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Published Version

Arnell, N. W. ORCID: https://orcid.org/0000-0003-2691-4436 and Freeman, A. (2022) The impact of climate change on policy-relevant indicators of temperature extremes in the United Kingdom. Climate Resilience and Sustainability, 1 (2). e12. ISSN 2692-4587 doi: https://doi.org/10.1002/cli2.12 Available at https://centaur.reading.ac.uk/99555/

To link to this article DOI: http://dx.doi.org/10.1002/cli2.12

Publisher: Wiley

Received: 23 February 2021 | Revised: 28 May 2021 | Accepted: 16 June 2021

DOI: 10.1002/cli2.12

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change
Open Access
RMetS

ORIGINAL ARTICLE

The impact of climate change on policy-relevant indicators of temperature extremes in the United Kingdom

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Funding information
UKRI, Grant/Award Number: NE/S016481/1; UKRI, Grant/Award Number: NE/S016481/1

Abstract

Climate change will increase the frequency of heatwaves in the United Kingdom and reduce the frequency of cold spells. This paper evaluates the effect of changes in climate as represented by UKCP18 climate projections on a series of indicators of heat and cold extremes relevant to policy in the United Kingdom. These indicators are expressed in terms of current critical thresholds beyond which alerts are issued or specific actions implemented, rather than impacts on health and well-being. The frequency and duration of heatwave and heat–health alerts increase under all scenarios, with the greatest absolute number of events in the south and east of England where the chance of hot weather events affecting worker productivity doubles by the 2020s. Cold weather events – triggering health and social care plans and benefit payments – will become less frequent, but the effects of climate change on cold events are much smaller than on hot events and they will continue to occur. Until at least the 2040s, the projected effects of climate change do not depend strongly on the assumed change in global emissions, and the range in possible changes is primarily determined by uncertainty in the change in temperature in the United Kingdom for a given emissions pathway. Beyond the 2050s, the impacts are strongly dependent on future emissions. Impacts in a high-emissions world will be considerably larger than in low-emissions world. The projected increase in heatwave alerts, and the duration and intensity of heatwaves, implies not only a need to review heatwave emergency planning arrangements – looking in particular at what should become regarded as 'normal' summer weather – but also increased efforts to reduce vulnerability to extreme heat events. At the same time, cold weather events will still continue to occur with a sufficient frequency that plans need to be maintained.

KEYWORDS

cold weather, emergency planning, Heatwaves

1 | INTRODUCTION

It is widely accepted that climate change due to an increasing concentration of greenhouse gases will lead to increased temperatures. At the most general level, high temperature extremes will become more frequent and low temperature extremes less frequent, although the changes will depend on the rate of increase in emissions of greenhouse gases and how the dynamics of the climate system changes in response to increased forcing. In common with many other countries, changes in temperature extremes will have consequences for people, the economy and the provision of public services in the United Kingdom (Kovats & Osborn, 2016). Many of these will be adverse, but some will potentially be beneficial. The 2nd UK Climate Change Risk Assessment (Committee on Climate Change, 2016) identified risks to health, well-being and productivity from high temperatures as one of the top two priorities for adaptation action. Christidis et al. (2020) estimated that summers with days with temperatures above 40°C – currently extremely rare – could occur once every 3–4 years with high emissions by 2100.

Heatwaves in the United Kingdom have been associated with increased ill-health, increases in mortality and reduced capacity for work (Costa et al., 2016; Hajat et al., 2014; Vardoulakis et al., 2014; Green et al., 2016; Smith et al., 2016; Arbuthnott & Hajat, 2017), although the consequences have varied with the characteristics of the event and the effects of policy interventions. Since the major European heatwave of 2003, the Department for Health and Social Care in England has developed the Heatwave Plan for England, which is triggered when temperatures exceed specific thresholds (PHE, 2019). Heatwaves are categorized as high-likelihood, moderate-impact events in the UK National Risk Register (Cabinet Office, 2017), and emergency responders are required to prepare for them. However, U.K. planning for heatwaves has been criticized in a House of Commons report (Environmental Audit Committee, 2018) as being fragmented amongst a wide range of national and local departments and agencies, and characterized by a lack of awareness of how heatwave risks are changing.

Cold-related ill-health and mortality is a major public health problem in the United Kingdom (Hajat, 2017), and cold winter weather places significant challenges on health and social care. The Department for Health and Social Care therefore also plans for cold weather events (PHE, 2018), and the Department for Work and Pensions (DWP) makes automatic payments to some categories of social security recipients during defined cold spells (DWP, 2018). Severe cold spells are categorized as high-likelihood, high-impact events in the National Risk Register.

This paper presents an evaluation of the effects of climate change on a series of policy-relevant indicators of high and low temperature extremes across the United Kingdom, using UKCP18 climate projections (Lowe et al., 2018). These indicators represent triggers for policy interventions or planning purposes, focusing on health and well-being. The study evaluates these indicators with high emissions – to support resilience planning – and assesses the effects of reductions in global emissions to inform high-level national climate policy. It is part of a broader multi-sectoral analysis of the effects of climate change on a range of indicators of climate risk for the United Kingdom (Arnell et al., 2021), which also considers indicators of temperature extremes relevant for transport (Arnell et al., 2021) and agriculture (Arnell & Freeman, 2021).

2 | INDICATORS, DATA AND CLIMATE PROJECTIONS

2.1 | Overall approach

The effects of climate change on the indicators are calculated at the 12 × 12-km resolution, using HadUK gridded observed daily climate data (Hollis et al., 2019) and UKCP18 climate projections (Lowe et al., 2018) applied using a transient version of the delta method. Results are aggregated to the regional level (Figure 1), weighted by 2011 population.

2.2 | Indicators of temperature extremes

Five groups of heat and cold extreme indicators are calculated (Table 1), relating to public communications and four areas of public policy. Arnell et al. (2021) present projections for change in the likelihood of Met Office heatwaves and amber heat–health alerts: the analysis here presents changes in a wider range of indicators.

In 2019, the Met Office published a new definition of 'heatwave' (McCarthy et al., 2019), primarily designed for public communications purposes: the House of Commons Environment Audit Committee in 2018 had highlighted the lack of a consistent definition. With this new definition, a 'heatwave' is deemed to occur when maximum daily temperatures exceed region-specific thresholds for at least three consecutive days. These thresholds differ by county across the United Kingdom and range from 28°C in parts of the south east of England to 25°C in northern England, Scotland, Wales and Northern Ireland (Figure S2). This indicator ('Met Office heatwave') is here expressed as the average number of times a heatwave occurs (a 'declaration') per year, the average number of days in a declared

FIGURE 1 Regions in the United Kingdom

TABLE 1 Indicators of heat and cold extremes

Indicator	Definition	Reference
Met Office heatwave	Maximum temperature above region-specific thresholds for at least 3 days	McCarthy et al. (2019)
Heat–health alerts ('Amber alerts')	Maximum and minimum temperatures above region-specific thresholds for at least 2 days (Table 2)	PHE (2019); Sanderson & Ford (2016)
Cold weather alerts ('Amber alerts')	Average temperatures below 2°C for at least 2 days	PHE (2018)
Cold Weather Payments	Average temperature below 0°C for at least 7 days, in at least one of 94 locations	DWP (2018)
Occupational heat stress	Wet Bulb Globe Temperature (WBGT) above 27°C	Morabito et al. (2019)

TABLE 2 Temperature thresholds for heat–health amber alerts (PHE, 2019)

Region	Day temperature (T_{max})	Night temperature (T_{min})
London	32	18
South East	31	16
South West	30	15
Eastern England	30	15
West Midlands	30	15
East Midlands	30	15
North West	30	15
Yorkshire and Humberside	29	15
North East	28	15

heatwave per year calculated over years with at least one heatwave (a measure of heatwave duration) and the likelihood of having a declaration in a year.

The second and third indicators are explicit triggers for the implementation of emergency plans by Public Health England. The Heatwave Plan for England (PHE, 2019) is primarily concerned with avoiding excess mortality due to extreme heat. The plan contains a number of components, including strategic planning (long-term) and seasonal preparedness, an alert system and the provision of advice to healthcare professionals and the public. The heat–health watch alert system (Sanderson & Ford, 2016) has five levels, currently operates from 1 June to 15 September, and is based on temperature forecasts from the Met Office (Table 2 shows the regional thresholds: an alert may also be triggered if the official Central England Temperature (CET) daily mean temperature (Parker et al., 1992) exceeds 20°C). Level 2 (yellow) is triggered when an event is forecast, and Level 3 (amber) when an event actually begins. Level 4 represents a national emergency and would be declared if the heatwave were prolonged or severe and affected sectors other than health: this declaration is not based on strict quantitative meteorological criteria. In this study, the 'heat–health alert' indicator is based on the actual exceedance of the temperature thresholds, which is equivalent to a Level 3 amber alert. Like the Met Office heatwave indicator, this is expressed as the average number of events (declarations) per year, the average number of days in a declared heatwave per year calculated over years with at least one heatwave (a measure of heatwave duration) and the likelihood of having a declaration. Public health heatwave planning policies are different in Wales, Scotland and Northern Ireland and the Met Office heat–health watch alert system does not apply, and there are therefore no temperature thresholds. For this analysis, thresholds for neighbouring regions were used to indicate the risk of having to implement heatwave emergency plans. A prototype revised alert system has been developed (Masato et al., 2015) using different temperature thresholds more closely related to mortality, but this has not yet been implemented. The heat–health alert system differs from the new Met Office heatwave warning system by using higher temperature thresholds and incorporating information on night-time temperatures.

