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On the present and future changes in heatwave characteristics over the UK using RegCM4

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Abstract

Anthropogenic warming is increasing the frequency and severity of extreme heat events, with implications for human health across the globe. This study evaluates the ability of HadGEM3 and dynamically downscaled RegCM4 simulations to reproduce the characteristics of UK heatwaves and assesses projected changes in their frequency, intensity, spatial extent and associated heat stress under contrasting Shared Socioeconomic Pathway scenarios. Heatwave behaviour was analysed using near-surface air temperature, the Heat Index, Wet-Bulb Globe Temperature, tropical-night frequency and summer atmospheric blocking. HadGEM3 reproduced the temperature characteristics of historical heatwave periods but exhibited regional biases, particularly over complex topography. RegCM4 provided a more detailed representation and generally reduced these biases. Future projections show substantial increases in heatwave frequency, persistence and geographical coverage, with consistently stronger changes under SSP5 than SSP2. Differences between the scenarios are evident during 2030–2060. Under SSP2, areas experiencing three heatwaves per summer cover 21% of the UK mainland in 2030–2060 and 22% in 2070–2100. Under SSP5, areas experiencing five heatwaves per summer expand from 33% to 36% over the corresponding periods. Tropical nights also become more frequent and geographically widespread, indicating increasing nocturnal heat stress. RegCM4 further projects a shift towards less frequent but more persistent summer blocking under SSP5: although the total number of blocked days declines slightly, established events last approximately 21% longer, while summers without blocking become more common. These findings demonstrate that future UK heat risk is strongly emission-dependent and that near-term mitigation could substantially constrain long-term heatwave intensification and associated health impacts.

Keywords: Climate Change, Heatwave, RegCM4, dynamical downscaling.

1. Introduction

Global temperatures have risen by approximately 1.1˚C in the recent decades, relative to 19th century levels, primarily as a result of anthropogenic greenhouse gas emissions. Under a very high-emission scenario, and in the absence of strong measures to reduce these emissions, global warming could exceed 4˚C by the end of the century (IPCC, 2021). This increase in global mean temperature contributes to increase in the frequency and severity of such life-threatening weather events (IPCC, 2021). These extreme events include hurricanes (Elsner, 2006), floods (Milly et al. 2002; Panda et al. 2016, Pattnayak et al. 2018) and heatwaves (Maharana et al. 2023; Norgate et al. 2024). This study focuses specifically on heatwaves[1]. Heatwaves are among the deadliest weather-related disasters (Yang et al. 2018), and in many countries, are associated with higher mortality rate than any other natural hazards (Kolusu et al. 2021; Kumar et al. 2021). Beyond mortality, the impacts of such extremes extend to societal and infrastructural damages (Gariazzo et al. 2023). Thompson et al (2018) associates heatwaves with increased crime rates, emotional and mental distress, and worsened social cohesion. Furthermore, heatwaves could also place considerable strain on power grids (Stone et al. 2021) and damage railway infrastructure (Davies and Andrews, 2021).

Climate change can increase the intensity, frequency and duration of heatwaves (Clarke et al. 2022). It may also lead to higher atmospheric humidity, thereby worsening heat-related mortality during these extremes (Wang and Zhu 2020). Heatwaves may further contribute to positive feedback loop process. For example, during heatwaves electricity demands can soar, which leads to increased greenhouse gas emissions when energy systems rely on fossil fuels. Extreme heat can also impact vegetation and cause wide-spread death of leaves. This reduces carbon uptake and potentially results in concentration of CO_2 in the atmosphere (Geddes et al. 2014) overall contributing to further warming and an increased risk of future heatwaves.

The mechanism through which global warming influences localised heatwaves are complex but increasingly well understood. Heatwaves are typically associated with persistent high pressure (anticyclonic) systems or atmospheric blocking which can promote trapping of hot air, clear skies with reduced cloud cover over a particular region for an extended period of time (Perkins 2015). It is understood that global warming can lead to rise in anticyclonic blocking phenomena. Though these impacts tend to weaken over long term with climate

[1] Heatwaves are broadly defined as an extended period of anomalously high temperatures prevailing over a localised geographical area. Although, the precise definition of a heatwave, varies considerably across the literature (Xu et al, 2016; You and Jiang et al, 2017) the studies cited in this paper broadly refers to the same phenomenon.

change, this weakening is offset by the increased severity of localised high temperature anomaly attributed to raised global temperatures (Purich et al. 2014). Heatwaves may also interact with drought through soil moisture-temperature feedback. Dry soils reduce evaporative cooling, causing increased heating of air above the surface. Elevated temperatures can then further reduce soil moisture, coupled with persistent high-pressure conditions that supress precipitation and cloud formation. This reinforces both extreme heat and drought conditions (Rohini et al. 2019) [2]. Moreover, changes in large-scale atmospheric circulation, including cyclonic activities (Chang et al. 2016), storm tracks and jet storms may also influence heatwave development. A further contested mechanism holds that the melting of the Antarctic due to climate change disrupts the Jet Stream in ways that lead to greater blocking and therefore more heatwaves in Northern Hemispheric summer (Pidcock 2015).

These studies provide evidence to supporting the claim that anthropogenic climate change has intensified many of the modern heatwaves, although the underlying precise mechanisms for the causation are very complex. In some cases, it is appropriate to examine these processes at the global scale by analysing the overall temperature trends over extended time period. Such research often uses simulations produced through the Coupled Model Intercomparison Project (CMIP), which provides a coordinated framework for comparing various climate models under standardised experiments and scenarios. CMIP5 projection commonly used Representative Concentration Pathways (RCPs) whilst CMIP6 introduces scenarios based on Shared Socio-economic Pathways (SSP), together with associated emissions and radiative-forcing trajectories. Furthermore, the SSPs describe detailed societal responses to climate change (Riahi et al. 2017).

Argüeso et al. 2016 state that, although heatwaves share some universally applicable physical traits, the mechanisms influencing these events and the effects of anthropogenic climate change can vary region-wise. In these cases, regional climate models are more appropriate than the global models. These regional models are designed to represent the relevant spatial and temporal boundaries relevant to the particular research question. Recent studies often use simulations developed through the Coordinated Regional Downscaling Experiment (CORDEX) models, which are produced by modifying the CMIP6 data, downscaled to the specific regions (Maharana et al. 2021; Kumar et al. 2021; Panda et al. 2016).

