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# A multi-variable constrained ensemble of regional climate projections under multi-scenarios for Portugal – Part I: An overview of impacts on means and extremes

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A B S T R A C T

Climate projections are a powerful tool that can help decision makers to timely prepare adaptation policies, which may then be efficiently implemented. In this study, a comprehensive analysis of how climate change may affect Portugal (located in a climate change hotspot) is conducted, providing the foundations to the first National Roadmap for Adaptation 2100. A multi-variable ensemble was built and tested, being the baseline for assessing future projections for three different emission scenarios (RCP2.6, RCP4.5, and RCP8.5) throughout the 21st century, accounting for the model's ability to simulate a set of variables. A warmer and drier future climate is projected for the mainland, being more severe in the interior regions. Even for the optimistic RCP2.6 scenario, results indicate increases in temperature between 1 and 2 °C in comparison with the historical period and can surpass 6 °C in some regions for RCP8.5. Extreme hot events will be more frequent and severe, with maximum temperatures above 45 °C being more common throughout the 21st century. A decline in precipitation is expected mostly in summer and intermediate seasons, with losses above 40 % for the end-of-century. However, an intensification of heavy short-term rainfall events is projected to increase in northern regions. A rising of maximum wind gusts is also expected in these regions. Such projections call for an urgent planning and adaptation measures to safeguard critical sectors of the Portuguese society. Finally, the information here produced and examined constitutes a key example of climate services for mitigation and adaptation in Portugal.

**Practical implications**

The climate observed and projected changes call for urgent adaptation and mitigation strategies. Climate modelling is a key tool for providing reliable climate change information to support these strategies. In recent years, a massive outreach effort has been pursued to produce specific and clear climate data within the climate services umbrella to allow a well-defined communication of climate information to different audiences that include stakeholders, decision-makers, and the general public.

Portugal is located in a known climate change hotspot where substantial societal, economic, and ecologic impacts are expected. Hence, the need for a national project focused on identifying and characterising climate change impacts on different socioeconomic sectors in agreement with the different greenhouse gas emissions scenarios, with the ultimate objective of defining adaptation storylines according to different projections, arose. The National Roadmap for Adaptation XXI – Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century (RNA2100) project is currently being developed, with the main objective of supporting public policy exercises of adaptation to climate change, at different levels of territorial intervention, specifically (1) identifying and characterising climate change impacts on the most vulnerable domains in Portugal; (2) characterising socio-economic impacts on different territorial scales and assess financial needs; and (3) contributing to the implementation of a National Spatial Planning Policy Programme by identifying and mapping vulnerable territories to climate change. To effectively reach targeted audiences this project is focused on three main outcomes: (1) defining adaptation storylines according to different greenhouse gas emissions scenarios for Portuguese territories/

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regions; (2) identifying and converting the physical impacts into socioeconomic territorial impacts; and (3) assuring effective communication to an audience from sectoral stakeholders and policymakers to the general public.

In the aforementioned context, the aim of this study is presenting the main findings concerning national level climate projections, divided into two articles (Part I and Part II). Climate means and extremes (detailed in Part 1), and climate indices (detailed in Part 2) are explored from highly- to non-mitigated emission scenarios based on a multi-variable constrained ensemble from the EURO-CORDEX regional downscaling project. This work further aims at establishing a baseline for future studies to delve in sectorial impact modelling, such as water resources, agriculture, forests, wildfire danger, and coastal areas, with the purpose of translating physical anthropogenic-driven climate change effects into social and economic impacts, both with and without adaptation measures.

EURO-CORDEX climate model projections are a powerful tool for simulating the future under different scenarios of human development and related greenhouse gas emissions. The EURO-CORDEX experiment aggregates many RCM simulations to ensure large continental scale climate ensembles, with an enhanced depiction of inter-model uncertainty, to provide robust regional climate projections over a shared European domain, a paramount baseline tool for climate information.

To offer accurate multi-variable climate information and, at the same time, preserve physical consistency, crucial for impact modelling, we propose a robust method to refine the construction of a multi-model ensemble using based on multi-variables evaluations. This improvement allows to incorporate information from different variables, giving more weight to models which better reproduce the observed climate. For impact modelling, this is a valuable method due to the importance of assess the quality of models and built accurate multi-model ensembles. In this article, the multi-variable RCM-based high-resolution ensemble is built and applied to characterize climate change on precipitation, temperature, and wind speed, as well as their extremes over Portugal, for the first time, including the three RCP emission scenarios. For example, the results over the southern region of Portugal in spring, assuming the moderate emission scenario (RCP4.5), point to:

- A decrease in total accumulated precipitation, expected to reach 40 % by the end of the 21st century.
- Projected increases in maximum and minimum temperatures up to 2–3 °C.

Such values are attenuated if projections assuming the CMIP5 scenario (RCP2.6), closer to the Paris agreement target, with virtually no losses of precipitation and increases in temperature of 1–2 °C, being much aggravated when the worst-case scenario (RCP8.5) is assumed. In this case, precipitation is projected to decrease up to 50 % and temperatures rises within 3 and 4 °C. In that specific region, sectors like agriculture and tourism are very relevant, and such results indicate a wide range of climate change potential impacts, which cascade into the food supply sector, local economy, human health, and the overall societal development. Different adaptation measures and strategies need to be designed according to different emission scenarios. The results point out for different impacts regarding the different emission scenarios, from highly- to non-mitigated scenarios, which has strong implications for the costs associated with the implementation of such strategies to mitigate and adapt to climate change. We urge for the need to timely prepare adaptation measures and strategies at the national, subnational, and sectorial levels, with this work serving as a baseline, further translated into storylines, articulated, and integrated with the stakeholders' and policymakers' point-of-view.

**Data availability**

Data will be made available on request.

## Introduction

Continental Portugal (hereafter Portugal) is located in the western tip of the Mediterranean basin, in the transition zone between the arid to semiarid climates of subtropical regions and the humid climates typical of northern Europe. This region has been identified as a climate change "hotspot", with observed and projected rates of climate change exceeding global trends for most variables (Cramer et al., 2018; Giorgi, 2006; Lionello and Scarascia, 2018). Humid mild winters, and dry warm/hot summers are a common feature that characterises Portuguese as well as Mediterranean climates. Indeed, observational records between 1860 and 2005 already show a general trend for warmer and drier mean atmospheric conditions over these areas (Giorgi and Lionello, 2008; Trenberth, 2011; Turco et al., 2018). According to the Fifth and Sixth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013, 2021), the observed increase in mean temperature over the western Mediterranean basin during the last decades has been particularly pronounced in summer months, and the warming and drying trends across the Mediterranean will continue throughout the twenty-first century (Lionello and Scarascia, 2018; Tuel and Eltahir, 2020).

Several studies have been developed to assess the impact of climate change on Portuguese climate regarding changes on temperature, precipitation, and wind speed. Soares et al. (2017a) and Cardoso et al. (2019) characterised the climate change signal of precipitation, and maximum and minimum temperatures over Portugal, respectively. Reported results indicated a significant projected decrease in precipitation during spring and autumn, as well as a significant reduction of wet days. Projections of temperatures for Portugal pointed to a significant increase of maximum and minimum temperatures, which in turn leads to an increase in frequency and intensity of heatwaves. In Nogueira et al. (2019), the future projections for land mean 10-m wind speed showed a reduction during winter and autumn, and a slight increase in summer. Similar projections were found for offshore wind speed, where it is expected a rise in summer and a reduction in the remaining seasons (Soares et al., 2017b,c).

In general, future projections point to Portugal being extremely vulnerable to climate change (Cardoso et al., 2019; Nogueira et al., 2019; Soares et al., 2017a,b; Soares and Lima 2022; Vicente-Serrano et al., 2014), both because of the severity of climate projections and the limited adaptation preparedness. However, it is important to stress that the projected changes differ depending on factors such as the emission scenario considered, the number of RCMs selected, the weights attributed to each model and their dependence on the performance for specific variables, among others. Consequently, different results may lead to different adaptation needs and policies. Most of the studies show projections that focus on a single 30-year period, typically focused on the end of the 21st century and considering the moderate- and high-emissions scenarios. Hence, there is a lack of a consistent and solid body of climate information concerning the evolution of the Portuguese climate throughout the entire 21st century and including all the scenarios available within the RCM community, namely the highly mitigated emission scenario. Consequently, a detailed assessment of the Portuguese climate projections covering climate means, extremes, and indices, and considering highly- to non-mitigated emission scenarios throughout the 21st century, must be endeavoured with the aim of assisting decision-makers to timely prepare adaptation measures. In this sense, the National Roadmap for Adaptation XXI – Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century (RNA2100) project is currently being developed with the main objective of supporting public policy exercises of adaptation to climate change, set at the different levels of territorial intervention, specifically (1) identifying and characterising climate change impacts on the most vulnerable domains in Portugal; (2) characterising socioeconomic impacts on different territorial scales and assess financial needs; and (3) contributing to the implementation of a National Spatial Planning Policy Programme by identifying and mapping vulnerable territories to climate change. To effectively reach targeted audiences this project is focused on three main outcomes: (1) defining adaptation storylines according to different greenhouse gas emissions scenarios for Portuguese territories/regions; (2) identifying and converting the physical impacts into socioeconomic territorial impacts; and (3) assuring effective communication to an audience from sectoral stakeholders, policymakers to the general public.

Climate modelling is crucial to provide climate change information to support adaptation and mitigation strategies. In this way, Regional Climate Models (RCMs) forced by Global Climate Models (GCMs) output are a powerful tool for simulating the future climate of Earth under different scenarios of human development and related greenhouse gas emissions. When comparing with GCMs, RCMs are available at higher spatial resolution and often more sophisticated parametrization schemes over a limited domain of interest, which allows for a more realistic representation of local and regional circulations due to land–atmosphere interactions (Cardoso et al., 2019; Giorgi and Mearns, 1999; McGregor, 1997; Nogueira et al., 2019; Rummukainen, 2010; Soares et al., 2017a). The Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al., 2009) and its European branch (EURO-CORDEX; Jacob et al. (2014, 2020) provide regional climate projections for Europe at a horizontal grid resolution of about 12 km, obtained by dynamically downscaling a CMIP5 GCM ensemble using a set of RCMs. One of the shortcomings that must be addressed while constructing optimized regional climate projections based on the EURO-CORDEX is the fact that it is an ensemble of opportunity. This means that while some aspects are coherent among the ensemble members (*e.g.*, the spatial domains), others are strongly heterogeneous, namely the number of members of each of the modelling systems used (*i.e.*, the number of GCMs downscaled by a model) and the IPCC emission scenarios covered by each model/member. An additional issue with ensembles of opportunity is the lack of independence between certain models (Abramowitz and Bishop, 2015; Bishop and Abramowitz, 2013; Sanderson et al., 2015). A further source of complexity arises when the ensemble is built considering the individual performance of its members, since it depends on the chosen error metrics, variables and analysed region (Casanueva et al., 2016; Frei and Isotta, 2019; Jacob et al., 2020; Knist et al., 2017; Kotlarski et al., 2015; Prein et al., 2016). Overall, a careful analysis is required prior to the selection of the models and criteria used to build the ensemble climate projections. Furthermore, a previous study reported that giving equal weight to all models (the so-called "democratic" ensemble) is a suboptimal approach (Eyring et al., 2019). In fact, weighting individual models based on their performance over the specific domain and for the variables and metrics of interest has been shown to improve the quality of the climate projections derived from ensembles (Brunner et al., 2019; Christensen et al., 2010; Eyring et al., 2019; Knutti et al., 2017; Lorenz et al., 2018; Nogueira et al., 2019; Sanderson et al., 2017; Wenzel et al., 2016). Indeed, this method allows to constrain the uncertainty of climate modelling and to obtain more accurate regional climate projections. Here, we propose a new method to refine the multi-model ensemble using multi-variables to provide improved climate projections for Portugal based on three different emission scenarios. Such method allows to incorporate information from observations of precipitation, maximum and minimum temperature, giving more weight to models that better reproduce the observed climate. A multi-variable approach is key for sectorial adaptation since impact models rely often in multi-variable information and the physical consistency must be preserved.

