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High-resolution surface temperature changes for Portugal under CMIP6 future climate scenarios

D. Carvalho

Future changes in the mean, maximum and minimum temperature in continental Portugal were investigated using high-resolution future climate projections based on the latest IPCC AR6 CMIP6 climate scenarios. The results show that the mean, maximum and minimum temperatures are projected to substantially increase in all continental Portugal, particularly at the south-central inland regions. For the near-term future (2046–2065 period), SSP3-7.0 is the future climate scenario that projects higher increases, of around 1 °C, 1.5 °C and 2 °C for the daily mean, maximum and minimum temperatures, respectively. For the long-term future (2081–2100 period), the projected warming is higher, particularly under the SSP5-8.5 future climate scenario with projected warmings of 3 °C, 3.5 °C and 2.5 °C for the daily mean, maximum and minimum temperatures, respectively. Occurrences of hot days (maximum temperature above 30 °C), very hot days (maximum temperature above 40 °C) and tropical nights (minimum temperature above 20 °C) are all projected to increase up to 35–40, 12–15 and 50 more days per year, respectively, mainly in the interior areas of Portugal. Oppositely, the occurrence of frost days is projected to decrease in practically all mountainous areas in Portugal. These results show a clear tendency of a significant increase in the surface temperatures and frequency of occurrence of extreme temperature episodes in continental Portugal, which can have severe impacts on the population, environment, economy and vital human activities such as agriculture.

Keywords Climate change, Global warming, Portugal, CMIP6, WRF, MPI-ESM-1.2-HR

Portugal is located at the western Iberian Peninsula Atlantic coast, the south-westernmost tip of Europe, and its climate is mainly characterized by a warm temperate, Mediterranean climate with a distinct wet season in winter. According to the Koppen-Geiger climate classification provided by the Portuguese Institute for the Sea and the Atmosphere (IPMA, https://www.ipma.pt/en/oclima/normais.clima), Portugal is classified as a warm temperate moist forest climate, with wet/mild winters and dry/warm summers. Although a relatively small country in terms of spatial extension, Portugal shows large spatio-temporal gradients of temperature and precipitation: the northern part of Portugal is substantially cooler and wetter than the southern part, which often shows a semi-arid landscape; and the coastal areas show a much milder climate, both in winter and summer, when compared to the inland regions. Due to its geographical location and climatic characteristics Portugal is very vulnerable to climate change and its impacts. It is considered as one of the climate change "hotspots", expected to witness large increases in the temperatures and occurrence of extreme weather events such as heat waves and reductions in cold spells[1–5].

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) constitutes the latest assessment of the current evidence on the physical science of climate change[6]. According to this report, widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred at unprecedented rates and the observed changes in climate extremes such as heatwaves, heavy precipitation, droughts, tropical cyclones, and, in particular, their attribution to human influence, has strengthened since IPCC Fifth Assessment Report[7]. It also warns that a global warming of 1.5–2°C will be exceeded during the current century, unless strong reductions in greenhouse gas (GHG) emissions occur in the upcoming decades, and this warming will lead to increases in the frequency and intensity of climatic extremes such as heatwaves, heavy precipitation and droughts, intensification of tropical cyclones, and reductions in Arctic sea ice, snow cover and permafrost.

CESAM - Department of Physics, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal. email: david.carvalho@ua.pt

IPCC AR6 is based on future climate scenarios and projections from the Coupled Model Intercomparison Project phase 6 (CMIP6), the latest state-of-the-art global future climate scenarios that resulted from a collaborative climate modeling process coordinated by the World Climate Research Programme (WCRP). CMIP6 future climate projections, the Shared Socioeconomic Pathways (SSPs) (described in detail in[8]), evolved from a combination of new future pathways of societal development and were designed to characterize the future development of the society as a whole more realistically than its predecessors (CMIP3, CMIP5), taking into account not only future GHG emissions but also the present and future social, economical and political panoramas. Recent research shows the progress from CMIP5 to CMIP6, reporting major improvements in the new CMIP6 GCMs in terms of agreement with observations, representation of climate variability, mean state and extremes[9–11].

CMIP6 future climate projections are computed from Global Circulation Models (GCMs), which typically show coarse spatial resolutions (in the order of ~ 100–150 km). Therefore, GCMs are not able to realistically represent atmospheric/climatic processes at regional scales (~ 10 km). Such limitations from global climate simulations pose increased problems in the investigation of climate change impacts in small geographical regions with large spatio-temporal temperature and precipitation gradients, complex topography and coastlines as is the case of Portugal. In order to realistically investigate the present climate and its future evolution at smaller scales, dynamical downscalling of global climate projections to regional scales is typically carried out, where a regional circulation model (RCM) is forced by initial and boundary conditions from GCMs and the resulting output provide climatic data at spatial resolutions that allow a realistic investigation of present and future climate projections at regional and local scales[12].

In the recent past, future warming projections for the Iberian Peninsula were investigated[3–5,13], although using older future climate projections such as CMIP3 and CMIP5, or its respective downscalling initiatives (ENSEMBLES, PRUDENCE and CORDEX). These studies showed solid consensus in the increase of future temperatures and extreme events such as heat waves in the Iberian Peninsula, particularly at central-south regions mainly located in Spanish territory. Specifically for Portugal, an older study[14] used future climate projections from a CMIP3-driven ensemble of regional climate simulations (PRUDENCE) and projected increases in the maximum surface temperatures in the order of 3.2 °C (4.7°C) for the CMIP3 B2 (A2) future climate scenario in summer and ~ 3.4°C in both scenarios for spring, and for the minimum temperatures an increase in the summer (spring) of 2.7°C (2.5°C) in the B2 scenario to 4.1°C (2.9°C) in the A2 scenario. A more recent study[1] investigated mean and extreme temperatures in a warming climate for Portugal using an ensemble of CORDEX regional downscallings of CMIP5 GCMs, projecting a significant increase in the upper tails of the minimum and maximum temperature distributions. This study aims to move forward in this investigation, by developing new high-resolution regional future climate projections for Portugal by dynamically downscalling the latest IPCC AR6-CMIP6 future climate scenarios, and present an updated and detailed investigation on the future changes in the mean, maximum and minimum surface temperature and its extremes for Portugal.

Data and methods

CMIP6 future climate scenarios

Three different CMIP6 future climate scenarios from ScenarioMIP Tier 1 were used to investigate future changes in the mean, maximum and minimum surface temperature and its extremes for Portugal. The chosen CMIP6 SSPs reflect three distinct paths of human evolution: SSP2-4.5 reflects a more sustainable path of human evolution, consisting in a middle-of-the-road scenario where effective GHG emissions reductions are included. It projects growing CO_2 emissions until mid-century (~ 2040), which then steadily decline until the end of the century when the radiative forcing peaks at 4.5 W/m^2 by 2100. Such GHG emission rates will translate in a global mean temperature increase of ~ 2.5 (~ 1.5 °C) when compared to pre-industrial (our current) era. SSP5-8.5 consists in a "business as usual" scenario, where a fossil-fueled development with very limited actions to decrease GHG emissions is foreseen. In this scenario, CO_2 emissions strongly increase until 2080 and then slightly decline until 2100, when the radiative forcing peaks at 8.5 W/m^2 that will originate a global mean temperature increase of ~ 5 (4) °C when compared to pre-industrial (our current) era. The third SSP investigated is SSP3-7.0, a gap-filling baseline scenario with a medium to high radiative forcing by the end of century, where CO^2 emissions steadily increase throughout the current century and the radiative forcing peaks at 7.0 W/m2 by 2100. Under SSP3-7.0 the global mean temperature increases ~ 4 (3) °C when compared to pre-industrial (our current) era. A full description of these SSPs is available in[8].

SSP2-4.5 was chosen because, although it lies slightly outside of the upper threshold of the Paris Agreement goal to limit global warming below 2 °C when compared to pre-industrial levels, it might be the best scenario possible to achieve given the present global socio-economical and political circumstances. SSP5-8.5 was chosen to illustrate the worst-case scenario, but that at the same time represents the current path of GHG emissions, and SSP3-7.0 was chosen because, although relatively similar to SSP5-8.5 in terms of radiative forcing and projected global warming, represents the medium to high end of plausible future pathways and fills a gap in the precedent CMIP5 forcing pathways that is particularly important since it represents a forcing level common to several SSP baselines.

High-resolution downscalling with WRF

The dynamical downscaling of CMIP6 future climate projections was carried out with the Weather Research and Forecast (WRF) atmospheric model, a widely known and used RCM developed under a collaborative partnership of the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA) and the National Centers for Environmental Prediction (NCEP). A full description of WRF can be found in[15]. A two-way nested domains strategy was employed (Fig. 1), where the outermost domain (D1)

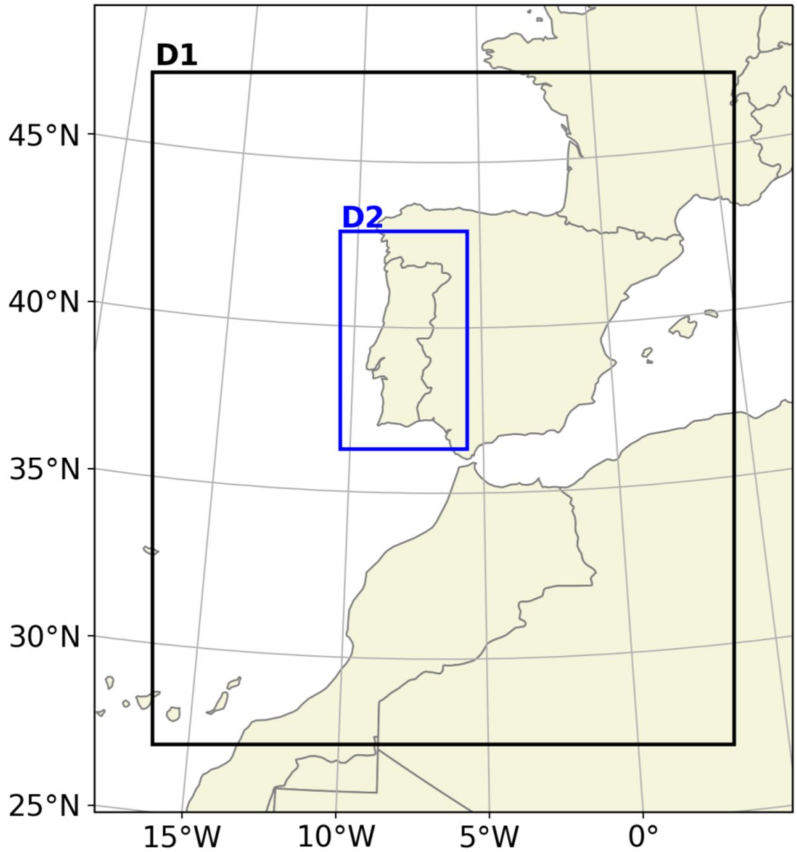

Figure 1. WRF simulation domains.

has a horizontal spatial resolution of 30 km and the high-resolution innermost domain (D2), comprising all Portuguese mainland territory, has a spatial resolution of 6 km.