[2] Anticyclones developed under different circumstances can lead to both wet and dry heatwaves, which are to be understood as heat waves of different levels of humidity; wet heatwaves, although humid and therefore deadlier, are still characterised by extremely low precipitation as they are born from the same phenomena, just in a different way. (*Ha et al. 2022*)

This study aims to assess the changes in the characteristics of heatwaves in the United Kingdom (UK), under different future emission scenarios using global HadGEM3 simulations and dynamically downscaled RegCM4 simulations. Specifically, the study focusses on the changes in heatwave frequency, spatial extent and Wet-Bulb Globe Temperature (WBGT) across both the near- and far-future periods. Section 2 describes the model, methodology and data used in the study; Section 3 presents and discusses the principal results and Section 4 provide the conclusions.

2. Model, Methodology, Data used

The global climate model utilised in this study is the UK Met Office's Hadley Centre Global Environment Model (HadGEM3). This model features a coupled atmosphere-ocean configuration, extending vertically to incorporate a well-resolved stratosphere. Moreover, the Earth-System configuration of HadGEM3 encompasses dynamic vegetation, ocean biology, and atmospheric chemistry. The atmospheric component boasts a horizontal resolution of 1.4˚ and includes 38 vertical levels. The ocean model has a horizontal resolution 1˚×1˚, increasing 1/3˚ in the equatorial belt, and includes 40 vertical depth levels. Further details of the model are provided by William et al. (2017) and Kuhlbrodt et al. (2018). The Regional Climate Model version 4.7 (hereafter RegCM4) used in this study was developed at the Abdus Salam International Centre for Theoretical Physics in Italy. It employs a hydrostatic dynamical core similar to that of the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Grell et al. 1993). Like other Regional Climate Models (RCMs), RegCM4 is configured with multiple levels. In this study, it consists of 24 vertical sigma levels and as per its default configurations, five of these levels are situated in the lower troposphere (Elguindi et al. 2017; Giorgi et al. 2012). Several studies (Tiwari et al. 2016; Pattnayak et al. 2018, Maharana et al. 2021) have indicated that RegCM4, when configured with these standard vertical levels, effectively simulates the principal features of the regional climate, including atmospheric circulations and precipitation patterns. The model configuration adopted in this study is summarised in Table 1.

We examined the present and future changes in in heatwaves across the UK (Fig. 1). In this study, we define historical time-period from 1984 to 2014, for which observational dataset was obtained from the Climate Research Unit (CRU) which has a horizontal resolution of 0.5˚× 0.5˚ (Harris et al. 2013. The CRU dataset was used to evaluate HadGEM3 against the observed data to assess the fidelity of the model. Moreover, the initial and lateral boundary conditions from HadGM3 were utilised to drive the RCM for both historical and future time

periods. For the future scenario simulations, two time slices were considered: the near-future (NF; 2030-2060) and the far-future (FF; 2070-2100). We achieved this, using two different Shared Socioeconomic Pathways (SSPs), namely SSP2 and SSP5 (Riahi et al. 2017); these represent medium, and high challenges to mitigation respectively. For this study, a heatwave event is defined as a period of at least three consecutive days during which the daily mean temperature exceeds the climatological June-July-August (JJA) mean temperature by more than 5˚C. All analyses as well as figures were restricted to JJA season. The future changes in near-surface air temperature (TAS)[3] are shown using a probability distribution function (PDF). In addition to TAS, both the WBGT and Heat Index (HI) were analysed for the NF and FF periods. These are to assess the possible human health impacts for different SSP scenarios for NF and FF periods.

3. Results and discussion

Firstly, we have looked into HadGEM3 and noticed that it's able to reproduce the broad spatial pattern of TAS across the UK during the historical period (Fig. 2), although some regional biases were evident. These biases demonstrate that the model simulations failed to capture some of the complexities of the real data. The largest warm biases occurred over inland Wales and the Scottish Highlands; where relatively cooler observed conditions were not well captured by the model. In some locations the simulated temperature exceeded the CRU observations by 2 ˚C. Regions exhibiting the largest warm and cold biases, generally coincided with areas where the difference between the observations and simulations where statistically significant; determined using Student's t-test. These discrepancies may partly reflect the limited spatial resolution of the HadGEM3 simulation and its representation of complex mountainous terrains of Wales and Scottland. Previous studies (Das et al. 2021, Tiwari et al. 2016) have similarly reported difficulties in representing temperature over regions with complex topography using GCMs. Nonetheless, the magnitude of these biases was within the acceptable bounds, to use HadGEM3 dataset in the subsequent analysis of future climate projections.

Following the assessment of the historical model performance, HadGEM3 were utilised to also study projected changes in heating conditions across the UK. Figure 3 presents the PDF of TAS for all the three time periods (historical, NF, and FF) under SSP1, SSP2 SSP5. The historical HadGEM3 distribution closely matches the CRU observations, although some

[3] Air temperature measured 2m above the surface, abbreviated TAS.

differences remain. All three future projections display a shift towards higher temperatures relative to the historical period's distribution. Under SSP1, TAS distribution shifts moderately towards the higher temperatures during the NF period; with modal temperatures increasing to about 15.5 ˚C from the 14 ˚C observed in the historical period. Only a limited additional increase is evident during the FF period. Similar to SSP1, the other two future scenarios display shift towards higher temperature in the NF period but diverge clearly during the FF period. By the FF period the modal temperature soars to 17.5˚C under SSP2, and 19˚C under SSP5. The largest projected increase therefore occurs under the SSP5 scenarios in the FF period.

The projected HI (Fig. 4) and WBGT (Fig. 5) exhibit a similar temporal divergence between emission pathways, combined with the marked spatial variation across the UK. Though during the NF period, the differences between the scenarios remain relatively limited, by the FF period, the highest HI value occurs in Londen and its surrounding areas. Notably, under the SSP5 scenario (FF), the HI index is projected to exceed 29˚C in parts of this region, whilst changes under SSP1-2.6 remain comparatively limited post NF period. The WBGT predictions display comparable divergence between the scenarios. The highest values are concentrated in the southern England, although affected areas extend beyond London and the surrounding counties. In the north, particularly parts of Scotland, generally experiences smaller increase than southern regions.

