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Water scarcity down to earth surface in a Mediterranean climate: The extreme future of soil moisture in Portugal

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ABSTRACT

Climate change constitutes a major threat for all the Mediterranean countries due to the combination of large precipitation reductions and temperature increases and the higher frequency of climate extremes, especially driving water scarcity and all the derived multi-sectoral impacts. Portugal, as most of the Mediterranean countries, already endures larger frequencies of droughts and deficits in soil moisture and water storage. In the current study, the future projections of soil moisture are examined using a multi-model EURO-CORDEX regional climate ensemble, in agreement with three future emission scenarios (RCP2.6, 4.5 and 8.5). The drivers of future soil moisture dynamics are also analysed and its effect on relative humidity and evaporation rates. As expected, the projections show a clear reduction of soil moisture through the entire annual cycle, in response to the large decrease in precipitation and temperature increase, via a massive growth of potential evapotranspiration. The overall total soil moisture decreases ranges from −5% for the RCP2.6 to −20% (-10%) for the RCP8.5 (RCP4.5), w.r.t. the present climate. In the historical period, soil moisture deficits rarely reach values 3x over the standard deviation, but projections reveal that for the RCP4.5 (RCP8.5) for the mid-century deficits up to 5x (6x) are projected to occur, and for the end-of-century even 7x for the RCP8.5. The annual cycle of soil moisture is in present and future climate determined by precipitation and potential evapotranspiration, and deficit is both enhanced and covers a wider monthly window in the future, especially for the RCP8.5. The surface humidity also decreases importantly, up to −4% and −8% in spring and summer in the end-of-the-century, in agreement with RCP4.5 and RCP8.5, respectively. Resulting from the projected changes in precipitation and potential evapotranspiration, the typical semi-arid climate, which in present climate is confined to a small south-eastern region of Portugal, is expected to cover almost 2/3 of the mainland in the case of RCP8.5. Finally, this study was developed in the framework of the National Roadmap for Adaptation XXI - Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century (RNA2100) project and aims at delivering a deeper and different featuring of terrestrial water for adaptation purposes in a Mediterranean country.

1. Introduction

Portugal, in the western Iberia, is considered a climate change hotspot, in a great extent due to the known projections of large temperature increases and reduction of precipitation (Cardoso et al., 2019; Lionello et al., 2014; Soares et al., 2017a; Turco et al., 2015), of the linked drought larger frequencies and severity (Hoerling et al., 2012; Spinoni et al., 2017) and impacts on water, agriculture, forest and other sectors.

The Portuguese mainland is characterized by large climate gradients associated with its location and geomorphological complexity - located in southwestern Europe, facing the North Atlantic, in the transition between the sub-tropical anticyclone and the subpolar storm tracking areas. This geographical setting, its orography and the land–ocean thermal contrast defines large gradients of temperature and precipitation: mean maximum temperatures peak at 35 °C in the southeast and 24 °C in the northwest (Soares et al., 2012); this latter region is one of the wettest areas in Europe, with recorded mean annual accumulated precipitation more than 3,000 mm, and in the SE barely surpassing 400 mm (Soares et al., 2012). These climate gradients also have associated a large interannual variability, the occurrence of drought and desertification (Páscoa et al., 2020), and, in fact, the Portuguese mainland climate spans from humid cold in the north to semi-arid in the southeast.

Future projections for the Portuguese climate are extremely worrying, revealing widespread large temperature increases and

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precipitation reductions, namely, summer maximum temperature increase up to 7 °C inland and −40% of annual precipitation decrease in the southern areas (Cardoso et al., 2019; Soares et al., 2017a). Subsequently, large increases of extremes, as heatwaves, consecutive dry days, aridity and drought frequency and severity are projected (Miralles et al., 2019; Molina et al., 2020; Spinoni et al., 2018; Tramblay et al., 2020; Vicente-Serrano et al., 2014). The latter have been assessed in a few studies based on drought indices, such as PDSI (Palmer Drought Severity Index), SPI (Standardized Precipitation Index) and SPEI (Standardized Precipitation Evapotranspiration Index).

Soil moisture is a key hydrologic state variable driving the exchange of water and heat energy between the land surface and the atmosphere (Berg et al., 2017; Brocca et al., 2012; McColl et al., 2017; Miralles et al., 2014), through evaporation and plant transpiration, regulating surface temperature, humidity and potentially affect precipitation, though recycling processes (Eltahir, 1998; Ford et al., 2018; Miralles et al., 2012; Rios-Entenza et al., 2014). Soil moisture constitutes a fundamental element of the surface water budget, determining the health or stress on land surface ecosystems and managed systems such as those in agriculture and agroforest (Chen et al., 2014; Miralles et al., 2019). The surface water budget, and therefore the soil moisture, depends on precipitation, plus irrigation when present, soil infiltration, surface runoff, baseflow, and evapotranspiration (Rockström et al., 2010; Seneviratne et al., 2010). Furthermore, soil moisture-based indices are used as indicators of agricultural droughts (Watson et al., 2022), and soil moisture drought is one of the preconditioning effects for the development of extreme temperatures following the onset controlled by atmospheric dynamics (Hirschi et al., 2014; Humphrey et al., 2021; Seneviratne et al., 2006; Yin et al., 2014). Finally, soil moisture is acknowledged as an Essential Climate Variable by the Global Climate Observing System (Albergel et al., 2013; Zhang et al., 2019).

Global climate models (GCMs), or the new generation Earth System Models (ESMs), and Regional Climate Models (RCMs) are the state-of-the-art tools to understand the future climate in response to external forcings as the anthropogenic greenhouse gas emissions and land-use changes (IPCC, 2021, 2013). GCMs and ESMs represent the large-scale processes in a suitable way but fail to capture local to regional fundamental processes due to the coarse resolution often used and to shortcomings in the parametrization schemes, in particular linked to convection and clouds (Randall et al., 2007). RCMs or limited area models, focusing in smaller areas use much finer resolutions representing in an improved way local to regional processes, such as the land–atmosphere interactions and orographic and thermal circulations (Cardoso et al., 2019; Giorgi and Mearns, 1999; McGregor, 1997; Rummukainen, 2010; Soares et al., 2017b, Soares et al., 2017a). Climate models simulate in a physical consistent way the climate system processes and in particular the water hydrologic cycle (Di Luca et al., 2012; Feser et al., 2011; Rummukainen, 2010; Soares and Cardoso, 2018). Recent studies reveal that PDSI, SPI and SPEI metrics often overestimate future increases in drought and decreases in water availability (Milly and Dunne, 2016; Roderick et al., 2015; Swann et al., 2016). Consequently, projections of future aridity should be grounded on direct model output of the land water balance (precipitation, evapotranspiration, runoff, and soil moisture) instead of based on offline aridity and drought indices (Berg et al., 2017; Swann et al., 2016). Furthermore, soil moisture constitutes a key information to define adaptation strategies aiming at decreasing damage due to rainfall reductions and warming and determine methods of optimization the management of natural ecosystems in the context of climate change.

The Coordinated Regional Climate Downscaling Experiment (CORDEX) has the main goal of developing many RCM simulations to ensure an ensemble of high-resolution projections throughout the 21st century for all regions of the world, to support climate change impact and adaptation research. The RCM simulations produced within EURO-CORDEX (an European branch of CORDEX) provides regional climate projections for Europe at a horizontal grid resolution of about 12 km, obtained by dynamically downscaling the GCMs from CMIP5 using a set of RCMs. The EURO-CORDEX simulations constitutes the most valuable dataset for assessing future climate change in Europe, and therefore in Portugal. Many studies were performed evaluating EURO-CORDEX results over the full continent (Katragkou et al., 2015; Kotlarski et al., 2014), specifically focusing on soil moisture and land–atmosphere coupling (Knist et al., 2017) and assessing the added value of RCMs for precipitation and temperature (Cardoso and Soares, 2022; Soares and Cardoso, 2018). Knist et al. (2017) revealed an overall good performance of EURO-CORDEX runs in simulating the soil moisture interannual variability, whilst Soares and Cardoso (2018) and Cardoso and Soares (2022) reported the significant added value in the description of precipitation and temperature patterns over the European domain, especially for extremes. Focusing in Iberia, (Herrera et al., 2020) evaluated extensively the EURO-CORDEX evaluation runs and recently (Careto et al., 2022a, 2022b) also quantified the added value of EURO-CORDEX RCMs for Iberia regarding temperatures and precipitation. Important gains in the representation of precipitation and temperature patterns and particularly in extremes over the Iberian Peninsula were identified by Careto et al. (2022a, 2022b). For Portugal mainland EURO-CORDEX models were also extensively evaluated and used to project the future precipitation (Soares et al., 2017a), temperatures (Cardoso et al., 2019) and wind resources (Nogueira et al., 2019), based on the building of multi-model ensembles and also depicting uncertainty. The future evolution of surface soil moisture and aridity evolutions were still not addressed and have not been deeply examined for Portugal to the best of our knowledge.

The present study takes advantage of the large EURO-CORDEX regional climate modelling database to project the future evolution of soil moisture and aridity in Portugal and its main drivers. EURO-CORDEX, forced by CMIP5 models, is considered the best modelling portrayal of the regional climate evolution across Europe for the twenty-first century atmosphere, in agreement with the Representative Concentration Pathways (RCPs) emission scenarios. Specifically, our main goals are: 1) characterize the pattern of soil moisture in Portugal in present climate; 2) depict the RCM future projections for soil moisture and aridity; 3) to portray the main drivers associated with such a future evolution. These questions are addressed in the framework of a weighted multi-model ensemble of EURO-CORDEX models and the three different RCP emission scenarios (RCP2.6, RCP4.5 and RCP8.5). In this way, we aim at contributing to assist adaptation needs in Portugal under the new National Roadmap for Adaptation XXI – Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century (RNA2100). This multi-variable, multi-model and multi-scenario climate information is crucial to the development of storylines for mitigation and adaptation strategies for Portugal, regarding the water, agriculture and forest sectors and ecosystems linked to the global emission trajectories.

The manuscript is organised as follows: the datasets and the methodology applied are described in Section 2; the main results regarding the future evolution of soil moisture and aridity over Portugal are shown in Section 3, and the main conclusions are presented in Section 4.

