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How persistent and hazardous will extreme temperature events become in a warming Portugal?

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ABSTRACT

The impact of rising greenhouse gases (GHGs) in the atmosphere on the temperature distributions is felt not only in the mean values but primarily in the extremes. The temperature distributions are becoming slightly flattened and more broadened towards higher values, leading to a decrease in extreme cold events and more importantly to a considerable increase in the frequency and intensity of extreme hot events. These changes are no longer simple projections but are already occurring. It is thus imperative an assessment of the projected changes even under reduced emissions scenarios for the entire 21st century. In this study, a multi-variable ensemble based on 13 EURO-CORDEX high-resolution simulations at 0.11° resolution, was used to analyse the extreme heat events as well as the Universal Thermal Climate Index (UTCI) for such extremes between March and November over Portugal. The 13 simulations have in common three Representative Concentration Pathways (RCP), RCP2.6, RCP4.5 and RCP8.5 as well as data covering a historical period (1971–2000) and three future consecutive periods, 2011–2040, 2041–2070 and 2071–2 100. The results show that severe future heatwaves will develop beyond the extended summer months in all scenarios. Even under a high mitigation scenario (RCP2.6), the number of heatwaves will more than double in number, relative to the historical record. In the high emission scenario (RCP8.5), a sharp increase in the number, severity and areal extension of heatwaves is projected for the end of the 21st century. The analysis of the heat stress indicates that most of the projected future heatwaves will induce heat stress and the projected increase in areal extension and the number of occurrences will have an impact on morbidity and mortality rates simply due to the shear rise in the number of the affected population and the increased frequency of occurrence.

Contributions

RMC designed the paper contributed to the writing of all sections, conducted all computations and produced some figures; DCA Lima contributed to the writing of all sections and produced some figures. PMMS contributed to the writing of all sections. All authors revised and approved the manuscript.

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1. Introduction

It is undisputed that global surface temperatures have been increasing since the pre-industrial period (IPCC et al., 2013; 2021). The last decade (2011–2020) was 1.09 [0.95 to 1.20] °C warmer than the 1850–1900 period (IPCC et al., 2021) and the past six years were the hottest since 1850. In addition to the rising of mean temperatures, the frequency and intensity of extreme heat events, such as heatwaves and droughts, have also escalated (Schär et al., 2004; Meehl et al. 2004; Barriopedro et al., 2011; Perkins et al., 2012; Schleussner et al., 2017; Cardoso et al., 2019; Seneviratne et al., 2021; Fischer et al., 2021). In recent years an increase in the frequency of occurrence of heatwaves and the number of warm days and nights in some parts of Europe (Giorgi and Lionello, 2008; IPCC et al., 2021; 2013; Trenberth, 2011), as well as the decrease in the number of cold days, is undeniable. According to the future projections from the Fifth and the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC et al., 2013; 2021), the present observed trends will continue to rise throughout the 21st century over 80% of the world's land regions. Extreme high temperatures are expected to increase at a steeper rate than the mean temperature (Weisheimer and Palmer 2005; Meehl et al., 2007; Schär et al., 2004; Schoetter et al., 2015). Although this increase is mostly

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attributable to shifts in the median, an amplification factor greater than 1.5 is associated with the broadening of the maximum temperature probability density functions (Schoetter et al., 2015). Heatwaves are events where extreme temperatures occur during consecutive days and as greenhouse gas concentrations continue to rise according to the projections for future scenarios, these are expected to increase in frequency, intensity (or severity) and duration as well as geographical extension (or spatial extent) (Fischer et al., 2008; Russo et al., 2014; King and Karoly, 2017; Dosio et al., 2018; Cardoso et al., 2019; Molina et al., 2020). However, there is no universal definition for heatwave (Jacob et al., 2014). According to the World Meteorological Organization (WMO), a heatwave is an extreme weather event with marked warming of the air over a large area, lasting more than 5 days. In Frich et al. (2002), a heatwave is defined as a period where the maximum temperature is above the 90th percentile for more than 5 consecutive days. Similarly, in Fischer and Schär (2010) a heatwave is defined as a period where the maximum temperature is above the 90th percentile for more than 6 consecutive days. In Russo et al. (2015) a heatwave is an event where the temperature is above the 90th percentile for more than 3 consecutive days. In Schoetter et al. (2015), a heatwave event is considered with 3 consecutive days above the 98th percentile. The historical European heatwaves from 1979 to 2019 are evaluated by Becker et al. (2022) using different metrics and through four distinct indices (the heat wave magnitude index daily (HWMId), excess heat factor (EHF), wet-bulb globe temperature (WBGT) and universal thermal climate index (UTCI)). Even following different definitions, a similar assessment can be performed through the description of its duration, severity, and spatial extent. This allows a portrayal of present heatwaves occurrences but also an evaluation of its evolution throughout the 21st century. Heatwave events result in higher morbidity and mortality rates and increases in many risks besides health-related ones, such as rises in agricultural losses (Sivakumar, M.V. 2020), wildfires, and energy and water consumption, among others (Horton et al., 2016). The duration of the heatwaves has, however, a lower impact on mortality rates than the intensity of the event (Xu and Tong, 2017). As the recent European extreme heat waves demonstrated, their impact on human health has led several countries to implement heat warning systems (Casanueva et al., 2019). In 2003, more than 70, 000 additional deaths occurred during summer in Europe (Robine et al., 2008) as a result of the massive heatwaves that hit Europe. With rising temperatures and the associated increase in the occurrence of extreme events, robust information on heatwaves is crucial to help decision-making by the different sectors to adopt measures to minimise the risks and potential damages and design adaptation strategies.

Located in the western tip of the Mediterranean basin, Portugal has been identified as a climate change “hotspot”, exposing human and natural systems to new sources of risk (Turco et al., 2015). In line with the future projections over the Mediterranean basin, an increase in the frequency and intensity of the heat extremes are expected (Cardoso et al., 2019; Molina et al., 2020; Sánchez-Benítez et al., 2020; Lorenzo et al., 2021; Díaz-Poso et al., 2023). It is also undeniable that these changes are attributable to the rise in greenhouse gas concentrations from anthropogenic sources (Beniston et al., 2017; Vautard et al., 2020, IPCC et al., 2021). Adaptive measures are thus needed to alleviate problems, even under scenarios with strong mitigation (IPCC et al., 2021). Thus, robust information about the geographical and temporal extent, in addition to the intensity and duration of heatwaves is needed for the development of mitigation and adaptation strategies, encompassing future projected climates ranging from highly-to non-mitigated emission scenarios.

Extreme heat events affect thermal comfort conditions, and consequently human health (Karyono et al., 2020). The increase in heat stress associated with these extremes compromises the body’s thermoregulatory ability, leading the body to absorb or generate more heat than it can dissipate (Kovats and Hajat, 2008). This induces an increase in core internal temperature which can disrupt underlying health conditions and in extreme situations death (Koppe et al., 2004). The projected increase in heatwave events is thus unfavourable to public health which will be greatly deteriorated if greenhouse gas emissions are not considerably reduced (Kang and Lu, 2012). The Universal Thermal Climate Index (UTCI) aims to assess the outdoor thermal conditions in the major fields of human biometeorology (Bröde et al., 2012). It describes the heat stress to which the human body is exposed, considering a combined contribution of human physiology, meteorological parameters, and human clothing. The UTCI has been used to obtain a heat stress characterization and to analyse the related effects on human health (Di Napoli et al., 2019; Jendritzky et al., 2012; Fiala et al., 2012). Days with high UTCI are associated with increased mortality and in the number of outpatients independently of any underlying condition (Nastos and Matzarakis 2012; Urban and Kyselý 2014; Burkart et al., 2016; Błażejczyk et al., 2017; Di Napoli et al., 2018). Conditions of moderate and strong heat stress are related to summer mortality rates in Portugal and the slope between mortality and monthly average UTCI becomes steeper at 26 and 32 °C (Di Napoli et al., 2018). In an analysis of the UTCI for France, Di Napoli et al. (2019) found that the UTCI 95th percentile is a good threshold for the induction of health-related problems due to heat stress. Thus, the UTCI is an important index which can be used as an indicator of the impact of heatwave health hazards and to characterise the impact of future projections concerning extreme events on human health.