Figure 6 presents the WBGT predictions in the downscaled RCM simulations. During the NF period, SSP2 and SSP5 produce broadly similar spatial trends and minimal differences; several areas in the southeast reaching 29-32˚C. The spatial coverage of the values is greater under the SSP5-8.5 projections. Likewise, in the FF period, WBGT increases across most parts of the UK for both the simulations, with smaller gains over the Scottish Highlands. The southeast remains as the most strongly affected region, while the WBGT remain elevated across substantial portion of the country. Similar to NF period, the FF period maximum WBGT values under SSP2 remain within 29-32˚C range but, with greater coverage. Under SSP5, WBGT values are higher the SSP2 across most of the mainland, with parts of the southeastern England reaching approximately 32˚C. Such conditions indicate significantly elevated heat stress and may pose a serious threat to human health, particularly during the prolonged exposure.

Two broader trends emerge from these results. TAS, HI and WBGT all show a clear divergence between the SSP scenarios over time. Although the projected changes are relatively similar in the NF period, the effects of higher greenhouse-gas emissions become significantly more prominent by end of the twenty-first century. Under the low emission scenarios, warming begins to stabilize after several decades, whilst under the higher emission cases, TAS, HI, and WBGT continue an upward trend throughout the FF period. These findings highlight the modest differences between the scenarios may develop into substantially larger contrasts by the end of the twenty-first century.

These results are broadly consistent with the literature; Norgate et al. (2024) reported a comparable divergence among SSP scenarios between NF and FF periods over India, while Nazarenko et al. (2022) identified a similar pattern at the global scale. A comparable effect can be seen when comparing differential emissions in the older RCP paradigm (Chong-Hai and Ying, 2012).

A second major finding of this study is the noticeable geographical variation in projected heat stress across the UK. The HI and WBGT results generally indicate a smaller increase in the northern regions and the largest change in the southeastern parts, particularly around London and the Home Counties. Although HadGEM3 is limited by its moderate spatial resolution, the broader pattern is plausible; high degree of urbanisation the southeast may partly contribute the enhanced heat exposure facilitated by the Urban Heat Island Effect (UHIE; Deilami et al, 2018). It can be noticed Beyond London and its neighbouring areas, extreme heat has historically affected southern parts of the UK more severely, than the norther regions; many of the highest recorded temperatures occurred in the southern England. Future heatwaves are therefore likely to have pronounced impact on London and its surrounding regions, although substantial gains in temperature are also projected across other parts of the UK.

Figure 7 shows the spatial extent of the heatwaves across the UK. In both the NF and FF, heatwaves under SSP5 affect a larger area than those under SSP2. Unlike several other results in this study, where the noticeable changes are seen in the FF, a marked difference for between SSP5 and SSP2 is apparent in the NF period. Under SSP5, spatial coverage increases further from the NF to FF period albeit modestly.

Under SSP2, significant spatial coverage occurs for regions experiencing three heatwaves per summer, accounting for 21% of the mainland in NF period and 22% in FF period. By contrast, under SSP5, the largest coverage occurs for locations experiencing five heatwaves

per summer for accounting for 33% of the UK in NF period and 36% in FF period. SSP5 also produces a greater spatial coverage for all heatwave frequencies when compared to SSP2. These results indicate that higher greenhouse-gas emissions are associated more frequent heatwaves that affect larger area of the UK. Further we have looked into changes in tropical nights (Figure 8) for near and far future. It is noticed that the tropical nights rise from about 1-6 nights/year across southern England in 2030–2060, reaching 12–15 near London, and expand by 2070–2100, with southeastern areas commonly experiencing 6–15 nights/year. We have also analyzed changes in summer (JJA) atmospheric blocking dynamics over the UK region (10°W – 2°E) using the Tibaldi and Molteni (TM90) index, contrasting the historical ERA5 reanalysis baseline (1984–present) with near future (2030–2060) and far future (2070-2100) model projections under the SSP2 and SSP5 emission pathways (Table 2). It can be noticed from the table that the total percentage of blocked summer days decreases by 1.4% from the historical baseline to the high emission SSP5 pathway. Individual blocking events that manage to establish themselves last 21% longer on average under SSP5 (increasing from 3.42 to 4.15). Further it can be noticed from the table that the probability of experiencing a summer with no atmospheric blocking events almost triples i.e. rising from 6.5% to 19.4%.

4. Conclusion

This study assessed the ability of climate-model simulations to reproduce the features of extreme heatwaves over the UK and analysed how the frequency, intensity and spatial extent of comparable events may change under different future emission scenarios.

- The results indicate that HadGEM3 simulations reproduced broader temperature characteristics of the historical periods, but displayed regional biases, especially over complex topography; however, downscaled RCM simulations provided more detailed representation of the temperature with reduced bias over the UK.
- RegCM4 simulations indicate that heatwave frequency and spatial extent increase significantly under higher emission pathway. It is noticed that the SSP5 produces consistently greater spatial coverage than SSP2, with clear differences emerging in the near-future period. Under SSP2, areas experiencing three heatwaves per summer cover 21% of the UK mainland in 2030–2060 and 22% in 2070–2100. Under SSP5, areas experiencing five heatwaves per summer cover 33% and 36% of the mainland, respectively. Further it is noticed that there is a clear increase in the frequency and geographical extent of tropical nights.

- RegCM4 projections shows a shift towards less frequent but more persistent summer blocking under SSP5. Although the overall occurrence of blocked days declines slightly, established events last approximately 21% longer, while summers without blocking become markedly more common. This suggests that future UK blocking may become increasingly intermittent but more persistent once established.

Overall, these findings that near term emission reduction could greatly help in limiting the long-term intensification of heatwaves and associated heat stresses across the country.

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Consent for publication: All the authors gave due consent to collaborate in the study.