2. Data and methods

2.1. EURO-CORDEX regional climate modelling data

In this study, the EURO-CORDEX high resolution regional climate simulations (0.11° resolution) (Giorgi et al., 2009; Jacob et al., 2020, Jacob et al., 2014) are used to investigate the climate projections for soil moisture and the related variables across mainland Portugal. Three different future greenhouse gas emission scenarios, RCP2.6, RCP4.5 and RCP8.5 are considered, and three future time periods are analysed (2011–2040, 2041–2070 and 2071–2100) to portray the soil moisture and the land water budget evolution in the 21st century. The future changes rely on the comparison with the historical runs output for the period 1971–2000. In total, 13 EURO-CORDEX simulations are considered, covering all the experiments (Table 1).

A set of variables were retrieved through the Earth System Grid Federation (ESGF) data portal and were used in this study, such as: daily total precipitation, 2-m maximum and minimum daily temperatures, 2-m specific humidity, surface pressure, daily mean 10-m wind speed, upward latent heat flux, total soil moisture content, total runoff, and evaporation flux.

2.2. GLEAM dataset

The Global Land Evaporation Amsterdam Model (GLEAM) dataset version 3 is used to evaluate the soil moisture (Martens et al., 2017). This dataset provides data of surface soil moisture based on satellite-observed soil moisture that assimilates soil moisture from the European Space Agency Climate Change Initiative (ESA CCI), vegetation optical depth and snow water equivalents. This dataset spans from 1980 to 2020 and it provides data at a 0.25° horizontal resolution.

2.3. Soil moisture and land water balance properties

To assess the future evolution of soil moisture and the land water balance, a set of climate variables are needed. Some variables were directly retrieved from the ESGF data portal as output of EURO-CORDEX RCMs (identified in previous section), and others needed to be estimated, such as evapotranspiration rate, potential evapotranspiration, and near-surface air relative humidity.

In what concerns the total soil moisture, the land surface models within the EURO-CORDEX RCMS have different soil characteristics, especially the number and depths of soil layers and the saturation levels (Knist et al., 2017). Consequently, a direct comparison of the total soil moisture content is not meaningful, however it is expected that the RCMs can reproduce the typical intra-annual and interannual variabilities, as well as consistent future changes within the model system. For each model, the climatological mean total soil moisture, *SM*, was computed from the daily average EURO-CORDEX integrated soil moisture content. In addition, the standardised soil moisture anomaly was computed with respect to the daily means of the historical period and standardised by the daily standard deviations of the historical period (Orlowsky and Seneviratne, 2013).

For precipitation and total runoff, the climatological mean accumulation was computed from the daily average EURO-CORDEX data.

The evapotranspiration rate, *ET*, was determined from the daily EURO-CORDEX upward latent heat flux at the surface, *hfls*, using the following equation:

$$ET = \frac{hfls}{\lambda} \tag{1}$$

where λ is the latent heat of vaporization ($\lambda = [2.501 - 0.00237 \times T] \times 10^6 Jkg^{-1}$), considering the 2-meter air temperature, T. The climatological mean accumulation of evapotranspiration was then computed.

The potential evapotranspiration for the reference culture, *PET*, was estimated from the Food and Agriculture Organization (FAO) Penman-Monteith equation (Allen et al. 1989):

$$PET = [0.408\,\Delta\,(R_n - G) + \gamma[900/(T_m + 373)]\,V_{h2}\,(e_s - e_a)]\,/\,(\Delta + \gamma(1 + 0.34V_{h2}) \tag{2}$$

where R_n is the net radiation at the surface, G is the soil heat flux density, T_m is the daily mean 2-m air temperature (obtained by computing the average between the maximum and minimum 2-m temperature), V_{h2} is the daily mean 2-m wind speed (obtained using a power-law approximation using the daily mean 10-m wind speed), e_s is the saturation vapor pressure, e_a is the actual vapor pressure, γ is the psychrometric constant, and Δ is the slope of the vapor pressure curve.

The land water balance expression was used to estimate the change of water content, $\frac{dS}{dt}$, and it is expressed as (Seneviratne et al., 2010):

$$\frac{dS}{dt} = P - ET - R_s - R_g \tag{3}$$

where $\frac{dS}{dt}$ is the change of water content within the given layer, P is the precipitation, ET is the evapotranspiration, R_s is the surface runoff and R_g is the drainage. Here, we used the total runoff, R_t, output from the EURO-CORDEX RCMs, which is the sum of the surface runoff and the drainage. The change of water content term includes the soil moisture, surface water, snow, ice cover and groundwater (that depends on the depth of the soil layer).

The near-surface air relative humidity, *RH*, was computed from EURO-CORDEX 2-m air mean temperature, 2-m specific humidity, q, and surface pressure, p_s, using the following approximation:

$$RH = \left[\left(\frac{mr}{mr_{sat}}, 1\right), 0\right] x100 \tag{4}$$

where mr and mr_{sat} are the mixing ratio and saturation mixing ratio computed as described in (Hardy, 1998).

Finally, the aridity index, *AI*, is defined as the ratio between the annual precipitation, P, and the annual potential evapotranspiration, *PET*, following the Eq. 5.

$$AI = \frac{P}{PET} \tag{5}$$

It is a critical environmental factor affecting the evolution of natural vegetation and therefore rain erosivity by considering rainfall and air temperature. The Aridity index climate classification system used here follows the description presented in Table 2.

2.4. Weighted multi-model ensemble based on precipitation and temperature

A weighted multi-model, multi-variable EURO-CORDEX were used in the present study to consistently assess the soil moisture and water balance budget. In climate studies, weighted multi-model ensembles have been used since it improves the climate projections derived from

Table 1
EURO-CODEX RCMs used in this study, along with the forcing GCMs and the responsible institute.

RCM	Institute	GCM
CCLM4-8–17	CLM	EC-Earth
ALADIN63	CNRM	CNRM-CM5
HIRHAM5	DMI	EC-Earth
		HadGEM2-ES
REMO2015	GERICS	NorESM1-M
RACMO22E	KNMI	CNRM-CM5
		EC-Earth
		HadGEM2-ES
REMO2009	MPI	MPI-ESM-LR
RCA4	SMHI	EC-Earth
		HadGEM2-ES
		MPI-ESM-LR
		NorESM1-M

Table 2
Aridity index classification.

AI value	Classification
≥ 0.65	Humid
[0.5, 0.65[	Dry Subhumid
[0.2, 0.5[	Semi-arid
[0.05, 0.2[	Arid
less than 0.05	Hyper-arid

ensembles (Brunner et al., 2019; Christensen et al., 2010; Eyring et al., 2019; Knutti et al., 2017; Sanderson et al., 2017). It allows to generate more reliable regional climate projections and to constrain the uncertainty of climate modelling. Weighted methods are based on the individual model performance, giving more weighting to models that better simulate the present climate of a given variable over a specific domain (Cardoso et al., 2019; Nogueira et al., 2019; Soares et al., 2017a).

Based on this assumption, a new multi-variable approach is used in this study. This new approach is key to preserve the physical consistency among climate simulations and fosters the use of the multi-model, multi-variable ensemble for impact modelling that often needs multi-variable information.

In this way, an extensive evaluation of the EURO-CORDEX available simulations was performed by comparing the historical results of precipitation, maximum and minimum temperature against the Iberia-01 dataset, the recent observational gridded dataset (Herrera et al., 2019). Since the historical climate simulations has a non-synchronised climate when compared to observations, only statistical comparisons over climatology outputs can be performed. A wide set of error metrics were considered to perform the assessment of the historical simulations for the 1971–2000 period: mean bias, mean absolute error, root mean squared error, normalized standard deviation, spatial correlation, Willmott-D Score (Willmott et al., 2012), Perkins skill score (Perkins et al., 2007), and Yule-Kendall skewness (Ferro et al., 2005). The assessment between the Iberia01 and EURO-CORDEX models was done from monthly to yearly timescales. Only the PDF skill score measurements (Perkins skill score, and Yule-Kendall skewness) use daily values. From this evaluation a weighted multi-model ensemble was proposed relying in the ability of RCMs to capture the maximum and minimum temperatures and precipitation across Portugal mainland. To consider the multi-variable approach, a new weight for each model is computed where the precipitation weight corresponds to 50% and the maximum and minimum temperatures both contributes 25%. The multi-model ensemble is then computed with those weights for all the variables. This new multi-variable approach enhances the consistency to the assessment of future conditions of soil moisture and its main drivers (such as precipitation, evapotranspiration, and runoff). This new approach allows to preserve the physical consistency among climate simulations.

2.5. Analysis

To assess the future evolution of soil moisture and the land water balance, three future time periods are considered (2011–2040, 2041–2070 and 2071–2100), from highly- to non-mitigated emission scenarios (RCP2.6, RCP4.5 and RCP8.5).

Firstly, the future climate of soil moisture is analysed through the spatial pattern and interannual variability. In addition, the PDFs (probability density function) of the standardised soil moisture anomaly are also examined. Then, the drivers of the soil moisture depletion are investigated through the analysis of the land water balance components and other relevant variables. Finally, the projected changes in the aridity index are explored in context of the previous analysis. For all variables, we computed the standard deviation of the multi-model signal projections to characterize the spread and therefore the uncertainty associated with the corresponding projections.

The multi-model ensemble V_{ens} for each variable, v_n, analysed in this study is obtained by computing a weighted average over the N ensemble members as:

$$V_{ens} = \frac{\sum_{n=1}^{N} w_n v_n}{\sum_{n=1}^{N} w_n} \tag{5}$$

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

$$Vp_{ens} = \sum_{n=1}^{N} w_n p_n \tag{6}$$

The weights w_n were obtained following the methodology described in the previous sub-section.

All the analysis is performed over Portugal domain (Fig. S1a) and at the regional level (Fig. S1b), following the Nomenclature of Territorial Units for Statics (NUTS).

3. Results

3.1. Future climate soil moisture

As referred in the methods section for analysing the results it is rather important to keep in mind that the diverse RCMs (more precisely the land surface models within) have different soil properties, from the number and depths of sub-surface layers to the specific characteristics represented. Therefore, a direct comparison of the available total (i.e., vertically integrated) soil moisture is not meaningful. Notwithstanding the different mean total soil moisture values, the RCMs are expected to reproduce typical intra-annual and interannual variabilities, as well as coherent future changes within each model system (Knist et al., 2017).