Incorporated in the RNA2100 project and for the first time, the present study proposes a characterisation of climate change projections based on a set of relevant variables. Climate means, extremes, and indices are explored from highly- to non-mitigated emission scenarios based on a multi-variable constrained ensemble of EURO-CORDEX. This work further aims at establishing a baseline for future studies to delve in sectorial impact modelling, such as water resources, agriculture, forests, wildfire danger, and coastal areas, with the purpose of translating physical impacts into social and economic ones, both with and without adaptation measures. This assessment is carried out into two parts and published in companion papers. In Part I, a multi-variable RCM-based high-resolution ensemble is built and applied to characterize climate change on precipitation, temperature, and wind speed, as well as their extremes over Portugal, while Part II focuses on the assessment of climate projections on a set of sectoral climate indices. The multi-model ensemble is built by taking in consideration the individual performance of the available EURO-CORDEX models during historical climate, *i.e.*, by estimating different weights for each model for the three main meteorological variables (precipitation, maximum and minimum temperature). Although the future projections of wind speed will be characterised, this variable was not evaluated due to lack of observational data, and for that reason it is not considered in the multi-model ensemble building. Three future Representative Concentration Pathways (RCPs; van Vuuren et al. (2011)) are considered: the strongly mitigated scenario RCP2.6, the moderate emission scenario RCP4.5, and the high emission RCP8.5.

The manuscript is organized as follows: the datasets and employed methodologies are described in Section 2; the main results of the comprehensive EURO-CORDEX RCM error assessment and of the future climate change signals and extremes over Portugal are described in Section 3; the discussion of the results is presented in Section 4, and the main conclusions are shown in Section 5.

## Data and methods

### *EURO-CORDEX simulations*

The CORDEX experiment (Giorgi et al., 2009) aggregated many RCM simulations to ensure large continental scale climate ensembles. The EURO-CORDEX simulations were developed under the CORDEX effort, providing regional climate projections over a shared European domain with a horizontal grid resolution of 0.11°, obtained by dynamically downscaling CMIP5 GCMs.

Four EURO-CORDEX experiments are considered here, namely-one for the historical period (1971–2000), and three for the future periods (2011–2100) considering a different emission scenario: RCP2.6, RCP4.5, and RCP8.5. Three future 30-year timeframes were assessed: 2011–2040, 2041–2070 and 2071–2100. The full set of available EURO-CORDEX simulations through the Earth System Grid Federation (ESFG) data portal was analysed. It is worth noticing that the number of ensemble members varies depending on the experiment, ranging between 20 and 45 (Table 1). Of these, only 13 RCMs concurrently cover all experiments. The variables retrieved and used in this study were daily total precipitation, 2-m maximum and minimum daily temperatures, daily mean wind speed at 10 m height, and maximum of daily maximum wind gusts.

EURO-CORDEX RCMs were extensively validated against observations. Kotlarski et al. (2014) and Katragkou et al. (2015) evaluated some of the simulations against the daily gridded observational dataset for Europe (E-OBS), providing a description of model's ability in reproducing precipitation and temperature in historical climate. However the representation of precipitation patterns over Portugal has severe limitations associated with the reduced number of rainfall observations considered in E-OBS. Soares et al. (2017a) and Cardoso et al. (2019) assessed the ability of these simulations to respectively represent precipitation and temperature patterns over Portugal against the Iberia02 observational gridded dataset, revealing good agreement with

**Table 1**
EURO-CODEX RCMs used in this study, along with the forcing GCMs, the responsible institute, and the available RCP scenarios. In grey are highlighted GCM-RCM combinations available for all experiments.

| RCM | Institute | GCM | RCP2.6 | RCP4.5 | RCP8.5 | Acronym |
|---|---|---|---|---|---|---|
| CCLM4-8–17 | CLM | CNRM-CM5 | | X | X | CLM1 |
| | | EC-Earth | X | X | X | CLM2 |
| | | HadGEM2-ES | | X | X | CLM3 |
| | | MPI-ESM-LR | | X | X | CLM4 |
| COSMO-crCLIM-v1-1 | CLM | EC-Earth | | | X | CLM-E1 |
| | | HadGEM2-ES | | | X | CLM-E2 |
| | | MPI-ESM-LR | | | X | CLM-E3 |
| | | NorESM1-M | | | X | CLM-E4 |
| ALADIN63 | CNRM | CNRM-CM5 | X | X | X | CNRM1 |
| | | HadGEM2-ES | | | X | CNRM2 |
| | | MPI-ESM-LR | | | X | CNRM3 |
| HIRHAM5 | DMI | CNRM-CM5 | | | X | DMI1 |
| | | EC-Earth | X | X | X | DMI2 |
| | | HadGEM2-ES | X | X | X | DMI3 |
| | | MPI-ESM-LR | | | X | DMI4 |
| | | NorESM1-M | | X | X | DMI5 |
| REMO2015 | GERICS | CNRM-CM5 | X | | X | GERICS1 |
| | | IPSL-CM5A-LR | X | | | GERICS2 |
| | | MPI-ESM-LR | | | X | GERICS3 |
| | | NorESM1-M | X | X | X | GERICS4 |
| | | GFDL-ESM2G | X | | | GERICS5 |
| RegCM4-6 | ICTP | EC-Earth | | | X | ICTP1 |
| | | HadGEM2-ES | X | | X | ICTP2 |
| | | MPI-ESM-LR | X | | X | ICTP3 |
| WRF381P | IPSL | CNRM-CM5 | | | X | IPSL1 |
| | | EC-Earth | | | X | IPSL2 |
| | | IPSL-CM5A-MR | | X | X | IPSL3 |
| | | HadGEM2-ES | | | X | IPSL4 |
| | | NorESM1-M | | | X | IPSL5 |
| RACMO22E | KNMI | CNRM-CM5 | X | X | X | KNMI1 |
| | | EC-Earth | X | X | X | KNMI2 |
| | | IPSL-CM5A-MR | | | X | KNMI3 |
| | | HadGEM2-ES | X | X | X | KNMI4 |
| | | MPI-ESM-LR | X | | X | KNMI5 |
| | | NorESM1-M | X | | X | KNMI6 |
| HadREM3-GA7-05 | MOHC | EC-Earth | X | | X | MOHC1 |
| | | HadGEM2-ES | X | | X | MOHC2 |
| | | MPI-ESM-LR | | | X | MOHC3 |
| REMO2009 | MPI | MPI-ESM-LR | X | X | X | MPI |
| RCA4 | SMHI | CNRM-CM5 | | X | X | SMHI1 |
| | | EC-Earth | X | X | X | SMHI2 |
| | | IPSL-CM5A-MR | | X | X | SMHI3 |
| | | HadGEM2-ES | X | X | X | SMHI4 |
| | | MPI-ESM-LR | X | X | X | SMHI5 |
| | | NorESM1-M | X | X | X | SMHI6 |

observations. The use of high-resolution EURO-CORDEX simulations revealed a significant added value in describing precipitation and temperature patterns, especially for extremes (Cardoso and Soares, 2022; Careto et al., 2022a,b; Soares and Cardoso, 2018). Finally, these simulations were shown to be able to describe near-surface wind speeds over land (Moemken et al., 2018; Nogueira et al., 2019; Vautard et al., 2021) and offshore (Soares et al., 2017b).

The present study was conducted for Portugal (Fig. 1a) and five sub-regional domains (Fig. 1b), identified as the Nomenclature of Territorial Units for Statistics (NUTS) regions. The NUTS is based on Regulation (EC) No. 1059/2003 of the European Parliament on need of a common classification of territorial units for statistics. The five regions are illustrated in Fig. 1b and are divided in Norte (northern Portugal), Centro (central Portugal), A.M. Lisboa (the metropolitan region of Lisbon), Alentejo and Algarve regions.

*Iberia01 observations*

The Iberia01 observational gridded dataset was considered as reference to evaluate the performance of the historical EURO-CORDEX simulations. Iberia01 covers the 1971–2015 period, with a horizontal resolution of 0.1°, providing daily values for precipitation, and maximum and minimum temperatures based on a dense network of weather stations over the Iberian Peninsula, including 3486 and 275 stations for precipitation and temperature, respectively (Herrera et al., 2019). For comparison with the EURO-CORDEX historical simulations, the 1971–2000 time-slice was considered, being the common period between observations and the historical runs. Over Portugal and for the considered period, the number of stations for precipitation was around 500, whilst for temperature was around 50.

Herrera et al. (2019) showed that Iberia01 reproduces well the spatial pattern of precipitation and temperature in what concerns both mean and extremes. Concerning temperature, there is a lack of stations in almost all country, with special emphasis in the northeast region and along some coastal areas. Regarding precipitation, the available observational networks cover all the country, with highest the temporal missing data in northwest regions and along coastal regions north of Lisbon (Herrera et al., 2019). These issues increase the observational uncertainty in the mentioned regions.

*Model evaluation metrics*

The ability of the EURO-CORDEX simulations to reproduce the main properties of the observed climate within mainland Portugal was

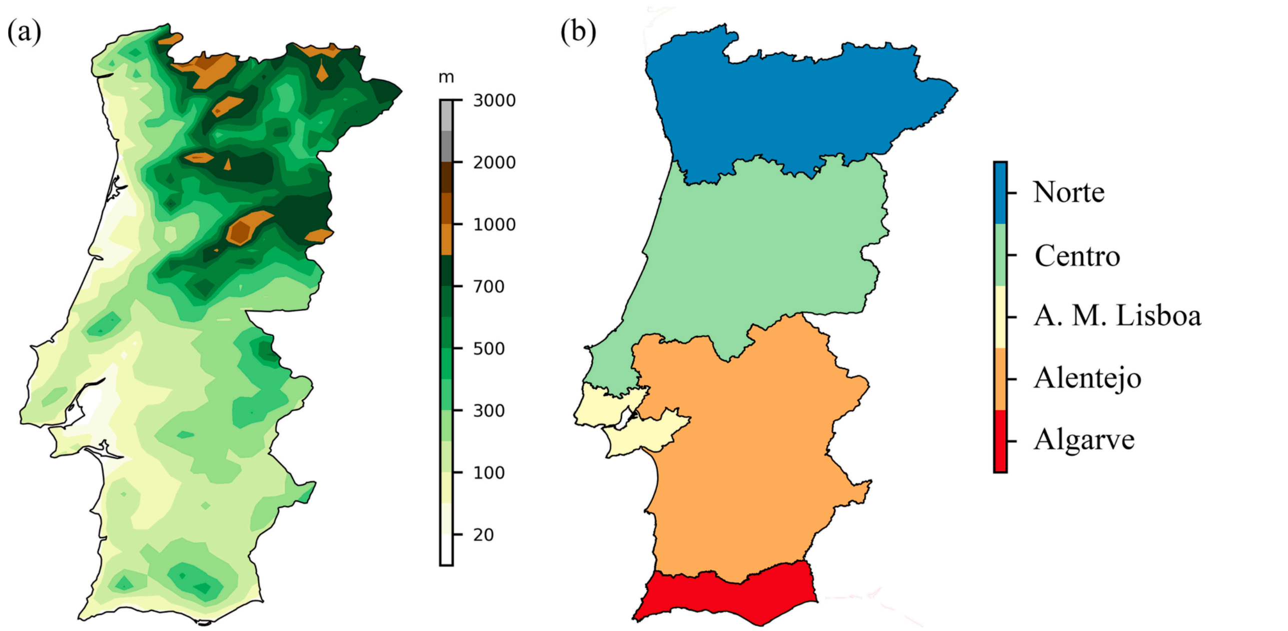


**Fig. 1.** (a) The Portuguese domain, where the colours represent the topographic height (in meters). (b) The five sub-regional domains, identified as the Nomenclature of Territorial Units for Statistics (NUTS) regions: Norte (northern Portugal), Centro (central Portugal), A. M. Lisboa (the metropolitan region of Lisbon), Alentejo and Algarve regions.

assessed at each grid-point, considering Iberia01 (IB-01) as reference. The IB-01 does not have an observational gridded dataset for the 10-m wind speed. Hence, only precipitation, maximum and minimum temperatures were evaluated. Nevertheless, EURO-CORDEX 10-m wind speeds have been previously evaluated revealing good performances over Portugal, corresponding to mean and extreme (95th percentile) biases generally lower than 1 m/s and 3 m/s, respectively (Moemken et al., 2018; Nogueira et al., 2019; Vautard et al., 2021).

Since the EURO-CORDEX RCMs and the regular gridded observational dataset have different spatial resolutions, the higher-resolution daily precipitation and temperature results (observational grid IB-01 at 0.1°) were conservatively interpolated (Suklitsch et al., 2008) to the EURO-CORDEX grid at 0.11°. To account for differences in surface height between the grid-points in IB-01 and target grid-points in the RCM grid, the temperatures were corrected beforehand with an adiabatic adjustment (6.5 K/km) to mean sea level. After the interpolation, they were adiabatically adjusted again to the RCM grid topography.

The historical climate simulations use GCM outputs as lateral boundary conditions, resulting in daily non-synchronised climate when compared with the observations. Consequently, only statistical comparisons over climatological outputs can be performed between EURO-CORDEX RCMs and IB-01. Therefore, a Julian year with 366 daily means was computed for each RCM and IB-01. The use of such daily climatologies makes the comparison between observations and EURO-CORDEX possible, from monthly to yearly timescales, allowing the assessment of the non-synchronised historical climate.