Data Availability: The CMIP6 dataset is available at the ESGF data repository (https://esgf-data.dkrz.de/search/cordex-dkrz/. CRU and ERA5 datasets can be downloaded using the link https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05;https://cds.climate.copernicus.eu/cdsapp#!/home/ respectively.

Code availability: The codes used in the analysis are available on reasonable request.

Author Contributions: Conceptualization: JM and PRT; Data Curation, Analysis and Visualization: MN, BS and JM; Writing: all the authors; Editing: PRT, and SD.

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467 Figure 4. Heat Index over the UK using HadGEM3 for SSP1 (a, b), SSP2 (c, d) and SSP5 (e,
468 f). The first column (a, c, e) shows the NF and the second column (b, d, f) show the FF.

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471 Figure 6. WBGT using RegCM4 for NF (a, b) and FF (c, d) under SSP2 (a, c) and SSP5 (b,
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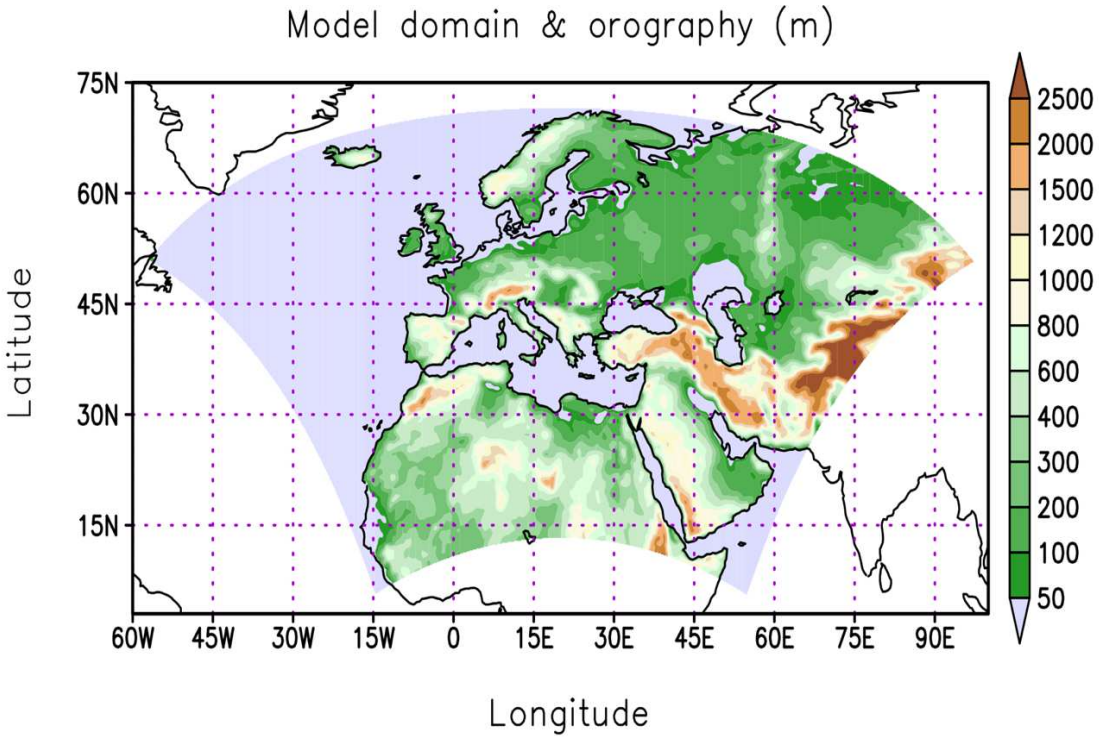


Figure 1: Model domain and orography (m) used in the present study.

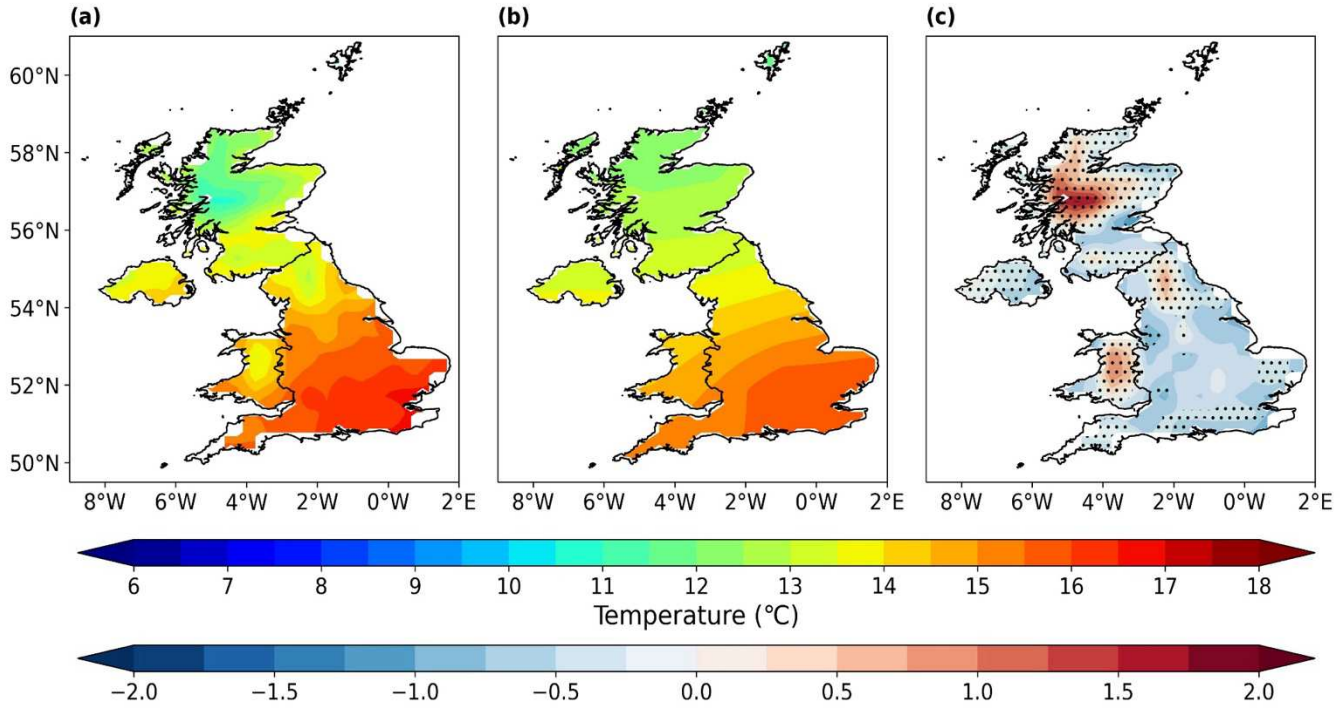


Figure 2: Mean TAS over the UK for (a) observed, (b) HadGEM3 and (c) model bias for the period 1984-2014. The dots represent areas with 95% significance level.

