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Projections of severe heat waves in the United Kingdom

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ABSTRACT: Climate change is expected to impact upon public health via changes in mortality rates associated with rising temperatures. This study analysed changes in characteristics of heat waves in the UK using an ensemble of regional climate model simulations generated with the Special Report on Emissions Scenarios (SRES) A1B scenario. The heat wave definitions are employed by Public Health England for issuing warnings to vulnerable people in England. In agreement with previous studies, the numbers and frequencies of heat waves are projected to increase across the UK as the climate warms. In the model, the number of heat wave days increased by up to 2 d decade^{-1} during the twenty-first century, with the highest rates in South East England and the lowest in western coastal regions. The heat wave season, represented as the months affected by heat waves, was projected to expand from July and August in the present day climate to May to September by the middle of the twenty-first century, with occasional heat waves in April and October by the end of the century. In some parts of England and Wales, extreme heat waves lasting >20 d were projected to occur once per decade by the end of the twenty-first century. By the end of the century, over half of the UK would be under heat wave conditions at some point in every year. The most extreme heat wave would affect between 62 and 85% of the UK land area and would last for 8 consecutive days.

KEY WORDS: Heat waves · Mortality · Climate models · Projections · UK

1. INTRODUCTION

Warming of the Earth's climate is unequivocal. Many of the observed changes in annual and regional temperatures since the 1950s are unprecedented over decades to millennia (IPCC 2013). Global mean temperatures in each of the past 3 decades have been warmer than in any other decade since 1850 (IPCC 2013). The year 2015 is currently the warmest on record since 1880 (NOAA 2016), and 2016 is likely to be warmer still (Met Office 2015a). Temperatures in November and December 2015 were unusually warm in many European countries, and some records were broken. In the United Kingdom, the 8 warmest years have occurred since 2001 with record temperatures for July (exceeding 35°C) measured on 1 July 2015 (Met Office 2015b).

This trend towards more extreme and longer periods of warm temperatures can have a significant impact on public health (e.g. Gasparrini & Armstrong 2011). One of the earliest studies (Gover 1938) showed that mortality in many cities in the USA increased during periods of hot weather. Those most vulnerable were the very young (<1 yr old) and those aged >70 yr. In the UK, elevated temperatures are a cause of death among the very old and very young, and those with pre-existing diseases such as respiratory problems and pulmonary diseases (Basu & Samet 2002). Prolonged heat can cause heat exhaustion and dehydration, which if not addressed can then lead to heat stroke when the body can no longer cool itself, resulting in organ failure and death. Hot conditions have also been associated with increased hospital admissions, placing additional strain on the

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health service (Jenkins et al. 2014). Despite the low frequency of heat waves, they have a potentially high impact, posing a significant challenge to healthcare decision makers faced with uncertainty and constraints on resources.

Heat waves are periods of sustained high temperatures which usually occur in July or August in the UK but have been recorded occasionally in June (1976; Shaw 1977) and September (1906, 1911; Burt 2004). The excess mortality observed during heat waves is often enhanced by a long duration, or both a long duration and very high temperatures (D'Ippoliti et al. 2010). A very severe heat wave affected most of Europe during 2003, characterised by a prolonged period of very high day- and night-time temperatures. In England and Wales there were over 2000 excess deaths compared with the previous 5 yr (Johnson et al. 2004). The greatest impact was felt in London, where deaths of those aged ≥75 yr rose by nearly 60%. In response, a heat wave plan was set up, which has been published annually since 2004, and is currently operated by Public Health England (PHE; PHE 2015). This plan was created to raise awareness of the dangers of excessive heat amongst healthcare organisations and the public (particularly those with pre-existing conditions that increase their vulnerability to heat), so that they are prepared and able to take appropriate action. Excess deaths in England following the 2006 and 2013 heat waves were 2323 and 301 respectively, but the reasons for the smaller number of deaths in 2013 are not clear (Green et al. 2016).

