as an example, for the summer 18 UTC over the Great Britain and Ireland region.

The DQM technique successfully adjusts the model distribution to the ERA5 reference, preserving the climate change signal from the GCMs. Some deviations are detected for extreme values, particularly in the highest wind values. Some differences in the correction are visible among simulations.

Wind capacity factors





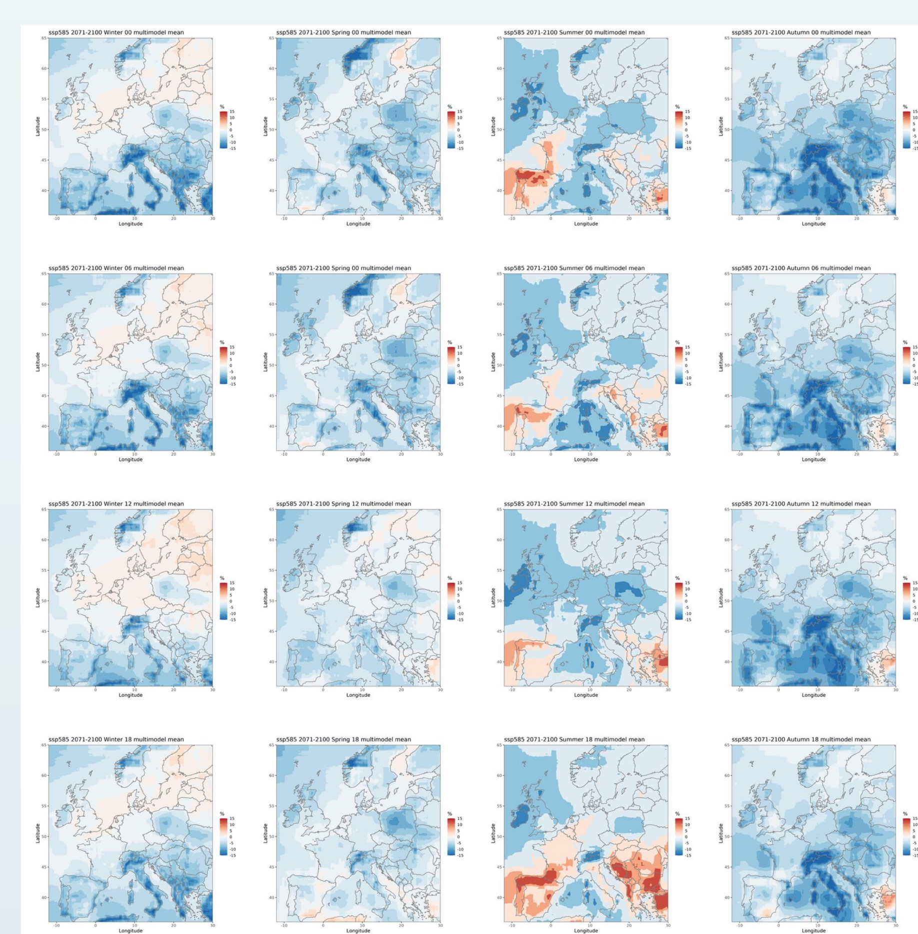
Diurnal cycles of the WCF (IEC I turbine) for the summer and winter seasons (top, bottom), expressed as a percentage. Results are presented for various scenarios and time periods (coloured lines), as well as for each sub-region in Europe. Lines indicate the multi-model ensemble mean, while the spread corresponds to the standard deviation.

The cycles show clear differences across regions and between summer and winter. Maximum WCF are found for the late hours of the day during summer, especially in regions like Iberia and Western Europe, whereas this maximum is located in the mid-day during winter.

Changes vary across periods and scenarios. Increases in WCF are expected for Iberia in summer, while general decreases are seen in most of Europe, including Great Britain and Ireland.

Spread is larger during winter, particularly in high latitudes. However, the relationship between periods and scenarios is not linear, evidencing the complexity in wind changes and indicators.