Vertically, both simulation domains comprise 33 vertical levels between the surface and 50 hPa. In order to keep the large-scale atmospheric main characteristics from the CMIP6-forcing GCM, spectral nudging was applied for D1 (outside of the planetary boundary layer only). The ability and performance of the WRF model for dynamical downscalling of global future climate projections was previously shown in[16]. WRF setup used in the present work builds on the one described in[16], where a full description of the model setup can be found.

The CMIP6 GCM chosen to drive WRF's dynamical downscalling for Portugal was the Max Planck Institute for Meteorology (MPI-M) High-Resolution Earth System Model version 1.2 (MPI-M-ESM-1.2-HR), a coupled atmosphere-land–ocean global climate model described in[17]. The following atmospheric fields were obtained from MPI-M-ESM-1.2-HR through the Earth System Grid Federation (ESGF) data portal (https://esgf-node.llnl.gov/): 3D fields on pressure levels of temperature, UV wind components, geopotential height and relative humidity; and 2D fields of the surface variables pressure, mean sea level pressure, skin temperature, sea surface temperature, 2-m temperature, 2-m relative humidity, 10-m UV wind components, soil temperature, soil moisture and soil height.

WRF was run for three 20-year reference time periods used in IPCC AR6: 1995–2014 (historical, which serves as baseline), 2046–2065 (medium-range future) and 2081–2100 (long-range future). The two future periods were simulated for the three future climate scenarios described in section "CMIP6 future climate scenarios". Daily means of the mean, maximum and minimum temperatures were then computed.

Statistical analysis

Validation of WRF simulations

To validate the WRF-MPI-M-ESM-1.2-HR simulations (henceforth called WRF-MPI), in terms of their ability to realistically represent the real temperature climate over Portugal, an additional WRF simulation (with the exact same domains and configuration as the WRF-MPI ones) was carried out forced by ECMWF ERA5 reanalysis, which served as validation reference. WRF-ERA5 surface temperature fields were then compared with the corresponding WRF-MPI ones for the baseline period. This comparison analyzed, for each gridpoint located over land of the D2 simulation domain (Fig. 1), the overlap percentage (OP) between WRF-MPI and WRF-ERA5 mean, maximum and minimum temperature data. OP measures the degree of similarity between the modeled (WRF-MPI) and reference (WRF-ERA5) surface temperature probability density functions (PDFs), and was calculated according to Eq. (1):

$$P = \sum_{1}^{n} \text{minimum}(Z_m, Z_0).100 \quad (1)$$

where n is the number of temperature bins used to calculate the PDFs (50 in this study), Z_m and Z_0 are the frequency of the temperature values in a given bin from WRF-MPI and WRF-ERA5 data, respectively. An OP equal to 100% means that the WRF-MPI data perfectly matches the reference (WRF-ERA5) data. This method is described in[18] and has been frequently used as validation metric for climatic simulations[19–25] .

Furthermore, a comparison between the WRF-MPI simulation for the historical period and an observational dataset was also carried out. For that, the IBERIA01 gridded dataset of daily precipitation and temperatures over Iberia, described and validated in[26], was used as observational reference.

Climate change signal of the WRF-MPI simulations

The WRF-MPI simulations climate change signal was assessed through the differences between the historical and future mean, maximum and minimum temperatures spatial and temporal distributions. For each variable, the median of the differences between the baseline (1995–2014) and future periods (2046–2065 and 2081–2100) daily temperature data were computed. The seasonality of the mean, maximum and minimum temperature climate change signal was also assessed, where the previous methodology was followed but now aggregating the 20-year historical and future periods into seasonal bins.

Additionally, future changes in the occurrence of extreme temperature events was also analyzed, where the historical vs. future differences in the occurrences of four different extreme temperature indicators were computed: hot days (days with maximum surface temperature above 30 °C); extreme hot days (days with maximum surface temperature above 40 °C); frost days (days with minimum surface temperature below 0 °C); and tropical nights (days with minimum surface temperature above 20 °C). For each one of these extreme temperature indicators, the historical vs. future differences were computed in terms of the median of the differences in the number of occurrences (averaged per year) between the historical and future periods.

The statistical significance of all median differences was quantified using the Mann–Whitney non-parametric test[27] with a 5% significance level. The Mann–Whitney tests the null hypothesis of two data samples belonging to continuous distributions with equal medians, against the alternative that they do not. In all the climate change signal spatial maps, stippling is used in gridpoints where the Mann–Whitney test showed that the median differences were not statistically significant.

Results and discussion

Validation of the daily mean, maximum and minimum surface temperature WRF-MPI historical simulations

Figure 2 shows spatial maps of the OP between WRF-MPI and WRF-ERA5, calculated at each gridpoint, for the mean (left panel), maximum (middle panel) and minimum temperatures (right panel).

Figure 2 shows that, for the three temperature variables, WRF-MPI simulations show very high OP values (above 90%) for practically all continental Portugal territory. The lowest OP values are seen in the northwestern and coastal areas, but even so always above 85%. These lower OP values are seen in areas with complex

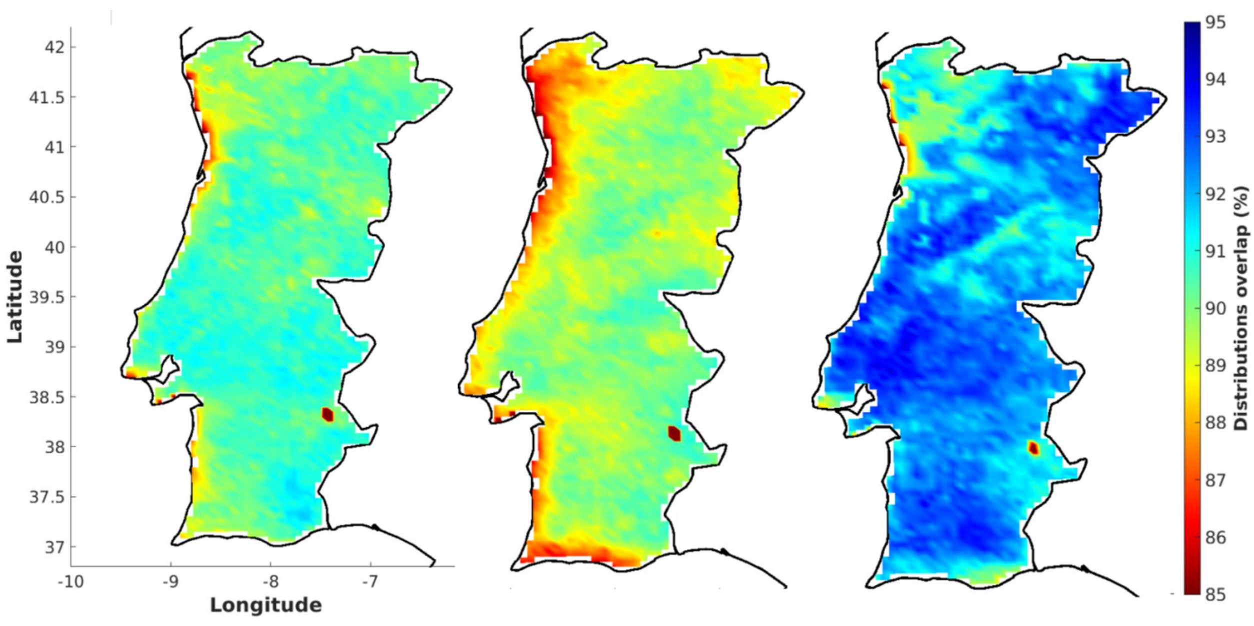

Figure 2. Overlap percentage (OP) between WRF-MPI and WRF-ERA5 for the mean (left panel), maximum (middle panel) and minimum temperatures (right panel). The red spot corresponds to the location of the Alqueva dam.

topography such as mountain ranges and coastal areas, which are prone to terrain-induced meso/local scale atmospheric circulations that strongly influence the local temperature fields. Such circulations are typically not very well represented in GCMs with coarser resolutions, such as is the case of MPI-ESM-1–2-HR[28,29]. Since WRF-MPI simulations are driven by a GCM with a much coarser spatial resolution than WRF-ERA5 ones (100 vs. 25 km), the lower OP values between WRF-MPI and WRF-ERA5 for these areas with complex topography might be related to WRF-MPI poorer ability to realistically represent these terrain-induced meso/local scale atmospheric effects. It is also visible in Fig. 2 a small localized area in the southeastern part of Portugal, close to the border with Spain, with very low OP values particularly for the mean and minimum temperatures. This is the location of Alqueva dam, which is home to the largest artificial lake in Europe with 250 km^2. MPI-ESM-1–2-HR GCM, with a gridpoint size of ~ 10,000 km^2, is not able to properly represent this feature in its land-use information, and therefore WRF-MPI simulation will also misrepresent the temperature fields over this small area. This does not happen with the WRF-ERA5 reference simulation since the driving ERA5 reanalyses, with a much higher spatial resolution and assimilation of observations, is able to partially represent this important local terrain feature.

Comparing the three different temperature variables, it is visible that the minimum temperature field has the highest OP values (average OP for the whole Portuguese continental territory is 92%), while the maximum temperature shows slightly lower OP values (average of 90%). The mean temperature field shows an intermediate OP mean value (~ 91%). Thus, no major differences are seen between the three temperature variables in terms of OP values. In terms of OP spatial distributions, they are very similar for the three temperature variables: lowest OP values in mountainous and coastal areas, and higher OP values in areas with smoother topography. As discussed above, this is due to the fact that MPI GCM has a coarser spatial resolution when compared to ERA5 reanalyses. Thus, WRF-MPI performance will be better (worse) in areas with smooth (complex) topography.

Next, Fig. 3 shows the comparison between WRF-MPI and Iberia01 daily mean, maximum and minimum daily temperatures medians for the whole of the historical (baseline) period. Since IBERIA01 has a spatial resolution of ~ 0.11° in latitude and longitude, the WRF-MPI data was regridded to the same grid of IBERIA01, following a first order conservative remapping strategy.