The evaluation of the historical simulations was performed for the 1971–2000 period, considering eight different error metrics, namely the mean bias, mean absolute error, root mean squared error, normalized standard deviation, spatial correlation, Willmott-D Score, Perkins skill score, and Yule-Kendall skewness. The selection of this set of error metrics provides different ways to quantify the performance of each model, giving a more robust assessment of the quality of simulations.

The mean bias or mean percentual bias, used for temperature and precipitation, respectively, measures the models' systematic errors, and are defined as:

$$Bias = \frac{1}{N}\sum_{k=1}^{N}(p_k - o_k) or Bias\% = \frac{\sum_{k=1}^{N}(p_k - o_k)}{\sum_{k=1}^{N}o_k} \quad (1)$$

where $o_k$ and $p_k$ are respectively the observed and simulated 366 daily means at grid-point k, and N is the total number of grid-points. The mean absolute error (MAE) for temperature or mean absolute percentual error (MAPE) for precipitation follow a similar formulation as bias and mean percentual bias but for absolute errors:

$$MAE = \frac{1}{N}\sum_{k=1}^{N}|p_k - o_k| or MAPE = \frac{\sum_{k=1}^{N}|p_k - o_k|}{\sum_{k=1}^{N}o_k} \quad (2)$$

Similarly, the root-mean squared error (RMSE) is defined as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(p_k - o_k)^2} \quad (3)$$

The normalized standard deviation measure is the ratio between the standard deviation of the modelled and observed time-series, and is expressed as:

$$\sigma_n = \frac{\sigma_p}{\sigma_o} = \frac{\sqrt{\frac{1}{N}\sum_{k=1}^{N}(p_k - \overline{p})^2}}{\sqrt{\frac{1}{N}\sum_{k=1}^{N}(o_k - \overline{o})^2}} \quad (4)$$

where $\sigma_o$ and $\sigma_p$ are standard deviations of the observed and simulated time-series, respectively, while $\overline{o}$ and $\overline{p}$ represent the respective mean values. The closer $\sigma_n$ is to the unit, the better the model is representing the observed variability. The spatial correlation (Wilks, 2006) is computed as:

$$r = \frac{\sum_{k=1}^{N}(o_k - \overline{o})(p_k - \overline{p})}{\sqrt{\sum_{k=1}^{N}(o_k - \overline{o})^2\sum_{k=1}^{N}(p_k - \overline{p})^2}} \quad (5)$$

The Willmott-D Score (Willmott et al., 2012) is a combined measure of the differences in mean and standard deviation between model and observations, with $D = 1$ for a perfect skill and $D = -1$ for no skill:

$$D = \begin{cases} 1 - \dfrac{\sum_{k=1}^{N}|p_k - o_k||p_k - o_k|}{2\sum_{k=1}^{N}|o_k - \overline{o}|}, if \sum_{k=1}^{N}|p_k - o_k| \le 2\sum_{k=1}^{N}|o_k - \overline{o}| \\ \dfrac{2\sum_{k=1}^{N}|o_k - \overline{o}|}{\sum_{k=1}^{N}|p_k - o_k|} - 1, if 2\sum_{k=1}^{N}|o_k - \overline{o}| \langle \sum_{k=1}^{N}|p_k - o_k| \end{cases} \quad (6)$$

The models' ability to reproduce the observed probability distribution functions (PDFs) is quantified by the Perkins skill score (Perkins et al., 2007), henceforth denoted S:

$$S = 100 \times \sum_{i=1}^{B} min[E_{p,i}, E_{o,i}] \quad (7)$$

where $E_p$ and $E_o$ are, respectively, the simulated and observed empirical PDFs and $min[E_{p,i}, E_{o,i}]$ is the minimum between the two values. B is the total number of bins used to compute the PDF. This score provides a measure of similarity between the simulated and observed empirical PDFs, with $S = 100\%$ if the model perfectly reproduces the observed empirical PDF. The $S$ score was computed following two different methods, one taking the full PDF (S), and the other the average of two sections as described in (Boberg et al., 2009). For precipitation and maximum temperature, the first section encompasses the data from the minimum value ($P_0$) to the 90th percentile ($P_{90}$) and another from $P_{90}$ to the maximum value ($P_{100}$), hereafter 90; for minimum temperature the two sections are from $P_0$ to the 10th percentile ($P_{10}$) and from $P_{10}$ to $P_{100}$, hereafter $S10$. Finally, the Yule-Kendall skewness measure (Ferro et al., 2005) quantifies the matching between the skewness of the simulated and observed PDFs:

$$YK = \left[\frac{(P_{95} - P_{50}) - (P_{50} - P_5)}{(P_{95} - P_5)}\right]_{model} - \left[\frac{(P_{95} - P_{50}) - (P_{50} - P_5)}{(P_{95} - P_5)}\right]_{obs} \quad (8)$$

where $P_j$ represents the j$^{th}$ percentiles computed from the simulated and observed daily time-series datasets. The closer the YK is to zero, the better the model represents the observed skewness.

*Multi-variable constrained ensemble building*

The ranked average model weighting ensemble building detailed in Christensen et al. (2010) was adapted for this study. The multi-model ensemble $p_{ENS}$ for a given variable $p$ is obtained by computing a weighted average over the $M$ ensemble members as:

$$p_{ENS} = \frac{\sum_{m=1}^{M} w_m p_m}{\sum_{m=1}^{M} w_m} \quad (9)$$

Similarly, the ensemble averaged PDFs $Z_{ENS}$ were obtained by computing a weighted average over all individual model PDFs:

$$Z_{ENS} = \sum_{m=1}^{M} w_m p_m \quad (10)$$

The weights $w_m$ were obtained considering the individual performance of each model (ensemble member) in reproducing the IB-01 observations, measured by the eight-error metrics presented in Section 2.3. First, for each error metric, the individual models were ranked in descending order from the best performing (ranked 1) to the worst performing (largest error, ranked M, corresponding to the number of ensemble members). Prior to the ranking, the inverse of the error was computed for the bias, MAE and RMSE, given that the best performances corresponded to the lowest values. In addition, since the best performance of normalized standard deviation $\sigma_n$ corresponded to a value of 1, this metric was transformed prior to ranking to a new normalized standard deviation $\vartheta_n$ spanning the values between 0 and 1:

$$\vartheta_n = \begin{cases} \sigma_n \; if \; \sigma_n < 1 \\ \dfrac{1}{\sigma_n} \; if \; \sigma_n > 1 \end{cases} \quad (11)$$

Following the same reasoning, the $YK$ was also transformed to a normalized $YK_{new}$ prior to ranking, as:

$$YK_{new} = \begin{cases} YK + 1 \; if \; YK < 0 \\ \dfrac{1}{YK + 1} \; if \; YK > 0 \end{cases} \quad (12)$$

Subsequently, an overall individual model rank was obtained by multiplying the ranks for all error metrics. Finally, the individual model weight was obtained by normalizing the overall individual model rank by the sum of all overall individual model ranks, such that the sum of the weights is equal to 1.

At this stage, three weights are attributed to each of the 13 models (one for precipitation, one for maximum temperature, and another for minimum temperature), factoring its quality when compared to IB-01. To build the multi-model ensemble, four different approaches were tested, considering different combinations of weights, which allow the assessment of the ability of each ensemble to simulate historical and future projected conditions, as well as the quantification of their uncertainty. The four preliminary multi-model ensembles, for precipitation, maximum and minimum temperatures are as follows:

1. For each variable, the ensemble is built assuming the respective model weight, *i.e.*, the weighted sum of the 13 models using the weights for that variable, hereafter called ENS1:

$$ENS1 = \sum_{m=1}^{M} V_m w_{V_m} \quad (13)$$

2. For each variable, the ensemble is built assuming the average of the weights of the three variables, *i.e.*, a new weight is computed as the average of the three weights and the ensemble of each variable is computed with that weight, hereafter called ENS2:

$$ENS2 = \sum_{m=1}^{M} V_m \left(\frac{w_{p_m} + w_{tx_m} + w_{tn_m}}{3}\right) \quad (14)$$

3. ENS3 is computed as ENS2 but the precipitation weight corresponds to 50 %, and the maximum and minimum temperature contributes with 25 % each one:

$$ENS3 = \sum_{m=1}^{M} V_m \left(0.5 w_{p_m} + 0.25 w_{tx_m} + 0.25 w_{tn_m}\right). \quad (15)$$

4. The last ensemble is built following the so-called "democratic approach", where the 13 models are equally weighted, and each ensemble variable consists of the simple average between the models:

$$ENS4 = \frac{\sum_{m=1}^{M} V_m}{M}. \quad (16)$$

Finally, to analyse the future projections of climate variables over Portugal, only one of these 4 ensembles is selected. Multi-weighted ensembles, considering multi-variable performances, such as ENS2 and ENS3, may be advantageous when compared to democratic multi-model ensembles (Cos et al., 2022; Eyring et al., 2019). Therefore, ENS1 and ENS4 are estimated with the aim of having a comparable benchmark for the evaluation of the multi-weighted ensembles (ENS2 and ENS3).

*Definition of climate means and extremes*

The climatological mean of daily maximum 2-meter air temperature, Tx, daily minimum 2-meter air temperature, Tn, daily 10-meter wind speed, Vh10, and maximum of daily maximum wind gust, MaxVgust, were computed from daily EURO-CORDEX data considering the four periods of study: 1971–2000 (historical), 2011–2040 (begin-of-21st century), 2041–2070 (mid-of-21st century), and 2071–2100 (end-of-21st-century). For precipitation, the climatological mean accumulated precipitation was computed. The projected changes of these variables were investigated following three emission scenarios (RCP2.6, RCP4.5 and RCP8.5) throughout the 21st century. In addition, a Student's t statistical significance test was applied for each individual RCM. Following Tebaldi et al. (2011), the projected ensemble change is considered statistically significant if more than 50 % of the models have statistically significant differences and 80 % agree in the sign of the change.

To analyse the extreme precipitation, maximum temperature and maximum wind gust, the return levels for the 10-, 30-, 50-, and 100-year return periods were computed by fitting the annual maximum values from each grid-point to a GEV distribution, for each period and climate scenario. To perform an extreme event analysis, the duration of the climate records is a relevant parameter. Since each of the considered periods spans for 30 years, the process of fitting these data to a GEV distribution generates extrapolated values when the return periods are longer than 30 years, and therefore, the 50- and 100-year return levels should be considered within the scope of this limitation. A summary of the climate means and extremes considered in the current study is addressed in Table 2.

## Results

### *Performance assessment of the multi-variable constrained ensembles*

Here, an extensive evaluation of the precipitation and maximum and minimum temperature is performed, for both the complete set of EURO-CORDEX RCMs, and for the four multi-model ensembles, through comparison against the IB-01. Fig. 2 displays the mean bias, mean absolute error, and the daily *S* and *S*90 scores for precipitation, maximum and minimum temperatures, for the entire set of 45 available RCMs, the 13 selected RCMs, and the four multi-model ensembles built with the 13 RCMs. In addition, Tables S1–S3 (in Supplementary Material) describe the individual performance of each RCM.

The normalised bias and MAPE are represented in Fig. 2a and b (both in the left side), which are focused on the ability of the RCMs to describe the mean structure of precipitation at different time scales. The results from 12 out of the 45 models show normalized biases of less than 10 %, while 21 of them present values below 20 %. The simulations tend to overestimate precipitation, with only 10 out of 45 showing an underestimation. Overall, the results show that the EURO-CORDEX models have good performance in describing the mean precipitation patterns during the historical period. The MAPEs in Fig. 2b (left) also indicate a good performance since most simulations present values below 50 %, decreasing from monthly to yearly time scales. Considering simultaneously the normalized bias and MAPE, the overall performance of

**Table 2**
Summary of the climate means and extremes used in the present study.

| | |
|---|---|
| ***Temperature*** | |
| Tx | Daily maximum 2-meter air temperature |
| Tn | Daily minimum 2-meter air temperature |
| Tx.YY | YY-year return levels of daily maximum 2-meter air temperature |
| ***Precipitation*** | |
| Pr | Mean cumulative precipitation per period |
| Pr.YY | YY-year return levels of the daily total precipitation |
| ***Wind Speed*** | |
| Vh10 | Daily mean 10-meter wind speed |
| MaxVgust | Maximum of daily maximum wind gust |

KNMI2, 3 and 4, IPSL4 and MOHC2 stands out (Table S1). The high *S* and the *S*90 scores, above 85 %, suggest that over 85 % of the modelled PDFs match the one derived from observations (Fig. 2c, left). IPSL and ICTP are exceptions since most of them have scores below 85 %. All the CLM-E, CNRM, MPI and SMHI simulations show *S* and *S*90 skill scores in the range of 90 % to 98 % (Table S1).