While the 21st century’s escalation of temperature and its extremes for Portugal has already been assessed in previous studies (Ramos et al., 2011; Andrade et al., 2014; Cardoso et al., 2019), they were solely focused on temperatures above the 90th percentile, none has investigated the extreme temperatures above the 95th percentile, neither examined the progression of temperatures changes in spring and autumn nor analysed the high mitigation scenario RCP2.6. Additionally, the impact of these changes on human health has never been attempted. Here, we propose to evaluate the evolution of extreme heat which occurs during five or more consecutive days, i.e., heatwaves, using a multi-variable ensemble based on thirteen EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment over European domain) high-resolution simulations at 0.11° resolution. Extreme heat in mainland Portugal will be assessed through the exceedance of the 1971 to 2000 90th and 95th maximum temperature percentiles for five or more consecutive days. These, in conjunction with the UTCI health index, provide a depiction of the impact of the heatwaves on human health. Additionally, using the same methodology as for the assessment of temperature extremes, we examine the evolution of extreme heat stress (UTCI above the 95th percentile) for more than 5 consecutive days. The paper is comprised of 4 sections: introduction (section 1), data and the methodology (section 2), results (section 3) and their discussion and conclusions (section 4).

2. Data and methods

To quantify the heatwave and heat stress climate signal for the 21st century, we analyse the EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment over European domain) Regional Climate Models (RCMs) projections for three CMIP5 Representative Concentration Pathways (RCP) scenarios, RCP2.6, RCP4.5 and RCP8.5 (Van Vuuren et al., 2011). The analysis will focus on the historical period from 1971 to 2000 and three future time intervals: near future (2011–2040), mid-century (2041–2070) and end of the century (2071–2 100). The RCP scenarios presume that the effect of the greenhouse gases will be equivalent to three different radiative forcing increases, relative to the pre-industrial era, by the end of the 21st century (2.6 W/m^2 for RCP2.6, 4.5 W/m^2 for RCP4.5 and 8.5 W/m^2 for RCP8.5). In RCP2.6 the peak of global emissions occurs between 2010 and 2020 (Moss et al., 2010; van Vuuren et al., 2011), while in RCP4.5 these will peak around 2040 and stabilise until 2 100. RCP8.5 assumes that there are no cuts to emissions throughout the 21st century (Riahi et al., 2011).

2.1. EURO-CORDEX simulations

The EURO-CORDEX maximum and minimum daily temperatures (K), wind speed (ms^{-1}), surface pressure (hPa), specific humidity (1), upwelling and downwelling long and shortwave radiation (Wm^{-2}) at 0.11° resolution were retrieved from the ESGF[1] portal (*Earth System Grid Federation*). The dataset spans a historical period from 1971 to 2000 and a future period from 2006 to 2 100. A summary of the used RCMs and their driving GCMs (Global Climate Models) is supplied in Supplementary Material Table S1. There, are more than 100 EURO-CORDEX simulations stored in the portal, yet not all scenarios were simulated by all RCMs. Thus, to obtain a robust assessment across scenarios, only the pair GCM/RCM with projections for the three scenarios were employed here.

2.2. Heatwaves

Although there is no universal definition for heatwave, here we follow Frich et al. (2002) and Cardoso et al. (2019) i.e., a heatwave occurs whenever the maximum temperature is above the historical 90th percentile for five or more consecutive days. To account for extreme heatwaves and the changes in the temperature distributions due to climate change, heatwaves with temperatures above the 95th percentiles were also considered. To analyse the impact of these heatwaves, we assess the average number per year, duration, the areal extension, and severity. The latter follows Russo et al. (2015) and is the sum of the daily adimentionalised maximum temperature during the event:

$$M_d(T_d) = \begin{cases} \dfrac{T_d - P_{25}}{P_{75} - P_{25}} \; if \; T_d > P_{25} \\ \\ 0 \; if \; T_d \leq P_{25} \end{cases} \quad (1)$$

Where $M_d(T_d)$ is the daily maximum temperature magnitude of the consecutive days composing the heatwave, T_d is the daily maximum temperature above the daily percentile threshold (P_{90} or P_{95}), P_{25} and P_{75} are 25th and 75th annual percentiles, respectively, of the historical maximum temperature daily time series as in Cardoso et al. (2019). The daily percentile threshold is obtained for each day of the year using a 31-day window centred on the day (Russo et al., 2015). Using the entire time series allows the detection of early spring and late autumn heatwaves due to the lower 25th percentile. The daily severity is measured as a fraction of the interquartile difference, thus whenever $M_d(T_d)$ [eq. (1)] is above one, the maximum temperature is not only above the daily 90th or 95th percentile but also in the highest 25% of the entire time series (P_{75}). If $M_d(T_d) = 2$ then the temperature anomaly to the historical 25th percentile is twice the heatwave magnitude unit, i.e., the historical interquartile range. The maximum severity is given by the sum of $M_d(T_d)$ during each heatwave. This approach is intrinsically linked to the length of the event and, short heatwaves with high daily severities can be overshadowed by long mild heatwaves. Since the impact of the first can be stronger than the latter, here we will also analyse the mean severity (S_M), i.e., the mean of the daily severities during each heatwave. In this work, whenever a heatwave's S_M is above the historical' s mean severity 90th percentile, then it is considered an extreme event. Four degrees of severity will be contemplated: *low severity* when $S_M < 1$, *severe* when $1 < S_M < P_{75}$, *high severity* when $P_{75} < S_M < P_{90}$ and *extreme* $S_M > P_{90}$.

2.3. Universal thermal climate index (UTCI)

The Universal Thermal Climate Index (UTCI) was developed by the European Cooperation in Science and Technology (COST) Action 730 and was computed following the operational procedure presented by (Bröde et al., 2012), using the freely available code from http://www.utci.org/. This index aims to assess the human body's outdoor thermal stress in terms of one-dimensional quantity summarising the interaction of environmental temperature, wind speed, humidity, and long- and short-wave radiative fluxes. The assessment is based on the physiological response of the human body to thermal comfort/discomfort when walking at a speed of 4 km/h. To this end, a thermo-physiological model coupled to a clothing model is employed (Bröde et al., 2012; Fiala et al., 2012). The behavioural adaptation of clothing insulation, the distribution of clothing over different body parts, and the reduction of thermal and evaporative clothing resistances caused by wind and movement of the wearer is considered. The index is a function of the environmental air temperature, mean radiant temperature, T_{mrt} (the equivalent black-body temperature that exchanges the same net radiative energy with a human subject as the environment), wind speed and vapor pressure:

$$UTCI = f(T_{air}; T_{mrt}; WS; pv) = T_{air} + offset\,(T_{air}; T_{mrt}; WS; pv)$$

The environmental reference conditions were determined as a wind speed WS = 0.5 ms^{-1} at 10 m height, a mean radiant temperature T_{mrt} equal to air temperature Tair and vapor pressure pv that represents a relative humidity of RH = 50%. At high air temperatures (Tair ≥29 °C) the reference humidity is constant at 20 hPa (Blazejczyk et al., 2017).

T_{mrt} was calculated (Kántor and Unger, 2011), with a wet bulb globe temperature Tg that was approximated according to Liljegren et al. (2008) and Hall et al. (2022). Details can be found in Jendritzky et al. (2012), Fiala et al. (2012) or Havenith et al. (2012). Due to missing gridded observations, no bias correction was applied.