In this sense, we compare the total soil moisture from the multi-model ensemble against the surface soil moisture from GLEAM dataset. To be comparable, the standardised soil moisture anomaly was computed, and the results are presented in Fig. S2 (in Supplementary Material), for Portugal mainland (Fig. S2a) and for the NUTS II regions (Fig. S2b). The results presented need to be analysed carefully since there are important differences among the data used: (1) we are compared the surface soil moisture (in m^3/m^3) from GLEAM with the vertically integrated soil moisture (kg/m^2) from the EURO-CORDEX multi-model; (2) the number of grid-points considered in each region differ since the horizontal resolution is different in both data; and (3) the period considered for the comparison is not the same, for GLEAM we used a 30-year period from 1980 to 2009, and the multi-model ensemble is spans the 1971–2000 period. Despite those differences, the distribution of the soil moisture anomaly is quite similar between both data, which give us confidence in using the soil moisture from the multi-model ensemble to assess the future changes for Portugal, especially focusing on its distributional future changes.

The annual cycle of total soil moisture in Portugal (Fig. 1a), given by the models, corresponds to a typical Mediterranean climate cycle, where maximum values of soil moisture occur in late winter (for Portugal in February) and minimum values in late summer (September). This annual cycle is rather pronounced and reveals a soil moisture annual amplitude of around 200 mm, or one quarter of maximum winter values.

Looking to the future projections of soil moisture (Fig. 1), for the three time periods and three RCP scenarios, overall, as expected, a clear and monotonous decrease with time and RCP of the full annual cycle is identified, with much larger magnitudes when going from the RCP2.6 to RCP8.5. In fact, for the RCP2.6 a rather small decrease of soil moisture if projected for almost all months and time periods, under 3% in relative values and peaking in November. In fact, for this emission scenario a small recovery (little increase and less decrease) is seen when comparing the mid-century and the end-of-century in spring. For the RCP4.5, the reductions are gradually enhanced throughout the 21st century, especially between the beginning and mid-century and reaching −7% in November for 2071–2100. In spring and summer, from mid-century to end-of-century, a small recovery or stabilization of soil moisture is projected. For the RCP8.5, the soil moisture reductions are much more severe, and always increasing throughout the century, jumping from maximum reductions, in November, of around – 3% in 2011–2041, to −9% and −14% in mid- and end-of-century, respectively.

Overall, some changes in the annual cycle may be identified besides the omnipresent decreases of water availability in the soil. For Portugal mainland, the annual soil moisture amplitude is projected to augment

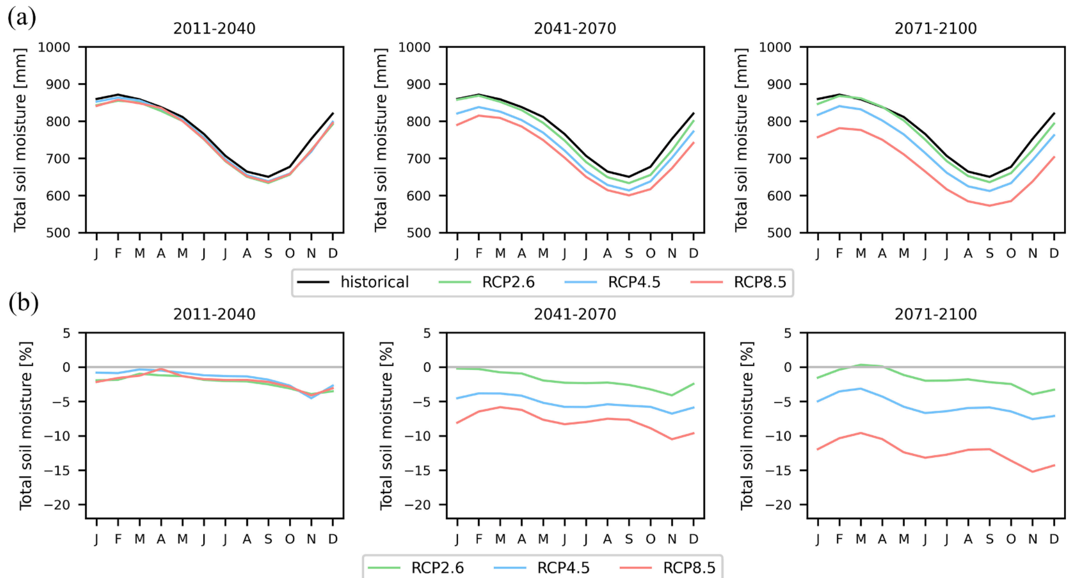

Fig. 1. (a) Annual cycle at the monthly scale of soil moisture for the historical and futures periods, (b) Annual cycle at the monthly scale of soil moisture differences for future climates (w.r.t. to the historical climate) in percentage (%) values, considering the three RCP emission scenarios - RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red).

slightly for the RCP2.6, the one showing a rather small diminishing of soil moisture, as well as for the RCP4.5 but in a mitigated manner. For the RCP8.5, the severe reductions of soil moisture throughout the year are accompanied by a decrease of the annual soil moisture amplitude in absolute values (Table S1).

A spatial view of the projected soil moisture changes at the annual and seasonal scales, for the three time periods and the three emission scenarios, is displayed in Fig. 2 focusing absolute (for relative values in Fig. S3). The future projections display a clear reduction of soil moisture, especially for the RCP4.5 and RCP8.5, pointing to a dramatic aggravation of water scarcity throughout the 21st century in Portugal, if emissions are not reduced. For the first future period, all scenarios have associated projections of a small reduction of annual soil moisture (smaller than 40 mm) but that intensifies greatly with time and scenario. For the mid-century, the projected reductions for the RCP4.5 are between −40 and −80 mm for all the southern of Portugal, and for the RCP8.5 almost those reach values in the range of −80 and −120 mm for the south and, −40 and −80 mm for the north. For the end of the century, the soil moisture decrease is enhanced for the RCP8.5, attaining values between −120 and −160 mm for large extensions of the southern regions. This change dynamics also applies in a great measure for all the seasons, with some exceptions. For spring, the projections according to the RCP2.6 reveals some increases of soil moisture for the end of the century in some mountainous and big river valleys, such as the Tagus; and, for autumn the decreases of soil moisture associated with the RCP8.5 are more homogeneous spatially.

In Fig. 3, the PDFs of soil moisture anomalies normalized by the respective standard deviations are displayed, for the historical and future periods and in agreement with the three RCP scenarios, for Portugal mainland (Fig. 3a) and for the NUTS II regions (Fig. 3b). Strikingly the soil moisture PDFs time evolution, in response to the emissions scenarios, reminds immediately the temperature classical shift and flattened PDFs, where a great increase of extreme temperature occurrence is identified both due to the lateral shift and the flattening of the temperature PDFs. In fact, the soil moisture PDFs reveal distinct shifts and flattening, in an increasingly manner with time and scenario, which corresponds to multiplying for various orders of magnitude the occurrence of soil moisture deficits, w.r.t. the historical climate.

For Portugal and the period 2011–2040 a very slight shift for lower soil moisture values and flattening of the PDFs is seen, for all RCPs. For the RCP2.6 the PDFs remain rather unchanged for all future time periods but for the RCP4.5 and RCP8.5 those PDF changes are enhanced in 2041–2070 and further in 2071–2100. In the historical period, soil moisture deficits rarely reach values 3x over the standard deviation, but projections reveal that for the RCP4.5 (RCP8.5) for the mid-century deficits up to 5x (6x) are projected to occur, and for the end-of-century even 7x for the RCP8.5.

The shift for lower values and the flattening of the soil moisture PDFs is projected for all Portuguese NUTS II regions, from north to south. However, the PDF's projected modifications are more severe for the two southern regions, Alentejo and Algarve. These regions are already presently the ones suffering recurrently of water scarcity problems, with impacts even on public water supply for human consummation. For these regions, in the case of RCP8.5, a dramatic decrease of the occurrences when soil moisture anomalies will be positive is projected, and for example, deficits of 3x the standard deviation (historical) are projected to increase from 0.06% in the historical period to 3% at mid-of-century and 4% at end-of-century, so as impressive as 67x. Noteworthy, if mitigation is pursued and RCP2.6 achieved the PDFs for those regions almost do not change when compared with the historical period.

3.2. Drivers of future soil moisture and humidity depletion

The dramatic decrease in soil water availability, soil moisture, in the context of climate change is primarily linked to the projected reductions of precipitation (Cos et al., 2022; Soares et al., 2017a) and large increase of temperature (Cardoso et al., 2019; Cos et al., 2022), but its physical interdependences, overall and at the seasonal cycle setting, are explored next. In Fig. 4, an overall view of the land soil water balance for mainland Portugal is presented. The change of water content depends on the budget between precipitation, evapotranspiration, and total runoff.

In all periods, from present to future climates, the water balanced at the annual scale is firstly controlled by precipitation and then evapotranspiration and runoff. For the first period (2011–2040) there is a small reduction of all water balance terms for all scenarios. These decreases are much enhanced in the mid-century period, in agreement with the RCP4.5 and RCP8.5 – to the projected decrease in precipitation an important reduction in runoff and water content follows. The evapotranspiration suffers a smaller relative decrease. For the RCP2.6 the overall precipitation and runoff increase slightly. The mid-century