Figure 3 shows that there are no relevant differences between WRF-MPI and Iberia01 daily mean, maximum and minimum temperatures medians for the historical (baseline) period. The only remarkable difference is that the Iberia01 temperature maps appear to be smoother and less spatially detailed than the WRF-MPI ones, which is related to the fact that Iberia01 has a lower spatial resolution (0.1° in latitude and longitude, which for

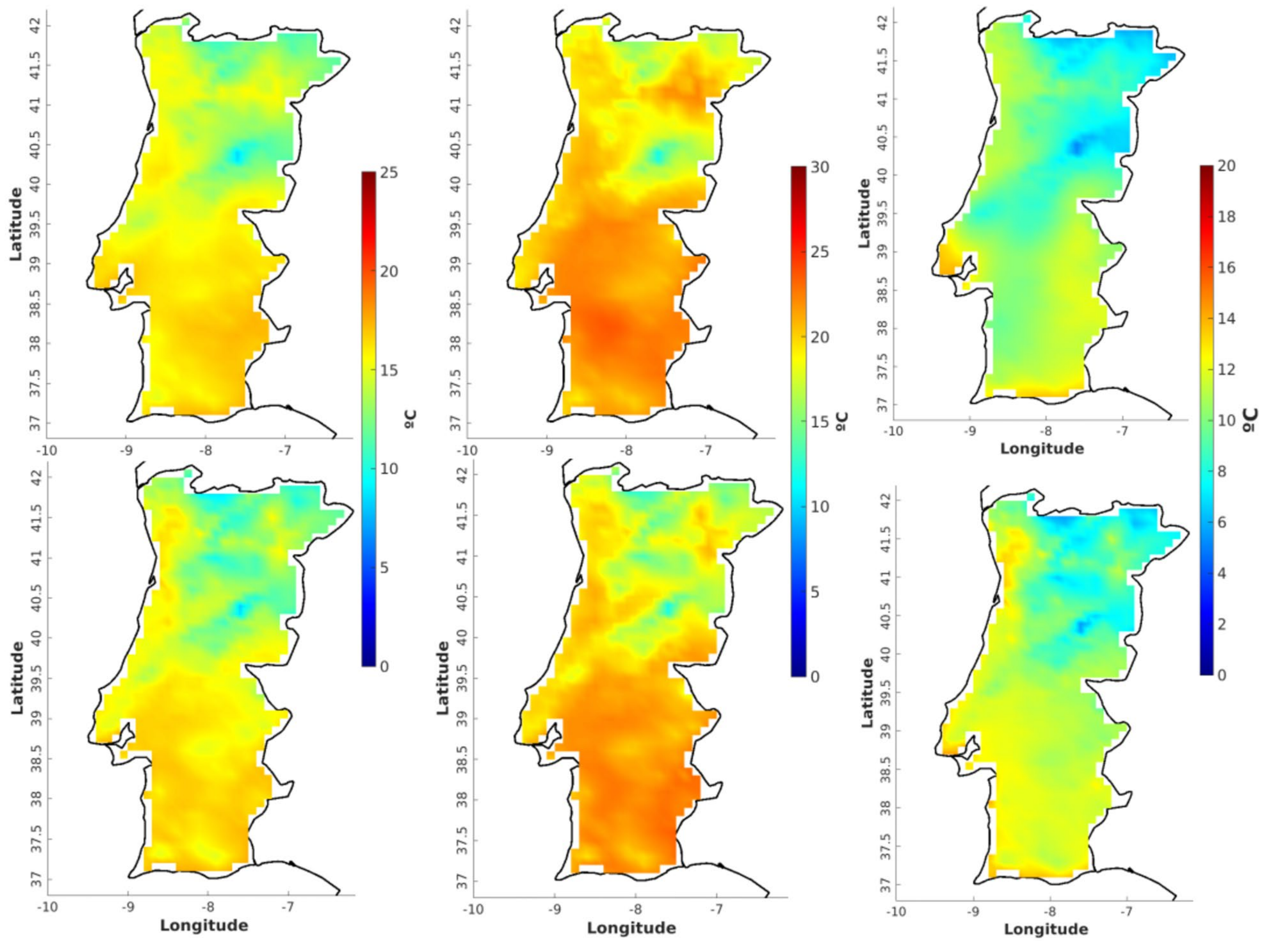

Figure 3. Iberia01 (top row) and WRF-MPI (bottom row) daily mean (left panels), maximum (middle panels) and minimum temperatures (right panels) medians for the historical period (1995–2014).

Portugal geographical location is approx. 10 km) than the WRF-MPI simulations (6 km of spatial resolution). Considering the results shown in Figs. 2 and 3, it can be concluded that the WRF-MPI simulations are able to realistically represent the climatology of the daily mean, maximum and minimum temperatures over Portugal.

One important issue that could cast additional uncertainty to the results presented in this work is related to the fact that all the results presented in this study only considered future climate projections derived from one single CMIP6 GCM, which may not be representative of the many available CMIP6 GCMs. In order to investigate this issue, temperature changes derived from the MPI-M-ESM-1.2-HR GCM (the driving model of all results presented in this work) were compared with the ones derived from an ensemble of 10 CMIP6 GCMs. Details about the data and CMIP6 ensemble used can be found in[2]. Figures 4 and 5 show the median differences between the historical and future periods daily mean temperatures for SSP2-4.5, SSP3-7.0 and SSP5-8.5 future climate scenarios, computed using the MPI-M-ESM-1.2-HR and CMIP6 ensemble temperature data.

From the results presented in Figs. 4 and 5, it can be concluded that the MPI-M-ESM-1.2-HR daily mean temperature changes are well in line with the ones derived from the CMIP6 ensemble and, thus, can be considered as representative of the CMIP6 future climate projections, which adds confidence to the results presented in this study.

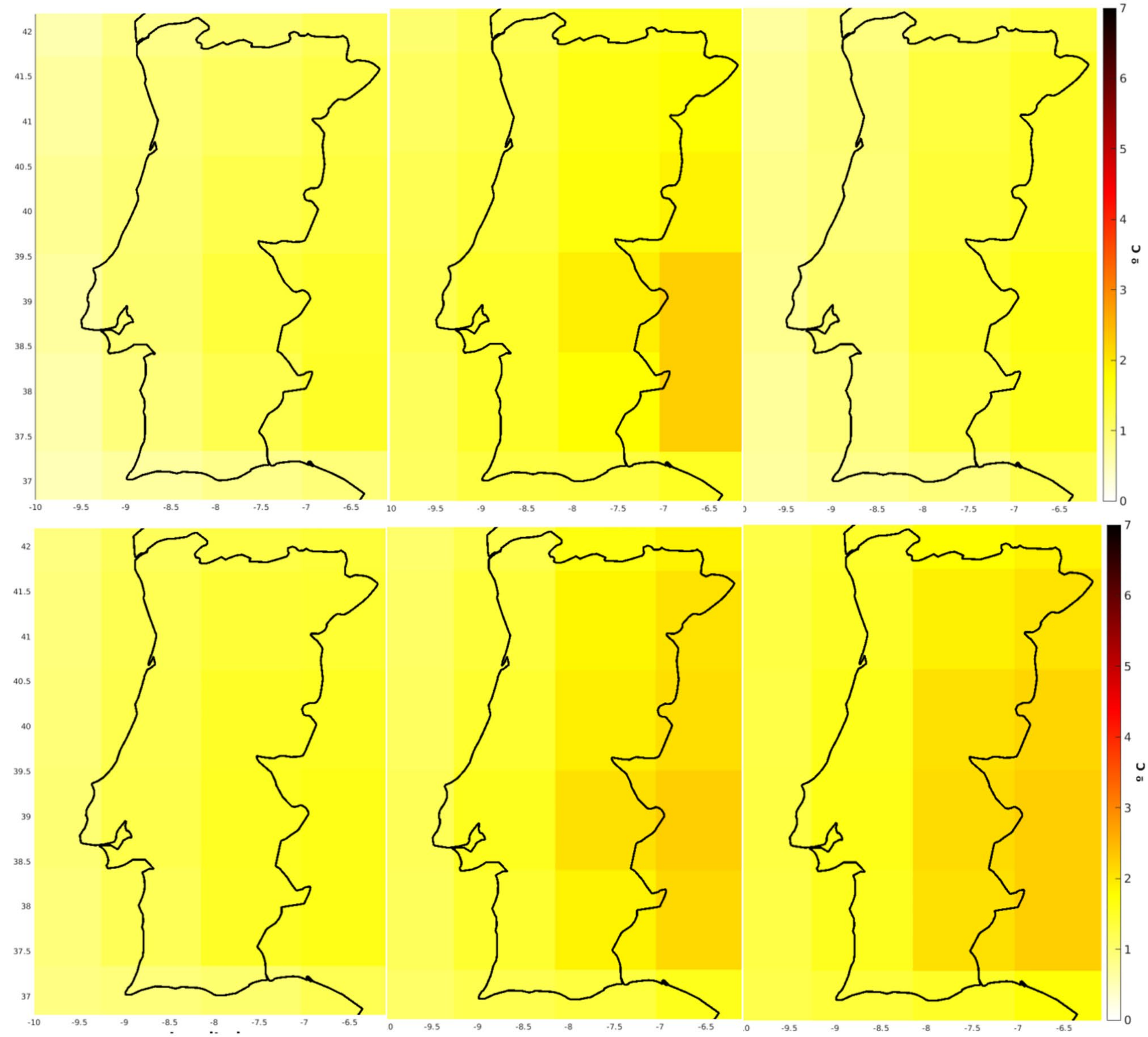

Figure 4. MPI-M-ESM-1.2-HR (top row) and CMIP6 ensemble (lower row) spatial map of the median differences between the historical (1995–2014) and future (2046–2065) daily mean temperatures for SSP2-4.5 (left panels), SSP3-7.0 (middle panels) and SSP5-8.5 (right panels).

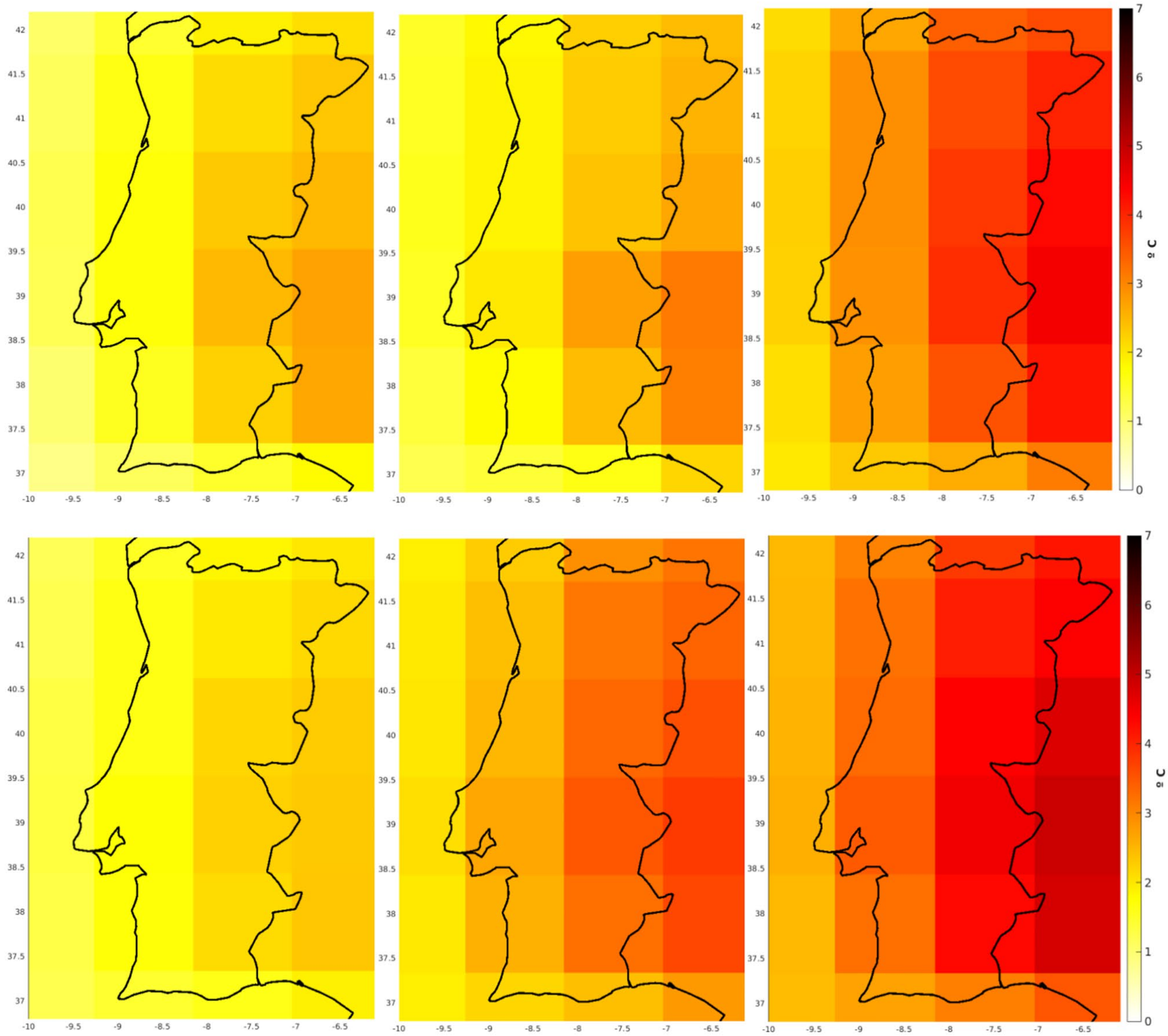

Figure 5. MPI-M-ESM-1.2-HR (top row) and CMIP6 ensemble (lower row) spatial map of the median differences between the historical (1995–2014) and future (2081–2100) daily mean temperatures for SSP2-4.5 (left panels), SSP3-7.0 (middle panels) and SSP5-8.5 (right panels).