The UTCI was employed to obtain a heat stress characterization using the classes presented in Table 1.

2.4. Methods

2.4.1. Ensemble building

As in Cardoso et al. (2019) and Lima et al. (2023), a multi-model ensemble is built, based on weighted scores for maximum, and minimum 2-m air temperature and precipitation. Firstly, each RCM precipitation, maximum and minimum temperatures time series were compared with the regular gridded observational dataset Iberia 0.1 (Herrera et al., 2019) using eight metrics (Cardoso et al., 2019): bias, mean average error, root-mean-square, normalised standard deviation (ratio between model and observations' standard deviation), spatial correlation, Willmott-D Score, Perkins Skill Score and Yule-Kendall skewness measure. Secondly and for each variable, each RCM is ranked individually for each time series. For each variable and model, weights were, then, constructed by multiplying the ranks and by dividing this value by the sum of all model ranks. Thus, for each variable, the sum of the weights is one. Finally, the ensemble weights for the three variables were obtained by a weighted average of the individual variable weights where precipitation has a 50% load and maximum and minimum temperatures have a 25% load each. These weights are used to summarise the climate change signal from the 13 RCM heatwave metrics (length, severity, number, and areal extension) and daily UTCI (see

Table 1
UTCI based event classification.

UTCI value	Classification
≥ 46	Extremely hot
[38, 46[	Very hot
[32, 38[	Hot
[26, 32[	Moderately hot
]9, 26[	No heat stress
]0, 9]	Slightly cold
] − 13, 0]	Moderately cold
] − 27, − 13]	Cold
] − 40, − 27]	Very cold
≤ 40	Extremely cold

[1] ESGF-LIU - Home | ESGF-CoG

previous sections for definitions). Additional details of the methodology for the development of the ensemble and a discussion of its performance are provided in Lima et al. (2023).

2.4.2. Percentiles

The procedure used to determine the different percentiles follows Zhang et al. (2011) and is the methodology recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI – Zhang et al., 2011). A bootstrapping methodology is applied to the maximum temperature time series and the percentile times series is built. In this way, artificial percentile discontinuities are avoided at the end of the historical period percentiles time series.

2.4.3. Heatwave assessment

To analyse the impact of the heatwaves three methodologies were pursued.

1) Following Cardoso et al. (2019), yearly 25th and 75th percentiles (30 values) were obtained from each RCM's entire maximum temperature historical time series. Following Russo et al. (2015), 90th and 95th percentiles were obtained for each day of the year centred on a 31-day window (30 × 366 days). The heat temperature exceedances were obtained from March to November to account for changes in the temperature distribution due to climate change and capture all relevant heatwaves from early spring to late autumn. The weighted ensemble mean is then obtained for the number, length, areal extension (percentage of land pixels under heatwave conditions) and severity. Note that the results for heatwaves with a temperature above P_{90} also encompass the results for temperatures above P_{95}, thus a heatwave with $T_{\max} > P_{90}$ can contain an extreme event with 5 or more days with maximum temperatures above P_{95};
2) The days within a heatwave (determined by the maximum temperature threshold) were then used to analyse the UTCI index to assess the impact on the human body of consecutive extreme heat;
3) The 95th percentile for each day of the year centred on a 31-day window and the yearly 25th and 75th percentiles were obtained from each RCM's entire daily UTCI index historical time series. A similar methodology to the maximum temperature (point 1) was applied to the UTCI time series.

The future projections, in points 1 and 3, were obtained using the historical percentiles as thresholds.

3. Results

3.1. Heatwaves

In the historical period, the average number of heatwaves per year fluctuates between 1 and 2 over continental Portugal (Fig. 1). Within the historical heatwaves, there is at least one period of temperatures above the 95th percentile, on average (Fig. 1b). For all the scenarios and future periods, the rise in the number of heatwaves is larger in the interior than near the coast. For all heatwaves ($T_{\max} > P_{90}$) and at the beginning of the century, all RCPs project 2 to 3 events near the coast and 3 to 4 in the remaining regions. Additionally, in some localised regions near the border, 4 to 5 heatwaves are projected in RCP8.5 (Fig. 1a). During this period, the coastal areas will continue to experience on average one to two very extreme events ($T_{\max} > P_{95}$) per year in all scenarios, whilst the remaining areas in RCP2.6 and RCP8.5 will endure 2 to 3 (Fig. 1b); only in RCP4.5 will the number of events not change. The west-east gradient increases for the middle of the century, and as expected, the escalation in GHGs corresponds to a steeper gradient. For the end of the century, the GHG reduction from 2020 onwards in RCP2.6 leads to a scenario like the beginning of the century. In RCP4.5, 5 to 6 heatwaves are projected for the middle of the century near the Spanish border, of which 3 to 4 will encompass consecutive extreme temperatures above P_{95} for 5 or more consecutive days. At the end of the century, the tapering of emissions from mid-century onwards still implies an increase of one heatwave relative to mid-century. In the worst-case scenario (RCP8.5), the average

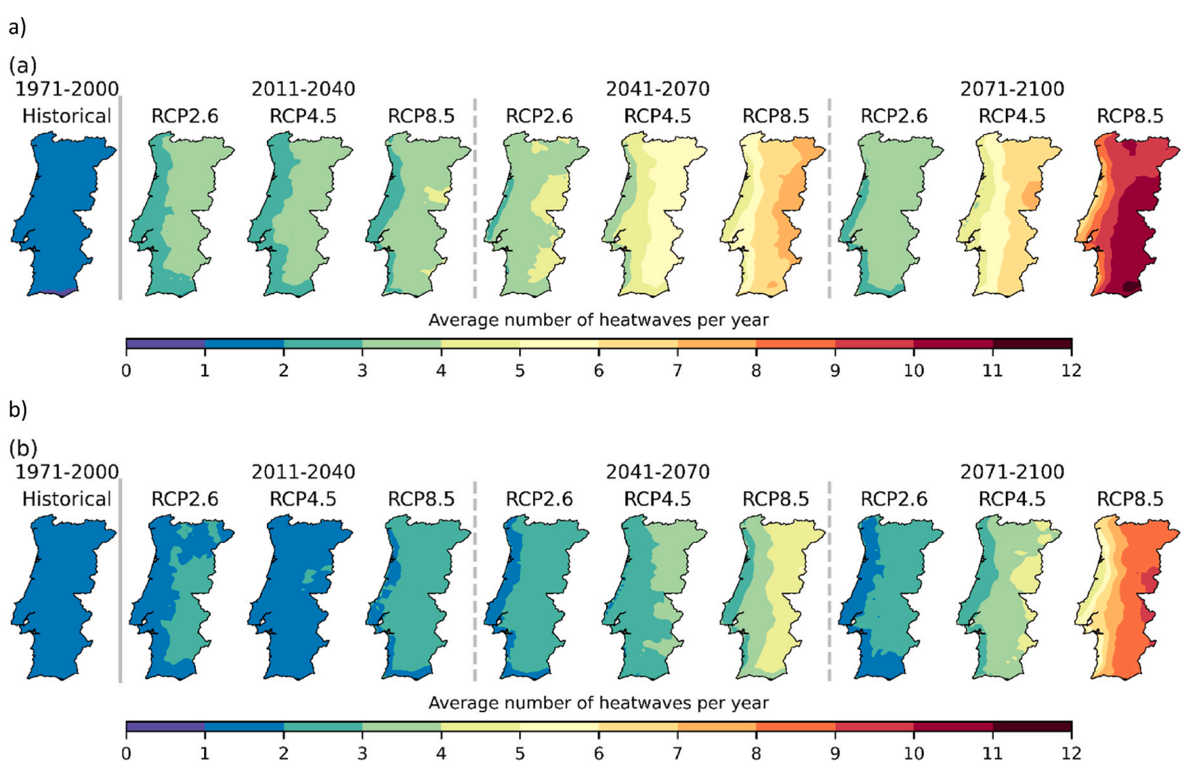

Fig. 1. Annual average number of heatwaves per year over mainland Portugal, for the historical period (1971–2000) and the future periods considering different GHG emission scenarios. Maximum temperature above a) 90th percentile; b) 95th percentile.