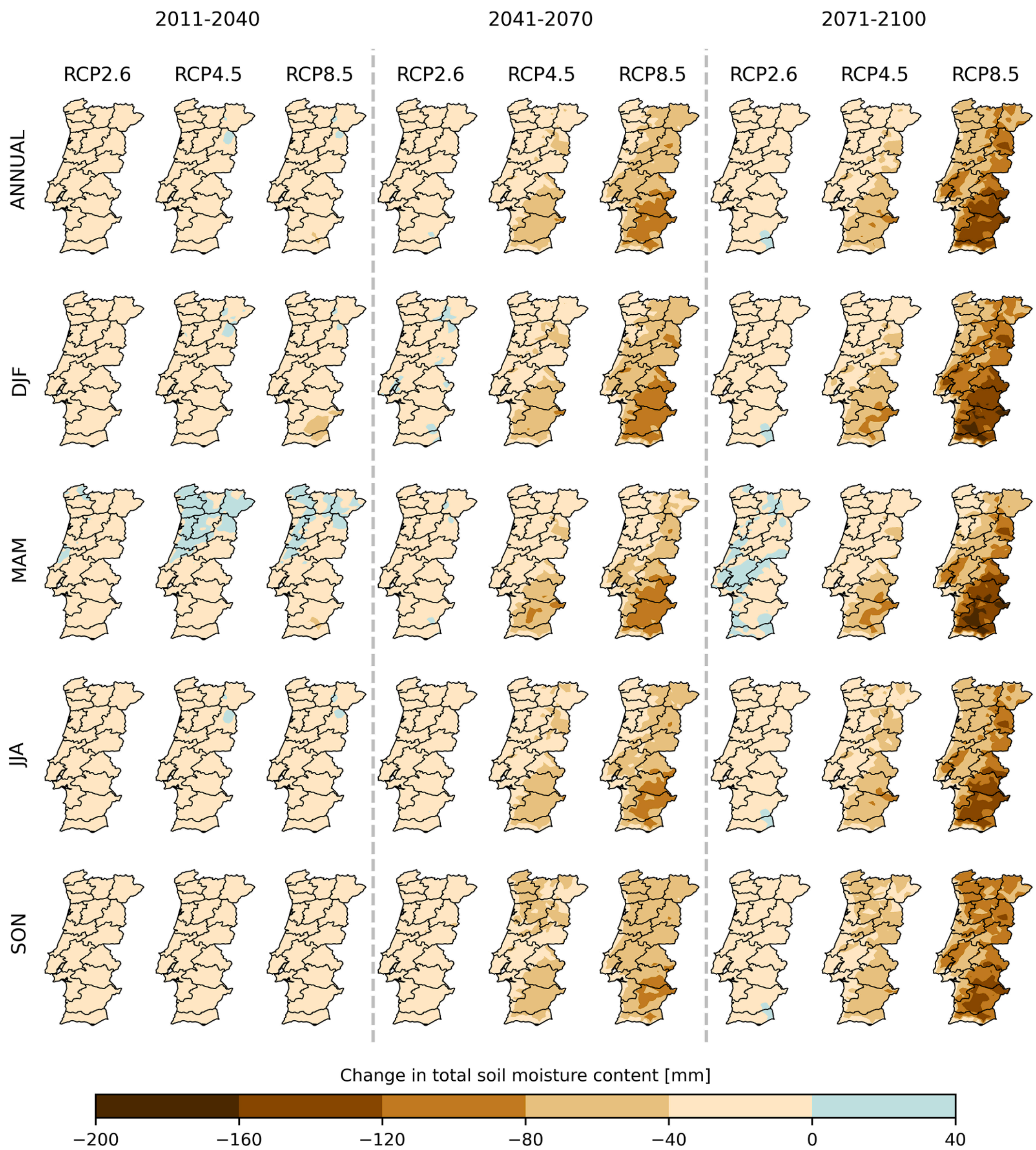

Fig. 2. Future projected changes in total soil moisture content over mainland Portugal, considering the 1971–2000 period as reference. The different rows from top to bottom represent averaged taken over all months, DJF, MAM, JJA and SON, respectively. The different columns represent the future periods considering the three RCP emission scenarios.

changes for all term contributions are accentuated in the end of the century, especially for the RCP8.5. All terms increase slightly w.r.t. present climate but the water content appears a bit reduced, for the RCP2.6. In agreement with the RCP8.5, precipitation, evapotranspiration, and runoff diminish relatively −21%, −10% and −35%, which results in a water content depletion of –23%.

Looking at the annual cycle of the water budged terms and related variables for the historical period allows understanding the soil moisture dynamics and its projected depletion in future climate scenarios. Fig. 5a shows the seasonal cycle of precipitation, estimated potential evapotranspiration, evapotranspiration, their balance, and total runoff; as well in Fig. 5b the total soil moisture annual cycle is displayed. The seasonal dynamics is dominated by precipitation, which is almost inexistent in summer, and it is maximum in winter. In opposite sense, evapotranspiration (potential evapotranspiration) displays minimum values in winter and maximum in May-June (July); in fact, evapotranspiration (potential evapotranspiration) exceeds precipitation in May through September (April to September), which results in a major net soil water deficit in those periods. Total runoff seems to respond quickly to precipitation in the first half of the year and afterwards slower. The total soil moisture (Fig. 5b) closely follows the $P - PET$ ($P - ET$) seasonal cycle and the order of magnitude, with a time-lag of two-months, except for winter, meaning that soil moisture is drove by the climate forcing two months later.

Figs. 6 and 7 reveals how the water balance terms are projected to change accordingly to the three future scenarios. Overall, the larger precipitation reductions are projected to occur in spring and autumn, which will determine an earlier exceedance of both evapotranspiration and potential evapotranspiration over precipitation, i.e., an earlier reduction of water availability and a smaller amount of water to be deposit in the soil. This water deficit is further enhanced in summer and in autumn, both because of the precipitation reduction, the increase of potential evapotranspiration and the relatively small reduction in evapotranspiration. Again, future precipitation reductions seem to drive the total soil moisture decreases with a one-month to a two-month lag – the larger absolute reductions in total soil moisture will occur in late spring (May-June) and early winter (November-December), in the sequence of the larger deceases in precipitation of April and October-

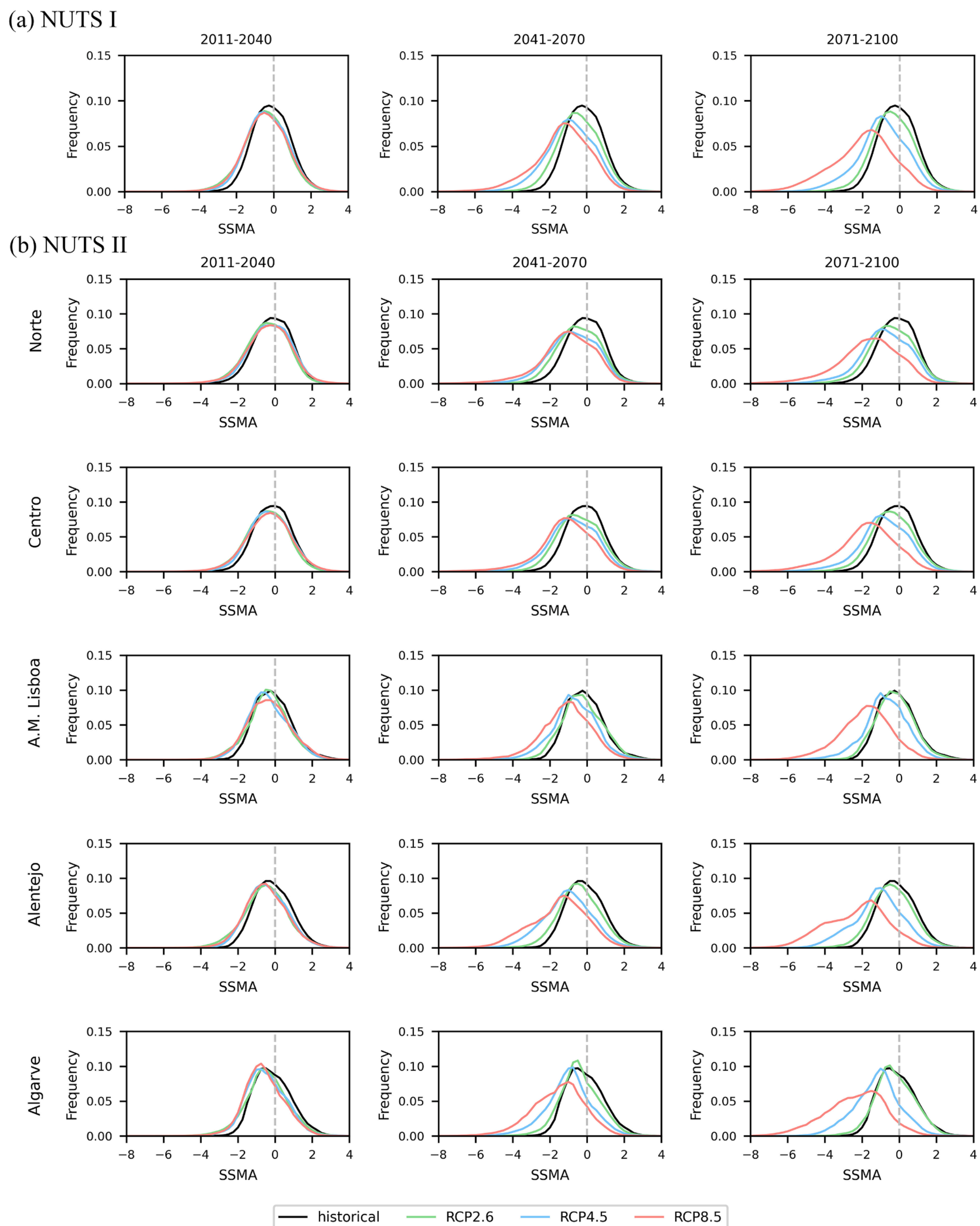

Fig. 3. PDFs of Standardised Soil Moisture Anomaly (SSMA) at the daily scale for mainland Portugal NUTS I and II, historical (black) and future periods considering the three RCP emission scenarios – RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red).

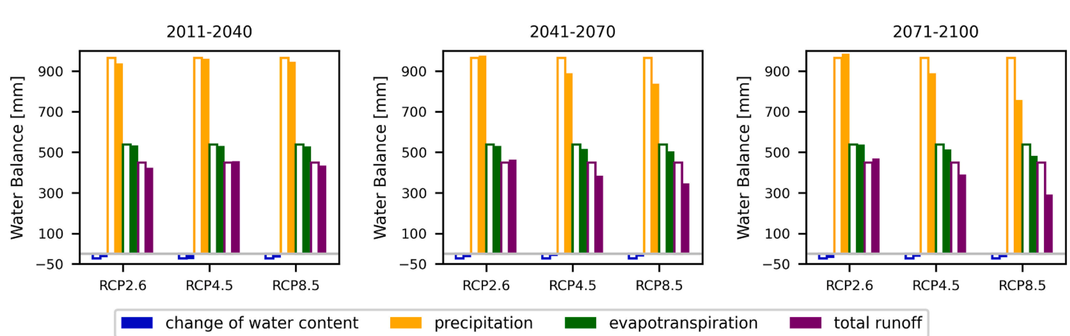

Fig. 4. Land water balance components average for mainland Portugal for historical (bar filled in white) and three future periods (bar filled in colour).