Climate change signal of the daily mean, maximum and minimum surface temperatures: historical versus future climates PDFs

Figure 6 shows the PDFs of WRF-MPI historical (1995–2014) and future (2046–2065 and 2081–2100) daily mean (left panels), maximum (center panels) and minimum (right panels) surface temperature, for the three future climate scenarios considered: SSP2-4.5 (top panels), SSP3-7.0 (middle panels) and SSP5-8.5 (lower panels). The median (P50) and tails of the PDFs (P10 and P90) were plotted to assess how they are projected to change in the future relative to the baseline period.

Figure 6 shows that for all temperature variables the future distributions are shifted to the right side of the x-axis, clearly indicating an increase of the mean, maximum and minimum temperatures. For SSPs 2–4.5 and 3–7.0 the magnitudes of the temperatures increases are higher between the baseline-medium term future than between the medium-long-term future, while for SSP5-8.5 the increases between these two temporal periods are very similar. This means that for SSPs 2–4.5 and 3–7.0, the majority of the warming projected up to 2100 occurs until the middle of the current century.

This is confirmed in Table 1, which summarizes the projected changes in the P10, P50 and P90 of the mean, maximum and minimum temperatures distributions, for the three different future climate scenarios and for the medium and long-term future periods.

Furthermore, the warming for the medium-term future is higher for SSP3-7.0 than for the most pessimistic scenario, SSP5-8.5, although the warming towards the end of the century is higher for the latter. Still for the three temperature variables, the increases appear to be higher in the upper moments of the distributions: the upper tail (P90) is the one showing higher increases in the future relatively to the baseline period, followed by the median

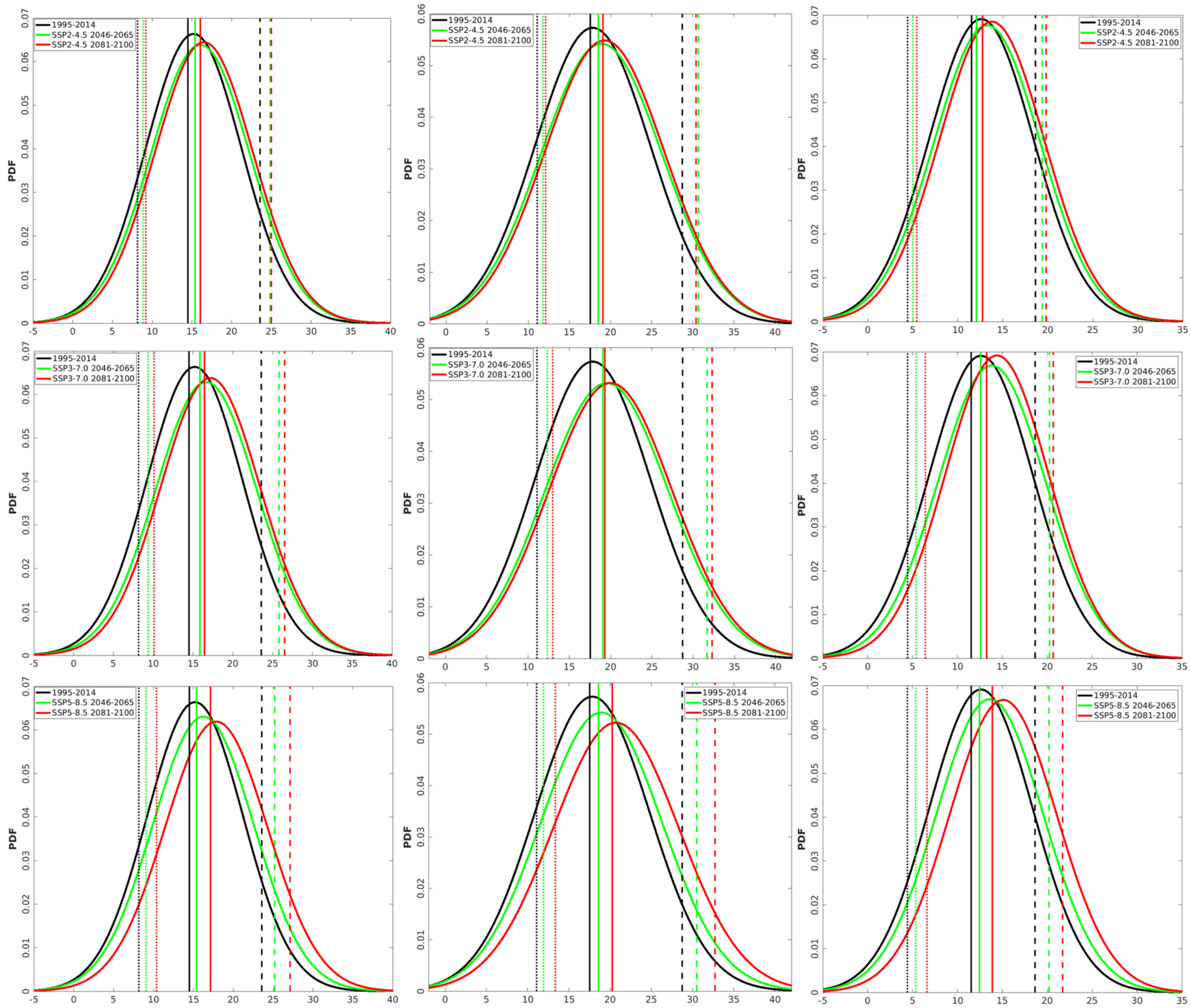

Figure 6. PDFs of the WRF-MPI historical (1995–2014) and future (2046–2065 and 2081–2100) daily mean (left panels), maximum (center panels) and minimum (right panels) surface temperature for the three future climate scenarios: SSP2-4.5 (top panels), SSP3-7.0 (middle panels) and SSP5-8.5 (lower panels). The dotted, solid and dashed lines represent the 10th, 50th and 90th percentiles respectively.

Future period	2046–2065 vs. Baseline (1995–2014)									2081–2100 vs. Baseline (1995–2014)								
SSP	SSP2-4.5			SSP3-7.0			SSP5-8.5			SSP2-4.5			SSP3-7.0			SSP5-8.5		
Percentil	P10	P50	P90	P10	P50	P90	P10	P50	P90	P10	P50	P90	P10	P50	P90	P10	P50	P90
Tmed	0.7	0.9	1.3	1.2	1.4	2.2	0.9	0.9	1.6	1.0	1.5	1.4	1.9	2.0	2.9	2.2	2.6	3.6
Tmax	0.7	1.0	1.9	1.3	1.5	3.0	0.8	1.1	1.8	1.0	1.6	1.7	1.9	1.8	3.6	2.3	2.7	4.0
Tmin	0.6	0.6	0.7	1.0	1.1	1.6	0.9	0.9	1.6	1.0	1.2	1.2	2.0	1.7	2.0	2.2	2.4	3.1

Table 1. Projected changes in the P10, P50 and P90 of the mean, maximum and minimum temperatures distributions for SSP2-4.5, SSP3-7.0 and SSP5-8.5.

(P50), while the lower tail (P10) shows more modest increases. This suggests that extreme mean, maximum and minimum temperatures are the ones with higher projected increases, which indicate future increases in the occurrence of extreme temperature events. This is confirmed by the fact that, according to Fig. 1 and Table 1, the largest warming is seen for the daily maximum temperature P90 in SSP5-8.5, of 4 °C.

Climate change signal of the daily mean, maximum and minimum surface temperatures: spatial patterns of the climate change signal in the mean, maximum and minimum surface temperature

Figures 7 and 8 show spatial maps of the projected changes (median differences) between the WRF-MPI historical (1995–2014) and future (2046–2065 in Fig. 4) and 2081–2100 (in Fig. 5) daily mean (left panels), maximum (center panels) and minimum (right panels) surface temperature, for the three future climate scenarios considered: SSP2-4.5 (top panels), SSP3-7.0 (middle panels) and SSP5-8.5 (lower panels). Stippling indicates areas where the median differences are not statistically significant, as explained in section "Statistical analysis".

According to Fig. 7, for the 2046–2065 future period the mean, maximum and minimum temperatures are projected to increase in all of the Portuguese continental territory. The magnitude of this warming is clearly more pronounced for the daily maximum temperature, with values typically above 1°C that can reach ~ 2 °C for SSP3-7.0. For the mean and minimum temperatures the warming is typically below 1 °C under all future climate scenarios, with the exception of the mean temperature for SSP3-7.0 where the warming is of ~ 1.5°C for all Portuguese territory.

Comparing the different future climate scenarios, it is visible that SSP3-7.0 is the one that projects higher temperature increases for the 2046–2065 future period, particularly for the daily mean and maximum temperatures. In terms of spatial distributions of the temperature differences, the projected warming is somewhat uniform across continental Portugal, although the southern and inland areas show slightly higher warming projections.

Figure 8 shows the same information of Fig. 4 but now for the 2081–2100 future period.

For the long-term future period, Fig. 8 shows that the projected warming for continental Portugal is clearly higher than the one projected for the middle of the current century period. For all temperature variables, the projected warming is lower for SSP2-4.5 and higher for SSP5-8.5. The highest warmings are projected for the daily maximum temperature, while the lowest ones are seen for the minimum temperature. For the daily mean temperature, the projected warming is of around 1.5, 2–2.5 and 3–3.5 °C according to SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively. For the daily maximum (minimum) temperature , the projected warming is of around 2, 2.5 and 3.5 °C (1–1.5, 1.5–2 and 2–2.5 °C) according to SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively.