number of heatwaves is projected to become between 9 and 11 for most of the country, reaching 12 events per year in a small area in the south. For the first area, very extreme events will occur 6 to 9 times. The average length of heatwaves is 6–7 days within the historical period and increases considerably near the Spanish border, reaching an average of 13 days per event in RCP8.5 for the end-of-century. As before, a west-east gradient is observable, whereby the areas near the coast have smaller rises with an average duration of 8–10 days per heatwave (Fig. 2a). For RCP2.6 and RCP4.5, there is not such a marked west-east gradient but still increases of 1–2 days in the average duration of heatwaves can be expected. The average length of the very extreme events ($T_{\max} > P_{95}$) is smaller by one day in all scenarios. Looking at the future projections of the maximum duration of a heatwave, a significant increase is expected for RCP8.5 where the maximum duration of a heatwave can reach more than two months in the northeast (Fig. S1a). In this area, more than 40 consecutive days can have temperatures above P_{95}. Although in the other two RCPs, the increase is smaller, the projections show a maximum duration that can surpass one month. The multi-model spread in future projected heatwaves, considering the 1971–2000 period as a reference, is quantified by the standard deviation of the anomalies between different models (Figs. S2 and S3). The standard deviation is always lower than the change signal and at least 66% of the models agree with the change signal for all grid-points, periods, and scenarios, which shows high consistency between the ensemble members and low uncertainty in the projections.

The cumulative distribution of the length of the events for the entire country (Fig. 3a) shows that, for both percentile thresholds (90 and 95th), 60% of heatwaves in the historical period last between 5 and 6 days, with 90% of heatwaves persisting for less than 7 days and with a maximum length of less than 20 days. In RCP2.6 the median length is circa 6 days for the three time slots (2011–2040, 2041–2070, 2071–2 100), but even the small increase in GHGs leads to an expansion of the maximum temperature probability distribution function's tail and now 90% of the events have less than 11 days (an increase in the duration of 5 days). For the very extreme events, where the maximum temperatures are above the 95th percentile, there is no change in the median, but 90% of these events last less than 9 days at the beginning and end of the century and 10 days at mid-century. In RCP4.5, for the mid and late 21st century, 50% of heatwaves last one more day than in the historical period and 90% are also five days longer (12 days). At the end of the century, for RCP8.5, the number of the shortest heatwaves (5 and 6 days) are half of the historical and the median length is now close to 8 days. Now 40% of heatwaves (from the median to P_{90}) endure between 9 and 17 days, with the very extreme events where temperatures are consecutively above the 95th percentile, persevering between 8 and 15 days. The median of the mean severity (average of the daily severity during each heatwave) is 1.15, with 29% of events with low severity ($S_m < 1$) (Fig. 3b). Since heatwaves during the periods between May and September (MJJAS – enlarged summer) have mean severities above 1 (not shown), these lower severity events occur in early spring and late autumn. 90% of heatwaves have average severities lower than 2, i.e., in extreme events $S_m \geq 2$. High-severity events take place when $S_m \geq 1.8$. The average severity of the heatwaves does not change significantly with the length of the heatwave (not shown), i.e., when analysed for events with lengths of 5, 6, 7, 8, 9, 10, 15 and 20 days, it oscillates between 1.1 and 1.4 for the median number of events and 1.2 and 1.8 for 75% of events (higher values correspond to the smallest heatwaves, indicating the occurrence of extreme temperatures within the event which drive an increase in the average, as well as the presence of short events above P_{95}). Although the mean severity increases by 0.2 in all percentiles by mid-century, in RCP2.6; at the end of the 21st century the severity distribution is similar to the historical. In RCP4.5, the median of the events has an average severity of 1.2, with only 26% with low severity by the end of the century (a reduction of 3% relative to the historical period). In this scenario and by the end of the century, there is an increase in events in the early spring and late autumn with average severities larger than 1 (there is a 5% and 4% increase of high severity events for temperatures above P_{90} and P_{95} respectively). The stabilisation of the GHGs by mid-century has the potential to reduce the severity of the extreme heatwaves at the end of the century to values similar to

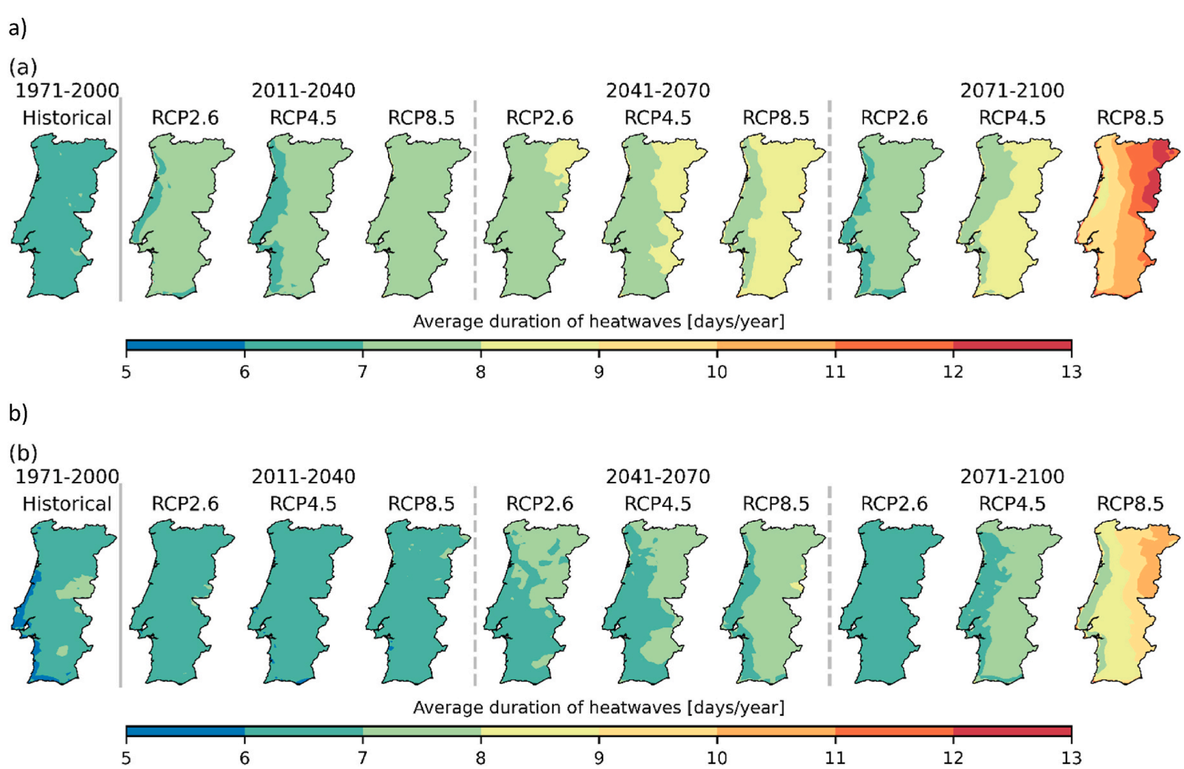

Fig. 2. Annual average length of heatwaves per year for the historical period (1971–2000) and for the future periods considering different GHG emission scenarios. Maximum temperature above a) 90th percentile; b) 95th percentile.