There is an underestimation of the maximum temperature, with only 3 out of 45 models showing positive biases (Table S2). Furthermore, 20 out of 45 models show negative biases lower than 1.5 °C. Regarding the MAEs, their magnitudes are mostly similar to those indicated by the bias. Such similarities could indicate a systematic temperature underestimation, which could be due to a cold bias in the forcing GCMs. This issue is, nevertheless, expected, since the mean bias found for the multi-GCM CMIP5 historical experiments is of around −1 °C, and MAE lays between 0.5 °C and 1.5 °C. The distributions show an overlap with observations of more than 75 % for most of simulations.

Opposite to the maximum temperature, the minimum temperature biases are not consistently negative, with around one-third of the models' simulations showing positive biases (Table S3). Nevertheless, as for the maximum temperature, the KNMI and SMHI simulations show a systematic negative bias, inherited from the respective GCMs. Biases and MAEs are lower for minimum than for maximum temperature. The similarity between simulated and observed distributions is also generally greater for this variable, which might be related to the cold bias of maximum temperature. The overlap between the distributions is greater than 75 % in most cases.

When analysing the ability of the four multi-model ensembles to represent accumulated precipitation, maximum and minimum temperatures, results show that ENS1 performs better than the other ENSs in each variable. This is expected since it is weighted considering the performance of each individual variable. Considering the remaining ensembles, ENS3 is the best performing one for precipitation and maximum temperature, and ENS2 for minimum temperature. Nevertheless, it is worth noticing that the differences between the error metrics are small between ensembles, being their overall performances better than the ones from the 45 and 13 individual RCMs.

Differences of yearly and seasonal accumulated precipitation, maximum and minimum temperatures between EURO-CORDEX multi-model ensembles (13 common RCMs) and IB-01 for mainland Portugal are presented in Fig. 3. In addition, the climatology spatial patterns of yearly total precipitation, maximum and minimum temperatures, and its differences from observations are depicted in the Figs. S1–S3. The known south-northwest precipitation gradient is visible in observations and in all ensembles (Fig. S1). Overall, the ensembles tend to overestimate the annual precipitation, with mean biases close to 100 mm, except for ENS1, which errors are lower. Looking to the spatial patterns, all the ensembles show an overestimation of the precipitation in northwestern region, less pronounced in ENS1 followed by ENS3. The remaining country present some regions with small rainfall overestimation/underestimation. Looking to the climatology of spatial patterns of maximum (minimum) temperature (Fig. S2 and S3, respectively), all the ensembles display the south-north (southwest-northeast) temperature gradient represented on observations. An underestimation is observed for all ensembles, except during summer, due to a negative bias found in the northern region and a positive bias in the southern region of Portugal (not shown). The main spatial discrepancy of maximum temperature between the ensembles and observations is found in the northeast region, where an underestimation is observed (Fig. S2). The same is found in minimum temperature, plus an overestimation is noted in some coastal areas. These spatial discrepancies between simulated and observed temperatures may be related with the lack of observational networks in the mentioned regions.

Despite the better generalized performance of ENS1, it should be noted that assigning different weights to different variables might lead to inconsistencies in the climate change assessment, especially when addressing minimum and maximum temperatures, both obtained from

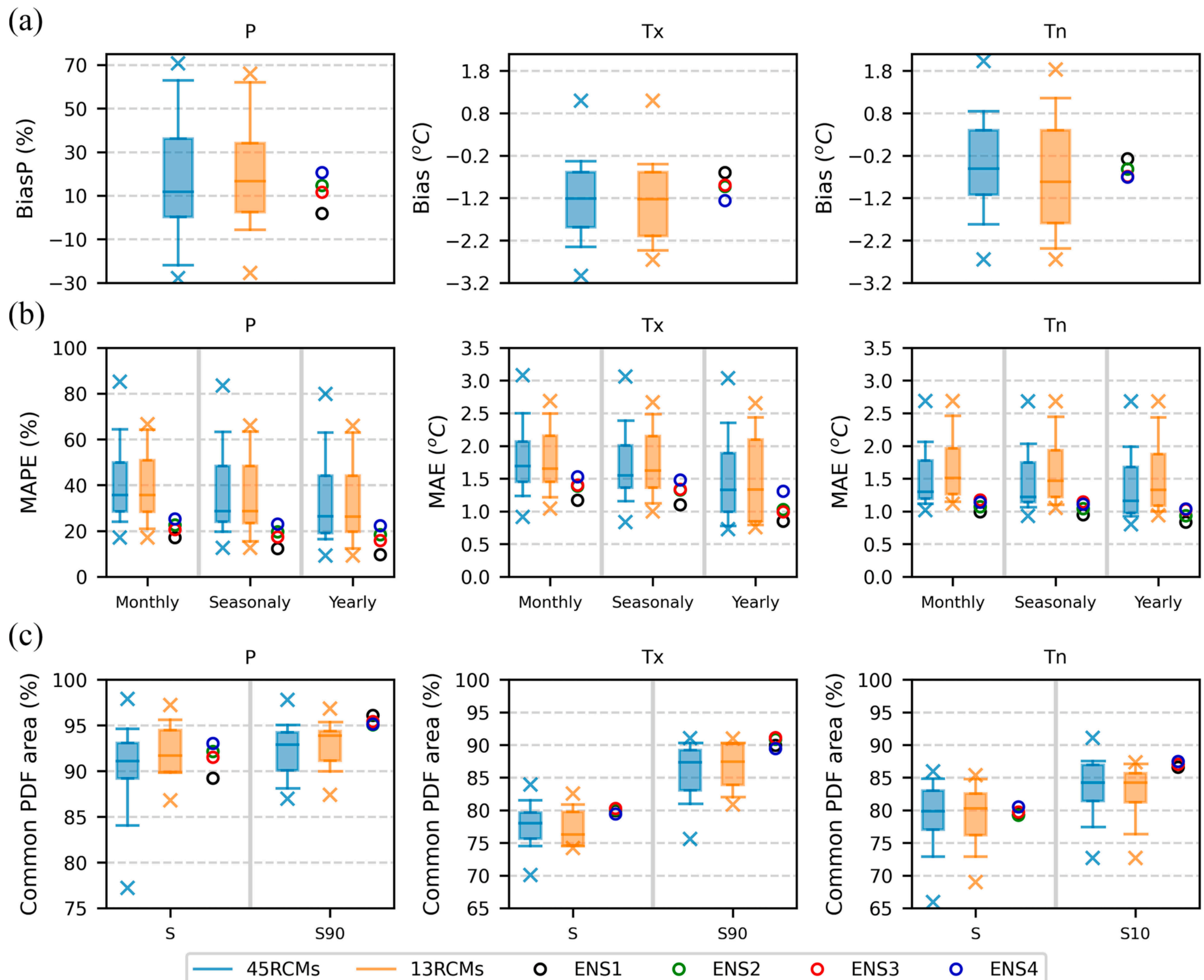


**Fig. 2.** Climatological error measures of EURO-CORDEX RCMs (45 models in blue and 13 models in orange) and of EURO-CORDEX multi-model ensemble common precipitation (left), maximum (middle) and minimum (right) temperature over Portuguese mainland (1971–2000). The bias is represented in (a), and MAE is represented in (b). For precipitation, both metrics were normalized by the mean, and the values are given in percentage (normalized bias and MAPE, respectively). The MAE/MAPE values are shown for different time periods (monthly, seasonally, and yearly). The S and S90 scores are represented in (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the same "mother"-variable: temperature. For this reason, ENS3 (Eq. (15)), which shows the second-best performance (after ENS1), as well as the lowest spreads in comparison with ENS2 and ENS4, was chosen as the 13-member EURO-CORDEX RCM multi-model ensemble to be considered in the characterization of Portugal's future climate, and associated uncertainties.

*Climate change assessment for Portugal*

The results presented from this section onwards are based on the EURO-CORDEX multi-model ensemble, computed following the formulation of the ENS3 (Eq. (15)), which considers a multi-variable weighting approach for each of the 13 RCMs.

*Changes in mean variables*

The future projected changes (in %) associated to the mean total accumulated precipitation over mainland Portugal, both at annual and seasonal scales, are presented in Fig. 4. The averaged values of projected changes in mean total accumulated precipitation averaged over the entire year for NUTS2 are presented in Table S4 in Supplementary Material. Overall, the annual projections indicate a decrease in precipitation throughout the 21st century. Considering the 2011–2040 period, the projected changes are comparable between the three scenarios, ranging from −10 % to +5 %, but without statistical significance. For the mid-21st century (2041–2070), projections indicate an amplification of the drying conditions, especially for the RCP4.5 and RCP8.5 scenarios, with negative values for the entire country, down to −20 % and −30 %, respectively. While the projected decreases for RCP4.5 tend to stabilize towards the end of the 21st century (2071–2100), between −20 % and −10 %, the ones for RCP8.5 show a further aggravation, culminating in values down to −40 % in southwestern Portugal. For the 2071–2100 period under RCP8.5, the absolute projected changes for total annual precipitation in mainland Portugal range between −150 mm and −250 mm, considering all the members from the EURO-CORDEX ensemble (not shown). The seasonal projections for the mean total accumulated precipitation show distinct features throughout the year. In fact, moister winters (DJF) are projected in most of mainland Portugal, considering RCP2.6 after 2041 (up to +30 % in interior north region), and for RCP4.5 before 2040 (but also visible for northern Portugal towards 2100; below +20 %), but without statistical significance in most of the points. During spring (MAM), the three scenarios agree on a projected increase (up to +20 %) in precipitation in northern

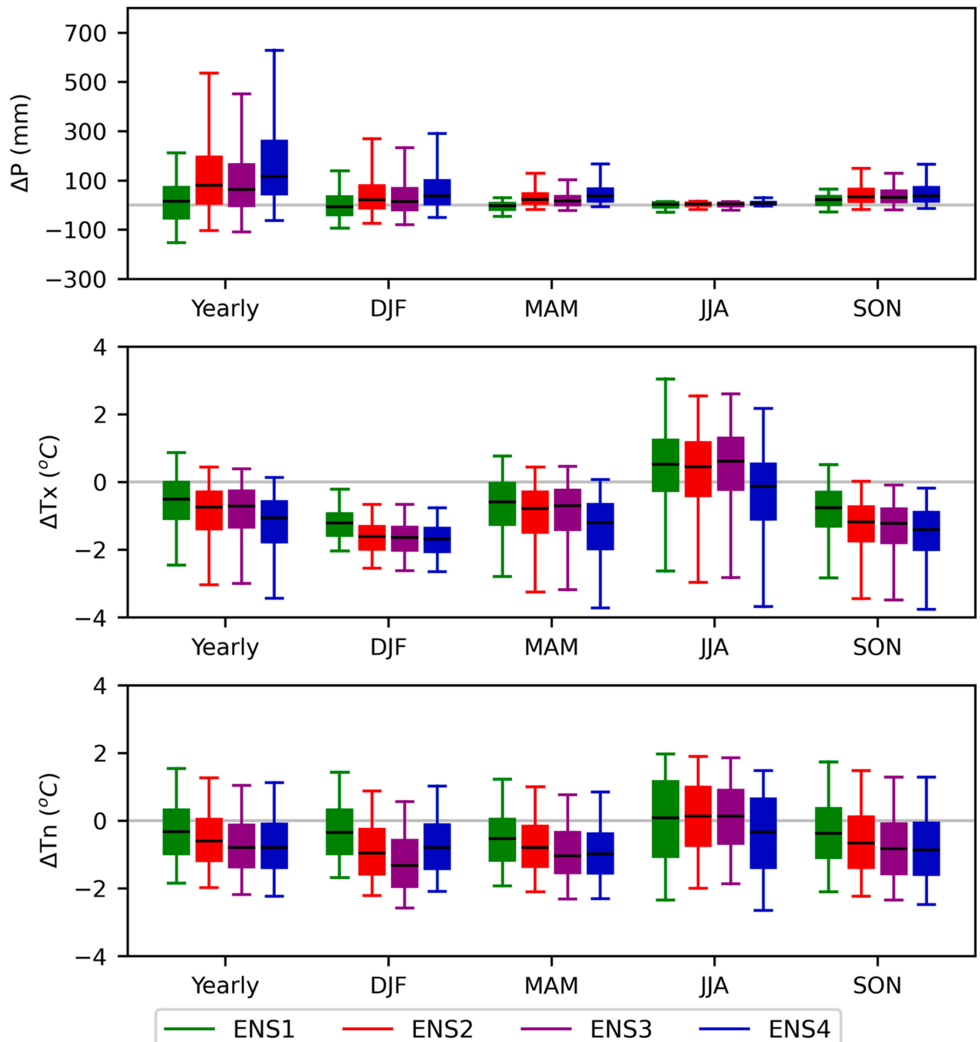


**Fig. 3.** Differences of yearly and seasonal mean precipitation (top), maximum temperature (middle) and minimum temperature (bottom) between EURO-CORDEX multi-model ensembles (ENS1 to ENS4) and the IB-01.