The third indicator looks at the other extreme and characterizes cold weather emergencies for healthcare and social care services. Pressures on the hospital system in the United Kingdom are currently typically greatest in winter, partly due to the prevalence of communicable diseases such as acute bronchitis and influenza which peak in winter, and partly due to increases in respiratory diseases linked to cold weather (Bone et al., 2014). In 2017–2018 for example some hospitals deferred non-emergency cases to deal with large influxes of patients. The Cold Weather Plan for England (PHE, 2018) therefore aims not only to reduce public ill-health and mortality, but manage pressures on the health system. Like the Heatwave Plan, it involves strategic planning and seasonal preparedness, communications and a 5-level alert system. A Level 3 (amber), 'cold weather' alert occurs when average temperatures are below 2°C for at least two consecutive days. This threshold is consistent across England. As with heatwave planning, different policies apply in Wales, Scotland and Northern Ireland, so in this analysis the same thresholds are applied there. This indicator ('cold weather alert') is expressed as the number of times the Level 3 declaration threshold is passed per year, and the annual likelihood of the threshold being passed.

These three indicators are all based on the occurrence of temperature extremes beyond a threshold, used to initiate an alert. In practice, alerts are based not just on exceedances at a location but also on the spatial extent of the event: this extent is not considered in the calculation of the indicators here. The heat–health and cold weather alerts are also issued at a regional level if the threshold is exceeded somewhere in that, or a neighbouring, region. Here, the indicators are expressed as the regional average number or chance of threshold exceedance. The two interpretations are similar, but not the same.

It is also important to note also that adverse health consequences of hot and cold spells emerge before the alert thresholds are reached, so the indicators should not be interpreted as representing direct health impacts: they represent operational thresholds used to initiate prepared plans.

The fourth indicator is the number of times cold weather payments are actioned under the DWP Social Fund Cold Weather Payments scheme (DWP, 2018) in England, Wales and Scotland, and its counterpart in Northern Ireland. This scheme provides an automatic payment of £25 to recipients of benefits in an area affected by a 'cold event'. It is based on temperatures recorded at 101 index weather stations across the United Kingdom, and each postcode area is assigned to one of the index sites. If the 7-day mean temperature is below 0°C at a site, then all the benefit claimants in the associated postcodes automatically receive the payment. Over the period 2011–2012 to 2018–2019, an average of approximately £55 million was paid each year in England, Wales and Scotland, although the annual totals range from zero (in the mild winter of 2013–2014) to £146 million in 2012–2013. In this analysis, the indicator ('Cold Weather Payments') was defined by counting the number of 'cold events' at these 101 locations (in practice the grid cells (Section 2.3) corresponding to these locations, rather than the sites themselves). The number of cold events in a year does not correlate directly with total payments because the number of recipients varies across the index sites.

The fifth indicator is a measure of occupational heat stress. In the United Kingdom, there is currently no legal upper limit on temperatures in the workplace (indoor or outdoor), although employers must ensure that temperatures are 'reasonable' (HSE, 2013). The Wet-Bulb Globe Temperature (WBGT) is a widely used heat-stress index, and published thresholds set standards for different types of labour. WBGT depends on air temperature, humidity, radiative temperature and wind. Here, WBGT is calculated from daily maximum temperature and relative humidity (using the same algorithms as Dunne et al. (2013)), and assuming shade (see the Supporting Information). This analysis uses a threshold of 25, which corresponds approximately to the threshold of 27 for WBGT in the sun used in the European HEAT-SHIELD occupational warning system (Morabito et al., 2019): at WBGT values above this threshold, the international standard ISO 7243 recommends increasing work breaks. The indicator is expressed in terms of the average annual number of days per year with WBGT (in the shade) greater than 25, and the likelihood of having at least 1 day in a year. This definition is different to that used by Kennedy-Asser et al. (2021), who used a different empirical function and calculated WBGT in the sun.

All the indicators are calculated at a resolution of 12 × 12 km across the United Kingdom, and are expressed as averages or likelihoods calculated over 30-year periods. Regional averages by administrative region are produced by weighting each grid cell by its 2011 census population (ONS, 2016) calculated by summing the Census aggregate data to the 12 × 12-km grids. For the cold weather payment indicator, the regional value is simply the number of grid cells passing the trigger threshold. Note that the regional average number or likelihood of heatwaves and cold spells is not the same as the number or likelihood of heatwaves or cold spells occurring somewhere within a region – which is how regional declarations are made in practice.

2.3 | Reference climate data

The indicators are calculated from minimum and maximum temperature and (for WBGT) relative humidity.

Observed climate data were taken from HadUK-Grid 12-km resolution observational data set (Met Office, 2018; Hollis et al., 2019), supplemented by ERA5 reanalysis (Copernicus Climate Change Service, 2017). The HadUK-Grid 12-km data set includes daily minimum and maximum temperature and rainfall up to 2018 (at the time of analysis), but relative humidity is only available as monthly averages. Daily relative humidity was therefore estimated from the ERA5 reanalysis, rescaling the ERA5 reanalysis so that the monthly mean equalled the HadUK-Grid monthly mean. The time period 1981–2010 is used to represent current climate.

The current urban heat island effect is reflected to a certain extent in the gridded observed data, although it is probably slightly underestimated due to the coarse spatial resolution (each grid cell represents 144 km^2, whilst inner London e.g. covers just over 300 km^2).

2.4 | Climate projections and their application

The UKCP18 land climate projections (Lowe et al., 2018; Murphy et al., 2019) contain projections of plausible future climates across the United Kingdom with different rates of future emissions of greenhouse gases. This paper concentrates on the probabilistic strand of projections with three levels of emissions: RCP2.6 (low), RCP6.0 (medium) and RCP8.5 (very high). For each level of emissions, the probabilistic strand contains 3000 equally plausible projections of monthly mean climate variables at a spatial resolution of 25 × 25 km, at an annual resolution up to 2100. The indicators were also calculated with the global (60 × 60 km, RCP2.6 and RCP8.5) and regional (12 × 12 km, RCP8.5) strands – both ensembles of climate model projections - and results for the global strand are presented in the Supporting Information (the regional strand gives very similar results to the corresponding projections from the global strand). The global and regional strands do not necessarily span the full range of uncertainty. Differences between the global and probabilistic strands are highlighted in the text.

For each of the 12 × 12 km observed data grid cells, time series of daily temperature and relative humidity for the period 1981–2100 were constructed by first repeating the historical period 1981–2010 to create a long ‘unperturbed’ baseline to 2100 and then applying the projected annual change in monthly mean climate from the corresponding climate projection grid cell from 2011 onwards. The gridded observations and the climate projections are at different spatial resolutions, and look-up tables were used to map each observed data grid cell to a corresponding climate model grid cell. This transient application of the delta method is described in the Supporting Information. The period 1981–2010 is therefore identical for all projections, and each time series incorporates a progressive change in climate over time from 2011. The approach maintains the observed pattern of day-to-day and year-to-year variability, and extreme temperatures in a month are changed by the same amount as the mean. High-resolution model simulations suggest that temperatures may increase by a proportionally greater amount on hot days (Kennedy-Asser et al., 2021), but this effect is not incorporated here: changes in high temperature extremes may therefore be underestimated.

The probabilistic projections do not necessarily maintain realistic physical relationships between variables for a given ensemble member, and UKCP18 guidance emphasizes that care should be taken when combining variables (Fung et al., 2018). Estimated changes in maximum and minimum temperatures in a month may be inconsistent, so changes in average temperature were here applied to both minimum and maximum temperatures. In summer, however, maximum temperatures increase faster than average temperatures and minimum temperatures increase at a lower rate. Applying the same increase to both therefore potentially leads to an underestimation of an increase in maximum temperatures, and an overestimation of the increase in minimum temperatures. This most affects the Met Office heatwave and the WBGT indicators, which may underestimate future change. Similarly, changes in temperature and vapour pressure may be inconsistent in the probabilistic strand, leading to potentially unrealistic variability in estimated changes in relative humidity. This implies that the uncertainty range for the WBGT projections may be too high.

The global and regional strands are based on much smaller numbers of individual climate model simulations: two ensembles of 15 and 12 models, respectively, for the global strand (the HadGEM3 set and the CMIP5 set), and one ensemble of 12 models for the regional strand (based on the HadGEM3 ensemble). They maintain physically realistic relationships between variables and across space. However, they only represent a portion of the uncertainty range, and are available for fewer emissions scenarios than the probabilistic projections.