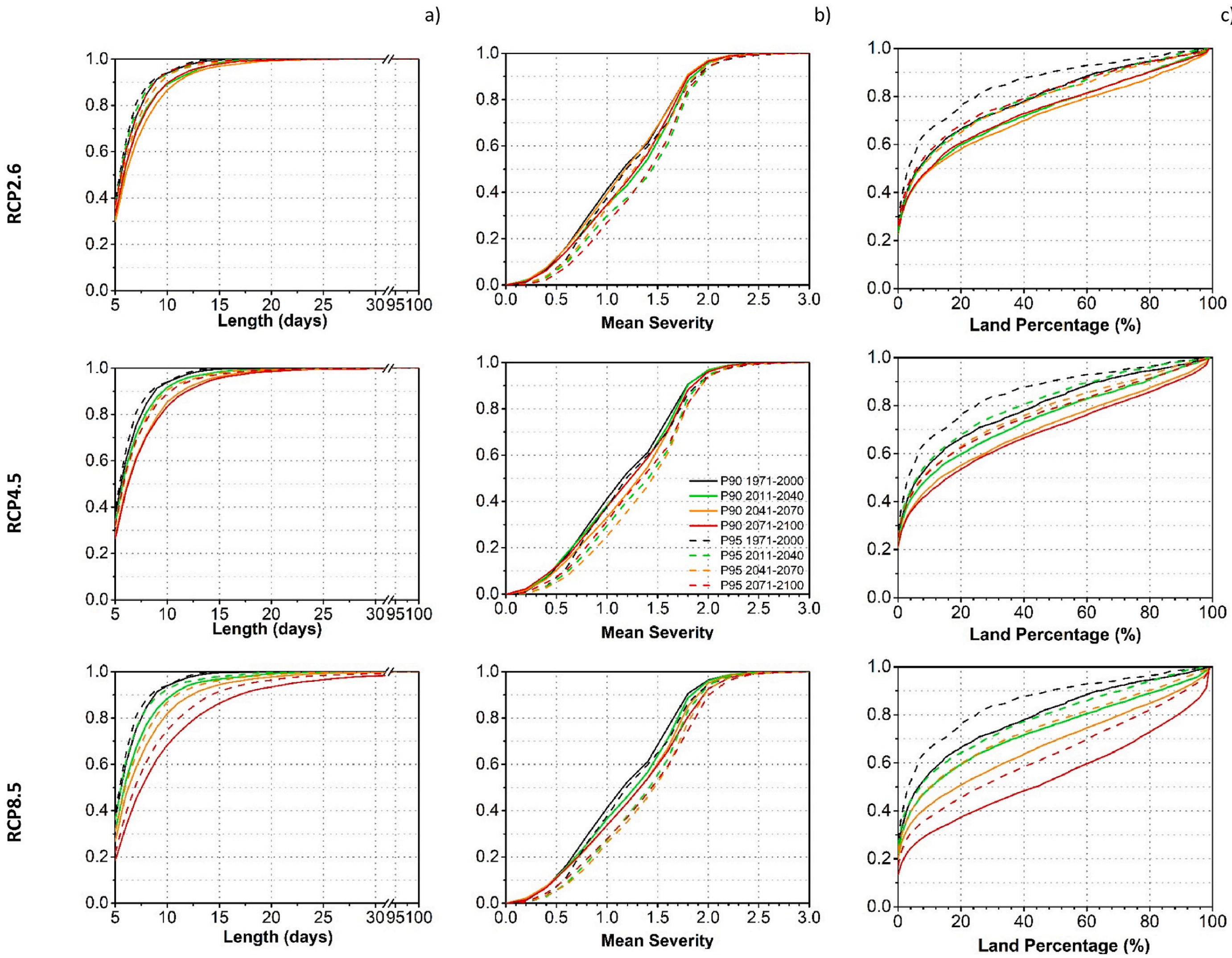

Fig. 3. Multi-model ensemble empirical cumulative distribution functions of heatwave a) length (days), b) severity and c) areal extension (%) for the historical period (1971–2000) and for the future periods considering different GHG emission scenarios.

the early 21st century. For RCP8.5, less than a quarter of heatwaves are projected to have low severities and the median of the events has mean severity of circa 1.3, indicating that the maximum temperature becomes more skewed to larger values. 50% have mean severities above 1.5. This is even more significant in the occurrence of the very extreme events, whereby an increase of 10% of the extreme events and the maximum mean severity is 3.8 (a value not registered in the historical time series). The land percentage covered by the heatwave events is shown in Fig. 3c. In the historical period, 50% of the events occupy less than 8% of continental Portugal, 75% cover only 35% of land and only 5% envelop more than 83%. As the GHGs increase, an areal expansion occurs. While in RCP2.6 and at the end of the century, 50% of heatwaves cover less than 11%, and 10% of the heatwaves expand beyond 80% of the territory; in RCP8.5, 50% of the events will envelop up to 45% of land and more than 90% of territory will be in heatwave in 20% of the events. In this most severe scenario, 50% of the extreme heatwaves ($T_{max} > P_{95}$) will overlay less than 27% of land and only 10% will fill more than 91%

3.2. UTCI

3.2.1. Spring to autumn UTCI climatology

The climatological spatial distributions of the universal thermal climate index (UTCI) for mainland Portugal (Fig. 4) shows that the entire country has no heat stress in the historical period during summer and that Portugal has a slight cold stress in most of the areas north of the Tagus River basin during spring and in the north-eastern region in autumn. Throughout the 21st century, in all scenarios, the land area with a slightly cold condition changes to no heat stress in spring, in RCP8.5, while in RCP2.6 and 4.5 the northeast will still experience slightly cold conditions. In summer and by mid-of-century, in RCP4.5 and RCP8.5, an area in the southeast, near the Spanish border, changes its thermal comfort condition to moderately hot stress, that expands to most of south and centre regions by the end-of-century in RCP8.5. In autumn, and from mid-century onwards, only some very limited areas in the northeast will feel slightly cold conditions in all scenarios.

3.2.2. UTCI under heatwave

To analyse the effect of heat stress during the occurrence of heatwaves, the analysis of daily UTCI was constrained to the days under a temperature driven heatwave (Fig. 5). In the historical period, 50% of heatwaves have a UTCI of less than 21, indicating that on average they do not pose much heat stress and alleviate cold spring and autumn temperatures (Fig. 5a). Only 24% induce a classification of moderately hot and only 1% are on average hot. However, from the maximum severity (Fig. 5b), 75% of these events have within them days with UTCI larger than 26 (moderately hot), and 15% can have hot conditions (UTCI