Similarly to what was seen in Fig. 5 for the medium-term future, for the long-term future the projected warming does not show clear spatial differences, being relatively homogeneous in all the Portuguese continental territory. However, the more inland and mountainous areas appear to show slightly higher projected temperature increases. These mountainous areas are typically the ones with the lowest climatological temperatures (mean, maximum and minimum) in Portugal, meaning that these colder areas are among the ones with higher projected warming. Oppositely, the areas with the highest climatological temperatures are seen in the inland regions. This means that the hottest areas in Portugal are also expected to witness significant temperature increases for the mean, maximum and minimum temperatures, which will significantly exacerbate the temperature stress in these areas. It should be noted that in Figs. 7 and 8, the absence of gridpoints with stippling means that all the plotted differences are statistically significant according to the Mann–Whitney test.

To analyze how these temperature differences vary intra-annually, Fig. 9 shows the monthly variation of the mean (top panels), maximum (middle panels) and minimum (bottom panels) surface temperature. Since no major spatial differences were seen in Figs. 5 and 6 in terms of temperature differences, Fig. 9 shows the results averaged over Portugal. Each month represents the median historical vs. future differences of the 20 months comprised in each time period: for example, the January difference represents the median differences of the 20 historical vs. future Januaries. The left (right) panels show the seasonal warming for the 2046–2065 (2081–2100) period.

Figure 9 shows that, for all future climate scenarios and future periods, the mean, maximum and minimum surface temperatures are projected to increase in all months, particularly in the spring and summer months. This is particularly visible for the long-term future (2081–2100, right panels) and for the future climate scenarios with higher radiative forcing (i.e., higher GHG emissions), where the warming in May–June can reach 3–3.5 °C averaged for all mainland Portugal territory. Again it is visible that the maximum (minimum) temperature is the one that shows higher (lower) increases. All these findings suggest that the occurrence of extreme temperature events is likely to increase in the future, since the highest increases will occur in the months with highest climatological temperatures.

For the medium-term future, Fig. 9 (left panels) shows that for the three temperature variables the highest increases are projected to occur in the months of May, June and July, while the lowest increases are expected to occur in the months of January, November and December. It is also visible that SSP2-4.5 (SSP3-7.0) is the future climate scenario that projects lower (higher) increases for all months, in general. A noticeable aspect is that, for this future period, the month of August shows a sharp drop in the projected daily mean, maximum and minimum temperature increases for SSPs 2–4.5 and 3–7.0. However, this does not happen for SSP5-8.5, in which August is the month with the highest warming for the three temperature variables. For the long-term future, Fig. 9 (right panels), it is visible that for the three temperature variables the highest increases are projected to occur in the months of May, June and July, according to SSPs 2–4.5 and 5–8.5. However, for SSP3-7.0 the highest temperature increases occur in different periods, mainly April, June and September. It is also visible that SSP5-8.5 is clearly the future climate scenario which projects higher temperature increases, for the three temperature variables.

One interesting aspect, when analyzing Figs. 7 and 9 (left panels), is that, unlike what would be expected, SSP5-8.5 appears to project lower temperature changes for the medium-term future (2046–2065) than SSP2-4.5 and SSP3-7.0, since this SSP is the one that consider the highest GHG emissions. However, SSP5-8.5 is clearly the one that projects the highest warmings for the long-term future (2081–2100). While it is outside of the scope of this work to analyze possible reasons for why SSP5-8.5 projects lower warmings than expected for the 2046–2065 period, we are presently investigating this issue in detail, and preliminary results seem to point out

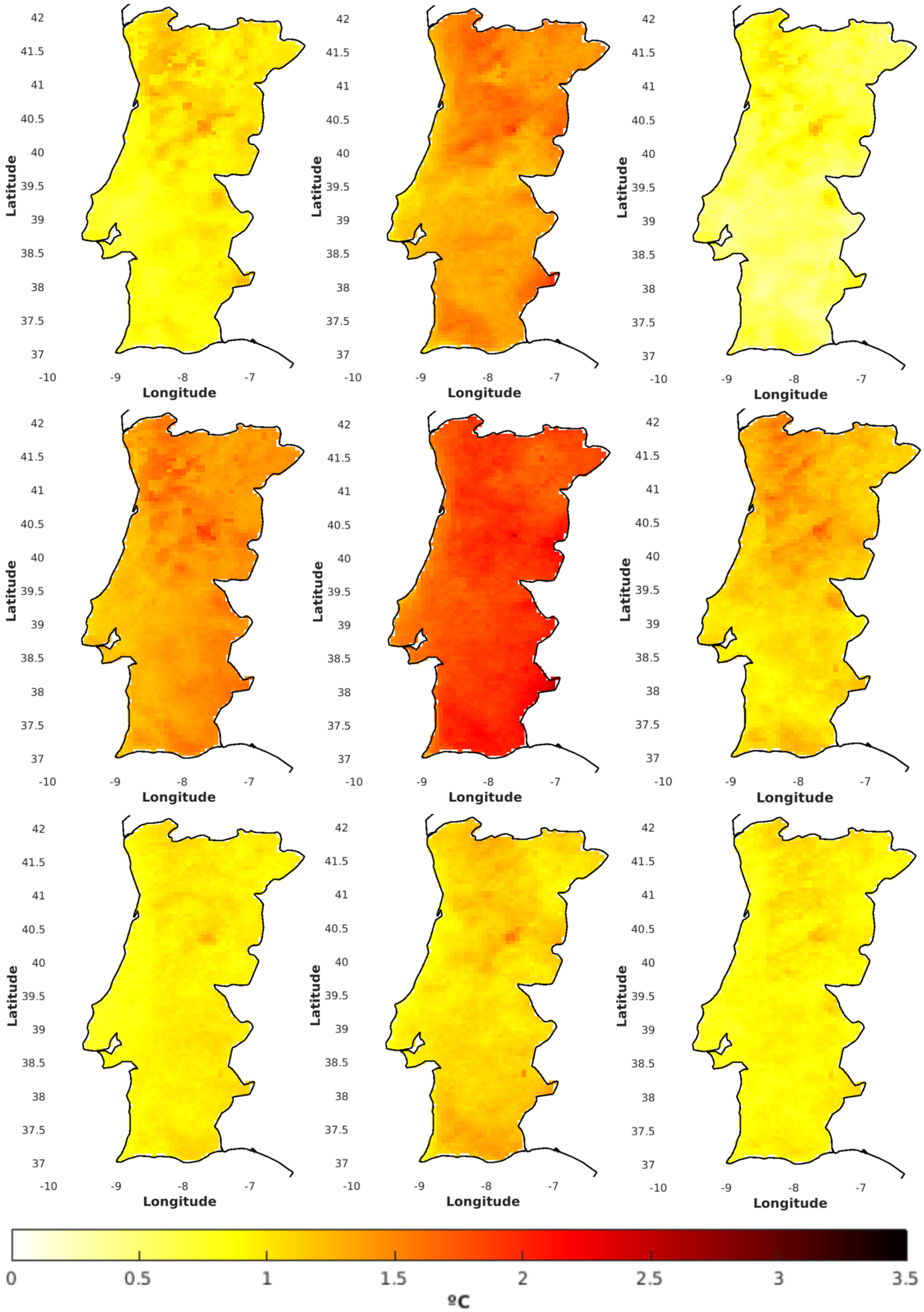

Figure 7. Spatial map of the median differences between the historical (1995–2014) and future (2046–2065) daily mean (left panels), maximum (center panels) and minimum (right panels) surface temperature, for the three future climate scenarios considered: SSP2-4.5 (top panels), SSP3-7.0 (middle panels) and SSP5-8.5 (lower panels). Stippling indicates areas where the median differences are not statistically significant.

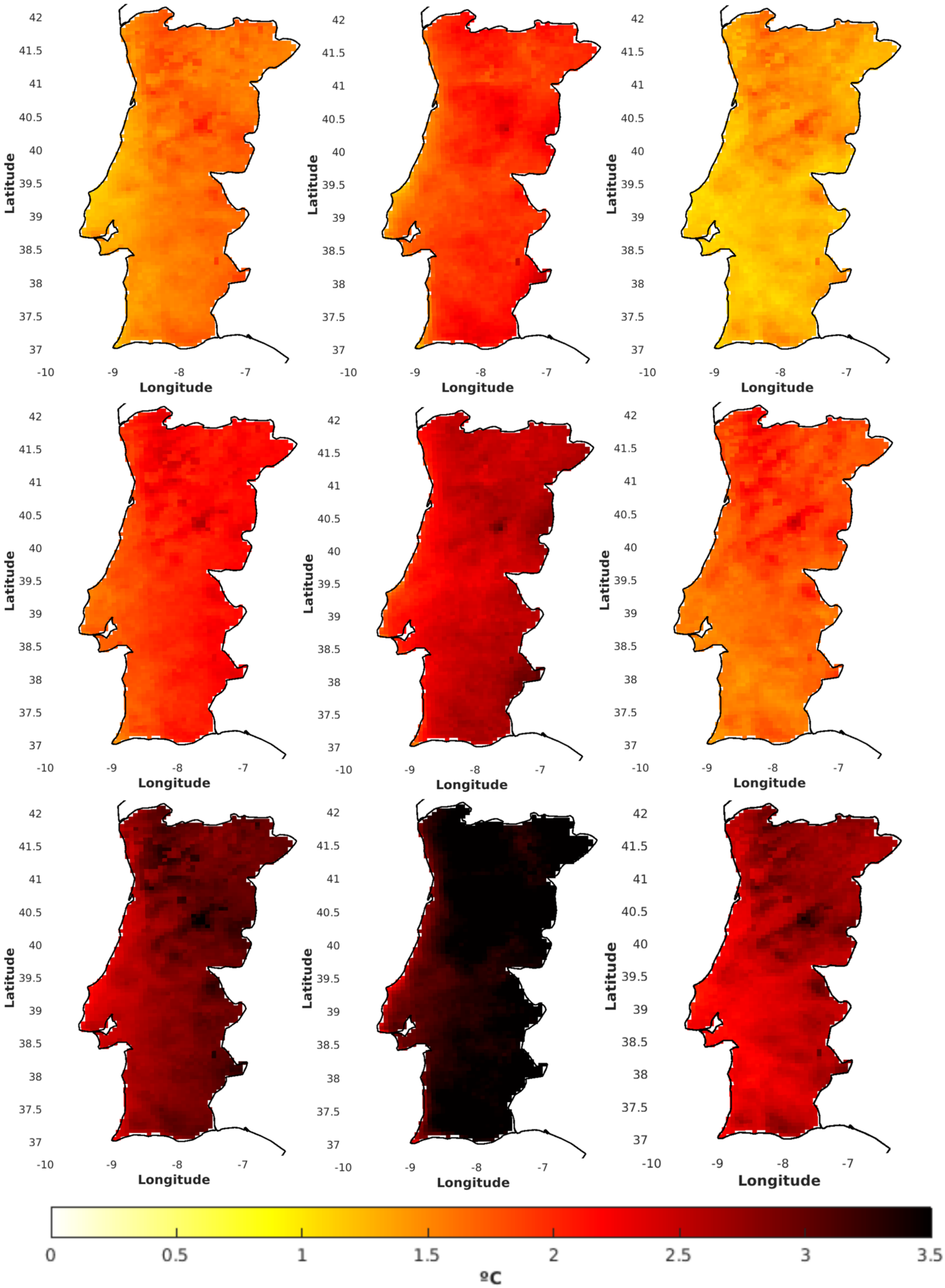

Figure 8. Spatial map of the median differences between the historical (1995–2014) and future (2081–2100) daily mean (left panels), maximum (center panels) and minimum (right panels) surface temperature, for the three future climate scenarios considered: SSP2-4.5 (top panels), SSP3-7.0 (middle panels) and SSP5-8.5 (lower panels). Stippling indicates areas where the median differences are not statistically significant.