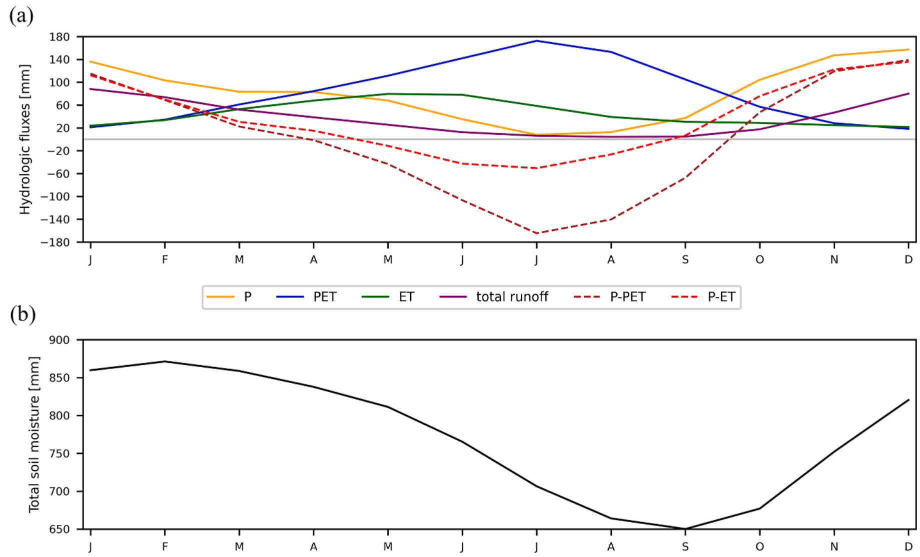

Fig. 5. Annual cycle of (a) hydrologic fluxes and (b) total soil moisture for historical climate (1971–2000).

November. In what concerns the projected changes of total runoff, it follows the signal of precipitation changes.

The projected changes of surface relative humidity (RH), linked to the response to the surface water balance is also shown in Fig. 6g for the annual cycle, and its spatial view on Fig. S4. The surface relative humidity is an important meteorological parameter that controls the atmospheric evaporative demand. Changes in relative humidity may have strong implications for ecosystems, hydrological cycle, climate aridity and drought events, through the evolution of the evaporative demand (Vicente-Serrano et al., 2018). With increasing surface temperature, the amount of water vapour in the atmosphere increases whenever the air is not saturated. Saturated vapour pressure increases exponentially with temperature as expected from the Clausius–Clapeyron relation and in some regions the amount of water vapour in the atmosphere has been increasing in excess of 7% per kelvin (Willett et al., 2010). However, increasing global temperatures are not translated into increasing relative humidity over land, the opposite or a plateauing of RH has been observed (Simmons et al., 2010). In large regions of the globe, the majority of moisture over land has origins over the oceans. Since oceans are warming at a lower rate than the land surface, the rate of evaporation over their surfaces is lower than over land. Thus, the amount of moisture advected from the oceans into the land areas is not enough to keep the ratio between the air's vapour pressure and the saturated vapour pressure constant and a decrease in RH is observed. In some areas like Portugal, changes to general circulation also imply a reduction in moister transport from the oceans, further reducing the moisture availability, escalating surface warming, and increasing the saturated vapour pressure.

For all scenarios the projected humidity reductions are larger from spring to autumn. In RCP 2.6 relative humidity (Fig. 6g) decreases by less than 2.5%, while in RCP 4.5 reductions reach 4% in the beginning and end of the summer (for areas near the coast and reductions up to 4% are expected near the Spanish border, Fig S4). In RCP 8.5, a reduction between 0 and 5% is projected by mid-century and a further reduction up to 8% in October (6% in areas near the border with Spain by the end of the century). In winter the advection of moist air accompanying the winter storms, with their expected increase in intensity (i.e., including more moisture), is enough to imply an increase in RH for mainland Portugal for RCP2.6 and for the regions above the Tagus River in RCP 4.5 (Fig. S4). In RCP 8.5 not only a decrease of precipitation is projected but also a significant increase in temperature, thus the projected decline of RH. The reduction in RCP8.5 is particularly severe in the north-eastern regions during summer, where relative humidity is projected to decrease between 6 and 8%, exacerbated by the extreme rise in surface temperatures. The uncertainty of the RH projections is high with the multi-model spread up to 75% of ensemble value for RCP2.6 and RCP 4.5 (not shown). In RCP 8.5, there is lower spread, about 50%.

Importantly, for water bodies and water saturated soils, the potential evapotranspiration increases in all scenarios up to mid-21st century (Fig. S5). The projected increase in PET primarily occurs due to similar processes that lead to the reduction in RH which leads to an increase in vapor pressure deficit over land and the nonlinear increase of saturation vapor pressure as a function of temperature associated to the Clausius–Clapeyron relationship (Scheff and Frierson, 2014; Sherwood and Fu, 2014). Since under the RCP2.6 scenario, temperature stabilises by mid-century (not shown) no further increase in PET is projected until the end of the century. Overall, a rise lower than 10% is projected. In scenario RCP4.5, temperature rises at a smaller rate from mid-century onwards, thus in most regions PET stabilises and an increase between 10 and 15% is projected at the end of the century. In RCP8.5, the sharp rise in temperature leads to an enhancement up to 30% in PET in the north by the end of the century. The highest rise in PET occurs in the northeast during autumn at the end of the century in RCP8.5. Once again, the multi-model spread is almost as large as the climate change signal, indicating a large uncertainty associated to the ET0 computation (not shown). The reduced soil moisture contributes to the overall reduction of evaporation at the surface (Fig. S5) particularly in summer and autumn, and in the south of the country. As before, the multi-model spread is large and in summer and autumn it is as large as the climate change signal in RCP8.5 (not shown).

3.3. Semi-arid climate overtaking Portugal

Subsequently to the water balance changes explored before and in agreement with the soil moisture depletion, it can be seen that Portugal is projected to become prevalently a semi-arid climate country. In Fig. 8, the aridity index is displayed, which relies on precipitation and evapotranspiration. Historically, the Portuguese climate is humid in north, centre, and a small southwest stripe, and in the rest of the south dry-subhumid and semiarid, in a small southeastern area. In the east of the country also two small areas are characterized by dry-subhumid climate. Looking at the projections in agreement with the RCP2.6 the Portuguese climate does not suffer almost any modification. For the RCP4.5, a small expansion of the dry-subhumid and semiarid climates is projected, especially in the south and centre regions. But, for the RCP8.5 those expansions are much more severe throughout the century: in the

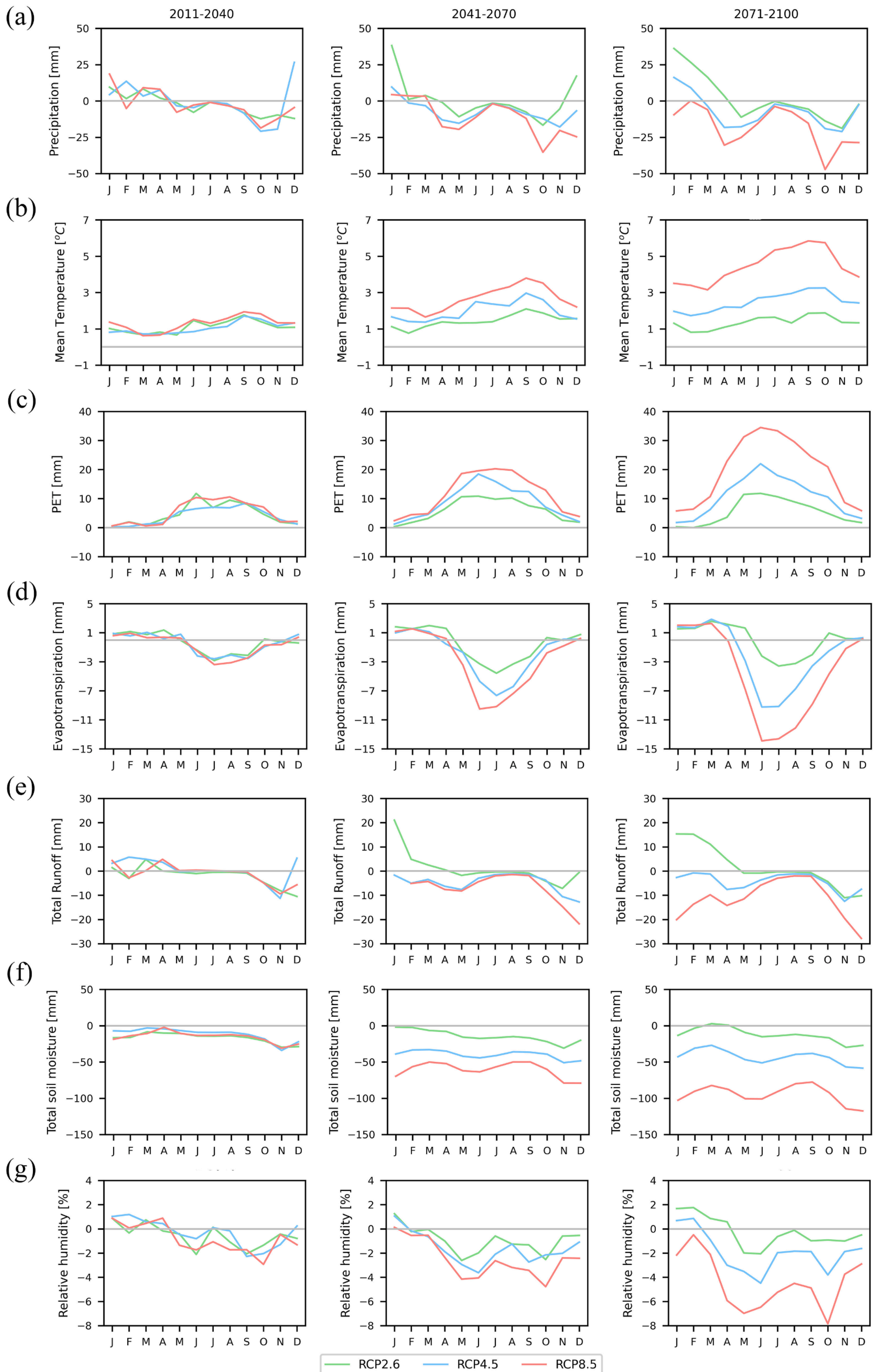

Fig. 6. Differences on Annual cycle at the monthly scale of (a) precipitation, (b) surface air temperature, (c) potential evapotranspiration, (d) evapotranspiration, (e) total runoff, (f) soil moisture and (g) surface air humidity, for future climates considering the three RCP emission scenarios - RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red).