Near-surface wind changes



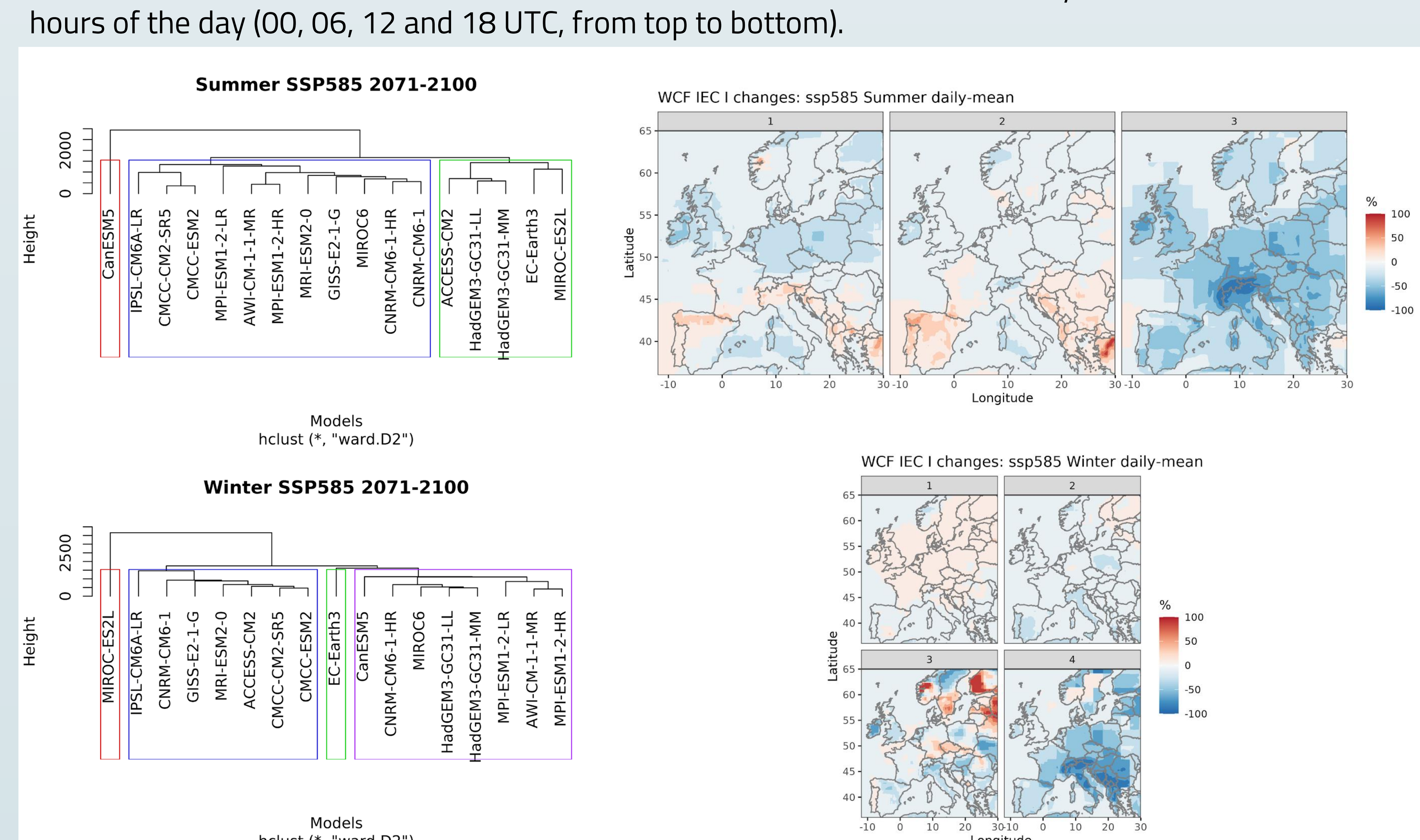
Results come from the multi-model ensemble. Winds are expected to decrease in most of Europe, especially in winter and autumn, but some regional differences are found, with evidenced increments in southern latitudes during summer.

Sub-daily differences are also detected, particularly in the maximum rates of change increases in Iberia and the Mediterranean (eastern) region and decreases in Central Europe and Italy.

When disentangling the change signal in different sub-clusters (bottom figure), some group of models present larger decreases in northern latitudes during summer, while one model (CanESM5) shows a generalized intense decrease over all the continent.

In winter, the different change signals are evident, with some clusters projecting slight increases in wind or larger rates in specific areas, while others present generalized decreases in WCF.

Changes in near-surface wind under the SSP585 scenario for the late 21st century (2071-2100). Results are shown for the multi-model ensemble mean for the different seasons of the year (columns) and for the four main hours of the day (00, 06, 12 and 18 UTC, from top to bottom).



Left: dendrogram representing the **cluster of model ensembles** according to the spatial patterns of near-surface wind changes for the summer and winter seasons (top, bottom) during the late 21st century (2071-2100) under the SSP585 scenario. The coloured boxes show the resulting clusters of models in each case (numbered from right to left, 1 to 3 or 4). Right: **WCF (IEC I turbine) changes** for the late 21st century, separated by cluster.

Conclusion

General decreases in near-surface wind and WCF are found, while regional change are evident as in the Iberia peninsula during summer and over Great Britain and Ireland.

The uncertainty in future projections of near-surface wind and WCF over Europe is due to:
(i) Sub-daily variability, needed to fully capture wind features and changes in a climate change scenario;
(ii) Internal variability;
(iii) Model differences: models project varied spatial patterns of changes across Europe;
(iv) Regional and seasonal differences, particularly in the larger spread during winter.

We highlight the importance of regional climate information coming from multi-member and multi-model ensembles to better provide climate services on wind indicators under climate change, useful for energy production and planning.

Acknowledgements

This publication is part of the PID2022-140673OA-I00 funded by MICIU/AEI/10.13039/501100011033 and FEDER, UE. Matías Ezequiel Olmo is funded by the AI4Science PN070500 fellowship within the "Generación D" initiative, Red.es, Ministerio para la Transformación Digital y de la Funión Pública, for talent attraction (C005/24-ED CV1). Funded by the European Union NextGenerationEU funds, through PRTR.

BOREAS CS4ENERGY — Gobierno de España, Ministerio de Ciencia e Innovación — AI4S BSC AI4Science Fellowships