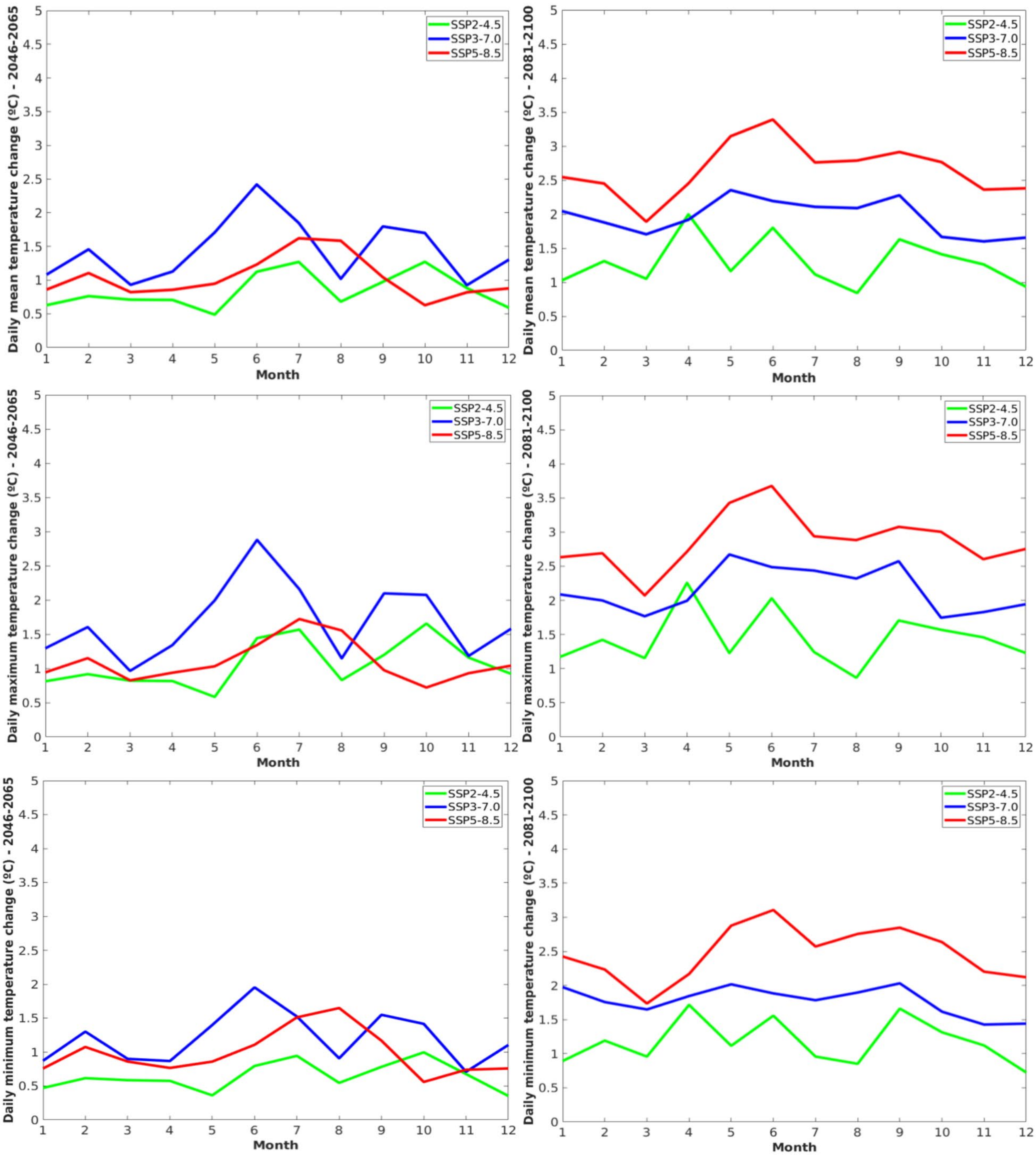

Figure 9. Monthly variation of the mean (top panels), maximum (middle panels) and minimum (bottom panels) temperature differences: historical vs. 2046–2065 (left panels) and 2081–2100 (right panels).

to the fact that SSP5-8.5 projects for 2046–2065, unlike the other SSPs, significant increases in the cloud cover and precipitation over mainland Portugal, which seem to act to lower the surface temperatures.

Climate change signal of the daily mean, maximum and minimum surface temperatures: Extreme temperature events

Figures 10, 11, 12, 13 show the historical vs. future differences in the number of occurrences, in terms of annual means, of hot days, very hot days, frost days and tropical nights, respectively. For each of these figures, the first (second) row shows the differences between the historical and the 2045–2065 (2081–2100) period, while the left, center and right panels show the results according to SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, respectively.

Figure 10 first row shows that, for the period 2046–2065, for SSP2-4.5 and SSP5-8.5 the number of occurrences of hot days can increase up to 20–25 days per year in the eastern (interior) part of Portugal, and also in

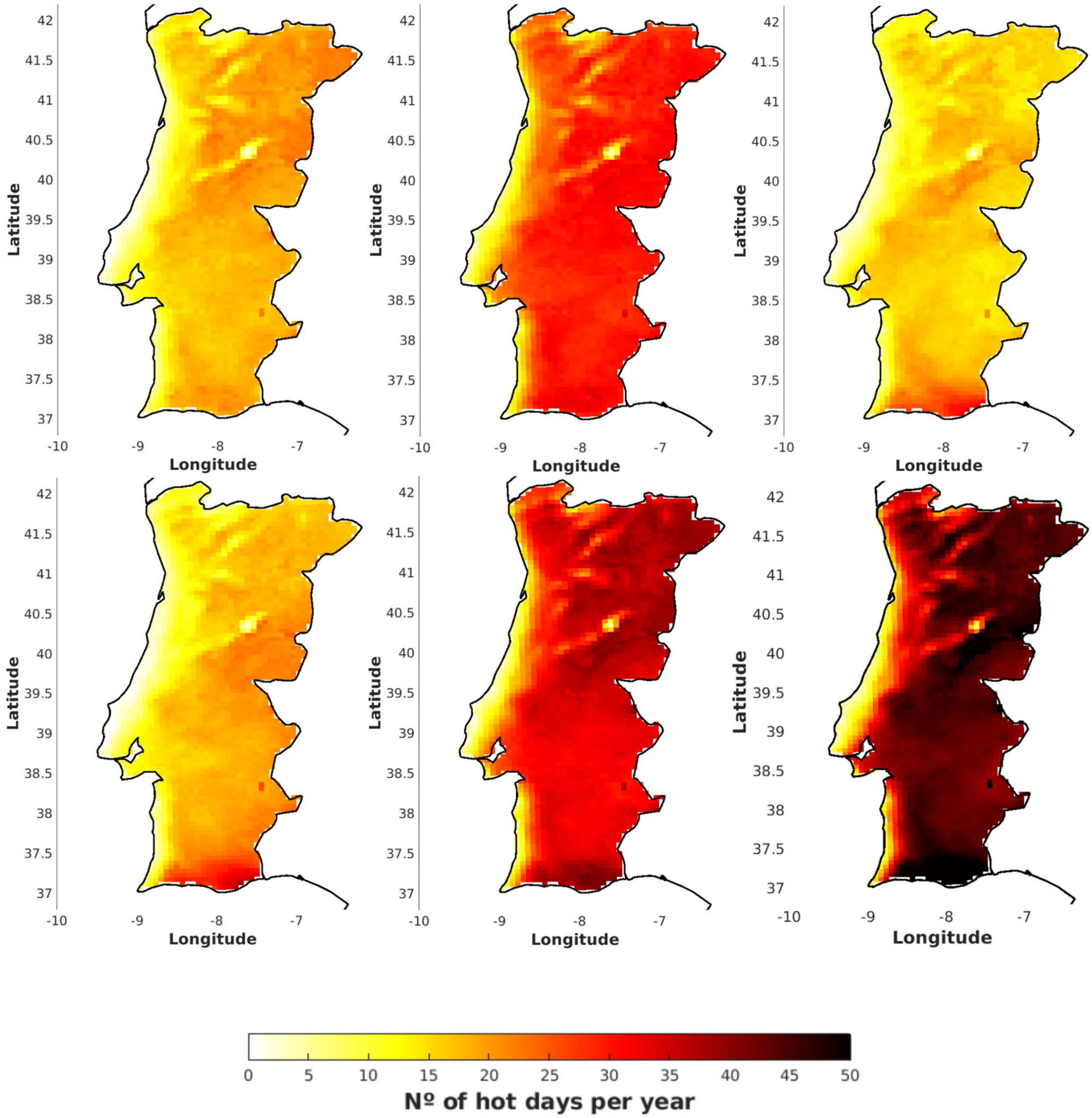

Figure 10. Difference in the number of occurrences (averaged per year) of hot days between the historical versus the 2045–2065 (first row) and 2081–2100 periods (second row) according to SSP2-4.5 (left panels), SSP3-7.0 (center panels) and SSP5-8.5 (right panels).

some areas in the south of Portugal. The increases are clearly lower (5 to 10 days per year) in the Atlantic coastal areas of Portuga. For this future period, SSP3-7.0 is the future climate scenario which projects higher increases of occurrences of hot days, of about more 25–30 days per year in practically all the country except at the coastal areas where the increases are lower (10–15 more hot days per year).

For the 2081–2100 period (Fig. 10 second row), the spatial patterns seen for the 2046–2065 period are similar: lower increases in coastal areas and gradual increase towards the interior of the country, where they reach their maximum. However, for this future period the increases are higher than the ones seen for the 2046–2065 period, particularly for the SSP5-8.5 scenario. Although no major differences are seen for SSP2-4.5 for the two future periods (increase of 5–15 hot days per year), for SSP3-7.0 and particularly SSP5-8.5 the increase in the occurrence of hot days is clearly higher towards the end of the century, where they can surpass 35 (SSP3-7.0) and 45 (for SSP5-8.5) more hot days per year, which is more than one month per year with maximum temperatures above 30 °C.

Figure 11 shows the same information as Fig. 10 but now for the occurrence of very hot days, defined as days with maximum temperature above 40 °C.