Portugal during 2011–2040 (only statistical significance for RCP8.5 in northeastern region), followed by a widespread decrease towards the end of the 21st century for RCP4.5 and RCP8.5, peaking below −30 % and −40 %, respectively. Summer (JJA) and autumn (SON) seasons are marked by consistent projected decreases for all periods and scenarios, peaking below −50 % for the RCP8.5 during summer. Finally, most ensemble members present statistical significance changes. Exceptions are visible for all scenarios, particularly for the begging of the century. Note that, for these instances, the expected changes in the mean total precipitation are mostly between −10 % and +10 %.

The projected changes for the annual mean daily maximum temperature (Fig. 5) show, in general, an eastward increasing pattern of projected changes, which are of relatively homogeneous magnitude for the 2011–2040 period for all emission scenarios, ranging between +1 °C and +2 °C, over most of Portugal, except for slightly lower values (below +1 °C) in the coastal regions for RCP4.5 and RCP2.6. Similar patterns but of rather different magnitudes are the projected increases observable among scenarios throughout the remaining of the twenty-first century, exceeding +5 °C during 2071–2100 for RCP8.5 over north-eastern Portugal, remaining, however, mostly below +2 °C for RCP2.6. Seasonally, it is during the local summer (JJA) that the greatest projected increases in maximum temperature occur, especially by the end of the 21st century, under RCP8.5, over north-eastern Portugal, surpassing +6 °C. During winter (DJF), projected increases for the maximum temperature are also present, for all periods and scenarios, particularly for 2071–2100, ranging between +3 °C and +4 °C over most of the country. The averaged values of projected changes in mean daily maximum temperature averaged over the entire year for NUTS2 are presented in Table S5 in Supplementary Material.

The projected changes for the annual mean daily minimum temperature (Fig. 6) show, overall, similar patterns to the ones found for the maximum temperature. During 2011–2040, relatively homogeneous projected increases are visible for all emission scenarios, ranging between +1 °C and +2 °C over most of Portugal. Throughout the 21st century, increasing differences between scenarios emerge, with the projections exceeding +4 °C by 2071–2100 for RCP8.5 over most of the country, but remaining mostly below +2 °C for RCP2.6 and +3 °C for RCP4.5. The maximum projected increases for minimum temperature are, however, approximately 1 °C lower than those from the maximum temperature. As before, seasonally, the minimum temperature projections display maximum values during JJA and SON, especially over north-eastern Portugal, exceeding +5 °C, and minimum values during DJF and MAM, generalized throughout the country, and ranging between +3 °C and +4 °C, both under RCP8.5. The averaged values of projected changes in mean daily minimum temperature averaged over the entire year for NUTS2 are presented in Table S6 in Supplementary Material.

The EURO-CORDEX multi-model ensemble future projections for

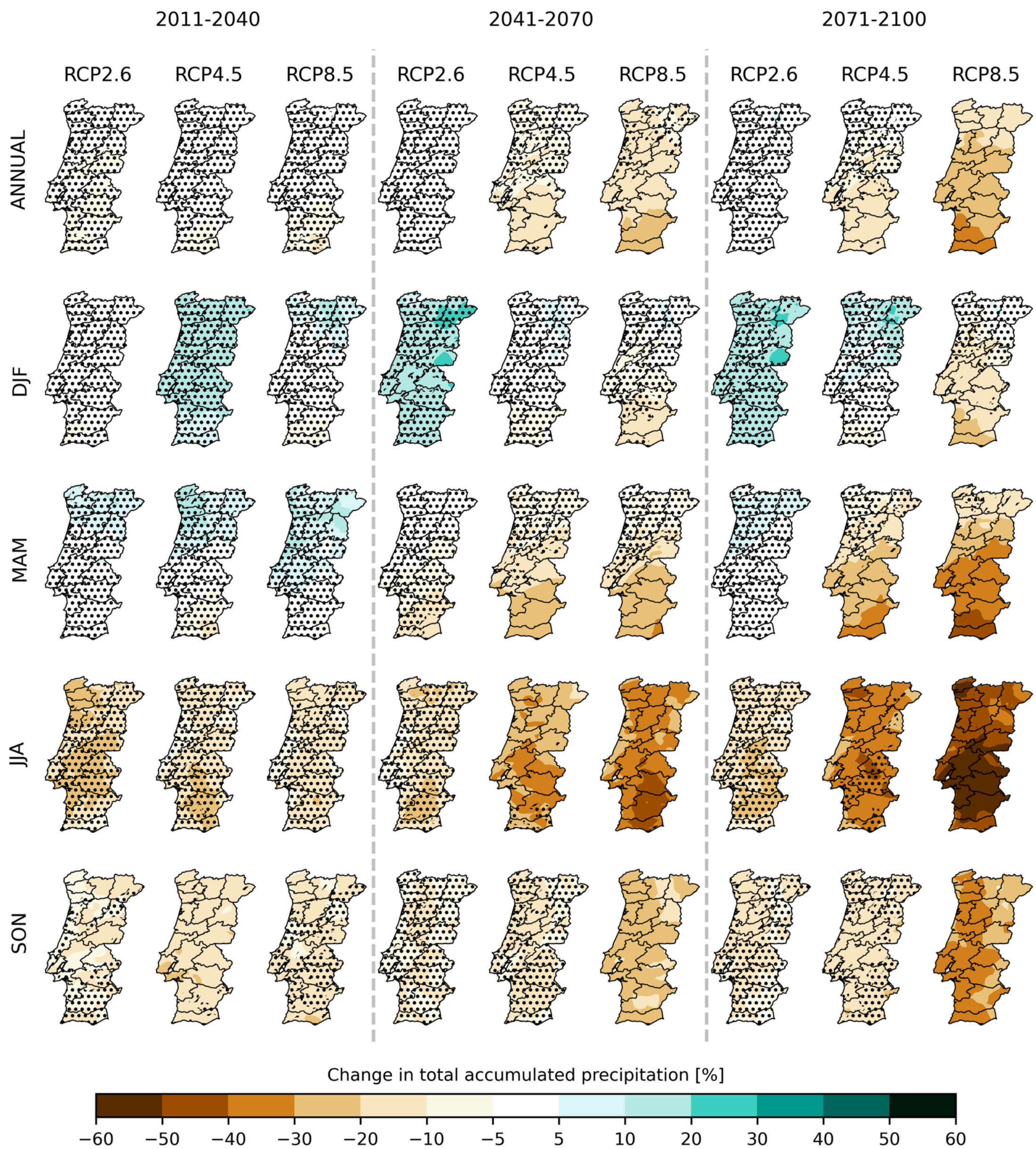


**Fig. 4.** Future projected changes in total accumulated precipitation over mainland Portugal, given as percentual change considering the 1971–2000 period as reference. The different rows from top to bottom represent averaged taken over all months, DJF, MAM, JJA and SON respectively. The different columns represent the future periods considering different GHG emission scenarios. Grid-points where the precipitation does not specify changes statistically significant are identified by dotted hatching.

mean wind speed at 10 m show small changes throughout all seasons (Fig. 7). At the annual scale, detectable projected changes are only visible for the 2071–2100 period under RCP8.5, for which a projected decrease in wind speed is visible, especially across north-western Portugal, but below −0.2 m/s. Seasonally, it can be observed that the largest changes are found during winter and autumn for the end of the 21st century, under the RCP8.5 scenario, with projected decreases in wind speed reaching −0.6 m/s. During summer, a projected increase in wind speed is found throughout central Portugal, especially over the A. M. Lisboa (before 2070), with an increase in the intensity and expansion area after 2071, comprising the Alentejo region and north-eastern Portugal, visible under both RCP4.5 and RCP8.5 scenarios, and reaching +0.4 m/s. Under RCP2.6, most of future projections of wind speed are close to zero, except for the autumn season where a small decrease is found over Portugal for the mid and end of the 21st century (−0.2 m/s). The lack of agreement in the signal of the anomalies and in statistically significant changes under all scenarios is merely a reflection of the near-zero magnitude changes in some of the grid points.

*Changes in extremes*

The return levels associated with the 10-, 30-, 50-, and 100-year return periods for daily accumulated precipitation, maximum temperature and maximum wind gust are displayed in Figs. 8, 9 and 11, respectively, for the five sub-regions of mainland Portugal (NUTS2). The return levels tend to increase when considering a higher return period, and there is a sub-regional variability. Note that the results for the 50- and 100-year events need to be carefully analysed, considering the limitations of computing such return levels using a 30-year time-slice, which increase the uncertainty in both results.

Norte is the region with higher return levels for precipitation, but also with larger spread between the models. For the historical period, a return level of 100 mm (220 mm) of daily rainfall is expected to occur every 10 (100) years. For the A.M. Lisboa, the return levels are less discrepant between return periods: between 70 mm and 100 mm in a

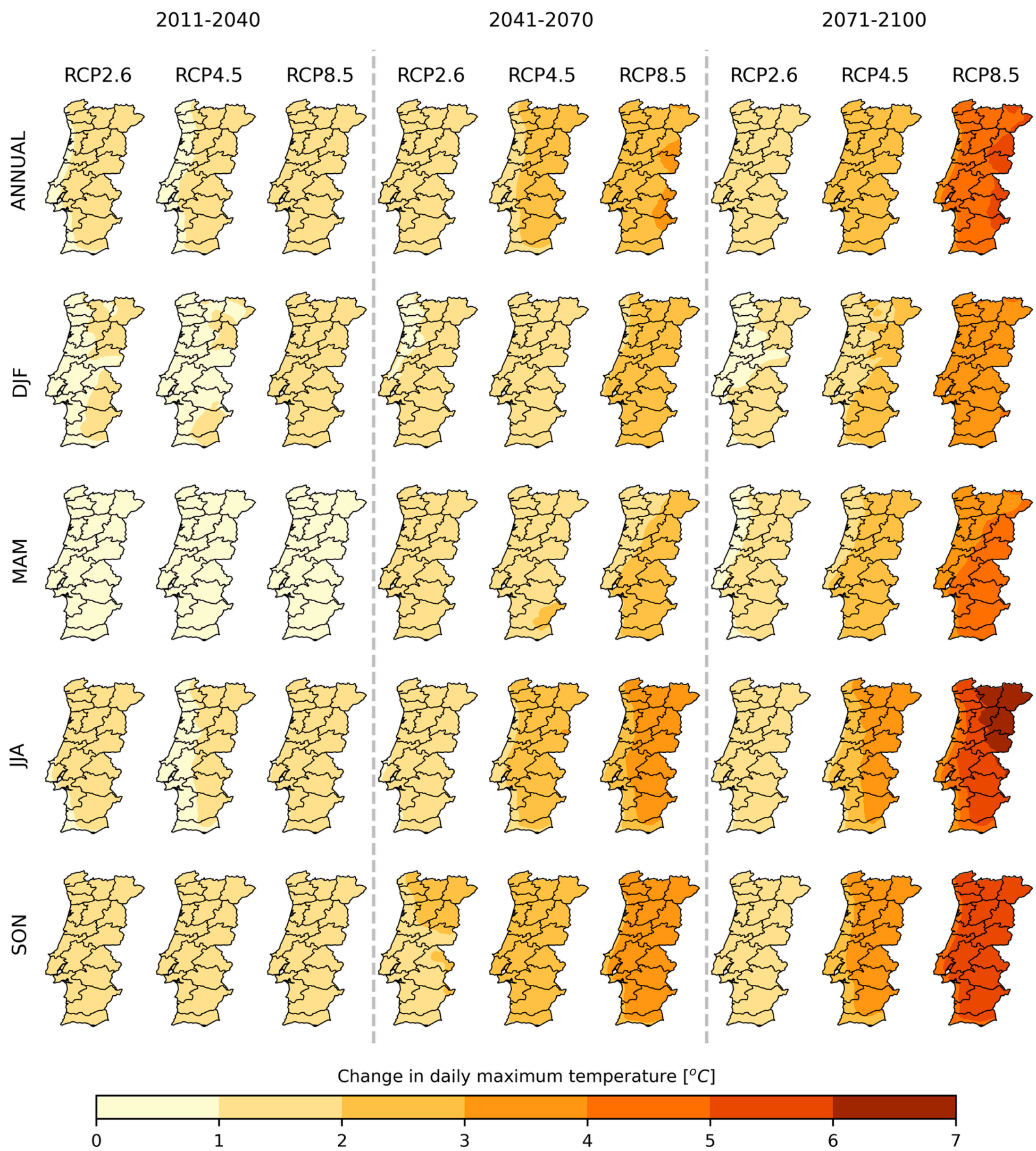


**Fig. 5.** Future projected changes in daily maximum temperature over mainland Portugal, considering the 1971–2000 period as reference. The different rows from top to bottom represent averaged taken over all months, DJF, MAM, JJA and SON respectively. The different columns represent the future periods considering different GHG emission scenarios. Grid-points where the temperature does not specify changes statistically significant is identified by dotted hatching (no occurrences for Tx).

day for 10 and 100 years, respectively. Overall, there is a projected increase in the return levels throughout the 21st century, although the reduction of the annual mean precipitation. During 2071–2100, and assuming the worst-case scenario (RCP8.5), it is expected that every 10 years an extreme precipitation event will increase to 150 mm in a day in the Norte area and increasing to 260 mm every 100 years. For the remaining regions, an increase is also expected, however, the return levels for the 100-year return period remain below 200 mm in a day. The projections for the RCP2.6 and RCP4.5 are closer to the ones for RCP8.5 but with slightly lower return levels.