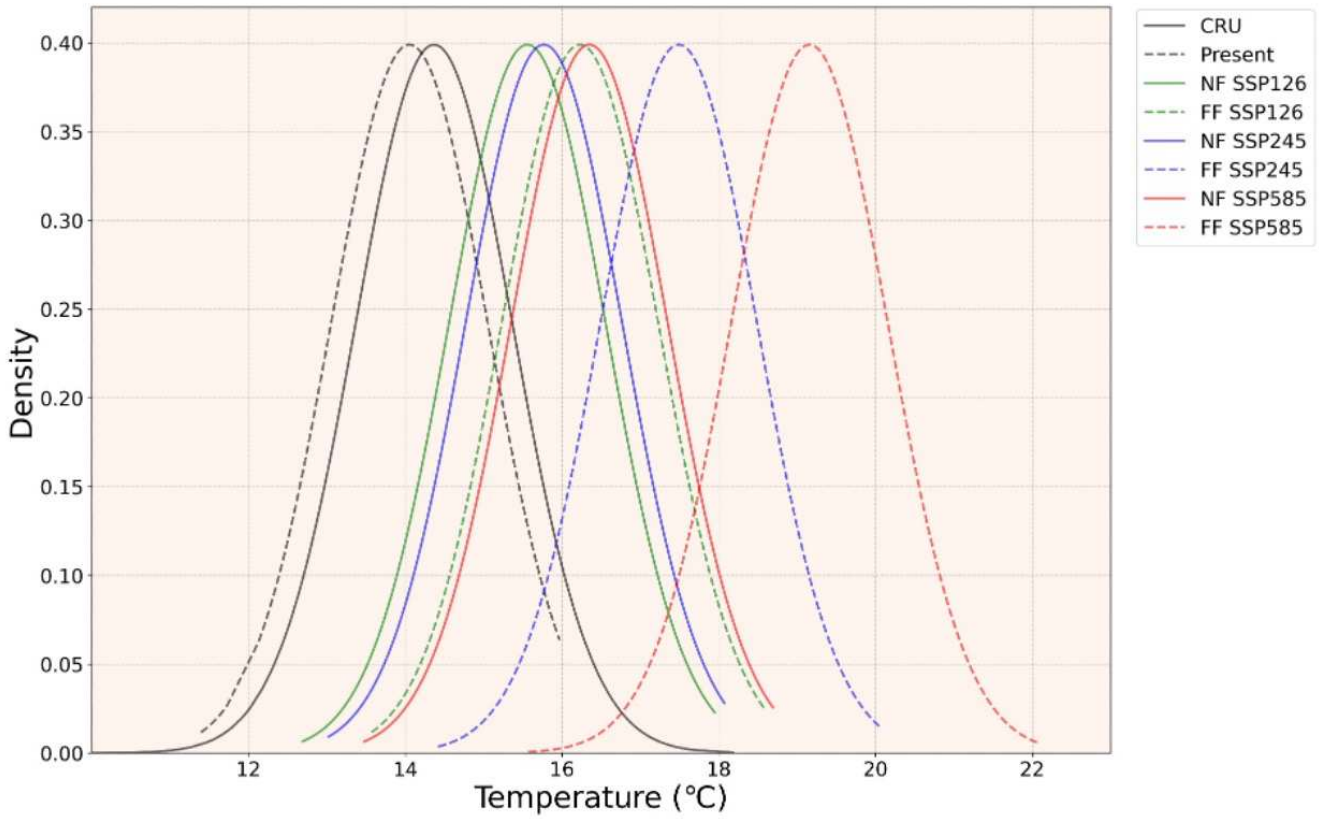


Figure 3: PDF distribution of TAS over the UK. Grey lines show the historical period (1984-2014), where solid grey is observed and dashed grey is HadGEM3. Green, blue and red represent SSP1, SSP2 and SSP5 respectively, where solid lines show the NF period (2030-2060) and dashed lines show the FF period (2070-2100).