Summer temperatures in London and the southeast of England are projected to increase by between 1.3 and 4.6°C between the 1970s and 2050s under a medium emissions scenario, with slightly smaller increases projected over northern England and Scotland (UKCP09 2009). These changes are likely to lead to increases in the number and lengths of heat waves in the UK. There are many published studies detailing projections of future heat waves globally and for Europe, but only a small number specifically include changes in the UK. However, these studies appear to tell a consistent story, with projections of hotter heat waves (Caesar et al. 2013), a greater number of severe heat waves (Russo et al. 2014, Jacob et al. 2014), more heat wave days (Koffi & Koffi 2008) and a combination of the above (Fischer & Schär 2010). In all of these studies, the projected changes were greater under higher emissions scenarios (e.g. A1B, IPCC 2000; RCP8.5, van Vuuren et al. 2011) when compared with lower emissions scenarios (e.g. RCP4.5). Lehner et al. (2016) showed that the risk of summers in the future being warmer than the hottest on record between 1920 and 2014 would be halved under moderate climate mitigation (RCP4.5) compared with no mitigation (RCP8.5).

The aim of this study was to evaluate how heat waves in the UK could change under a warming climate. A more complete understanding of how the characteristics of heat waves could change is important, given the projected increase in their frequency and severity in the studies summarised above. The heat wave definitions adopted by PHE (2015) for the issuing of heat alerts are employed here. Many previous studies have focused on changes in the number and lengths of heat waves only. In the present study, the spatial extents of heat waves, distributions of their maximum lengths and changes in their seasonality were also examined. These characteristics have rarely been considered, if at all. Temperatures and intensities of heat waves will be reported in a future study.

2. DATA AND METHODS

2.1. Observed temperatures

Daily maximum and minimum temperatures were created by Perry et al. (2009) on a regular 5 km grid over the UK from weather station observations. A regression and interpolation procedure was used to estimate temperatures on the regular grid which took into account factors including altitude, local topography, the latitude and longitude of the site and proximity to the coast and urban areas (Perry et al. 2009). The effects of changes in the station network are partially, but not entirely, removed by the gridding method. Temperatures on a 25 × 25 km grid equivalent to that used by the regional climate model (RCM; described in Section 2.2) were calculated by averaging all temperatures on the 5 km grid which lie within each 25 km grid. Gridded temperatures on the 5 and 25 km grids were available for 1960–2011.

2.2. Regional climate model projections

Simulated daily maximum and minimum temperatures were obtained from an ensemble of RCMs. This ensemble was used along with many other climate projections to produce United Kingdom Climate Projections 2009 (UKCP09; Murphy et al. 2009). The RCM ensemble consists of 11 versions of the Hadley Centre's RCM HadRM3, which has a horizontal resolution of 25 × 25 km and 19 vertical levels, and represents the atmosphere up to 40 km. One ensemble member is the standard version of HadRM3. The other 10 versions were created by perturbing 31 uncertain parameters simultaneously away from their standard values within ranges given by experts. These parameters directly influence the simulation of convection, cloud properties, radiation, boundary layer dynamics, synoptic-scale dynamics and land surface processes (Murphy et al. 2009, Burke & Brown 2010). The combinations of parameter perturbations were chosen to cover a range of climate sensitivity whilst retaining skill in reproducing the present day climate. These 11 models were used to downscale transient global climate simulations over Europe which were produced using the global climate model HadCM3 (Collins et al. 2011). Each HadRM3 simulation covered the period 1950–2099, and was forced at its boundaries by a version of HadCM3 with the same set of parameter perturbations. Observed emissions of greenhouse gases and aerosols were used up to 1990, and then emissions followed those in the A1B scenario from the Special Report on Emissions Scenarios (SRES; IPCC 2000). Global mean temperature increases under the A1B scenario are closest to those projected under the newer RCP6.0 scenario (Jacob et al. 2014), and hence are positioned between the RCP4.5 and RCP8.5 scenarios (van Vuuren et al. 2011). Further details of the global and regional model simulations are given in Murphy et al. (2009) and Burke & Brown (2010).