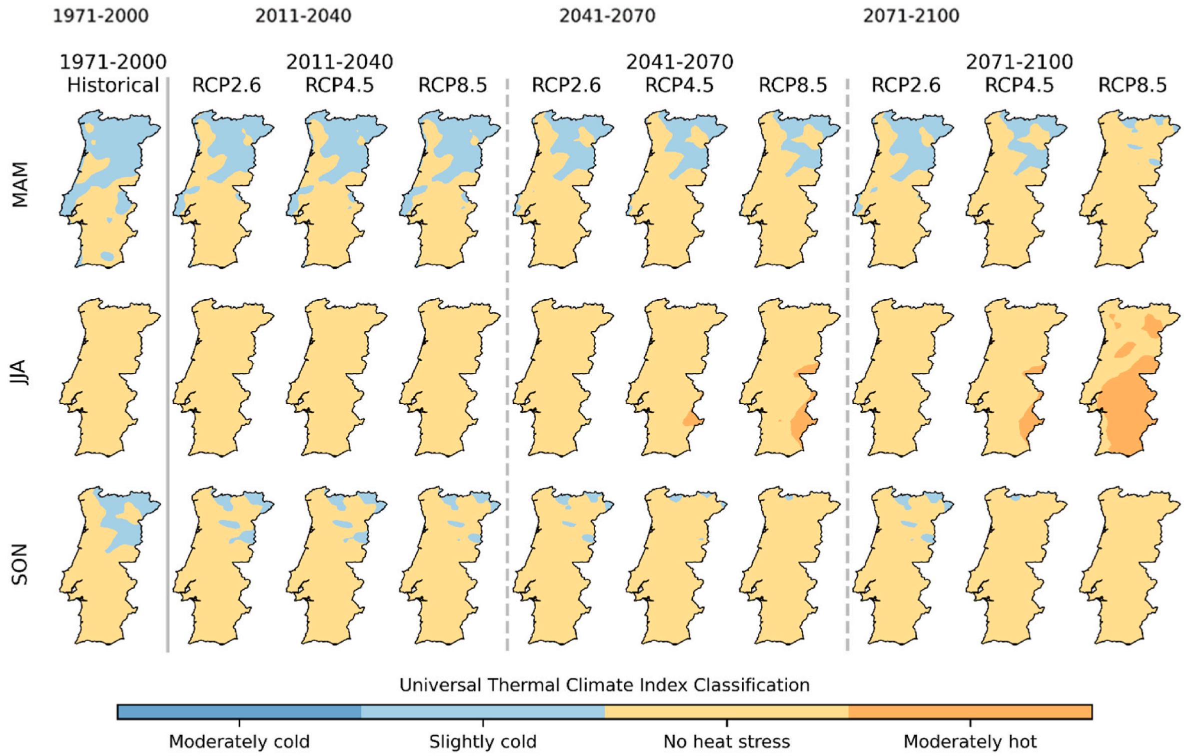

Fig. 4. MAM, JJA and SON Universal Thermal Climate Index Classification over mainland Portugal for historical climatological period (1971–2000) and for the future periods considering different GHG emission scenarios. The different rows from top to bottom represent averaged taken over all months. The different columns represent the future periods considering different GHG emission scenarios.

larger than 32). Even with the reduction in GHGs at the end of the 21st century, in RCP2.6, an increase of 7% of events with average moderately hot conditions, a 27% rise in heatwaves with moderately hot days within the event is projected and 56% of the heatwaves will have hot days within them. For the most severe scenario and by the end of the 21st century, 39% of heatwaves will be moderately hot on average and 10% will have an average of hot conditions. Within all heatwaves, only 1% will not have a moderately hot day, 89% will have at least a day with maximum UTCI above 32 (hot days) and most significantly will be the 32% with very hot conditions.

3.2.3. *UTCI heat stress*

Since the perception of extreme heat by the human body is not limited to the influence of temperature alone, here and following Di Napoli et al. (2019) we use the 95th percentile as a threshold for extreme heat and apply a similar methodology as in section 3.1. Hence, in this context, extreme heat stress occurs when UTCI's daily P_{95} is exceeded for 5 or more consecutive days. As with heatwaves, and in the historical period, the extreme heat stress events per year fluctuates between 1 and 2 over continental Portugal (Fig. 6). At the beginning of the century, the number of cases increases to 2 to 3 in all scenarios and areas, indicating that while the coastal areas are not subject to an increase in the number of events with consecutive very extreme temperatures (Fig. 1b), the events with maximum temperature above P_{90} (Fig. 1a) will also induce heat stress. Additionally, at least one of the events with maximum temperature above P_{90} (Fig. 1a) farther from the coast will not generate heat stress. In RCP2.6 the number of events, at the end of the century, does not change relative to the beginning of the century. For both RCP4.5 and 8.5, the number of extreme heat cases, increases throughout the 21st century and in the latter scenario, more than 7 occurrences of extreme heat stress will arise. As before, this value is in between the number of events for $T_{\max} > P_{90}$ and $T_{\max} > P_{95}$. The length of these extreme heat stress events is less than 7 days and in some coastal and northern areas is less than 6 days (Fig. 6b). In those areas, the days with heat stress is lower than the days under heatwave (Fig. 2). In RCP2.6, and at the end of the century, the north will experience on average 7–8 days of consecutive heat stress, while in central and southern continental Portugal these events will last 6–7 days. In the most severe scenario, the length of these cases will be 9–10 days in the south and 10 to 12 near the Spanish border.

Fig. 7 shows the empirical cumulative distribution functions of the extreme heat stress and heatwaves. As expected, the length of the extreme heat stress events is larger than the extreme heatwaves for all scenarios and time periods. This is more prominent in RCP8.5. Here, the severity of the events is measured in a similar way as for heatwaves, i.e., it is a normalised distance from the UTCI P_{25}. For all scenarios the severity above 1. in heat stress occurs for fewer percentage of events than for extreme heatwaves and less than 5% have severities above 2. While in the historical period, the heat stress events cover less land than extreme heatwaves, in the projections for the 21st century all of these occurrences have a similar areal extension in RCP2.6 and 4.5. Yet, in RCP8.5 from mid-century onwards, the extent of these extreme heat stress events is considerably larger than the extreme heat waves. By the end of the century, 50% of the events will cover more than 40% of the country.

4. Discussion and conclusions

In the current study, a thorough assessment of the future of heatwaves is performed, based on a multivariable weighted ensemble of the EURO-CORDEX simulations in agreement with three emission scenarios. A special focus is given to extreme heat events (maximum temperatures above the historical 90th and 95th percentile) which occur for 5 or more consecutive days. These events were analysed individually or in tandem with the Universal Thermal Climate Index (UTCI). Additionally, extreme heat stress was investigated through the assessment of the events with UTCI above the historical 95th percentile, occurring for 5 or more consecutive days.