The study uses the delta method to perturb observations rather than use (bias-adjusted) climate model output directly, for both practical and conceptual reasons. Observed data are used to characterize the current climate because this observed experience is familiar to stakeholders. The presentation here focuses on the UKCP18 probabilistic projections because they span a wider range of uncertainty than the global and regional projections and are available for more emissions scenarios, but they contain information only on changes in monthly means. The delta method is therefore the only practical method of

TABLE 3 Increases in global mean temperature with the RCP2.6, RCP6.0 and RCP8.5 projections

	Increase in temperature above pre-industrial levels (°C)		
	RCP2.6	**RCP6.0**	**RCP8.5**
2050s	1.6 (1.1–2.2)	1.7 (1.3–2.2)	2.3 (1.7–2.9)
2100	1.9 (1.3–2.6)	3.7 (2.8–4.7)	5.1 (4.0–6.5)

Note: The table shows the median estimate of increase in global mean temperature, with the 10th to 90th percentile range in brackets. The average global temperature over the period 1981–2010 was approximately 0.61°C warmer than pre-industrial levels. Data from Met Office Hadley Centre (2019)

creating daily time series of future weather data from the probabilistic projections. It would have been feasible to have applied bias adjustment to the global and regional strand projections, but these only span a part of the uncertainty range and there are known limitations to bias adjustment (e.g. Ehret et al., 2012; Maraun et al., 2017) with different methods producing different results. Extreme high and low temperatures in the United Kingdom are generally associated with blocking patterns, and climate models – including those used to construct the UKCP18 projections (Williams et al., 2017) – tend to underestimate blocking frequency across Europe. There is therefore low confidence in estimated changes in the frequency of the atmospheric conditions which generate extreme temperatures, and bias adjustment would not correct for this. The delta method is therefore a simple and pragmatic approach to constructing daily time series for climate change assessment, but its limitations are acknowledged and considered further in the discussion.

The climate projections do not explicitly incorporate potential increases in the urban heat island effect, but the current heat island effect is incorporated through the gridded reference data. Eunice Lo et al. (2020) estimated that an enhanced urban heat island would increase London's temperatures by an additional 0.5°C by the 2080s with high emissions.

2.5 | Change in temperature across the United Kingdom

The global average increase in temperature for the three levels of emissions is shown in Table 3. RCP2.6 is broadly consistent with an increase in global average temperature above pre-industrial levels of around 2°C by 2100, whilst RCP8.5 represents very high emissions.

Figure 2 shows regional average changes in seasonal temperature relative to the 1981–2010 mean with the three sets of projections. Temperature increases in each season consistently across the United Kingdom, with greater increases in southern and eastern England in summer. The changes are greatest with the higher emissions, and in summer. Summer average temperatures could be more than 5°C higher than the 1981–2010 average by the 2080s with high emissions – and possibly up to 8°C higher. Even with low emissions the increase could be around 2°C above the 1981–2010 mean. Figure 2 also shows, for context, the average number of 'hot days' (maximum temperature greater than 25°C) and 'tropical nights' (minimum temperature greater than 20°C): the current numbers and future change vary across the United Kingdom. 'Tropical nights' remain extremely rare until the 2040s in the south of England with high emissions. Relative humidity is projected to decrease (vapour pressure increases because the warmer atmosphere holds more water, but the increase in temperature means that saturation vapour increases by a greater amount), but with a wide uncertainty range: this range is overestimated for reasons outlined in the previous section.

The global strand HadGEM3 ensemble produces increases in average temperature that are at the top end of the probabilistic ensemble range, and the global CMIP5 ensemble is towards the middle and lower end of the range (Supporting Information): the two global strands are distinct. The HadGEM3 ensemble also produces greater increases in maximum temperatures than the probabilistic strand, and smaller increases in minimum temperatures, so projects a greater increase in the number of 'hot days' and a smaller increase in the number of 'tropical nights'. The uncertainty range in projected change in relative humidity is smaller with the global strand projections than for the probabilistic projections.

3 | CURRENT VALUES OF THE INDICATORS

Figure 3 shows the values of the indicators over the 1981–2010 reference period, and Figure 4 shows the time series of regional average numbers of (simulated) events between 1981 and 2018. The thresholds for the Met Office heatwave and the heat–health amber alert indicators vary across the United Kingdom. The number of 'hot' events is greatest in the south and east of England despite the variation in threshold, and the number of 'cold' events is greatest in the north and west of the United Kingdom. Note that the heat–health and cold weather thresholds do not apply in Scotland, Wales or Northern Ireland, so the high apparent

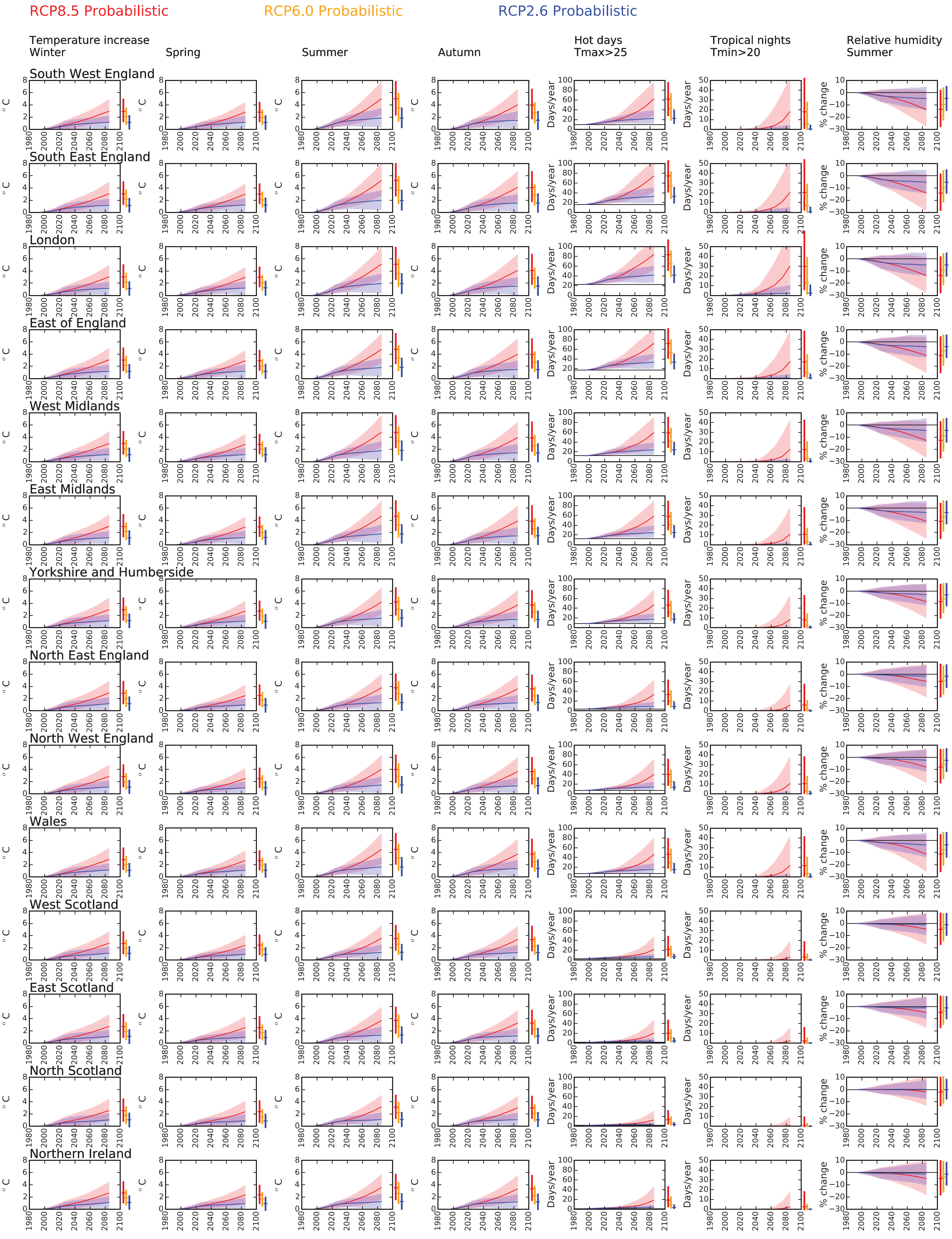

FIGURE 2 Change in seasonal and extreme temperatures by region, with RCP8.5, RCP6.0 and RCP2.6 emissions. The plots show the 30-year mean, plotted at the middle year of the 30-year period. The solid line shows the median, and the shaded area the 10th to 90th percentile range, which should be interpreted as 'low' to 'high'. The changes in seasonal temperature and humidity are relative to 1981–2010