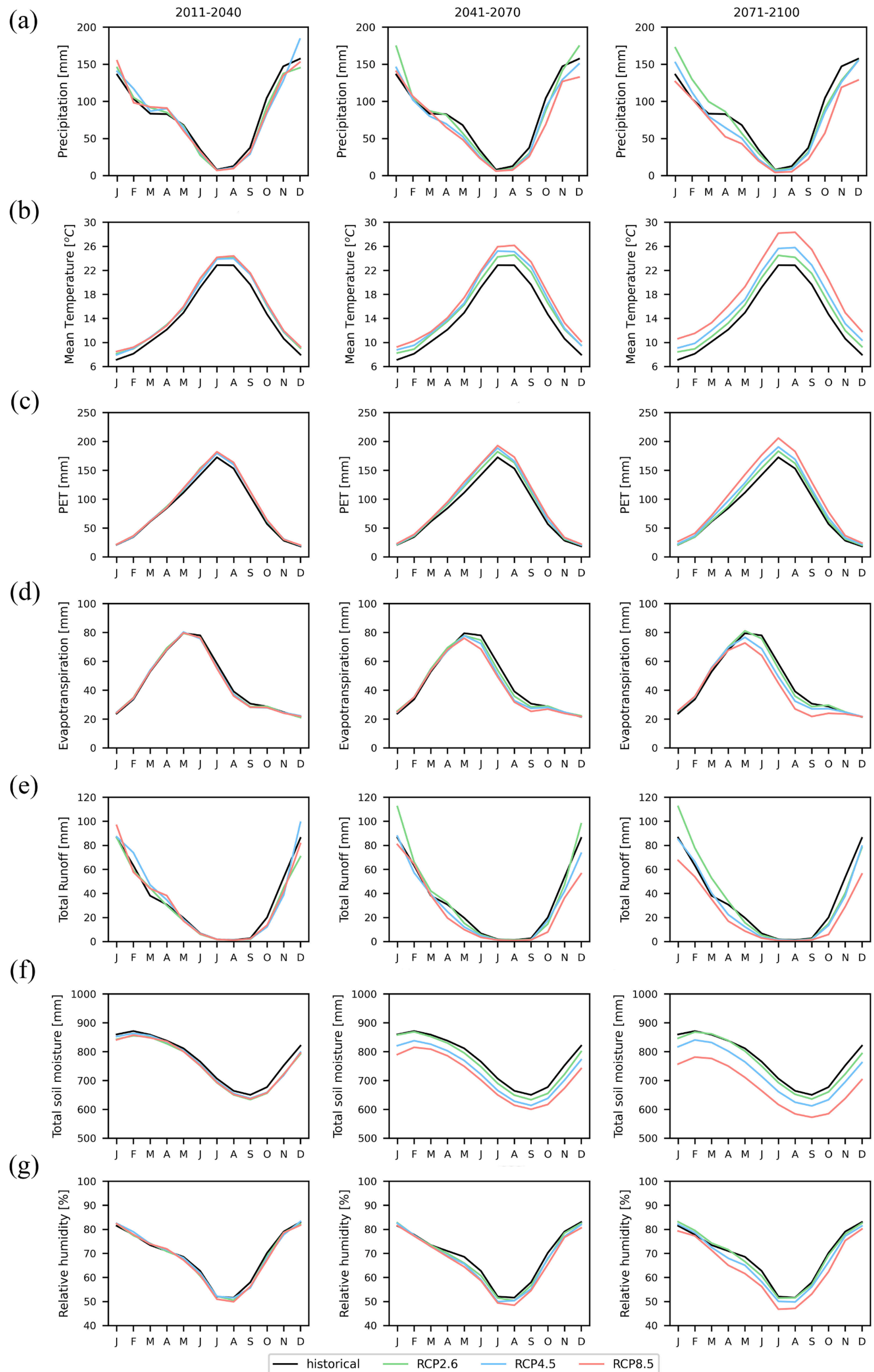

Fig. 7. Annual cycle at the monthly scale of (a) precipitation, (b) surface air temperature, (c) potential evapotranspiration, (d) evapotranspiration, (e) total runoff and (f) surface air humidity, for historical climate (black) and for future climates considering the three RCP emission scenarios - RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red).

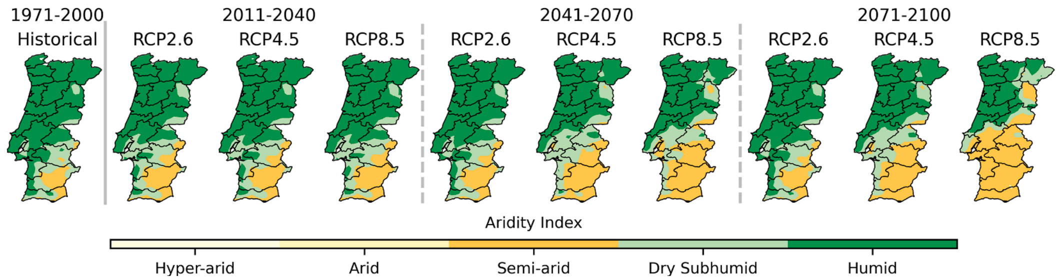

Fig. 8. Aridity Index over mainland Portugal for historical climatological period (1971–2000) and for the future periods considering the three RCP emission scenarios.

mid-century, the semiarid climate extends almost through all the south, the dry-subhumid migrates northerly and the small areas in the eastern border are replaced by semiarid climates. Furthermore, in the end-of-century only roughly the northwestern third of the country remains with humid climate, and the rest is almost all covered by semiarid.

4. Conclusions

The Mediterranean countries are considered a hotspot of climate change, in great measure due to the expected changes in water availability, linked to precipitation decrease and regional warming (Cramer et al., 2018; Giorgi, 2006; Lionello and Scarascia, 2018). Terrestrial ecosystems, agricultural and forests critically depend on water availability in the soils, i.e., soil water content and at the surface layer soil moisture (Chen et al., 2014; Miralles et al., 2019). Some studies have pointed clearly that associated with climate change the Mediterranean countries will endure faster and intense soil dissection enhancing droughts and water scarcity (Milano et al., 2013; Nguyen et al., 2016). Moreover, soil moisture depletion contributes as well to regional to local land–atmosphere feedbacks that promote the occurrence and mutual intensification of heatwaves and droughts. In the current study an analysis of the future soil moisture and aridity in Portugal was performed, using a high-quality multi-model ensemble from EURO-CORDEX, for three future time periods and three RCP emission scenarios: RCP2.6, RCP4.5 and RCP8.5.

In response to the severe projections of precipitation reductions, regional warming, and the subsequent large increase of potential evapotranspiration, a very impressive decrease in soil moisture is projected. The soil moisture depletion is reflected both on mean values, the full annual cycle and more severely on the occurrence of low extreme values when compared to the historical climate. The future projections display a clear reduction of soil water moisture, especially for the RCP4.5 and RCP8.5, pointing to a dramatic aggravation of water scarcity throughout the 21st century in Portugal, if emissions are not reduced. For the mid-century, the projected reductions for the RCP4.5 are between −40 and −80 mm for all the southern of Portugal, and for the RCP8.5 almost reach values in the range of −80 and −120 mm for the south and −40 and −80 mm for the north. For the end of the century, the soil moisture decrease is enhanced for the RCP8.5, attaining values between −120 and −160 mm for large extensions of the southern regions. These latter projected changes in the total soil moisture regard all the annual cycle with relative decrease values between −10% and −15% for the RCP8.5.

In what concerns to extreme total soil moisture values there is a pronounced shift for much negative values and as well a flattening of the distributions much like what is projected for temperature in many regions of the world. The shift for lower values and the flattening of the soil moisture PDFs is projected for all Portuguese NUTS II regions, from north to south. However, the PDF's projected modifications are more severe for the two southern regions, Alentejo and Algarve. In the historical period, soil moisture deficits rarely reach values 3x over the standard deviation, but projections reveal that for the RCP4.5 (RCP8.5), for the mid-century deficits up to 5x (6x) are projected to occur, and for the end-of-century even 7x for the RCP8.5.

The main drivers of future total soil moisture reductions are clearly determined as the precipitation decreases and the augment of potential evapotranspiration throughout the full annual cycle, also associated with the increase of evapotranspiration in winter when there is still water availability to evaporate, especially for the RCP8.5. In the rest of the annual cycle there is a decrease of evapotranspiration since soil moisture is greatly depleted. At the surface, relative humidity is projected to decrease for the RCP4.5 and RCP8.5, and in a less extent for RCP2.6. For FCP8.5 the RH reduction is particularly severe in the north-eastern regions during summer, where relative humidity is projected to decrease between 6 and 8%. It is important to mention that as in relative humidity and potential evapotranspiration, the multi-model spread is large conducting to uncertainty of climate change projections in soil moisture and evaporation. In result of all these projected changes in the water cycle related variables, the Portuguese climate is projected to become much more semi-arid. For the RCP8.5, for the end-of-century only roughly the north-western third of the country remains with humid climate, and the rest is almost all covered by semiarid. In opposite manner, for the RCP2.6, the spatial extension of semi-arid climate remains largely unchanged when compared to historical climate, confined to a small south-eastern region.

Finally, the future panorama of water scarcity here depicted will impact dramatically many Portuguese ecosystems and economic sectors dependent on them, such as agriculture, forests, and tourism. These are expected to have to face levels of adaptation immensely different according to the degree of global mitigation of greenhouse gas emissions. This study aimed at giving a less common view of the terrestrial water availability for the future of Portugal.

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.jhydrol.2022.128731.

References

Albergel, C., Dorigo, W., Reichle, R.H., Balsamo, G., Derosnay, P., Muñoz-sabater, J., Isaksen, L., Dejeu, R., Wagner, W., 2013. Skill and global trend analysis of soil moisture from reanalyses and microwave remote sensing. J. Hydrometeorol. 14, 1259–1277. https://doi.org/10.1175/JHM-D-12-0161.1.

Berg, A., Sheffield, J., Milly, P.C.D., 2017. Divergent surface and total soil moisture projections under global warming. Geophys. Res. Lett. 44, 236–244. https://doi.org/10.1002/2016GL071921.

Brocca, L., Moramarco, T., Melone, F., Wagner, W., Hasenauer, S., Hahn, S., 2012. Assimilation of surface- and root-zone ASCAT soil moisture products into rainfall-runoff modeling. IEEE Trans. Geosci. Remote Sens. 50, 2542–2555. https://doi.org/10.1109/TGRS.2011.2177468.

Brunner, L., Lorenz, R., Zumwald, M., Knutti, R., 2019. Quantifying uncertainty in European climate projections using combined performance-independence weighting. Environ. Res. Lett. 14, 124010 https://doi.org/10.1088/1748-9326/AB492F.

Cardoso, R.M., Soares, P.M.M., 2022. Is there added value in the EURO-CORDEX hindcast temperature simulations? Assessing the added value using climate distributions in Europe. Int. J. Climatol. https://doi.org/10.1002/JOC.7472.

Cardoso, R.M., Soares, P.M.M., Lima, D.C.A., Miranda, P.M.A., 2019. Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate high-resolution projections for Portugal. Clim. Dyn. 52, 129–157. https://doi.org/10.1007/s00382-018-4124-4.