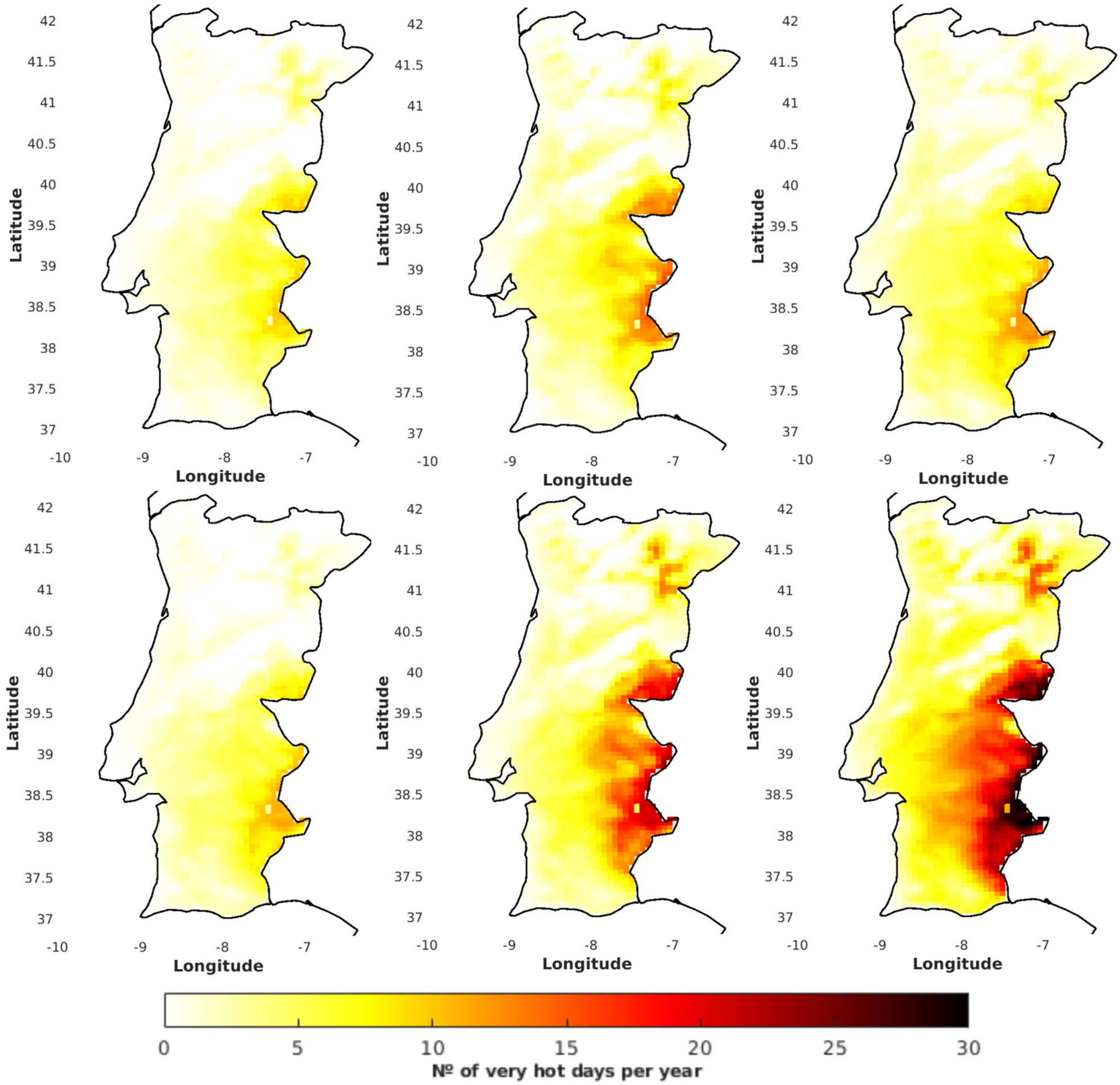

Figure 11. Difference in the number of occurrences (averaged per year) of very hot days between the historical vs. 2045–2065 (first row) and vs. 2081–2100 periods (second row) according to SSP2-4.5 (left panels), SSP3-7.0 (center panels) and SSP5-8.5 (right panels).

In terms of the occurrence of very hot days, Fig. 11 shows similar spatial patterns of Fig. 10: low increases in coastal areas and gradual increases towards the eastern interior part of the country, reaching their maximum in the center-south interior areas of the country. For the 2046–2065 period, SSP2-4.5 projects relatively low increases, of around 5–7 days per year but only in the east-south interior areas of the country. For these areas, SSP3-7.0 projects higher increases that can reach 12–15 more very hot days per year, while SSP5-8.5 projects an increase of around 10–13 very hot days per year. Figure 12 shows the difference in the number of occurrences (averaged per year) of tropical nights, defined as days with minimum temperature above 20 °C.

Figure 12 shows that for 2046–2065 (first row) the number of occurrences of tropical nights will increase in all the Portuguese continental territory, particularly in the north and interior areas where the increases are of 5–15 nights per year for SSP2-4.5, 10 to 25 nights per year for SSP3-7.0 and 10 to 20 for SSP5-8.5. For 2081–2100 the spatial patterns are very similar (higher increases in the north and interior areas) but the magnitude of increase is much higher: 10 to 20 for SSP2-4.5, 15 to 40 for SSP3-7.0 and 40 to above 50 tropical nights per year for SSP5-8.5, which is a dramatic increase of close to two more months per year under tropical nights regimes.

Finally, Fig. 13 shows the same information as Figs. 10, 11, 12 but for the occurrence of frost days, defined as days with minimum surface temperature below 0 °C. The occurrence of frost days is projected to decrease in practically all the Portuguese territory, particularly in mountainous areas in the center and north of the country. These reductions are mostly seen in mountainous and interior areas since these are the ones with lower

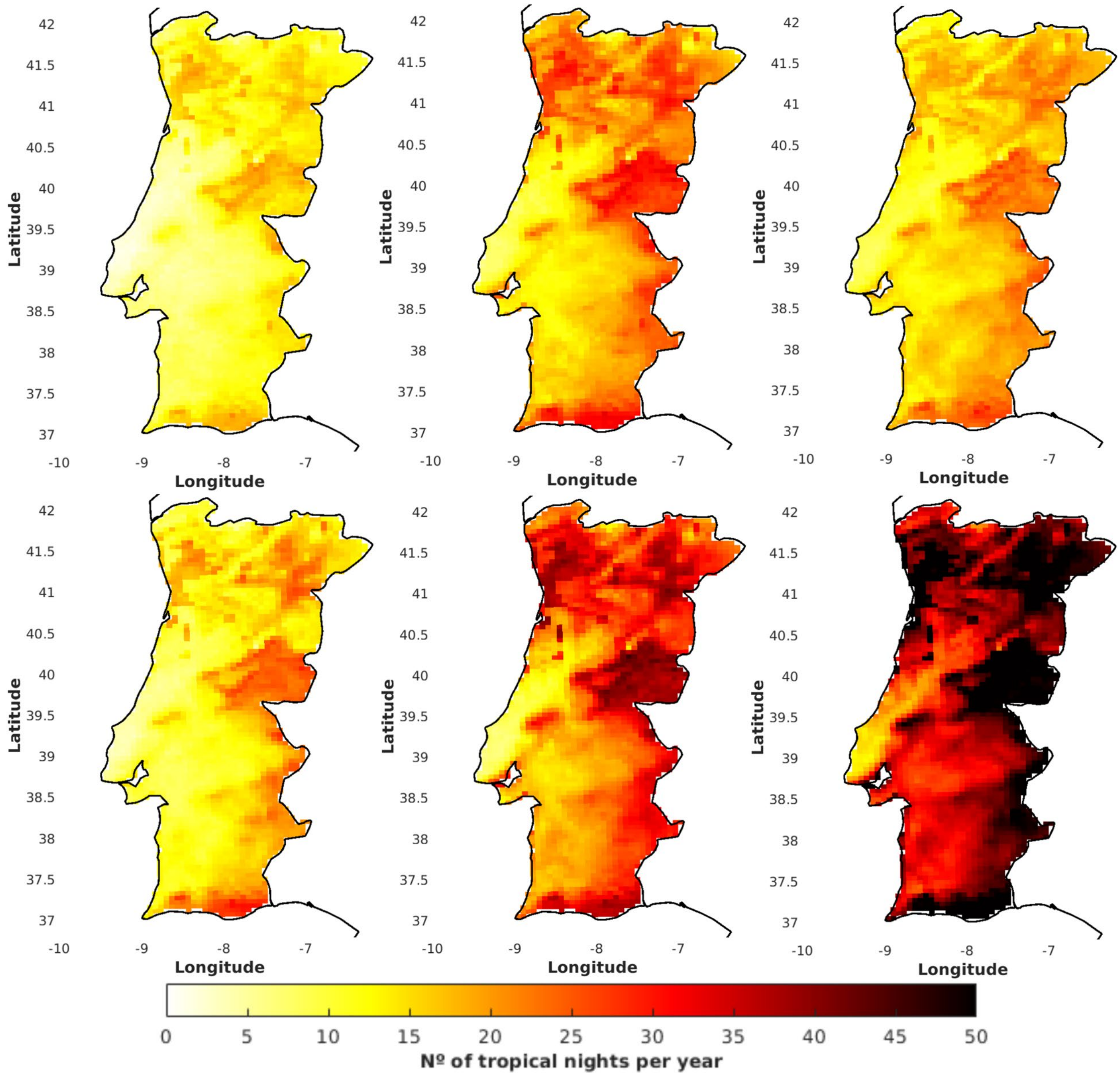

Figure 12. Difference in the number of occurrences (averaged per year) of tropical nights between the historical vs. 2045–2065 (first row) and vs. 2081–2100 periods (second row) according to SSP2-4.5 (left panels), SSP3-7.0 (center panels) and SSP5-8.5 (right panels).

temperatures where frost days usually occur. Other areas of the Portuguese territory, where few or no reduction of the number of frost days is seen such as coastal and southern regions, are areas where frost days occur with fewer (or null) frequency. The reduction in the occurrence of frost days is relatively small for the 2046–2065 future period, of around 5–10 fewer frost days per year except in the Serra da Estrela mountain range, usually the coldest area in the Portuguese territory, where the reduction in frost days can reach up to 15–20 days per year for the 2046–2065 period. However, towards the end of the century, the reduction of frost days is clearly higher particularly for SSP3-7.0 and SSP5-8.5, where they can reach less 25 to 35 frost days per year in practically all Portuguese northern/central mountainous areas. In Serra da Estrela, this reduction can even be above 40 days per year, which is a dramatic decrease and can mean the end of days with snow in this mountain range, the only Portuguese area where snow usually occurs during winter.