For the historical period, the return levels of maximum temperature are spatially less discrepant between the return periods, with differences of 2–3 °C between them, and with lower uncertainty among models. The A.M. Lisboa and Alentejo are the regions with higher return levels, between 42 °C and 45 °C in a day. For the beginning of the century, there is a slight increase in the return values in all regions. However, the differences are low between the RCPs. From the mid- to end-of-century, there is an increase in the return levels, strongest for the emission scenario without mitigation. Assuming the RCP8.5 during 2071–2100, it is expected that every 10 years an extreme value of maximum temperature of 49 °C (48 °C) occurs in the Alentejo (A.M. Lisboa) area, increasing to 51 °C (50.5 °C) every 100 years. For the remaining regions, it is projected that the return levels increase throughout the 21st century, 30-year return levels close (remaining regions) or higher (Alentejo) than 50 °C.

Winter storms are generally the cause of extreme wind gusts in mainland Portugal. For the historical period, the maximum values are found in the mountainous northwestern regions, peaking at 38 m/s (Fig. 10a). Along the west and south coastal regions, maximum wind gusts of 34 m/s are visible. In the interior regions, however, the maximum values do not exceed 30 m/s. For future scenarios and periods, the overall pattern is similar to the historical one, however, there are small changes for all periods and scenarios (Fig. 10b). For the beginning of the century, all RCPs agree to an increase of maximum

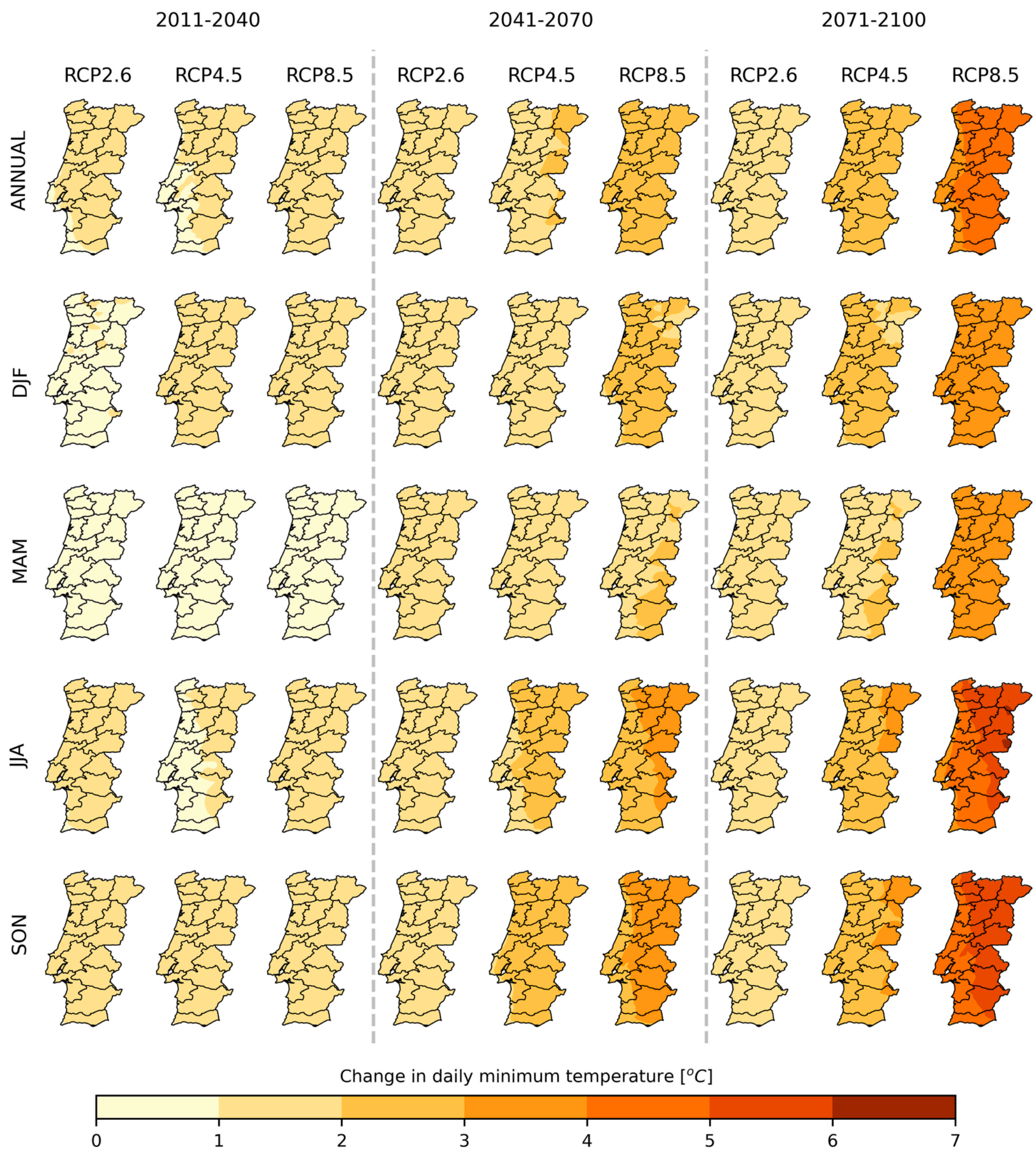


**Fig. 6.** Future projected changes in daily minimum temperature over mainland Portugal, considering the 1971–2000 period as reference. The different rows from top to bottom represent averaged taken over all months, DJF, MAM, JJA and SON respectively. The different columns represent the future periods considering different GHG emission scenarios. Grid-points where the temperature does not specify changes statistically significant is identified by dotted hatching (no occurrences for Tn).

wind gust in the A.M. Lisbon area greater than +2 m/s, without statistical significance. For mid- and end-of-century, the RCP2.6 projects an increase in the maximum wind gust value, with statistically significant changes in most of the country. For RCP4.5 and RCP8.5, during 2041–2070, a reduction in maximum wind gust is expected in most of the country, however without statistical significance in some grid points. In the northwestern regions, however, an increase is projected, greater than 1 m/s. For 2071–2100, under RCP4.5, an increase in maximum wind gust is expected for both the northwestern and southern regions, with statistical significance in this region. Regarding the RCP8.5, decreases (increases) in maximum wind gust are expected south (north) of Tagus River. As for precipitation, the Norte is the region where the return levels of maximum wind gust are higher (Fig. 11), followed by the A.M. Lisboa, where a maximum value of 31 m/s and 30 m/s (35.5 m/s and 34 m/s) in a day occurs every 10 (100) years during the historical period. The future projections point to a general slight reduction in the return level for each return period considered. For 2071–2100 and for all the return periods, the RCP8.5 scenario displays slightly lower return levels when compared to the other two future scenarios, noticeable especially in the South area. The projections from RCP2.6 and RCP4.5 emission scenarios are relatively similar, with projected increases (decreases) mainly in the A.M. Lisboa and Centro (remaining) regions.

## Discussion

In the present study, a weighted ensemble of EURO-CORDEX high resolution regional climate simulations is used to assess the climate change signal on the main climate variables and extremes, considered relevant for stakeholders and policymakers. Three different future time periods were considered (2011–2040, 2041–2070 and 2071–2100) according to RCP2.6, RCP4.5 and RCP8.5 scenarios. Firstly, the original 45 simulations for the historical period (1971–2000) were evaluated against the IB-01 reference dataset.

The ability of EURO-CORDEX RCMs to reproduce the historical

 

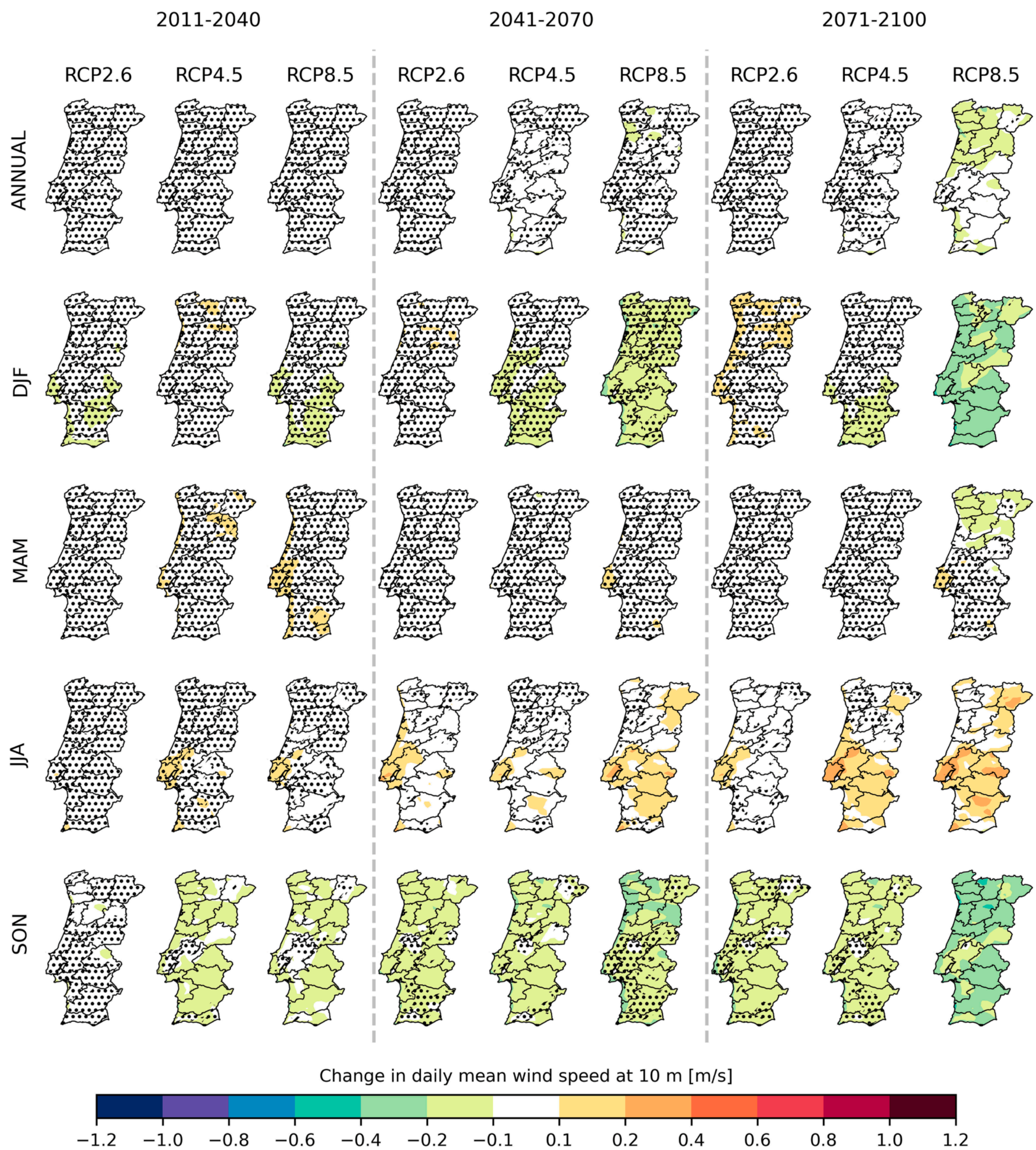


**Fig. 7.** Future projected changes in daily mean wind speed at 10 m over mainland Portugal, considering the 1971–2000 period as reference. The different rows from top to bottom represent averaged taken over all months, DJF, MAM, JJA and SON respectively. The different columns represent the future periods considering different GHG emission scenarios. Grid-points where the daily mean wind speed at 10 m does not specify changes statistically significant is identified by dotted hatching.

precipitation and temperature climates was extensively validated over Europe (Katragkou et al., 2015; Kotlarski et al., 2014) and Portugal (Cardoso et al., 2019; Soares et al., 2017a), revealing good agreement with the observations. The present evaluation results for precipitation showed that most models were able to simulate historical climate patterns. However, models tended to overestimate precipitation, with only 22 % (10) of the models showing an underestimation. Regarding maximum temperature, 93 % (42) of the simulations presented a cold bias, which in some cases could be linked to the forcing GCM (IPCC, 2013). This was not the case for minimum temperature, where one-third of the models depicted a warm bias. Even so, the simulations were able to represent both maximum and minimum temperature patterns in the historical climate. Furthermore, results revealed that the same model have different performances when simulating these variables.