Careto, J.A.M., Soares, P.M.M., Cardoso, R.M., Herrera, S., Gutiérrez, J.M., 2022a. Added value of EURO-CORDEX high-resolution downscaling over the Iberian Peninsula revisited – Part 2: Max and min temperature. Geosci. Model Dev. 15, 2653–2671. https://doi.org/10.5194/GMD-15-2653-2022.

Careto, J.A.M., Soares, P.M.M., Cardoso, R.M., Herrera, S., Gutiérrez, J.M., 2022b. Added value of EURO-CORDEX high-resolution downscaling over the Iberian Peninsula revisited – Part 1: Precipitation. Geosci. Model Dev. 15, 2635–2652. https://doi.org/10.5194/GMD-15-2635-2022.

Chen, T., de Jeu, R.A.M., Liu, Y.Y., van der Werf, G.R., Dolman, A.J., 2014. Using satellite based soil moisture to quantify the water driven variability in NDVI: A case study over mainland Australia. Remote Sens. Environ. 140, 330–338. https://doi.org/10.1016/J.RSE.2013.08.022.

Christensen, J.H., Kjellström, E., Giorgi, F., Lenderink, G., Rummukainen, M., 2010. Weight assignment in regional climate models. Clim. Res. 44, 179–194. https://doi.org/10.3354/cr00916.

Cos, J., Doblas-Reyes, F., Jury, M., Marcos, R., Bretonnière, P.-A., Samsó, M., 2022. The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. Earth Syst. Dynam 13, 321–340. https://doi.org/10.5194/esd-13-321-2022.

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.P., Iglesias, A., Lange, M.A., Lionello, P., Llasat, M.C., Paz, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M.N., Xoplaki, E., 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. Nat. Clim. Chang. 8, 972–980. https://doi.org/10.1038/S41558-018-0299-2.

Di Luca, A., de Elía, R., Laprise, R., 2012. Potential for added value in precipitation simulated by high-resolution nested Regional Climate Models and observations. Clim. Dyn. 38, 1229–1247. https://doi.org/10.1007/S00382-011-1068-3/FIGURES/10.

Eltahir, E.A.B., 1998. A Soil Moisture-Rainfall Feedback Mechanism: 1. Theory and observations. Water Resour. Res. 34, 765–776. https://doi.org/10.1029/97WR03499.

Eyring, V., Cox, P.M., Flato, G.M., Gleckler, P.J., Abramowitz, G., Caldwell, P., Collins, W.D., Gier, B.K., Hall, A.D., Hoffman, F.M., Hurtt, G.C., Jahn, A., Jones, C.D., Klein, S.A., Krasting, J.P., Kwiatkowski, L., Lorenz, R., Maloney, E., Meehl, G.A., Pendergrass, A.G., Pincus, R., Ruane, A.C., Russell, J.L., Sanderson, B.M., Santer, B. D., Sherwood, S.C., Simpson, I.R., Stouffer, R.J., Williamson, M.S., 2019. Taking climate model evaluation to the next level. Nat. Clim. Chang. 9, 102–110. https://doi.org/10.1038/s41558-018-0355-y.

Ferro, C.A.T., Hannachi, A., Stephenson, D.B., 2005. Simple nonparametric techniques for exploring changing probability distributions of weather. J. Clim. 18, 4344–4354. https://doi.org/10.1175/JCLI3518.1.

Feser, F., Rockel, B., Storch, H., Winterfeldt, J., Zahn, M., 2011. Regional climate models add value to global model data: A review and selected examples. Bull. Am. Meteorol. Soc. 92, 1181–1192. https://doi.org/10.1175/2011BAMS3061.1.

Ford, T.W., Quiring, S.M., Thakur, B., Jogineedi, R., Houston, A., Yuan, S., Kalra, A., Lock, N., 2018. Evaluating soil moisture-precipitation interactions using remote sensing: A sensitivity analysis. J. Hydrometeorol. 19, 1237–1253. https://doi.org/10.1175/JHM-D-17-0243.1.

Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. 33, 8707. https://doi.org/10.1029/2006GL025734.

Giorgi, F., Jones, C., Asrar, G.R., 2009. Addressing climate information needs at the regional level: The CORDEX framework. WMO Bull. 58, 175–183.

Giorgi, F., Mearns, L.O., 1999. Introduction to special section: Regional climate modeling revisited. J. Geophys. Res. Atmos. 104, 6335–6352. https://doi.org/10.1029/98JD02072.

Hardy, B., 1998. Its-90 formulations for vapor pressure, frostpoint temperature, dewpoint temperature, and enhancement factors in the range –100 TO +100 C Bob Hardy. Proc. Third Int. Symp. Humidity Moisture 1–8.

Herrera, S., Margarida Cardoso, R., Matos Soares, P., Espírito-Santo, F., Viterbo, P., Gutiérrez, J.M., 2019. Iberia01: A new gridded dataset of daily precipitation and temperatures over Iberia. Earth Syst. Sci. Data 11, 1947–1956. https://doi.org/10.5194/essd-11-1947-2019.

Herrera, S., Soares, P.M.M., Cardoso, R.M., Gutiérrez, J.M., 2020. Evaluation of the EURO-CORDEX regional climate models over the Iberian Peninsula: observational uncertainty analysis. J. Geophys. Res. Atmos. 125 https://doi.org/10.1029/2020JD032880.

Hirschi, M., Mueller, B., Dorigo, W., Seneviratne, S.I., 2014. Using remotely sensed soil moisture for land–atmosphere coupling diagnostics: The role of surface vs. root-zone soil moisture variability. Remote Sens. Environ. 154, 246–252. https://doi.org/10.1016/J.RSE.2014.08.030.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., Pegion, P., 2012. On the Increased Frequency of Mediterranean Drought. J. Clim. 25, 2146–2161. https://doi.org/10.1175/JCLI-D-11-00296.1.

Humphrey, V., Berg, A., Ciais, P., Gentine, P., Jung, M., Reichstein, M., Seneviratne, S.I., Frankenberg, C., 2021. Soil moisture–atmosphere feedback dominates land carbon uptake variability. Nat. 2021 5927852 592, 65–69. 10.1038/s41586-021-03325-5.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, the Fifth Assessment Report. Cambridge University Press.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press. 10.1017/9781009157896.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: New high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M., Benestad, R., Boberg, F., Buonomo, E., Cardoso, R.M., Casanueva, A., Christensen, O. B., Hesselbjerg Christensen, J., Coppola, E., De Cruz, L., Davin, E.L., Dobler, A., Domínguez, M., Fealy, R., Fernandez, J., Angel Gaertner, M., García-Díez, M., Giorgi, F., Gobiet, A., Goergen, K., JoséJos, J., JesúsJes, J., GonzálezGonz, J., AlemánAlem, G., Gutíerrez, C., Gutiérrez, J.M., Haensler, A., Halenka, T., Jerez, S., JiménezJim, P., Jones, R.G., Keuler, K., KjellströmKjellstr, E., Knist, S., Kotlarski, S., Maraun, D., van Meijgaard, E., Mercogliano, P., Pedro MontávezMont, J., Navarra, A., Nikulin, G., de Noblet-DucoudréDucoudr, N., Panitz, H.-J., Pfeifer, S., Piazza, M., Pichelli, E., PietikäinenPietik, J.-P., Prein, A.F., Preuschmann, S., Rechid, D., Rockel, B., Romera, R., Sieck, K., Soares, M.P.M., Somot, S., Srnec, L., Lund Sørland, S., Termonia, P., Truhetz, H., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2020. Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. Reg. Environ. Chang. 20 https://doi.org/10.1007/s10113-020-01606-9.

Katragkou, E., García-Díez, M., Vautard, R., Sobolowski, S., Zanis, P., Alexandri, G., Cardoso, R.M., Colette, A., Fernandez, J., Gobiet, A., Goergen, K., Karacostas, T., Knist, S., Mayer, S., Soares, P.M.M., Pytharoulis, I., Tegoulias, I., Tsikerdekis, A., Jacob, D., 2015. Regional climate hindcast simulations within EURO-CORDEX: evaluation of a WRF multi-physics ensemble. Geosci. Model Dev. 8, 603–618. https://doi.org/10.5194/gmd-8-603-2015.

Knist, S., Goergen, K., Buonomo, E., Christensen, O.B., Colette, A., Cardoso, R.M., Fealy, R., Fernández, J., García-Díez, M., Jacob, D., Kartsios, S., Katragkou, E., Keuler, K., Mayer, S., van Meijgaard, E., Nikulin, G., Soares, P.M.M., Sobolowski, S., Szepszo, G., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., Simmer, C., 2017. Land-atmosphere coupling in EURO-CORDEX evaluation experiments. J. Geophys. Res. Atmos. 122, 79–103. https://doi.org/10.1002/2016JD025476.

Knutti, R., Sedláček, J., Sanderson, B.M., Lorenz, R., Fischer, E.M., Eyring, V., Knutti, C., Sedláček, J., Sanderson, B.M., Lorenz, R., Fischer, E.M., Eyring, V., 2017. A climate model projection weighting scheme accounting for performance and interdependence. Geophys. Res. Lett. 44, 1909–1918. https://doi.org/10.1002/2016GL072012.

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2014. Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci. Model Dev. 7, 1297–1333. https://doi.org/10.5194/gmd-7-1297-2014.

Lionello, P., Abrantes, F., Gacic, M., Planton, S., Trigo, R., Ulbrich, U., 2014. The climate of the Mediterranean region: research progress and climate change impacts. Reg. Environ. Chang. 14, 1679–1684. https://doi.org/10.1007/S10113-014-0666-0.

Lionello, P., Scarascia, L., 2018. The relation between climate change in the Mediterranean region and global warming. Reg. Environ. Chang. 2018 185 18, 1481–1493. 10.1007/S10113-018-1290-1.

Martens, B., Miralles, D.G., Lievens, H., Van Der Schalie, R., De Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E., Dorigo, W.A., Verhoest, N.E.C., 2017. GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. Geosci. Model Dev. 10, 1903–1925. https://doi.org/10.5194/GMD-10-1903-2017.

McColl, K.A., Alemohammad, S.H., Akbar, R., Konings, A.G., Yueh, S., Entekhabi, D., 2017. The global distribution and dynamics of surface soil moisture. Nat. Geosci. 102 (10), 100–104. https://doi.org/10.1038/ngeo2868, 2016.

McGregor, J.L., 1997. Regional climate modelling. Meteorol. Atmos. Phys. 631 (63), 105–117. https://doi.org/10.1007/BF01025367.