The results presented here clearly point out to a generalized increase in the surface temperatures over practically all mainland Portugal, particularly for the daily maximum temperatures. When comparing the results of this study and the previous published literature that investigated changes in the surface daily mean, maximum and minimum temperatures, as well as changes in the occurence of hot, very hot and frost days, and tropical nights for Portugal, using dynamically downscaled, high-resolution, climatic datasets (summarized in Table 2), it can be seen that there are differences in the magnitudes of the increases, depending on the variable under analysis. However, these differences between the several studies can be explained by several reasons: some of the published

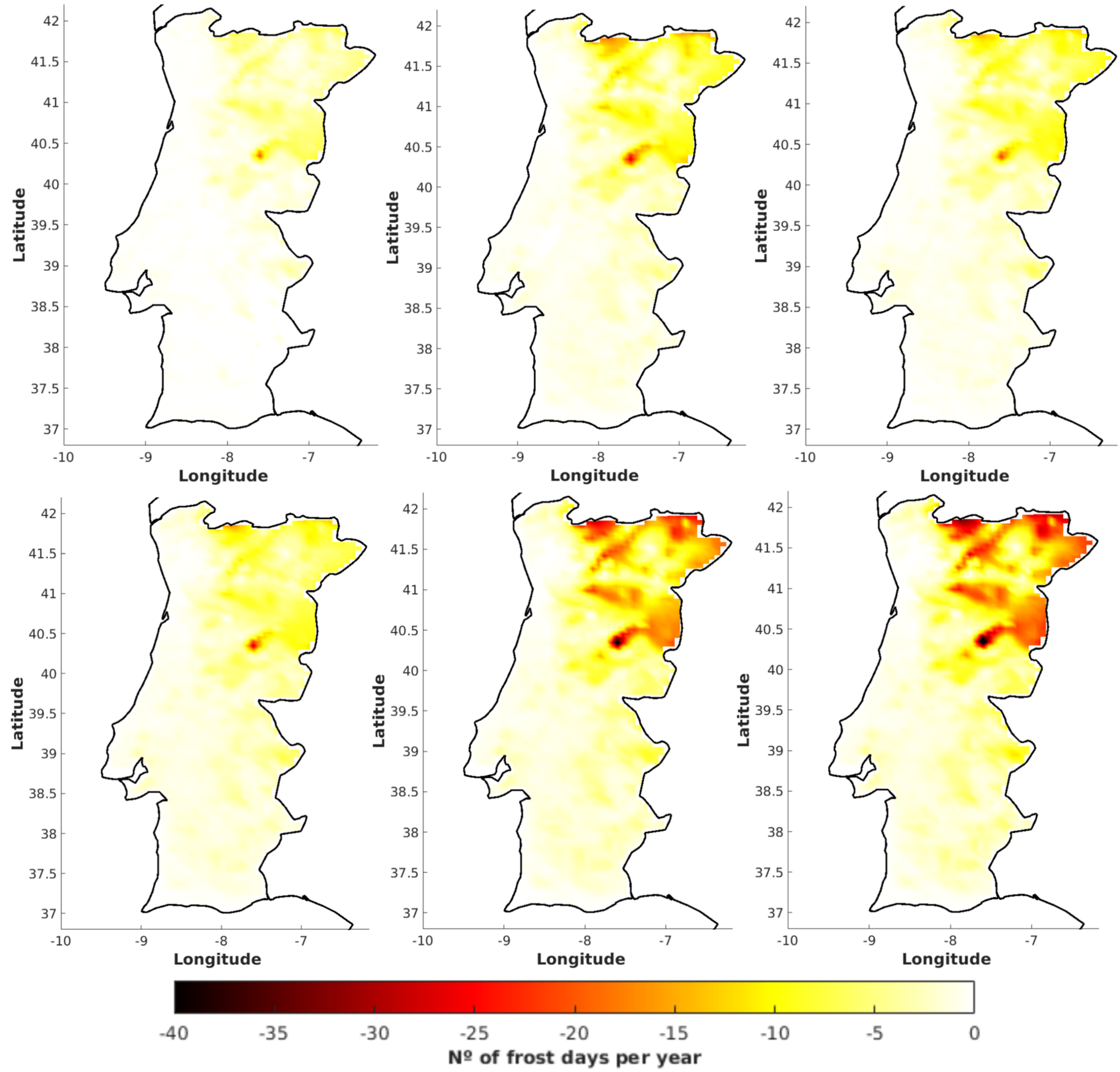

Figure 13. Difference in the number of occurrences (averaged per year) of frost days between the historical versus 2045–2065 (first row) and versus 2081–2100 periods (second row) according to SSP2-4.5 (left panels), SSP3-7.0 (center panels) and SSP5-8.5 (right panels).

literature considered older generations of future climate scenarios (CMIP3 and CMIP5), which differ from the most recent ones from CMIP6; the considered models (both driving GCMs and RCMs) also varied greatly among studies; some of the studies considered an ensemble of models while others used a single GCM-RCM realization; and the spatial resolutions of the climatic data used varied greatly (from 6 km of the present study, the highest spatial resolution among all studies, to 10–12 km of the studies which used CMIP5-CORDEX data, up to 50 km of the studies which used CMIP3-PRUDENCE data). As such, comparisons between studies that used a multitude of different climatic datasets, with different characteristics, should be done adopting a more qualitative and general perspective. Under such perspective, Table 2 shows that, in general, the results from the published literature and the present study point out to similar trends of warming. The results presented in this study are also coherent with the projected temperature changes derived from an ensemble of CMIP6 GCMs, available in the Copernicus Interactive Climate Atlas (https://atlas.climate.copernicus.eu/atlas), and also with the results presented in[2]. However, the spatial resolutions of the CMIP6 GCMs are too coarse to compare in detail with the results of this study, where dynamically downscaled high-resolution CMIP6 future climate projections are used.

	Type/generation of the climatic data used	Future climate scenario/future period	Changes in the daily mean, maximum and minimum temperatures (averaged for all mainland Portugal)	Changes in the occurence of Tropical nights	Very hot days	Hot days	Frost days
[1]	CMIP5-driven (EURO-CORDEX ensemble and a WRF single run)	RCP 4.5/2071–2100	Tmax: increase of 1.5–2 °C Tmin: increase of 1–1.5 °C	More 10–20 nights per year	More 10–20 days per year	More 10–30 days per year	Less 6–8 days per year
		RCP 8.5/2071–2100	Tmax: increase of 3.0–4.0 °C Tmin: increase of 2.5–2.8 °C	More 50–60 nights per year	More 30–50 days per year	More 30–70 days per year	Less 7–10 days per year
[5]	CMIP5-driven (WRF single run)	RCP 8.5/2046–2065	Tmax: increase of 0.5–1.5 °C Tmin: increase of 1–2 °C	More 20–40 nights per year	–	More 30 days per year	Less 5–10 days per year
		RCP 8.5/2081–2100	Tmax: increase of 3.0–4.5 °C Tmin: increase of 3.0–3.5 °C	More 50–70 days per year	–	More 60 days per year	Less 10–15 days per year
[13]	CMIP5-driven (EURO-CORDEX ensemble)	RCP 8.5/2046–2065	Tmean: increase of 1.5–2.0 °C Tmax: increase of 2.0–2.5 °C Tmin: increase of 1.0–1.5 °C	More 20–40 days per year	More 5–10 days per year	More 5–15 days per year	Less 5–10 days per year
		RCP 8.5/2081–2100	Tmean: increase of 3.5–4.0 °C Tmax: increase of 4.0–4.5 °C Tmin: increase of 3.0–3.5 °C	More 50–70 days more per year	More 15–35 days per year	More 20–40 days per year	Less 10–15 days per year
[14]	CMIP3-driven (PRUDENCE ensemble)	SRES B2/2071–2100	Tmax: increase of 3.0–3.5 °C Tmin: increase of 2.5 °C	–	–	–	–
		SRES A2/2071–2100	Tmax: increase of 3.5–4.5 °C Tmin: increase of 3–4 °C	–	–	–	–
This study	CMIP6-driven (WRF single run)	SSP2-4.5/2046–2065	Tmean: increase of 0.9 °C Tmax: increase of 1.0 °C Tmin: increase of 0.6 °C	More 5–15 days more per year	More 0–5 days more per year	More 5–10 days more per year	Less 0–5 days per year
		SSP2-4.5/2081–2100	Tmean: increase of 1.5 °C Tmax: increase of 1.6 °C Tmin: increase of 1.2 °C	More 10–20 days more per year	More 0–7 days more per year	More 5–15 days more per year	Less 0–7 days per year
		SSP3-7.0/2046–2065	Tmean: increase of 1.4 °C Tmax: increase of 1.5 °C Tmin: increase of 1.1 °C	More 10–20 days more per year	More 0–8 days per year	More 25–30 days more per year	Less 0–7 days per year
		SSP3-7.0/2081–2100	Tmean: increase of 2.0 °C Tmax: increase of 1.8 °C Tmin: increase of 1.7 °C	More 20–35 days more per year	More 2–12 days more per year	More 30–35 days more per year	Less 5–20 days per year
		SSP5-8.5/2046–2065	Tmean: increase of 0.9 °C Tmax: increase of 1.1 °C Tmin: increase of 0.9 °C	More 10–20 days more per year	More 0–5 days more per year	More 5–10 days more per year	Less 0–5 days per year
		SSP5-8.5/2081–2100	Tmean: increase of 2.6 °C Tmax: increase of 2.7 °C Tmin: increase of 2.4 °C	More 30–50 days more per year	More 10–25 days more per year	More 40–50 days more per year	Less 5–20 days per year

Table 2. Comparison between the results of this study and the previous published literature.

Conclusions

This work investigated future changes in the mean, maximum and minimum surface temperatures for continental Portugal in the context of climate change, using high-resolution regional future climate projections for Portugal, dynamically downscaled from the latest IPCC AR6-CMIP6 future climate scenarios. The main conclusions are summarized as follows:

The future mean, maximum and minimum surface temperatures are projected to significantly increase in all the Portuguese territory for the medium-term (2046–2065) and long-term (2081–2100) futures, for all the three future climate projections used in this work: SSP2-4.5, SSP3-7.0 and SSP5-8.5. The results show that the maximum temperatures are projected to increase more than the mean temperatures, while the minimum temperatures are the ones with the lowest projected increases.

For the near-term future (2046–2065 period), SSP3-7.0 is the future climate scenario that projects higher increases, of around 1 °C, 1.5 °C and 2 °C for the daily mean, maximum and minimum temperatures, respectively. For the long-term future (2081–2100 period), the projected warming is clearly higher, particularly under the SSP5-8.5 future climate scenario with projected warmings of 3 °C, 3.5 °C and 2.5 °C for the daily mean, maximum and minimum temperatures, respectively.

The temperature increases are practically uniform for all Portuguese territory, although the interior and mountainous areas appear to show slightly higher projected temperature increases. The mean, maximum and minimum surface temperatures are projected to increase in all months, but specially in spring and summer towards the end of the current century and under the future climate scenarios with higher radiative forcing.

The highest temperatures are the ones with higher projected increases, which can strongly impact the future occurrence of extreme temperature events. Occurrences of hot days (days with maximum temperature above 30 °C) are projected to increase up to 20–25 and 35–40 days per year for the medium and long-term futures, respectively, under the SSP5-8.5 and in the interior areas of Portugal. Occurrences of very hot days (days with maximum temperature above 40 °C) are also projected to increase, up to 12–15 more very hot days per year towards the end of the current century, according to SSP3-7.0 and at the center-south interior areas of Portugal. Also associated to the projected increases in the temperatures, it is projected a strong increase in the occurrence of tropical nights, which can go up to more than 50 nights per year towards the end of the century and according to SSP5-8.5, in large parts of the Portuguese continental territory. Oppositely, the occurrence of frost days is projected to decrease in practically all mountainous areas in Portugal.

These results show a clear tendency in a significant increase of the surface temperatures and in the frequency of occurrence of extreme temperature episodes in continental Portugal, which can have severe impacts on the population, environment, economy and vital human activities such as agriculture.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

D.C.: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to D.C.

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