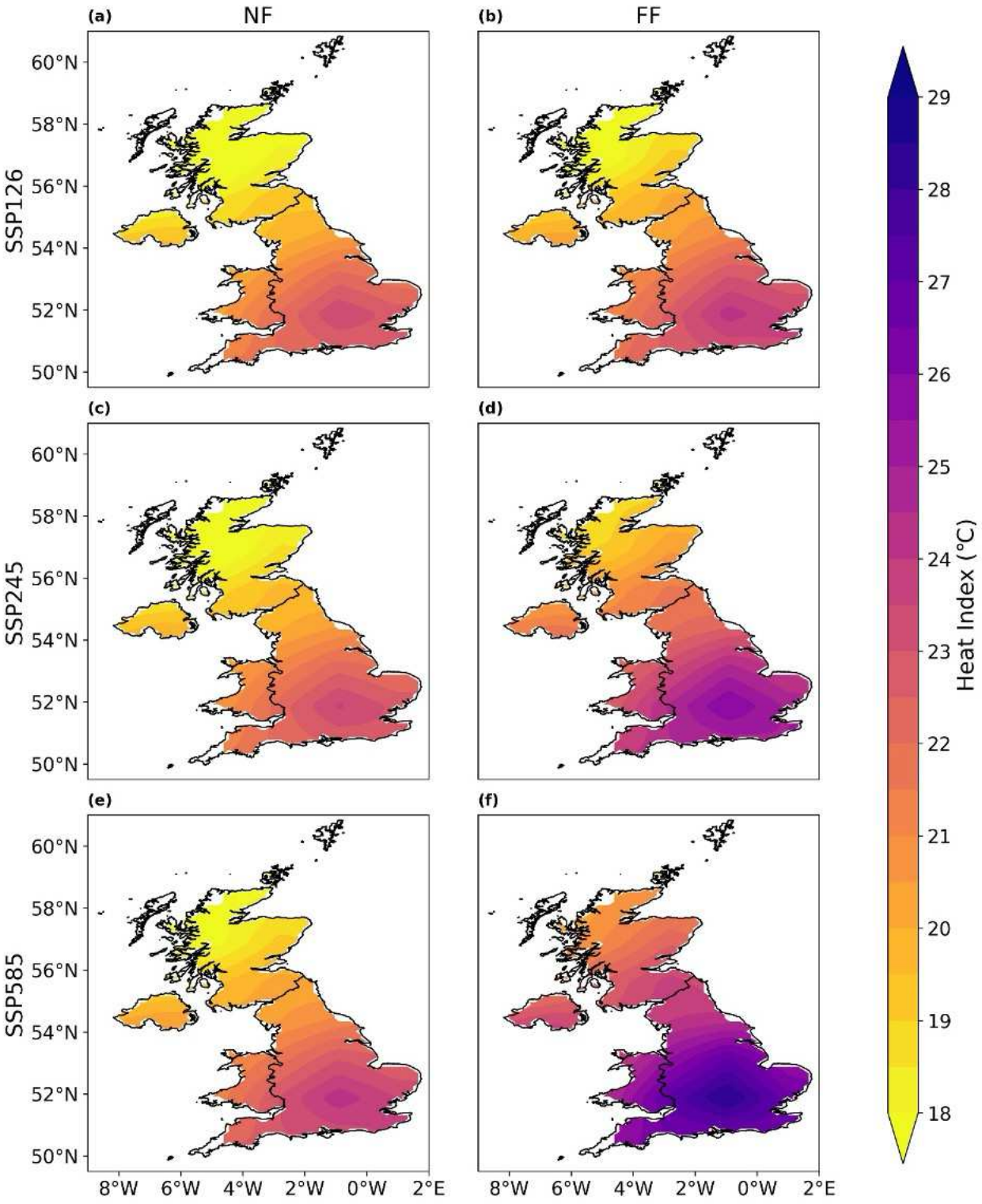


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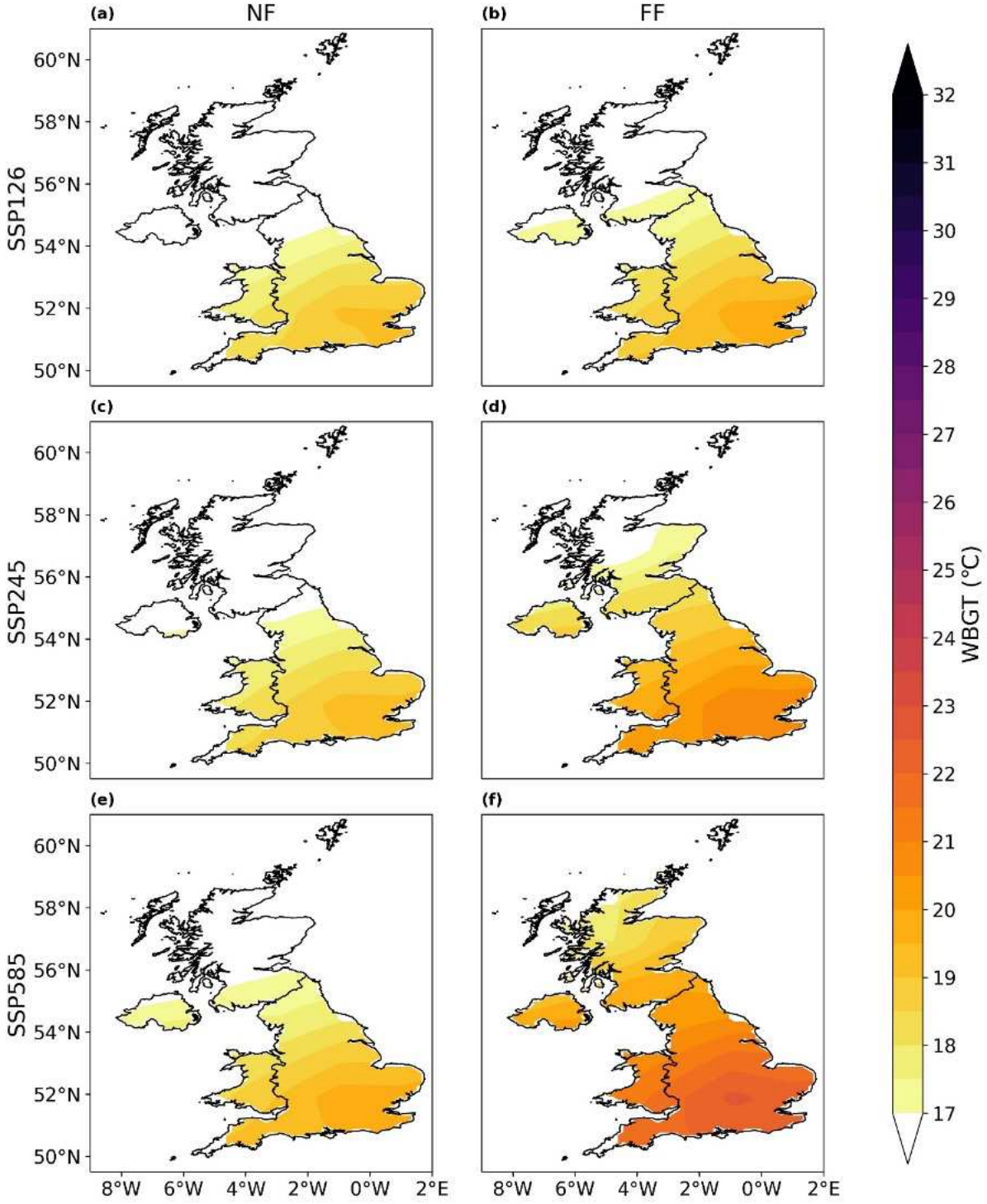