Previous works have evidenced that different members of large multi-model ensembles are characterized by different performances in simulating given variables (Knutti et al., 2017; Nogueira et al., 2019; Sanderson et al., 2017). Additionally, these studies have shown that model accuracy also depends on the region, variable, season, among other factors. Also, it is common for several models within large multi-model ensembles to share components (sometimes being different versions of the same model), thus not being truly independent (Abramowitz and Bishop, 2015; Bishop and Abramowitz, 2013; Sanderson et al., 2017, 2015). These issues raise doubts on the often assumed 'model democracy' (one model one vote), where each model contributes equally to the ensemble average. Indeed, this method has been argued to be suboptimal (Eyring et al., 2019). Our recent works showed the added value of using a ranked average model weighting ensemble when compared to 'model democracy' (Cardoso et al., 2019; Nogueira et al., 2019; Soares et al., 2017a,b). However, in these studies, the weighted ensemble was only dependent on the performance of the variable analysed.

Here, we constructed four different multi-model ensembles for a set of 13 RCMs (the ones ranging through all RCPs considered), based on the

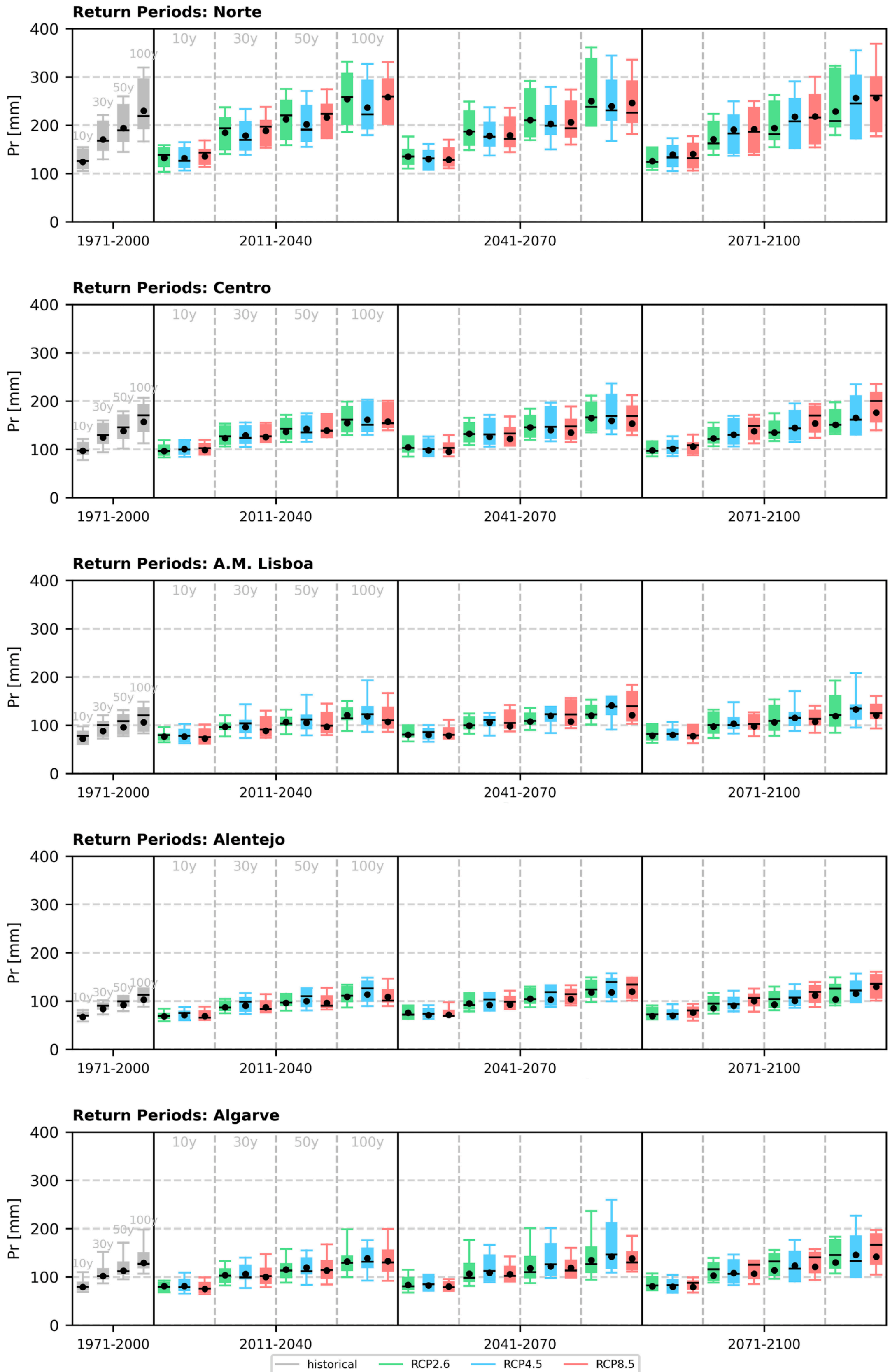


**Fig. 8.** Return levels associated with 10-, 30-, 50-, and 100-years events for daily precipitation for NUTS II regions: Norte, Centro, A.M. Lisboa, Alentejo and Algarve, from top to bottom. Three future periods are shown: 2011–2040, 2041–2070, and 2071–2100, under all emission scenarios – RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red), with historical period (grey) for 1971–2000 period. The black point represents the multi-model ensemble mean. Individual boxes span from the 25th to the 75th percentile, with the median represented by a straight line, and the whiskers span from 10th to the 90th percentile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

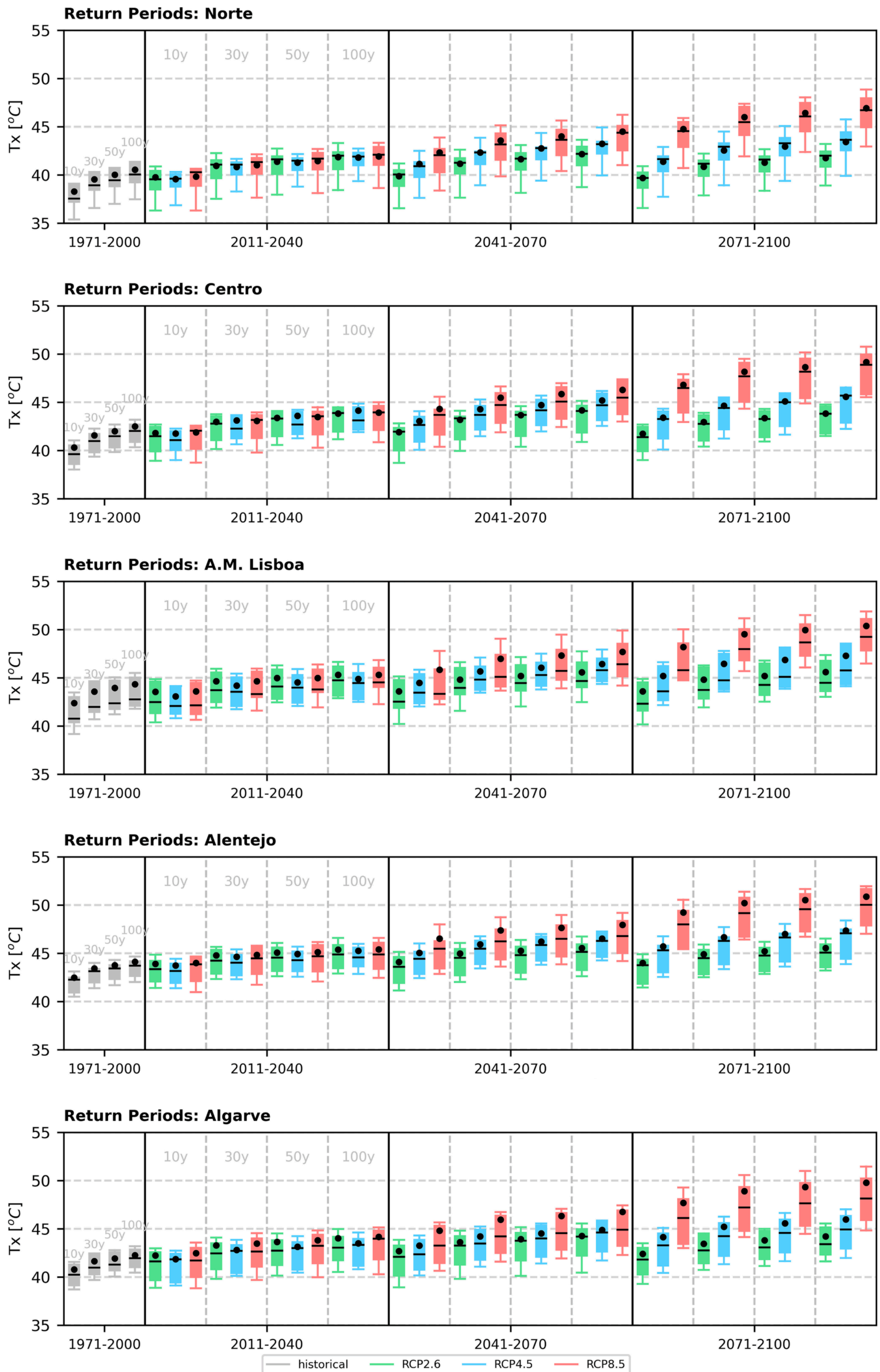


**Fig. 9.** Return levels associated with 10-, 30-, 50-, and 100-years events for daily 2-m maximum temperature for NUTS II regions: Norte, Centro, A.M. Lisboa, Alentejo and Algarve, from top to bottom. Three future periods are shown: 2011–2040, 2041–2070, and 2071–2100, under all emission scenarios – RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red), with historical period (grey) for 1971–2000 period. The black point represents the multi-model ensemble mean. Individual boxes span from the 25th to the 75th percentile, with the median represented by a straight line, and the whiskers span from 10th to the 90th percentile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

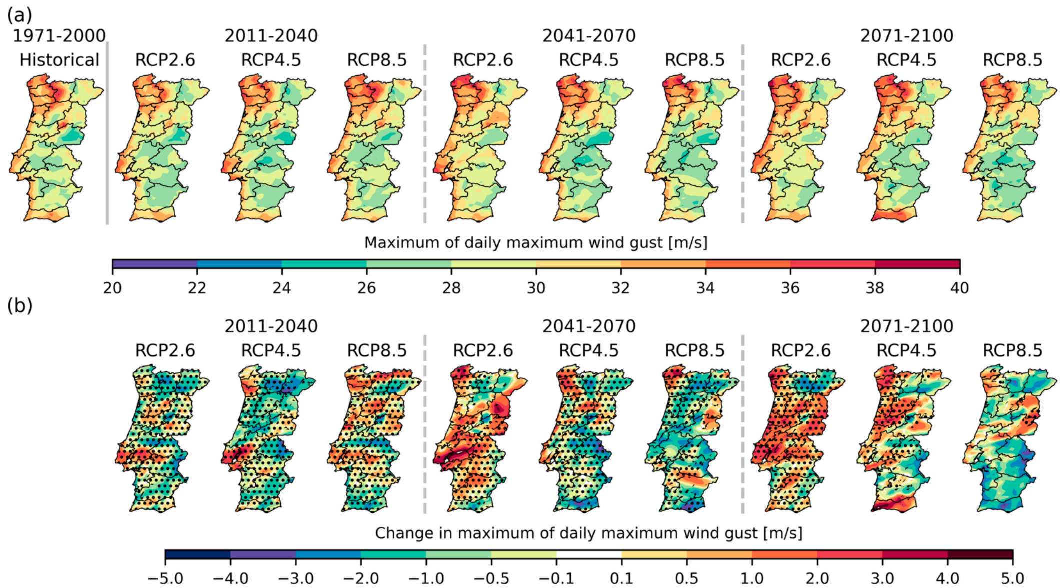


**Fig. 10.** (a) Maximum of daily maximum wind gust for historical period (1971–2000) and for the future periods considering different GHG emission scenarios. (b) Future projected changes in maximum of daily maximum wind gust over mainland Portugal, considering the 1971–2000 period as reference. Grid-points where the daily maximum wind gust does not specify changes statistically significant is identified by dotted hatching.

ranking of the models for precipitation and temperature (both maximum and minimum values). ENS1 was an ensemble produced for each variable based on its overall model performance weights; ENS2 and ENS3 were constructed based on a joint weighting of the three evaluated variables; and in ENS4 the weights were equal for all models ("model democracy"). In fact, ENS4 showed an overall worst performance when compared with the weighted ensembles. ENS1 showed the best performance for each variable. However, it was not considered since it is weighted for each variable individually, leading to potential inconsistencies in climate change assessment. The multi-variable ENS3 showed the best performance for precipitation and maximum temperature, whilst for minimum temperature ENS2 and ENS3 presented similar results. A multi-variable ensemble may be a better choice than a simple multi-model ensemble, since it is not only dependent on the model ability to simulate one variable, but on the performance of a set of variables, avoiding error compensation (García-Díez et al., 2015). Moreover, it was shown that temperature and precipitation are strongly correlated at long timescales (Nogueira, 2019). In this sense, we opted for the multi-variable ENS3 as the baseline for assessing future climate change projections. This multi-variable multi-model approach is crucial to preserve the physical consistency among the sectorial modelling since impact models are dependent on climate information from more than one variable.