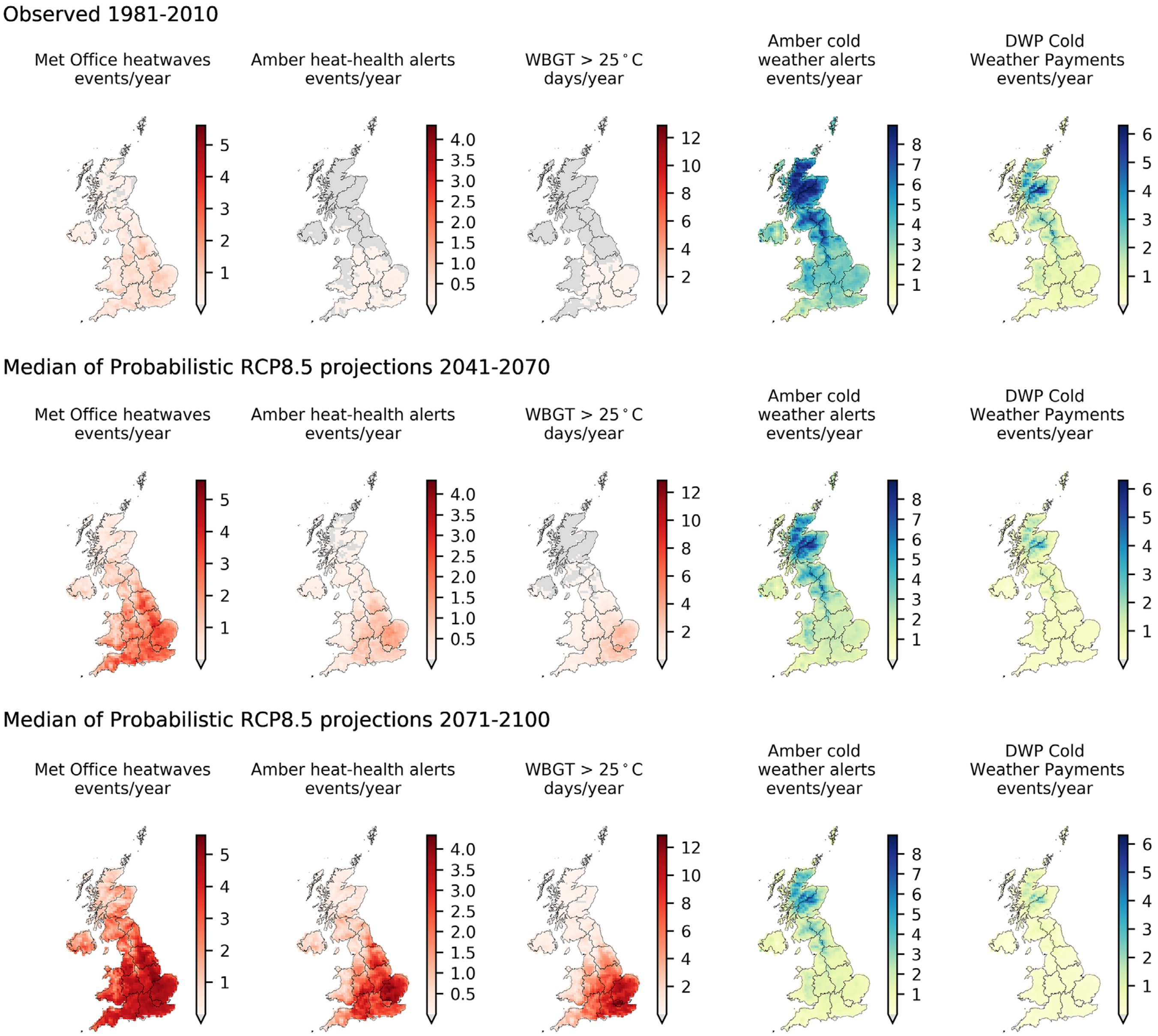

FIGURE 3 The spatial distribution of indicators of heat and cold extremes across the United Kingdom. Top row: observed, 1981–2010. Middle row: median estimate from RCP8.5 projections, 2041–2071. Bottom row: median estimate from RCP8.5 projections, 2071–2100

numbers of potential events here – particularly in Scotland – do not translate into cold weather alerts for the health service. The Met Office heatwave threshold was crossed, on average, in around 40% of years between 1981 and 2010 in southern and eastern England, but only around 20% of years in Scotland. Between 10% and 20% of years passed heat–health alert thresholds in the south and east of England, compared with fewer than 5% further north. The Met Office heatwave alert threshold is passed more frequently than the heat–health alert thresholds: not all Met Office alerts are heat–health alerts. The cold weather alert threshold was crossed in virtually every year.

Figure 4 highlights the considerable year-to-year variability in the five indicators plotted. A major heatwave in 1995 is apparent across most of the United Kingdom with both the Met Office and heat–health alert indicators, and the 2003 heatwave appears in southern and eastern England with the heat–health alert indicator and days with WBGT greater than 25: the Met Office heatwave indicator suggests that 2006 was more extreme. More recent heatwaves in 2013 and 2018 are highlighted. The difference between the indicators shows sensitivity to the precise definition of a heatwave or hot extreme. The cold weather alerts and cold weather payment indicators show a series of cold events in the mid-1980s and early part of the 21st century, and also highlight 2010 (actually winter 2009–2010) and 2018. There is no clear visual evidence of a trend in the occurrence of hot or cold spells – as defined

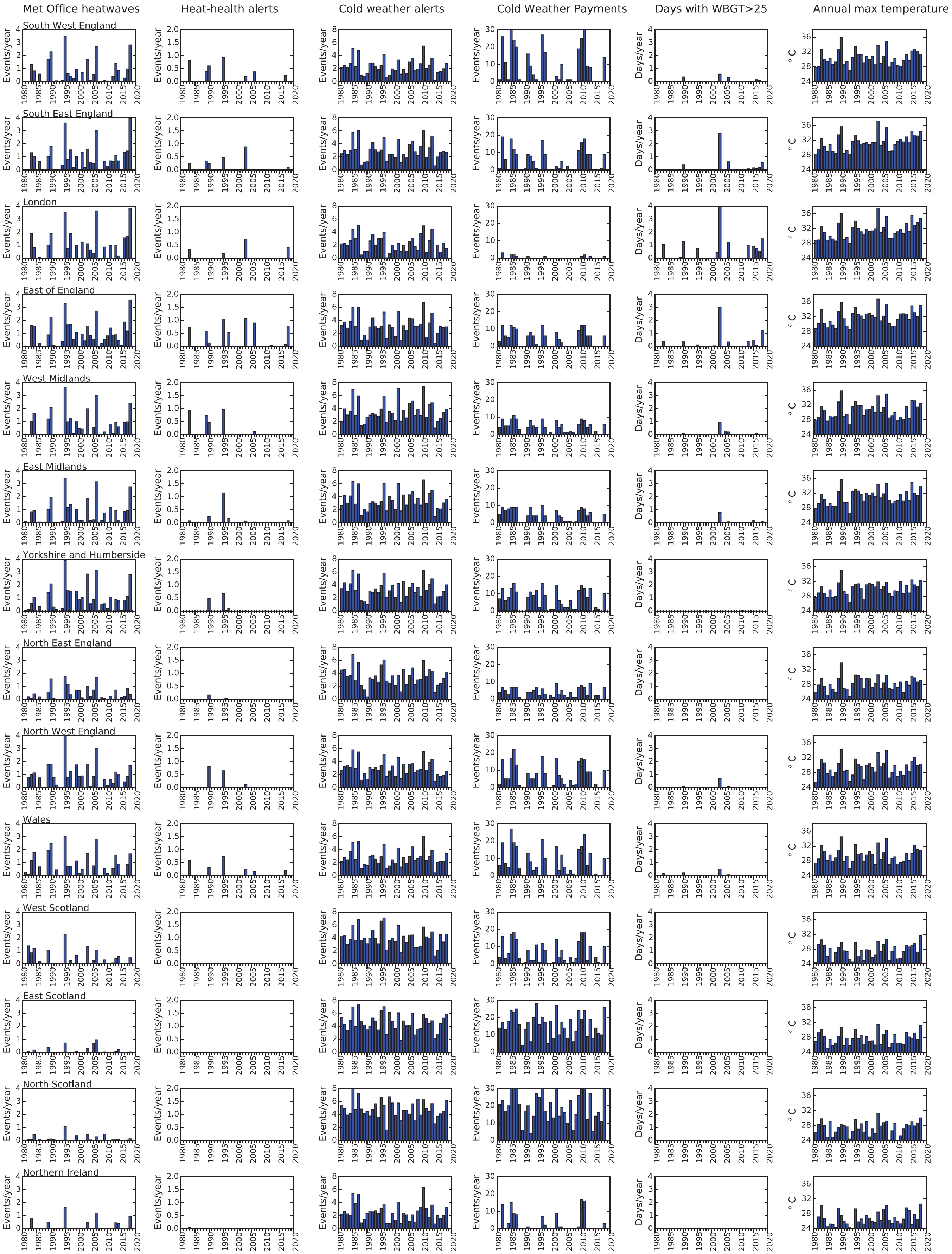

FIGURE 4 Time series of the heat and cold extreme indicators over the period 1981–2018, by region

here – apart from a suggestion of fewer hot events and more cold events in the 1980s and more frequent days with WBGT greater than 25 in the south and east of England since 2012. Sanderson et al. (2017), using a different definition of heatwave, also identified considerable year-to-year variability and variable trends in heatwaves at 29 weather stations. Figure 4 also plots the maximum daily temperature by region in each year, showing a slight increase since 2010 in some regions. This emphasizes that changes in extreme temperature do not necessarily translate directly into changes in heatwave occurrence, because heatwaves are defined over several days.