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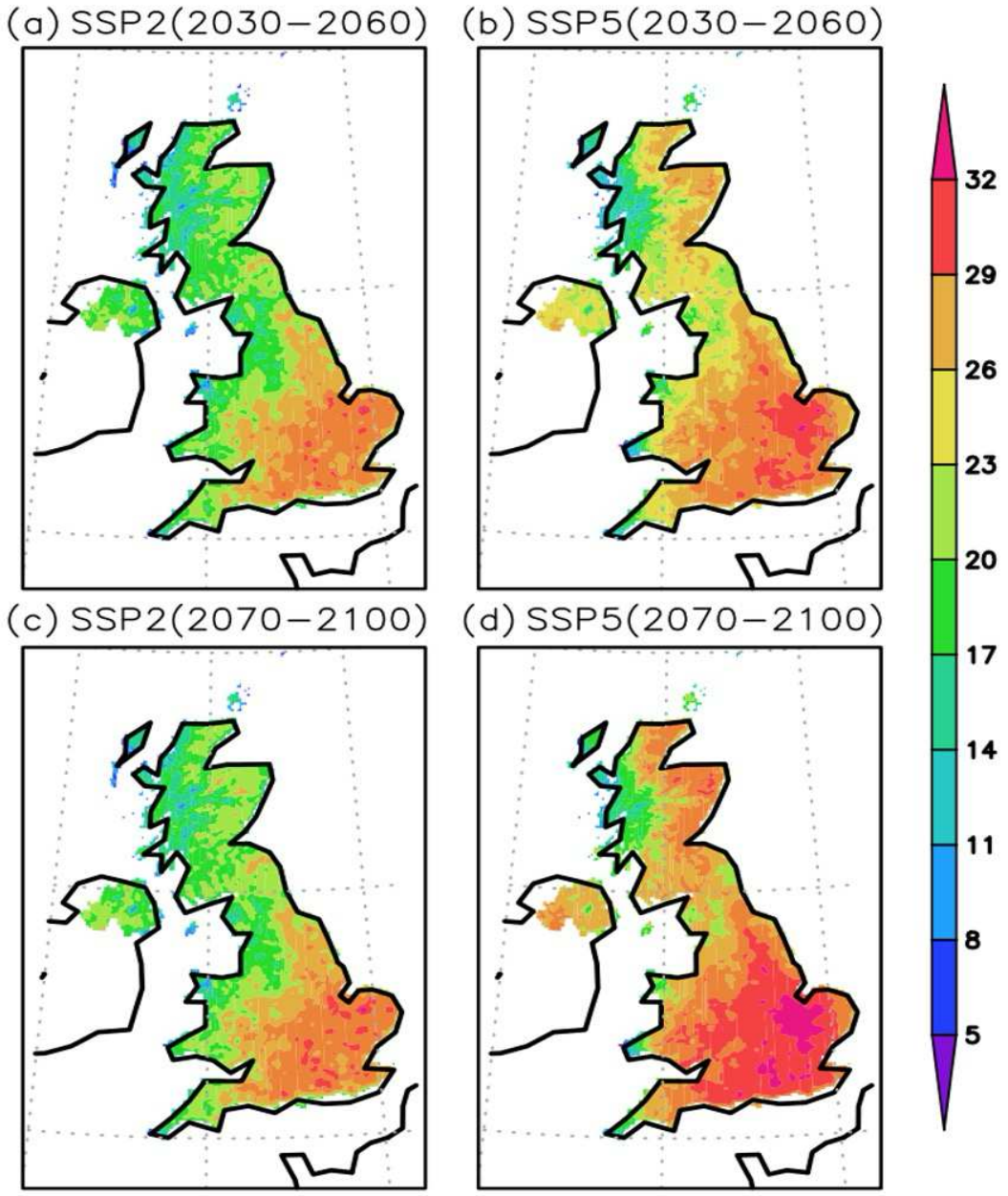


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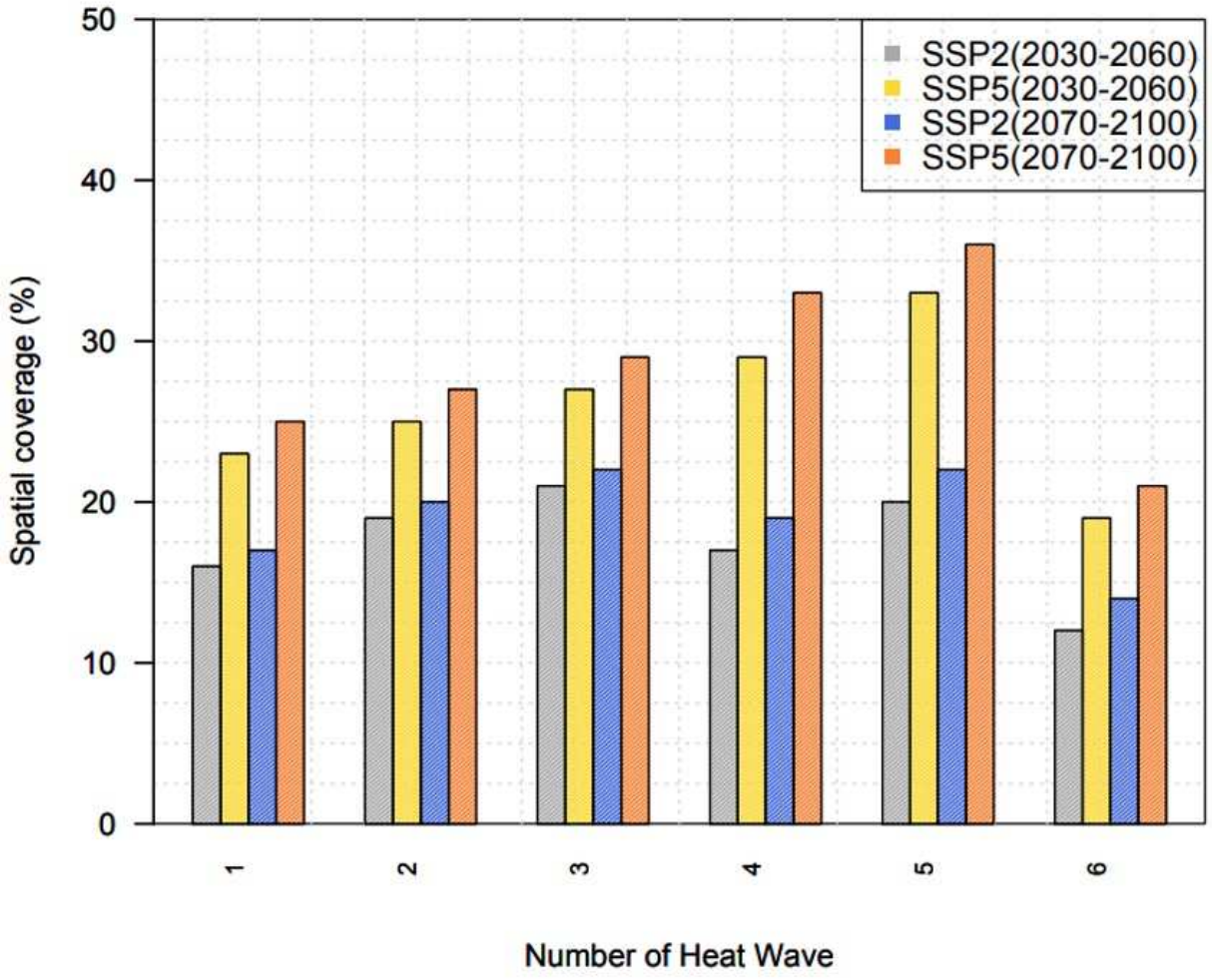