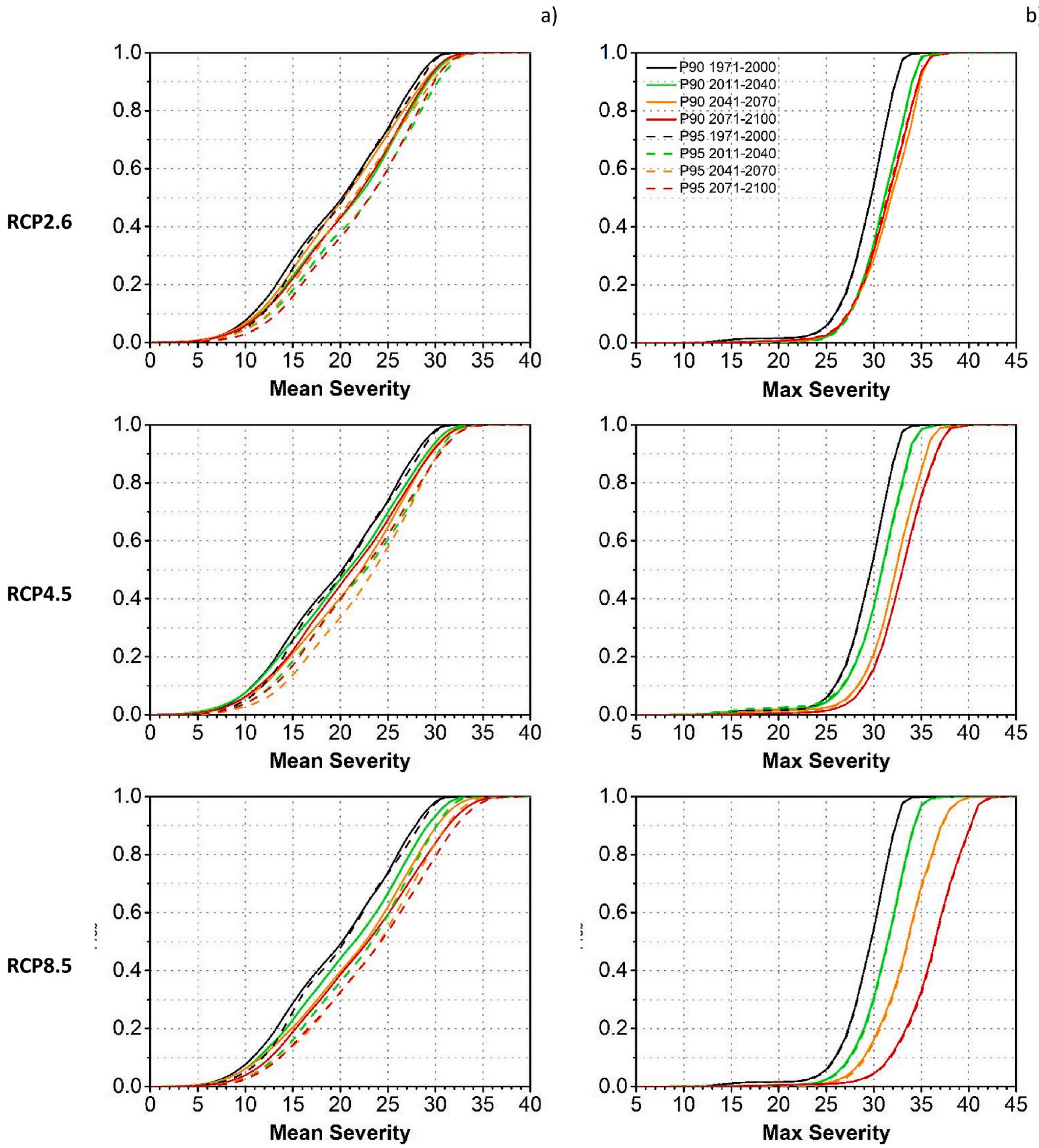

Fig. 5. Multi-model ensemble empirical cumulative distribution functions of Universal Thermal Climate Index Classification heatwave a) mean intensity and b) maximum intensity for the historical period (1971–2000) and for the future periods considering different GHG emission scenarios.

With the rising of temperatures and the associated increase in the occurrence of extreme events (Schär et al., 2004; Meehl et al. 2004; Barriopedro et al., 2011; Perkins et al., 2012; Schleussner et al., 2017; Cardoso et al., 2019; Seneviratne et al., 2021; Fischer et al., 2021; Lorenzo et al., 2021; Lima et al., 2023; Soares and Lima, 2022 Díaz-Poso et al., 2023), robust information of heatwaves is crucial to help different sectors to adopt measures to minimise the risks and potential damages. The results presented in this study show that in the historical period, in extreme events, $S_m \geq 2$ and high severity events take place when $1.8 \leq S_m < 2$. Even under a high mitigation scenario (RCP2.6), the number of heatwaves will more than double in number, relative to the historical record, with an additional 5% of severe events, and a further 3% will have high severities by the end of the century. In this scenario and the middle scenario (RCP4.5), the stabilisation of the GHGs by mid-century has also the potential to reduce the severity of the extreme heatwaves by the end of the century to values similar to the early 21st century. Nevertheless, these heatwaves will impact a larger number of people due to the rise in the percentage of the country enveloped. For the end of the 21st century and in the high emission scenario (RCP8.5), the effects of heatwaves are likely to be even harsher since a sharp increase in the number, severity and areal extension is projected. In most of the country, the number of events will increase 5 to 6-fold, with 40% of heatwaves enduring between 9 and 17 days, and less than 25% have low severity whilst 20% are extreme severe events. Additionally, events with unprecedented severity are also projected to emerge. The number of events, where temperatures are consecutively above the 95th percentile, are projected to rise 3 to 4-fold persevering between 8 and 15 days. Although the ensemble members and the model weights are different, Cardoso et al. (2019) also identified the development of unrecorded heatwaves (more severe and long-lasting) for the extended summer

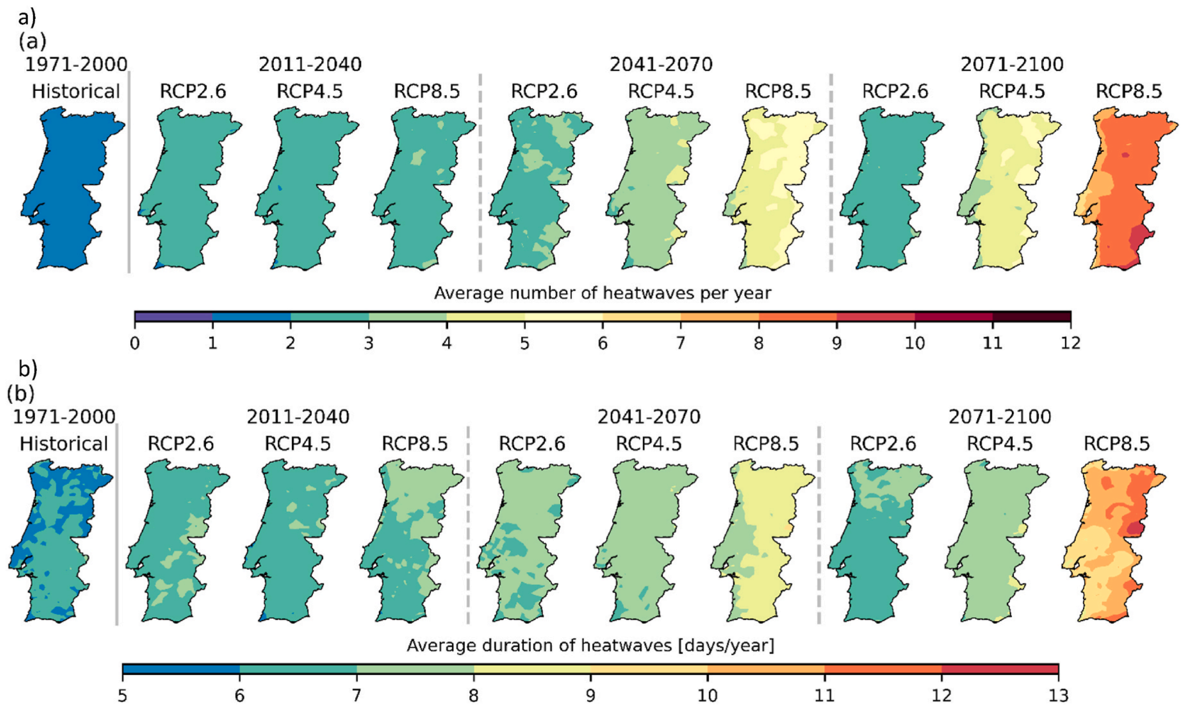

Fig. 6. Annual average number of heatwaves per year over mainland Portugal a) and annual average length of heatwaves per year b) for the historical period (1971–2000) and for the future periods considering different GHG emission scenarios.

(May to September) in RCP4.5 and 8.5. Perkins et al. (2012), Zschenderlein et al. (2019) as well as Cardoso et al. (2019), recognise that heatwaves occur beyond the summer months even in the historical period. Here, we also show that severe future heatwaves will develop beyond the extended summer months in all scenarios with possible extensive environmental and health impacts, increased energy demands and fire risk. The expansion of the areas under heatwave conditions projected for all scenarios as well as the increase in frequency, duration and severity is in line with other studies for Iberia, Europe (Fischer et al., 2010; Schoetter et al., 2015; Cardoso et al., 2019; Molina et al., 2020; Lorenzo et al., 2021).

As the recent European extreme heat waves demonstrated, their impact on human health is very significant and has led several countries to implement heat warning systems (Casanueva et al., 2019). According to Di Napoli et al. (2019), the UTCI 95th percentile is a good threshold for the induction of health-related problems due to heat stress and the UTCI is an important index which can be used as an indicator of impact for heatwave health hazards and to characterise the impact of future projections about extreme heat events on human health. At the seasonal scale (average), the UTCI indicates that Portugal is mostly under an environment of no heat stress for the entire 21st century. During the 21st century, the slightly cold conditions north of the Tagus River (spring) and northeast (autumn) either disappear or become limited to the northeast during spring, in RCP2.6 and 4.5. Equally and during summer a hot environment is projected southward from the middle of the country in RCP8.5. It is worth noting that here UTCI is calculated with daily mean values and that the “no thermal stress” category spans from UTCI equal to 9 to 26. Although temperature changes are the most relevant factor in UTCI changes (Becker et al., 2022), even relevant spring mean increases of 2–4 °C of mean temperature, as found by Lima et al. (2023), are not enough to change the UTCI category in most of the country. Similar reasoning can be applied to autumn. The change in the category in the north is however relevant for human comfort.