In principle, it should be possible to validate the calculated heat–health and cold weather alert indicators against the observed number of declarations of events (since warnings were first issued from 2012 or 2013). However, in practice events are declared on the basis of thresholds being crossed somewhere in a region: here the indicator is the average number of threshold exceedances in the region. Nevertheless, a comparison with observed declarations shows that most cold events are identified but many observed heat–health extremes are missed: Figure 4 for example shows events were identified in south west England in 2017, but in practice declarations were also made in 2013, 2015 and 2018. This underestimation primarily arises because the 12 × 12 km gridded maximum temperatures tend to underestimate point maximum temperatures, and therefore the chance of a threshold exceedance being identified. For example, the maximum observed temperature in London in the 2003 heatwave was 38.1°C, whilst the corresponding maximum 12 × 12 km value is 37.5°C.

The estimated number of Cold Weather Payments over the period 2011–2018 is very similar to the observed (504 estimated for England, Scotland and Wales compared with the 522 observed), with the slight difference occurring due to the use of gridded rather than actual weather station data.

4 | CHANGES IN INDICATORS THROUGH THE 21ST CENTURY

Figures 5 and 6 show the indicators calculated over successive 30-year periods by region across the United Kingdom through the 21st century with the UKCP18 probabilistic projections and low (RCP2.6), medium (RCP6.0) and high (RCP8.5) emissions. Indicators for the four nations of the United Kingdom are shown in Figure 7. Similar plots showing the global strand projections with high emissions are presented in the Supporting Information, which also contains regional tables of results. Tables 4 and 5 show a subset of the indicators for the 2050s and the 2080s. Maps showing the median estimates of the indicators in the 2050s and 2080s with high emissions are shown in Figure 3.

The number, duration and likelihood of Met Office heatwaves increase very substantially with high emissions, particularly in southern and eastern England, and also increase above current levels with low emissions. By the 2050s, the regional average annual likelihood of experiencing a Met Office heatwave increases from around 40% now to more than 80% in southern and eastern England, and there would be between 5 and 10 days in heatwave conditions on average each year (median estimate). In eastern Scotland, the increase in likelihood is from 10% to around 40%. The uncertainty range is large, however. The upper estimate – the 90th percentile – is typically around twice as large as the median estimate.

The number of amber heat–health alerts increases particularly significantly after the middle of the century, and again the uncertainty range is large and there are differences between the regions of the United Kingdom. By the 2050s, the regional average annual likelihood of an alert increases from around 10% to around 40% (with a range of approximately 20%–60%) in southern and eastern England. At present, the average duration of an alert (at a place) is between 1 and 2 days, but by the 2050s this would increase in southern England to between 3 and 4 days (and possibly up to around 7 days). There is little evidence of increases in the frequency of alerts outside the 1st June to 15th September window until the 2050s (Supporting Information), but this conclusion may be affected by the underestimation of actual heat-alert declarations: in 2016 a heat–health alert was issued for parts of southern and eastern England on 14th September.

In southern and eastern England the likelihood of experiencing a day with WBGT greater than 25 increases rapidly, and by the 2020s (2010–2039) may be double the likelihood over the period 1981–2010: by the middle of the century, such a threshold would be exceeded more than 1 year in two with high emissions. This is consistent with Casanueva et al.'s (2020) assessment at the European scale. In the United Kingdom, high temperatures typically occur on days with low relative humidity: at 30% relative humidity – typical of a hot U.K. day – a WBGT of 25 in the shade corresponds to approximately 33°C.

The number of times the cold weather alert threshold is exceeded decreases through the century, but events continue to occur even with high emissions. Even in London – the warmest region – there is a 40% chance of a cold weather alert by the 2080s with high emissions.

The average annual total number of cold weather payment activations declines from 98 over the period 1981–2010 to an average of 55 and 34 in the 2050s and 2080s, respectively, with high emissions. The proportional reduction in Scotland is very slightly less (65% reduction by the

FIGURE 5 Number, duration and frequency of Met Office heatwave and heat–health alerts through the 21st century, with RCP8.5, RCP6.0 and RCP2.6 emissions. The plots show the median and the 10th to 90th percentile ranges. The plots show the 30-year mean, plotted at the middle year of the 30-year period. The solid line shows the median, and the shaded area the 10th to 90th percentile range, which should be interpreted as 'low' to 'high'

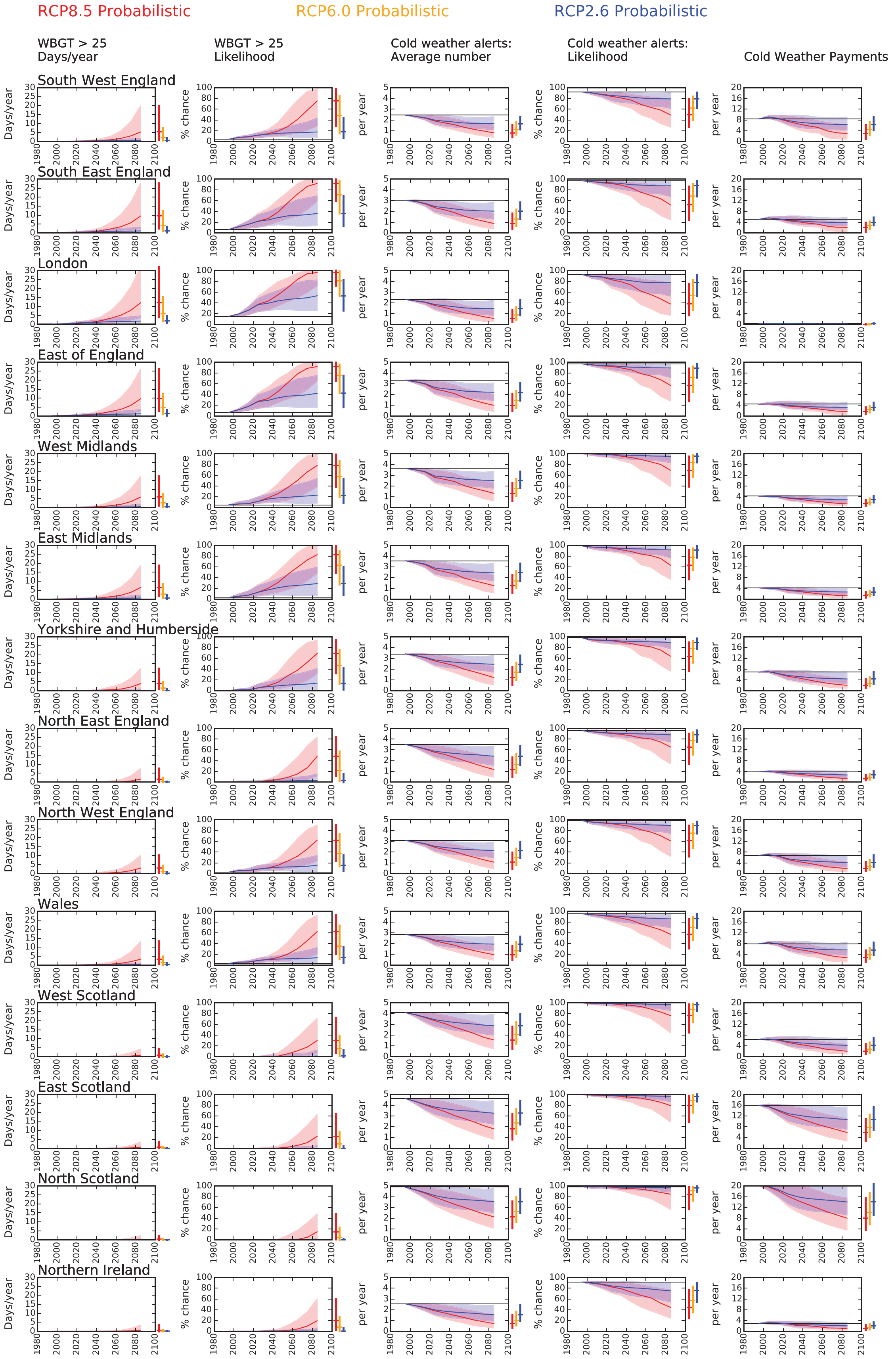

FIGURE 6 Number and frequency of days with WBGT greater than 25 and cold weather alerts, and number of cold weather payments, with RCP8.5, RCP6.0 and RCP2.6 emissions. The plots show the median and the 10th to 90th percentile ranges. The plots show the 30-year mean, plotted at the middle year of the 30-year period. The solid line shows the median, and the shaded area the 10th to 90th percentile range, which should be interpreted as 'low' to 'high'