The results presented in this study are obtained from the "raw" version of ENS3, in the sense that no further calibration of bias correction methods was employed, despite being common practice in recent studies (Applequist, 2012; Lemos et al., 2020; Li et al., 2010; Maraun, 2016; Terink et al., 2009). Our reasoning includes the fact that the reference dataset (IB-01) does not contain wind speed data, necessary for an homogeneous correction through all the variables. The alternative would be to consider an additional reference dataset to correct the wind speeds, however, this solution could lead to undesired inconsistencies between the variables. Furthermore, applying bias correction to the ensemble's future projections based on the same reference dataset has been shown to impact their associated robustness negatively, by reducing the naturally arising uncertainty between ensemble members (forced by different GCMs; (Ayar et al., 2021; Ehret et al., 2012; Maraun et al., 2017)). Finally, the ensemble weighting approach proposed in this study led to a better performance of the three main variables (precipitation and maximum and minimum temperatures), in comparison with IB-01 data during present climate. Although different from bias correction, it effectively reduced the original biases (considering the unweighted 13 simulations), keeping a good representation of the ensemble uncertainty, essential for an accurate assessment on the statistical significance of the future projections.

The projected warming and drying trends over Portugal were shown to be stronger for high anthropogenic emission scenarios, confirming the importance of the human component on the overall climate change projections when compared to the natural variability of the climate system, even at the regional scale (Barcikowska et al., 2018; Cramer et al., 2018). The goal of the Paris Agreement is to limit the global temperature increase to 1.5 °C relative to pre-industrial levels, while pursuing efforts to avoid the 2 °C warming threshold. Nonetheless, even in a 2 °C global warming scenario, a critical environmental situation will develop, related to the enhanced warming of land areas in summer and widespread reduction of precipitation, especially over the Mediterranean region. It was shown that, even for the optimistic scenario of strong mitigation (RCP2.6), Portugal is projected to experience an average warming between 1 °C and 2 °C, relative to the historical period. On the other hand, for the scenario without mitigation, *i.e.*, RCP8.5, a generalized warming over 6 °C is projected until the end of the 21st century. Temperature is projected to increase through all seasons and regions in Portugal during the 21st century, with a greater warming during summer (Cardoso et al., 2019), increasing the land-sea thermal contrast. In fact, the projected intensification of the Azores anticyclone and its expansion to northeast due to the northward expansion of the Hadley Cell (Kang and Lu, 2012; Miyasaka and Nakamura, 2005), together with the strengthening of the Iberian thermal low, forces more intense and frequent summer winds parallel to the coast, especially in the north of the Iberian Peninsula, which influences the north of Portugal (Cardoso et al., 2016; Soares et al., 2017b,c). In general, projections of maximum temperature were shown to have a slightly larger magnitude than those of minimum temperature, consistent with a slender amplification of the daily temperature range.

The frequency and intensity of extreme hot events was also shown to be projected to change considerably through most of the territory, evident even for 2011–2040, especially in the South region. In fact, the 100-year return levels during historical climate are generally exceeded by the projected 10-year return levels from 2041 to 2070 onwards. Moreover, the intensity of hot extremes is projected to increase for

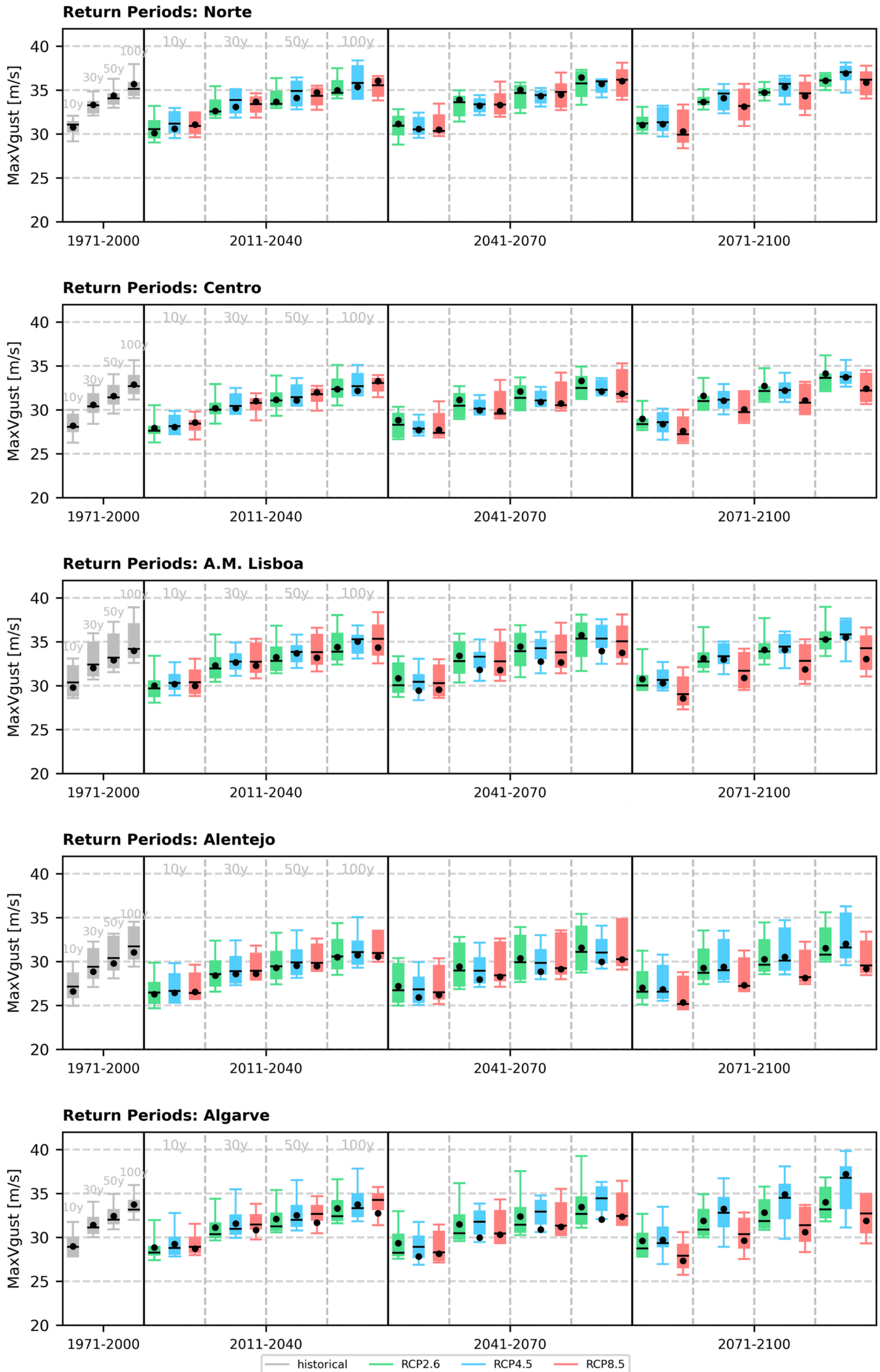


**Fig. 11.** Return levels associated with 10-, 30-, 50-, and 100-years events for maximum of daily maximum wind gusts for NUTS II regions: Norte, Centro, A.M. Lisboa, Alentejo and Algarve, from top to bottom. Three future periods are shown: 2011–2040, 2041–2070, and 2071–2100, under all emission scenarios – RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red), with historical period (grey) for 1971–2000 period. The black point represents the multi-model ensemble mean. Individual boxes span from the 25th to the 75th percentile, with the median represented by a straight line, and the whiskers span from 10th to the 90th percentile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

future events. Due to the expansion of the Azores high and/or its larger persistency in higher latitudes in winter, weather regimes that produce precipitation events are expected to reduce (Bengtsson et al., 2009), and the strengthening of pressure and temperatures gradients may increase the advection of warmer continental air. On the other hand, the increase of pressure gradient along the coast may intensify the across-shore winds limiting the advection of moist air inland, which may explain the reduction of precipitation projected for intermediate and summer seasons. Although summer precipitation does not have a significant contribution for the annual total due to its lower values, relative changes above 40 % are expected during 2071–2100. Warming and drying conditions may cause a decline in the relative humidity, and consequently an increase in potential evapotranspiration.

Such projected conditions are compatible with an increase in the frequency of occurrence of hazards driven by hydro-meteorological variability, such as droughts, heatwaves, and wildfires, severely impacting agriculture, forests, and water availability. Subsequently, the impacts on sectoral climate indices will be addressed in Part II.

The northward shift of the storm track over the north Atlantic – due to the northward expansion of the Haddley Cell – is also a known consequence of climate change, which leads to a reduction of wind speed and precipitation in Portugal (Bengtsson et al., 2006; Harvey et al., 2014; Kang and Lu, 2012; Ulbrich et al., 2008). In fact, the largest reductions of 10-m wind speeds are found in winter and autumn seasons over elevated terrain in northern and central-eastern regions, and over the southwestern coastal regions for the end of the 21st century. Precipitation changes depend on the season, region, and the emission scenario. The highly- (non-) mitigated emission scenario projections were shown to point to a moister (drier) winter. Although an overall decrease in the accumulated precipitation is expected, an intensification of heavy, short-term precipitation events is projected, especially over the northern region, which is in agreement with Soares et al. (2017a). In fact, although a reduction of stormy weather across Portugal is an expected reality, the intensity of individual storms may increase, originating not only concentrated precipitation events, but also increases in the maximum wind gusts in several areas of the country (Bengtsson et al., 2009).

## Final remarks

The projections in this study are based on the latest generation of climate models, a larger number of high-resolution simulations, an improvement in methods and a cardinal aim of building a climate change services dataset for sectoral impact modelling. Overall, the climate change projections presented here confirm the previous findings in other studies but importantly, the results are provided for three future RCP emission scenarios. In this way, paving the way to reflect the recent mitigation, social and technological trends, ensuring consistency among global climate assessments and offering baseline information for impact assessment and diverse adaptation needs. Additional variables and a more detailed assessment of climate extremes and indices is provided in Part II, in a regional, sectorial-directed assessment, easily translated into essential data for decision-makers. Incorporated in the RNA2100 project, the present study provides the most accurate, up-to-date, and coherent climate information available to support the assessment of climate change impacts and decision-making regarding adaptation and mitigation in Portugal, translating it into the storylines and exploiting climate indices for different sectors.

Future climate projections are subject to uncertainties, being its assessment more challenging for climate extremes and especially at regional scales, due to the influence of increased natural climate variability. Improvements on global and regional ESMs have been continuous in the last decades, and the recent phase 6 of the CMIP is expected to promote a further step ahead on the understanding of climate and future associated changes, with emphasis on the regional and local scales.

## CRediT authorship contribution statement

**Daniela C.A. Lima:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Gil Lemos:** Formal analysis, Writing – review & editing. **Virgílio A. Bento:** Writing – review & editing. **Miguel Nogueira:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Pedro M.M. Soares:** Conceptualization, Writing – review & editing, Supervision, Project administration.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2023.100351.

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