According to Di Napoli et al. (2018), for 06 and 09UTC, Portugal is under no thermal stress conditions, while for 12, 15 and 18UTC moderate heat stress is felt in the north and strong heat stress is experienced in the south. Hence, an underestimation of the impact of the extreme/high heat events is expected when daily mean values are used and the UTCI index will represent a low threshold of the maximum daily values. When looking at heat stress during heatwaves, most of the spring to autumn heatwaves (76%), pose, on average, no heat stress in the historical period. Yet, even with the reduction in GHGs at the end of the 21st century, in RCP2.6, an increase in 7% of events with average moderately hot conditions, and a 27% rise in heatwaves with moderately hot episodes within the event is projected. Most importantly, 56% of the heatwaves will have hot events within them. For the most severe scenario and by the end of the 21st century, circa 50% of heatwaves will have on average moderate to hot conditions, with the latter representing 10% of the heatwaves. Within all heatwaves, only 1% will not have a moderately hot episode, 89% will have at least a day with maximum UTCI above 32 (hot environment) and the most significant will be the 32% with very hot conditions. It is worth noting that the 2003 heatwave had a maximum UTCI of 33 in Portugal (Di Napoli et al., 2019), which illustrates as many as 89% of future heatwaves; further, in this scenario, 6% of all heatwaves will have an average UTCI above this value. The 2003 heatwave represented a deviation larger than 30% in the number of deaths in relation to the August average death toll in Portugal (Di Napoli et al., 2019).

The analysis of the heat stress indicates that most of the projected future heatwaves will induce heat stress and that for the extreme scenario, these events will last longer and envelop a larger spatial extension than the extreme heatwaves. The strong link between UTCI above 26 and the increase in morbidity and mortality rates and the rise in frequency of heatwaves and heat stress anticipate a dismal future if no action is taken. The results here disclosed imply, thus, the need for the development of mitigation and adaptation strategies to avert health problems and excess mortality rates for all scenarios and calls for an urgent design of adaptation measures to protect critical sectors, such as agriculture, water management, energy sector and forest. Thus, the information examined here will be fundamental for adaptation and mitigation in Portugal under the first National Roadmap for Adaptation 2100.

The upcoming EURO-CORDEX coordinated regional climate change simulations for the new CMIP6 scenarios will provide a further

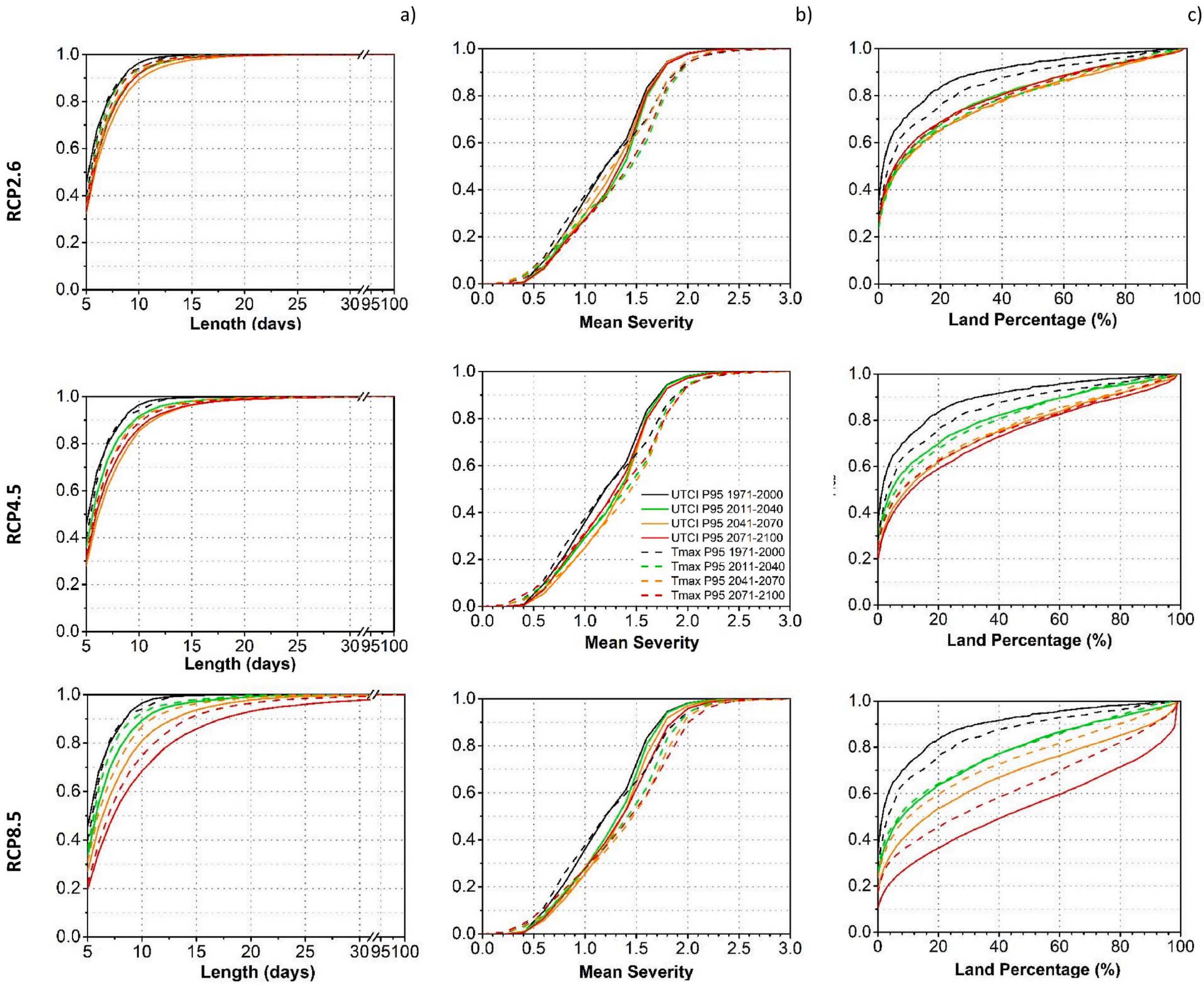

Fig. 7. Multi-model ensemble empirical cumulative distribution functions of UTCI (solid line) and Maximum temperature (hashed line) driven heatwaves a) length (days), b) severity and c) areal extension (%) for the historical period (1971–2000) and for the future periods considering different GHG emission scenarios.

understanding of the climate and its future developments. Particularly, since the new Earth System Models, which will be used as boundary conditions for those simulations, have higher climate sensitivities and the climate change signal spans a broader interval. The future regional climate change ensemble will remain an ensemble of opportunity yet, efforts within the EURO-CORDEX community, envision a better-constrained (more science-based) ensemble with reduced uncertainties. From these, the adaptation and mitigation measures which are based on these results will be able to be updated.

The impact of heat extremes can be exacerbated in an urban environment however, the EURO-CORDEX phase I runs, did not include any urban parameterization, thus their results have some limitations in these areas. Thus, a future major improvement for studies on temperature extremes will come from regional climate modelling ensembles with sophisticated urban schemes. The CORDEX Flagship Pilot study URBan environments and Regional Climate Change (URB-RCC) will provide an ensemble of very high-resolution simulations with urban parameterisations and from here, a better understanding of future climate in European cities will be obtained and updated mitigation/adaptation measures can be devised.

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Declaration of competing interest

The authors declare that they have no competing interests.

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.wace.2023.100600.

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