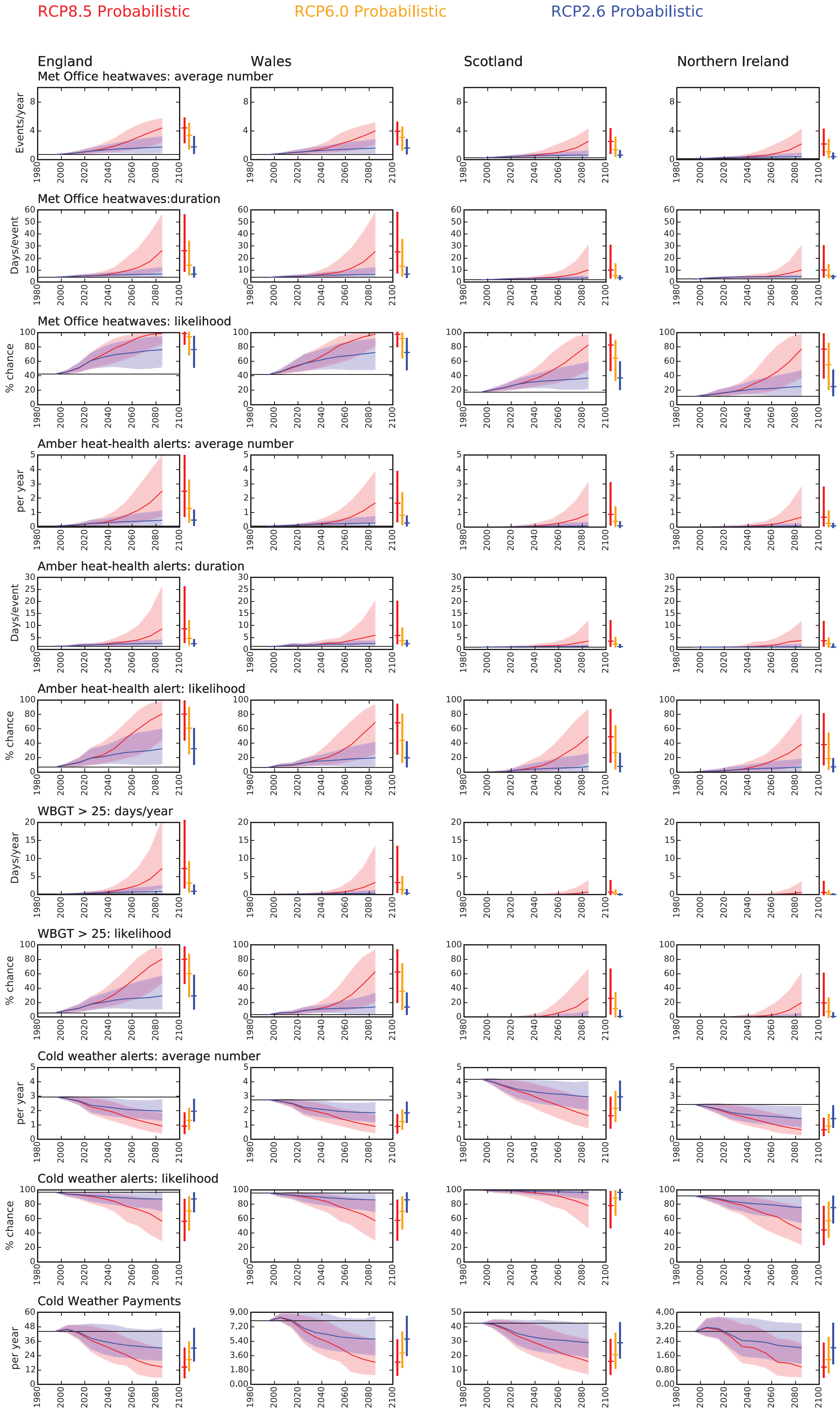

FIGURE 7 Indicators of temperature extremes by U.K. nations, with RCP8.5, RCP6.0 and RCP2.6 emissions. The plots show the median and the 10th to 90th percentile ranges. The plots show the 30-year mean, plotted at the middle year of the 30-year period. The solid line shows the median, and the shaded area the 10th to 90th percentile range, which should be interpreted as 'low' to 'high'. Note that the axis limits for the cold weather payment indicator varies between nations

TABLE 4 Regional average heat and cold extreme indicators in the 2050s and 2080s: Average number of events or days per year. Probabilistic projections

		2050s	2080s																
		RCP2.6			RCP6.0			RCP8.5			RCP2.6			RCP6.0			RCP8.5		
	1981–2010	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High
Met Office Heatwaves (events per year)																			
South West England	0.62	1.47	0.86	2.51	1.62	0.84	2.91	2.42	1.17	3.95	1.69	0.85	3.1	3.38	1.45	4.8	4.13	2.31	5.35
South East England	0.72	1.74	0.98	2.97	1.91	1.01	3.32	2.84	1.42	4.4	2.01	0.99	3.63	3.8	1.7	5.23	4.59	2.81	5.86
London	0.69	1.6	0.93	2.8	1.78	0.98	3.13	2.65	1.35	4.27	1.87	0.94	3.49	3.64	1.6	5.29	4.6	2.65	6.06
East of England	0.79	1.8	1.03	3	1.98	1.07	3.34	2.9	1.48	4.39	2.07	1.03	3.63	3.82	1.74	5.31	4.69	2.82	6.07
West Midlands	0.65	1.34	0.85	2.26	1.43	0.85	2.66	2.13	1.1	3.94	1.53	0.84	2.96	3.21	1.3	4.94	4.34	2.06	5.76
East Midlands	0.63	1.35	0.83	2.18	1.43	0.83	2.53	2.09	1.12	3.69	1.51	0.81	2.82	3.03	1.29	4.75	4.22	2.08	5.72
Yorkshire and Humberside	0.85	1.64	1.08	2.58	1.78	1.08	2.94	2.48	1.4	4.01	1.85	1.05	3.19	3.42	1.62	4.92	4.41	2.47	5.79
North East England	0.38	0.92	0.5	1.64	1.04	0.5	1.97	1.62	0.72	3.18	1.07	0.48	2.15	2.49	0.94	4.4	3.75	1.61	5.41
North West England	0.81	1.44	0.99	2.21	1.54	0.99	2.54	2.1	1.23	3.64	1.64	0.98	2.82	3.05	1.46	4.72	4.16	2.1	5.54
Wales	0.71	1.4	0.9	2.24	1.52	0.88	2.63	2.16	1.14	3.57	1.61	0.87	2.79	3.07	1.37	4.5	3.96	2.1	5.14
East Scotland	0.11	0.34	0.17	0.65	0.36	0.16	0.8	0.61	0.25	1.67	0.39	0.16	0.94	1.15	0.31	3.09	2.38	0.62	4.2
West Scotland	0.36	0.81	0.49	1.2	0.84	0.47	1.32	1.14	0.65	2.11	0.89	0.45	1.48	1.65	0.76	3.22	2.71	1.14	4.38
North Scotland	0.12	0.34	0.16	0.61	0.35	0.16	0.7	0.52	0.23	1.09	0.38	0.15	0.8	0.84	0.29	2.2	1.53	0.5	3.45
Northern Ireland	0.15	0.35	0.19	0.65	0.38	0.19	0.77	0.61	0.27	1.5	0.41	0.19	0.89	1.08	0.34	2.74	2.16	0.64	4.21
Heat–health amber alerts (events per year)																			
South West England	0.11	0.38	0.16	0.79	0.44	0.15	0.99	0.74	0.24	1.86	0.46	0.15	1.16	1.31	0.32	3.41	2.58	0.68	4.77
South East England	0.07	0.35	0.13	0.83	0.44	0.12	1.02	0.8	0.24	1.89	0.43	0.13	1.12	1.3	0.32	3.47	2.62	0.75	5.1
London	0.04	0.34	0.09	0.81	0.44	0.09	1.01	0.79	0.22	1.83	0.43	0.09	1.04	1.23	0.32	3.31	2.49	0.74	5.17
East of England	0.17	0.66	0.24	1.3	0.78	0.26	1.62	1.28	0.49	2.74	0.78	0.26	1.79	1.98	0.64	4.46	3.64	1.23	6.02

(Continues)

TABLE 4 (Continued)