Figure 7: Number of heat waves and associated spatial coverage (in %) for near and far future under SSP2 and SSP5 emission pathways.

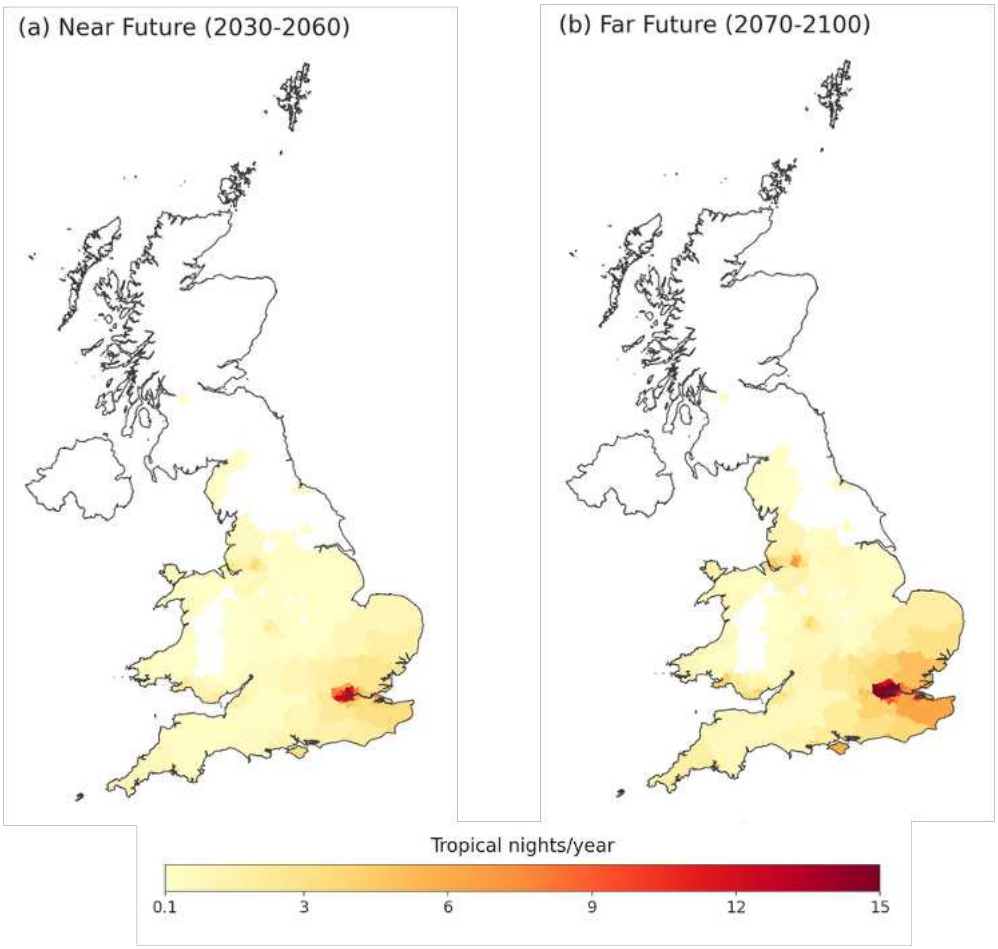


Figure 8: Tropical nights/year for (a) near 2030-2060) and (b) far future (2070-2100) under SSP2 and SSP5 emission pathways.

Table 1: Configuration of RegCM4 model used in the present study

Dynamics	Hydrostatics
Main Prognostic Variables	u, v, t, q and p
Horizontal grid distance	15 km
Map projection	Lambert conformal map projection
Vertical co-ordinate	Terrain-following sigma co-ordinate
Cumulus parameterization	Grell with Fritsch–Chappell closure (FC)
Land surface scheme	Community Land Model (CLM4.5)
Orography treatment	Envelop orography (5% increase from model mean height)
Radiation parameterization	NCAR/CCM3 radiation scheme
PBL parameterization	Holtslag
Simulation period	1980-2100
Analysis period	1984-2014, 2030-2060, 2070-2100
Emission pathway	Shared Socioeconomic Pathways (SSPs)-SSP2, SSP5
Driving CMIP6 model	Hadley Centre Global Environment Model version 3 (HadGEM3)

Table 2: Changes in the frequency and duration of summer (JJA) atmospheric blocking over the UK region

Emission Pathway	Period	Total Blocked days (% of Summer)	Mean event duration (Days)	Block free summers (%)
ERA5	Historical (1984-present)	7.2	3.42	6.5
SSP2	Near Future (2030-2060)	6.4	3.84	12.9
SSP5	Far Future (2070-2100)	5.8	4.17	19.4