Milano, M., Ruelland, M., Fernandez, D., Dezetter, S., Fabre, A., Servat, J., Fritsch, E., Ardoin-Bardin, J.-M., Thivet, S., 2013. Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. Hydrol. Sci. J. 58, 498–518. https://doi.org/10.1080/02626667.2013.774458.

Milly, P.C.D., Dunne, K.A., 2016. Potential evapotranspiration and continental drying. Nat. Clim. Chang. 610 (6), 946–949. https://doi.org/10.1038/nclimate3046.

Miralles, D.G., Teuling, A.J., Van Heerwaarden, C.C., De Arellano, J.V.G., 2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nat. Geosci. 75 (7), 345–349. https://doi.org/10.1038/ngeo2141.

Miralles, D.G., Van Den Berg, M.J., Teuling, A.J., De Jeu, R.A.M., 2012. Soil moisture-temperature coupling: A multiscale observational analysis. Geophys. Res. Lett. 39 https://doi.org/10.1029/2012GL053703.

Miralles, D.G., Gentine, P., Seneviratne, S.I., Teuling, A.J., 2019. Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. Ann. N. Y. Acad. Sci. 1436, 19–35. https://doi.org/10.1111/NYAS.13912.

Molina, M.O., Sánchez, E., Gutiérrez, C., 2020. Future heat waves over the Mediterranean from an Euro-CORDEX regional climate model ensemble. Sci. Rep. 101 (10), 1–10. https://doi.org/10.1038/s41598-020-65663-0.

Nguyen, T., Mula, L., Cortignani, R., Seddaiu, G., Dono, G., Virdis, S.G.P., Pasqui, M., Roggero, P.P., 2016. Perceptions of present and future climate change impacts on water availability for agricultural systems in the Western Mediterranean. Region 8, 523. https://doi.org/10.3390/w8110523.

Nogueira, M., Soares, P.M.M., Tomé, R., Cardoso, R.M., 2019. High-resolution multi-model projections of onshore wind resources over Portugal under a changing climate. Theor. Appl. Climatol. 136, 347–362. https://doi.org/10.1007/s00704-018-2495-4.

Orlowsky, B., Seneviratne, S.I., 2013. Elusive drought: Uncertainty in observed trends and short-and long-term CMIP5 projections. Hydrol. Earth Syst. Sci. 17, 1765–1781. https://doi.org/10.5194/HESS-17-1765-2013.

Páscoa, P., Gouveia, C.M., Russo, A.C., Bojariu, R., Vicente-Serrano, S.M., Trigo, R.M., 2020. Drought impacts on vegetation in Southeastern Europe. Remote Sens. 12, 2156. https://doi.org/10.3390/RS12132156.

Perkins, S.E., Pitman, A.J., Holbrook, N.J., McAneney, J., 2007. Evaluation of the AR4 climate models' simulated daily maximum temperature, minimum temperature, and precipitation over australia using probability density functions. J. Clim. 20, 4356–4376. https://doi.org/10.1175/JCLI4253.1.

Randall, D.A., Wood, R.A., Bony, Sandrine, Colman, Robert, Fichefet, Thierry, Fyfe, John, Kattsov, Vladimir, Pitman, Andrew, Shukla, Jagadish, Srinivasan, Jayaraman, Stouffer, R.J., Sumi, Akimasa, Taylor, K.E., Manzini, E., Matsuno, T., McAvaney, B., Wood, R., Bony, S, Colman, R, Fichefet, T, Fyfe, J, Kattsov, V, Pitman, A, Shukla, J, Srinivasan, J, Stouffer, R., Sumi, A, Taylor, K., 2007. Cilmate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M.C. Marq.

Rios-Entenza, A., Soares, P.M.M., Trigo, R.M., Cardoso, R.M., Miguez-Macho, G., 2014. Moisture recycling in the Iberian Peninsula from a regional climate simulation: Spatiotemporal analysis and impact on the precipitation regime. J. Geophys. Res. Atmos. 119, 5895–5912. https://doi.org/10.1002/2013JD021274.

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture—The need for a paradigm shift. Agric. Water Manag. 97, 543–550. https://doi.org/10.1016/J.AGWAT.2009.09.009.

Roderick, M.L., Greve, P., Farquhar, G.D., 2015. On the assessment of aridity with changes in atmospheric CO2. Water Resour. Res. 51, 5450–5463. https://doi.org/10.1002/2015WR017031.

Rummukainen, M., 2010. State-of-the-art with regional climate models. Wiley Interdiscip. Rev. Clim. Chang. 1, 82–96. https://doi.org/10.1002/WCC.8.

Sanderson, B.M., Wehner, M., Knutti, R., 2017. Skill and independence weighting for multi-model assessments. Geosci. Model Dev. 10, 2379–2395. https://doi.org/10.5194/GMD-10-2379-2017.

Scheff, J., Frierson, D.M.W., 2014. Scaling Potential Evapotranspiration with Greenhouse Warming. J. Clim. 27, 1539–1558. https://doi.org/10.1175/JCLI-D-13-00233.1.

Seneviratne, S.I., Lüthi, D., Litschi, M., Schär, C., 2006. Land-atmosphere coupling and climate change in Europe. Nature 443, 205–209. https://doi.org/10.1038/nature05095.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture-climate interactions in a changing climate: A review. Earth-Science Rev. 99, 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004.

Sherwood, S., Fu, Q., 2014. A drier future? Science 80-.) 343, 737–739. https://doi.org/10.1126/SCIENCE.1247620/SUPPL_FILE/SHERWOOD.SM.PDF.

Simmons, A.J., Willett, K.M., Jones, P.D., Thorne, P.W., Dee, D.P., 2010. Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets. J. Geophys. Res. Atmos. 115, 1110. https://doi.org/10.1029/2009JD012442.

Soares, P.M.M., Cardoso, R.M., 2018. A simple method to assess the added value using high-resolution climate distributions: application to the EURO-CORDEX daily precipitation. Int. J. Climatol. 38, 1484–1498. https://doi.org/10.1002/joc.5261.

Soares, P.M.M., Cardoso, R.M., Miranda, P.M.A., de Medeiros, J., Belo-Pereira, M., Espirito-Santo, F., 2012. WRF high resolution dynamical downscaling of ERA-Interim for Portugal. Clim. Dyn. 39, 2497–2522. https://doi.org/10.1007/s00382-012-1315-2.

Soares, P.M.M., Cardoso, R.M., Lima, D.C.A., Miranda, P.M.A., 2017a. Future precipitation in Portugal: high-resolution projections using WRF model and EURO-CORDEX multi-model ensembles. Clim. Dyn. 49, 2503–2530. https://doi.org/10.1007/s00382-016-3455-2.

Soares, P.M.M., Lima, D.C.A., Cardoso, R.M., Semedo, A., 2017b. High resolution projections for the western Iberian coastal low level jet in a changing climate. Clim. Dyn. 49, 1547–1566. https://doi.org/10.1007/s00382-016-3397-8.

Spinoni, J., Naumann, G., Vogt, J.V., 2017. Pan-European seasonal trends and recent changes of drought frequency and severity. Glob. Planet. Change 148, 113–130. https://doi.org/10.1016/J.GLOPLACHA.2016.11.013.

Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P., Dosio, A., 2018. Will drought events become more frequent and severe in Europe? Int. J. Climatol. 38, 1718–1736. https://doi.org/10.1002/JOC.5291.

Swann, A.L.S., Hoffman, F.M., Koven, C.D., Randerson, J.T., 2016. Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. Proc. Natl. Acad. Sci. 113, 10019–10024. https://doi.org/10.1073/PNAS.1604581113.

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S.M., Volaire, F., Boone, A., Le Page, M., Llasat, M.C., Albergel, C., Burak, S., Cailleret, M., Kalin, K.C., Davi, H., Dupuy, J.L., Greve, P., Grillakis, M., Hanich, L., Jarlan, L., Martin-StPaul, N., Martínez-Vilalta, J., Mouillot, F., Pulido-Velazquez, D., Quintana-Seguí, P., Renard, D., Turco, M., Türkeş, M., Trigo, R., Vidal, J.P., Vilagrosa, A., Zribi, M., Polcher, J., 2020. Challenges for drought assessment in the Mediterranean region under future climate scenarios. Earth-Science Rev. 210, 103348 https://doi.org/10.1016/J.EARSCIREV.2020.103348.

Turco, M., Palazzi, E., von Hardenberg, J., Provenzale, A., 2015. Observed climate change hotspots. Geophys. Res. Lett. 42, 3521–3528. https://doi.org/10.1002/2015GL063891.

Vicente-Serrano, S.M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., Espejo, F., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ. Res. Lett. 9, 044001 https://doi.org/10.1088/1748-9326/9/4/044001.

Vicente-Serrano, S.M., Nieto, R., Gimeno, L., Azorin-Molina, C., Drumond, A., Kenawy, A.E., Dominguez-Castro, F., Tomas-Burguera, M., Peña-Gallardo, M., 2018. Recent changes of relative humidity: regional connections with land and ocean processes. Earth Syst. Dynam 9, 915–937. https://doi.org/10.5194/esd-9-915-2018.

Watson, A., Miller, J., Künne, A., Kralisch, S., 2022. Using soil-moisture drought indices to evaluate key indicators of agricultural drought in semi-arid Mediterranean Southern Africa. Sci. Total Environ. 812, 152464 https://doi.org/10.1016/J.SCITOTENV.2021.152464.

Willett, K.M., Jones, P.D., Thorne, P.W., Gillett, N.P., 2010. A comparison of large scale changes in surface humidity over land in observations and CMIP3 general circulation models. Environ. Res. Lett. 5, 025210 https://doi.org/10.1088/1748-9326/5/2/025210.

Willmott, C.J., Robeson, S.M., Matsuura, K., 2012. A refined index of model performance. Int. J. Climatol. 32, 2088–2094. https://doi.org/10.1002/joc.2419.

Yin, D., Roderick, M.L., Leech, G., Sun, F., Huang, Y., 2014. The contribution of reduction in evaporative cooling to higher surface air temperatures during drought. Geophys. Res. Lett. 41, 7891–7897. https://doi.org/10.1002/2014GL062039.

Zhang, Q., Fan, K., Singh, V.P., Song, C., Xu, C.Y., Sun, P., 2019. Is Himalayan-Tibetan Plateau "drying"? Historical estimations and future trends of surface soil moisture. Sci. Total Environ. 658, 374–384. https://doi.org/10.1016/J.SCITOTENV.2018.12.209.