		2050s	2080s															
		RCP2.6			RCP6.0			RCP8.5			RCP2.6			RCP6.0			RCP8.5		
	1981–2010	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High
West Midlands	0.11	0.44	0.15	0.86	0.53	0.15	1.01	0.81	0.28	1.75	0.54	0.15	1.2	1.28	0.39	3.46	2.56	0.76	5.27
East Midlands	0.06	0.44	0.13	0.93	0.55	0.13	1.08	0.88	0.3	1.76	0.56	0.14	1.23	1.32	0.43	3.35	2.52	0.83	5.22
Yorkshire and Humberside	0.04	0.37	0.08	0.86	0.47	0.09	1	0.81	0.22	1.68	0.49	0.09	1.17	1.26	0.35	3.19	2.42	0.78	5.04
North East England	0.01	0.17	0.03	0.47	0.23	0.03	0.61	0.46	0.09	1.34	0.23	0.03	0.67	0.85	0.17	2.73	1.97	0.44	4.63
North West England	0.05	0.21	0.08	0.51	0.25	0.08	0.61	0.45	0.14	0.97	0.28	0.08	0.71	0.77	0.19	1.92	1.36	0.41	3.57
Wales	0.07	0.23	0.1	0.5	0.26	0.09	0.62	0.44	0.15	1.14	0.29	0.09	0.75	0.82	0.19	2.35	1.67	0.39	3.83
East Scotland	0	0.02	0	0.12	0.04	0	0.19	0.12	0.01	0.41	0.04	0	0.21	0.26	0.02	1.22	0.71	0.11	3.02
West Scotland	0	0.09	0	0.32	0.11	0.01	0.41	0.26	0.04	0.73	0.13	0.01	0.5	0.53	0.08	1.57	1.07	0.24	3.26
North Scotland	0	0.01	0	0.08	0.02	0	0.14	0.06	0	0.33	0.02	0	0.14	0.19	0.01	0.86	0.47	0.05	2.02
Northern Ireland	0	0.05	0.01	0.17	0.07	0.01	0.21	0.15	0.02	0.39	0.08	0.01	0.24	0.27	0.04	1.09	0.68	0.13	2.76
Days with WBGT >25 (days/year)																			
South West England	0.04	0.41	0.13	1.04	0.48	0.11	1.38	0.99	0.26	3.09	0.51	0.1	1.84	2.18	0.39	7.6	5.29	1	19.9
South East England	0.13	0.94	0.27	2.26	1.13	0.31	2.93	2.34	0.65	5.97	1.17	0.26	3.34	4.26	1.08	12.2	9.47	2.49	27.8
London	0.29	1.6	0.55	3.48	1.9	0.62	4.27	3.59	1.21	7.97	1.94	0.52	4.87	5.98	1.87	15.3	12.09	3.86	32.1
East of England	0.14	1.01	0.3	2.51	1.25	0.36	3.23	2.62	0.71	6.32	1.25	0.3	3.61	4.6	1.22	12.1	9.64	2.79	26.1
West Midlands	0.05	0.34	0.1	1.07	0.42	0.1	1.51	1.09	0.21	3.5	0.46	0.09	1.97	2.53	0.39	7.7	5.84	1.21	17.5
East Midlands	0.03	0.44	0.09	1.35	0.56	0.11	1.84	1.39	0.28	3.98	0.6	0.09	2.15	2.8	0.56	8.3	6.46	1.53	18.7
Yorkshire and Humberside	0	0.14	0.01	0.5	0.17	0.02	0.79	0.52	0.08	2.17	0.19	0.01	0.99	1.41	0.18	5.1	3.91	0.68	12.3
North East England	0	0.02	0	0.1	0.03	0	0.16	0.11	0.01	0.72	0.03	0	0.21	0.4	0.02	2.5	1.65	0.14	7.6
North West England	0.03	0.17	0.05	0.48	0.22	0.05	0.67	0.47	0.11	1.63	0.24	0.05	0.96	1.18	0.18	4.4	3.08	0.51	10.2

(Continues)

TABLE 4 (Continued)

		2050s									2080s								
		RCP2.6			RCP6.0			RCP8.5			RCP2.6			RCP6.0			RCP8.5		
	1981–2010	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High	Mid	Low	High
Wales	0.03	0.25	0.07	0.65	0.28	0.06	0.85	0.59	0.13	1.83	0.32	0.05	1.2	1.33	0.21	4.9	3.32	0.58	13.3
East Scotland	0	0	0	0.02	0	0	0.04	0.02	0	0.26	0	0	0.06	0.12	0	1.0	0.57	0.03	3.5
West Scotland	0	0	0	0.06	0	0	0.13	0.07	0	0.43	0.01	0	0.18	0.27	0	1.4	0.86	0.08	4.3
North Scotland	0	0	0	0.01	0	0	0.02	0.01	0	0.14	0	0	0.02	0.06	0	0.7	0.32	0.01	2.3
Northern Ireland	0	0	0	0.03	0	0	0.05	0.02	0	0.25	0.01	0	0.08	0.14	0	0.9	0.56	0.03	3.5
Cold weather alerts (events/year)																			
South West England	2.45	1.72	2.27	1.25	1.58	2.11	1.13	1.32	1.9	0.85	1.65	2.3	1.1	1.11	1.8	0.63	0.81	1.52	0.38
South East England	3.04	2.13	2.81	1.51	1.92	2.61	1.34	1.56	2.34	0.95	2.03	2.85	1.28	1.29	2.18	0.66	0.88	1.83	0.38
London	2.33	1.55	2.19	1.01	1.38	2	0.87	1.1	1.77	0.58	1.48	2.26	0.84	0.87	1.64	0.42	0.56	1.36	0.25
East of England	3.33	2.32	3.06	1.67	2.1	2.85	1.49	1.71	2.55	1.07	2.21	3.07	1.44	1.44	2.37	0.75	1	2.01	0.42
West Midlands	3.65	2.64	3.36	1.98	2.41	3.12	1.8	2.04	2.84	1.42	2.52	3.35	1.78	1.77	2.69	1.07	1.32	2.32	0.63
East Midlands	3.55	2.57	3.3	1.92	2.33	3.07	1.73	1.95	2.8	1.34	2.44	3.31	1.69	1.69	2.61	1	1.25	2.24	0.58
Yorkshire and Humberside	3.4	2.56	3.22	1.98	2.37	3.03	1.76	1.99	2.77	1.33	2.44	3.25	1.71	1.7	2.6	0.95	1.22	2.22	0.54
North East England	3.49	2.59	3.36	1.88	2.39	3.13	1.67	2	2.89	1.22	2.4	3.32	1.56	1.65	2.65	0.83	1.17	2.3	0.47
North West England	3.09	2.26	2.88	1.69	2.09	2.7	1.53	1.77	2.49	1.14	2.15	2.92	1.49	1.5	2.33	0.8	1.07	1.99	0.46
Wales	2.86	2.05	2.63	1.51	1.89	2.44	1.37	1.57	2.23	1.02	1.95	2.67	1.32	1.34	2.12	0.76	0.98	1.8	0.46
East Scotland	4.62	3.48	4.47	2.6	3.22	4.18	2.31	2.75	3.88	1.76	3.25	4.42	2.22	2.35	3.65	1.33	1.79	3.2	0.82
West Scotland	4.1	3.1	3.99	2.32	2.88	3.73	2.09	2.45	3.45	1.61	2.87	3.94	2	2.07	3.19	1.2	1.56	2.8	0.73
North Scotland	4.89	3.73	4.81	2.81	3.47	4.51	2.53	3	4.2	2	3.54	4.76	2.5	2.65	3.99	1.63	2.12	3.57	1.06
Northern Ireland	2.54	1.72	2.48	1.16	1.55	2.24	1.03	1.27	2.04	0.75	1.53	2.4	0.92	1	1.81	0.52	0.71	1.53	0.3

Note: 'Mid' denotes the median estimate, and 'low' and 'high' the 10th and 90th percentiles, respectively. Note that the table shows the average number of alert exceedances or day with WBGT above 25 in a region, which is different to the number of times an event occurs somewhere in the region. The heat–health and cold weather alert thresholds for Wales, Scotland and Northern Ireland are based on the nearest English region.

TABLE 5 Average annual number of occurrences of Cold Weather Payment declarations

	1981–2010	2050s RCP2.6 Mid	2050s RCP2.6 Low	2050s RCP2.6 High	2050s RCP6.0 Mid	2050s RCP6.0 Low	2050s RCP6.0 High	2050s RCP8.5 Mid	2050s RCP8.5 Low	2050s RCP8.5 High	2080s RCP2.6 Mid	2080s RCP2.6 Low	2080s RCP2.6 High	2080s RCP6.0 Mid	2080s RCP6.0 Low	2080s RCP6.0 High	2080s RCP8.5 Mid	2080s RCP8.5 Low	2080s RCP8.5 High
Cold weather payments																			
England	44	32	47	22	30	43	20	24	39	15	30	47	19	21	35	11	15	30	6
Wales	8	6	8	4	6	8	4	5	7	3	6	8	4	4	6	2	3	6	1
Scotland	43	31	44	21	28	41	19	24	38	14	29	43	19	20	35	11	16	31	7
Northern Ireland	3	2	4	1	2	3	1	2	3	1	2	3	1	1	3	1	1	2	1
Total	98	72	104	49	66	94	44	55	87	34	67	101	43	46	80	26	34	69	15

2080s from 1981–2010) than in England and Wales (67% reduction). Note that Figure 6 shows an apparent slight increase in some regions in cold weather payments in the 30-year period centred on 2015 (2001–2030). This is an artefact of the way the future time series is constructed. The period 2001–2030 consists of the observed 2001–2010 plus perturbed 1981–2000 representing 2011–2030. Due to natural variability, there were more cold weather payment events on average in 2001–2010 than 1981–2000 and – because the perturbed 1981–2000 is warmer than the original – the difference is even greater with the simulated period 2011–2030. The 2001–2030 mean is therefore higher than the 1981–2010 mean.

Figures 3, 5 and 6 show the strong spatial variability in change across the United Kingdom, along with the effects of different assumptions about future emissions: estimated impacts are relatively insensitive to future emissions to at least the 2040s, but after then increase much more with higher emissions. The figures also show the considerable uncertainty in estimated impacts for a given emissions scenario. This uncertainty is primarily due to uncertainty in the rate at which temperatures increase for a given emissions scenario (Table 3 shows an increase in global mean temperature of between 4 and 6.5°C with RCP8.5 emissions).

This is reflected in differences between the probabilistic and the two global strand ensembles. The HadGEM3 ensemble of climate model projections produces greater increases in temperature than the CMIP5 ensemble, so therefore produces greater changes in the indicators shown here (see the figures in the Supporting Information). In particular, the HadGEM3 global strand produces substantially larger increases in the number of days and likelihood that WBGT exceeds 25. This means that assessments based on the HadGEM3 ensemble alone sample from the higher changes, but understate the potential range in outcomes. Unlike the probabilistic projections, the global strand projections have greater increases in maximum temperatures than average temperatures, and the global HadGEM3 ensemble therefore produces even greater increases in the number of Met Office heatwaves and greater, and slightly earlier, increases in the days with WBGT greater than 25 than the probabilistic ensemble.

5 | CONCLUSIONS AND IMPLICATIONS

This paper has examined the effect of climate change on a series of policy-relevant indicators of hot and cold temperature extremes in the United Kingdom, relevant to different aspects of heatwave and cold spell planning. These indicators are all based on critical thresholds currently used to trigger alerts and plans. They therefore characterize the effect of climate change on actions and interventions, not directly on human health, well-being and mortality. Such impacts are better represented using relationships between temperature and mortality or indicators which are more directly related to health outcomes, such as the UTCI (di Napoli et al., 2019). Adverse health impacts of extreme temperatures can manifest themselves well before the critical thresholds used to activate heatwave and cold spell plans are reached (Williams et al., 2019). The study assumes that the critical policy thresholds remain unchanged over time – but of course in practice they will be revised through adaptation to climate change – and assumes no enhancement to the urban heat island effect over time. The effect of current urban heat islands is incorporated into the baseline climate used here, but increasing temperatures may lead to a larger urban heat island. The assessment used the delta method to create climate change scenarios. This is simple and pragmatic, but as implemented here assumes that extreme temperatures change by the same amount as the mean: high temperatures may increase by more than the mean, so the increases shown here in high temperatures and therefore heat alerts may be underestimates. This effect is small compared with the uncertainty range, but further analysis of high-resolution climate simulations is necessary to investigate its magnitude. As a final caveat, future changes in hot and cold extremes will depend on how the atmospheric conditions which trigger extreme events change in the future (such as blocking: Woollings et al., 2018; Charlton-Perez et al., 2019), and these are not necessarily well reproduced in the climate models used to build the UKCP18 climate projections.

The analysis presented here suggests that – despite a gradual observed increase in temperature across the United Kingdom – there is no clear trend since 1981 in the numbers of occasions that critical temperature thresholds have been exceeded, although there do appear to have been more days with WBGT greater than 25 in recent years. This is primarily because year-to-year variability is large relative to a trend in average temperatures.

However, the projections show that heatwave alerts will soon become more frequent, and critical cold weather events less frequent. By the 2030s, for example, the annual chance of experiencing a Met Office heatwave at a point in south east England will have increased to around 60% from 40% over the period 1981–2010, and the chance of a heat–health alert will have increased to 25% from around 10%. Heatwave and heat–health alert frequencies are lower further north, despite the lower thresholds, but still increase considerably. Heatwaves and heat–health alerts not only become more frequent, but also last for longer. In southern and eastern England, the chance of experiencing days with WBGT greater than 25 (approximately 27 in the sun) reaches 20%–40% by the 2030s (and more in London).

Cold weather alerts become less frequent through the 21st century, but the change is much smaller than for the hot weather extremes. In south east England, for example, the likelihood of a cold weather alert decreases from around 95% to around 80% by the 2040s: the reduction further north is even smaller. Similarly, the average number of cold weather payments falls, but typically by less than 25% by the 2040s. The difference in the effects of climate change between the hot and cold extreme indicators arises because the critical hot thresholds are more extreme than the critical cold thresholds. The cold thresholds are currently exceeded frequently, so a very large increase in temperature would be needed to reduce substantially the number of events. In contrast, a relatively small increase in temperature means more high temperature thresholds are passed. The increase in winter temperatures is also less than the increase in summer temperatures.

Until the 2050s, there is little difference in projected change between low, middle and high emissions, but after the 2050s the changes are considerably higher with high emissions. This demonstrates the importance of reducing emissions to limit the long-term impacts on heat extremes, but also shows how assumptions about emissions pathways have limited influence on potential impacts and resilience strategy over the next 30 years.

Over this shorter time scale, the estimated magnitude of change is largely determined by uncertainty in the projected effects on temperature in the United Kingdom of a given emissions pathway. The increases in the likelihood or occurrence of hot extremes could plausibly be considerably larger than the central estimate. Planning to enhance resilience to high temperature extremes should therefore consider using ‘upper bound’ estimates of change as a worst case.

The effect of scientific uncertainty on the estimated change in an indicator for a given emissions pathway of course continues beyond the 2050s, and by the 2080s can be extremely high for indicators based on high temperature thresholds. There are also large differences between the various strands of high emissions projections in the UKCP18 suite of projections, and the quantitative estimates of change – and particularly the range – therefore depend on which projections are used. The HadGEM3 global strand ensemble generally produces larger increases in heat extremes, particularly for WBGT.

Heat–health alerts and heatwaves, using current thresholds, will therefore become more frequent and last longer, and cold weather events will continue to occur. This has several implications.

First, high temperature extremes should be addressed through long-term strategic planning rather than emergency planning. Williams et al. (2019) note that heatwave planning in England is currently generally seen as an exercise in emergency preparedness focusing on 'warning and informing'. A significant proportion of excess deaths occur before alert thresholds are reached (Williams et al., 2019; Casanueva et al., 2019). It may become more effective to increase the general level of seasonal preparedness amongst healthcare and social care systems (and more widely across the economy and society) so that heat extremes are treated as 'normal' rather than emergencies. This could involve raising the threshold of what triggers an emergency response over and above 'normal' seasonal arrangements, or linking thresholds much more explicitly to step changes in impact. On a more specific operational level, it may be appropriate to remove time limits on the operation of warning systems: the heat–health alert system in England, for example, currently only operates between 1st June and 15th September.

Second, the increasing frequency of high temperature extremes means it will be increasingly important to raise awareness amongst the public and organisations about what to do during a heatwave (Hajat et al., 2010). Such awareness is currently low (Bruine de Bruin et al., 2016), partly because of a lack of public knowledge of appropriate measures and behaviours and partly because hot weather is typically seen favourably (Bruine de Bruin et al., 2016).

Third, more frequent high temperature extremes mean it will be necessary to address the underlying factors affecting exposure and vulnerability to hot weather. This includes poor-quality buildings and working environments, as well as underlying economic and social conditions (such as health, income, tenure, social networks) which affect vulnerability to high temperatures (Howarth & Brooks, 2017).

Fourth, cold weather events will continue to occur – and in northern England will continue to be more frequent than hot weather events – so planning for these should not be relaxed.

Finally, emergency planning is based on developing capabilities to cope with plausible extreme conditions (Reasonable Worst-Case Scenarios). The analysis here (and in Christidis et al., 2020) suggests that within a few years plausible extreme heatwaves will last longer and have higher peak temperatures than currently assumed – particularly in southern and eastern England – but the types of extreme cold events used to inform cold weather capabilities will still be plausible.

The House of Commons Environmental Audit Committee in 2018 was critical of planning for heatwaves in the United Kingdom, and Brimicombe et al. (2021) claimed that heatwaves remained largely a 'hidden risk' in the United Kingdom. This paper provides an information base to support strategic reviews of planning for heat and cold extremes in the United Kingdom.

ACKNOWLEDGEMENTS

This research was funded through the UKRI Climate Resilience programme (Grant NE/S016481/1). We thank Yolanda Clewlow of the Met Office Hazards and Resilience Team for providing information on heat–health and cold weather alerts.

AUTHOR CONTRIBUTION

Nigel Arnell designed the study, calculated the indicators, and was the primary author. Anna Freeman constructed climate scenarios, created maps and contributed to the text.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The regional and national data cited in the paper are provided in spreadsheets in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Arnell, N. W. & Freeman, A. (2021) The impact of climate change on policy-relevant indicators of temperature extremes in the United Kingdom. *Climate Resil Sustain*, 1–22. https://doi.org/10.1002/cli2.12