2.3. Bias correction approach

The heat wave definitions used in the present study (see Section 2.4) are based on absolute temperature thresholds. The numbers, lengths and spatial extents of heat waves identified in the model data will be particularly sensitive to any errors in the model climatology. The dynamically downscaled data from the RCMs will contain an improved simulation of local climate when compared with global climate model projections. However, important local inaccuracies still remain owing to insufficient resolution, representations of processes which occur on spatial scales smaller than the model's resolution (for example, convection and boundary layer processes) and uncertain parameter values. A comparison of modelled and observed temperatures over the period 1970–1989 showed that most of the ensemble members had a warm bias; that is, the modelled warm season (May–September) temperatures were consistently higher than observed values. These differences, or biases, in the modelled climate need to be corrected; otherwise, inferred changes in heat wave lengths and numbers could be too low or too high.

Various methods exist to bias-correct climate model output, some of which were compared by Räisänen & Räty (2013). They showed that no single method outperformed other approaches under all circumstances, but quantile mapping methods were the best overall. In the present study, the quantile–quantile mapping transformation of Amengual et al. (2012) was used to bias-correct modelled daily maximum and minimum temperatures. This method amends errors in the mean, variability and shape of the cumulative distribution functions (CDFs) of the variables of interest. A description of this method is given in Section S1 in the Supplement at www.int-res.com/articles/suppl/c071p063_supp.pdf. Briefly, changes between the baseline (1970–1989) and future daily modelled data were locally corrected quantile by quantile using a weighting factor based on the size of the model error. The corrected changes were then added to the observed CDF to create the bias-corrected future modelled data.

Amengual et al. (2012) used 15 yr baseline and future time slices to bias-correct their data. In the present study, successive 20 yr periods (Table 1) were used to increase the sample of very warm days and nights. An extra step was added in the present study, whereby bias-corrected time series of daily maximum and minimum temperatures were produced. As a check, time series of original and bias-corrected temperatures from the RCMs for the period 1990–2009 were compared with observed temperatures for the same period from randomly chosen locations. In all locations, the bias-corrected data were in closer agreement with the observations than the original (i.e. uncorrected) model data.

Since the bias correction method of Amengual et al. (2012) uses the addition of climate change factors to a series of observations, the future corrected time series will inherit some of the characteristics of the

Table 1. Time periods and names

Period	Name
1970–1989	Baseline
1990–2009	2000s
2010–2029	2020s
2030–2049	2040s
2050–2069	2060s
2070–2089	2080s

observed series. It is therefore implicitly assumed that the observations are representative of the historical period, and that a similar pattern of events could occur in the future. Amengual et al. (2012) found that the use of different baseline years had only a small effect on their bias-corrected data.

2.4. Heat wave definition

There is no universal definition of a heat wave (Perkins & Alexander 2013), and a wide variety of metrics have been used in previous studies. In the present study, heat waves are characterised using 2 threshold temperatures which are used to trigger alerts under the Heat-Health Watch System for England (PHE 2015, Masato et al. 2015). A heat wave is defined as 2 or more consecutive days when daily maximum temperatures exceed one threshold, and daily minimum temperatures exceed a second threshold. These thresholds are linked to the available epidemiology and have been shown to be consistent with a 15–20% increased risk of mortality (PHE 2015). The thresholds vary across the UK owing to relative adaptation to heat, with the highest values used for London and South East England, and the lowest in North East England. The regions of England used by PHE are shown in Fig. 1, and the thresholds for each region are listed in Table 2. Scotland, Wales and Northern Ireland do not have a heat wave plan in place, so thresholds from nearby areas of England were assigned to those regions.

The RCM has a resolution of 25 km (see Section 2.2), and so simulates average temperatures over areas of 625 km^2. In reality, if average daily maximum and minimum temperatures over such an area were close to their respective thresholds, temperatures at some points within the 625 km^2 areas would probably exceed the thresholds. Consequently, it may be necessary to lower the PHE thresholds to account for the averaging of temperatures at the RCM resolution. The following comparison was made for each 25 km grid box. Heat waves were identified using the PHE thresholds (Table 2) with the observed temperatures which had been aggregated to the same 25 × 25 km resolution used by the RCM for the period 1990–2009. Next, heat waves were searched for in the 5 km gridded data using all points that were contained within the 25 km grid box. The dates and lengths of heat waves identified in the 5 and 25 km gridded data were then compared.

Heat waves identified using the observed data at 25 km appeared in some or all of the 5 km data points

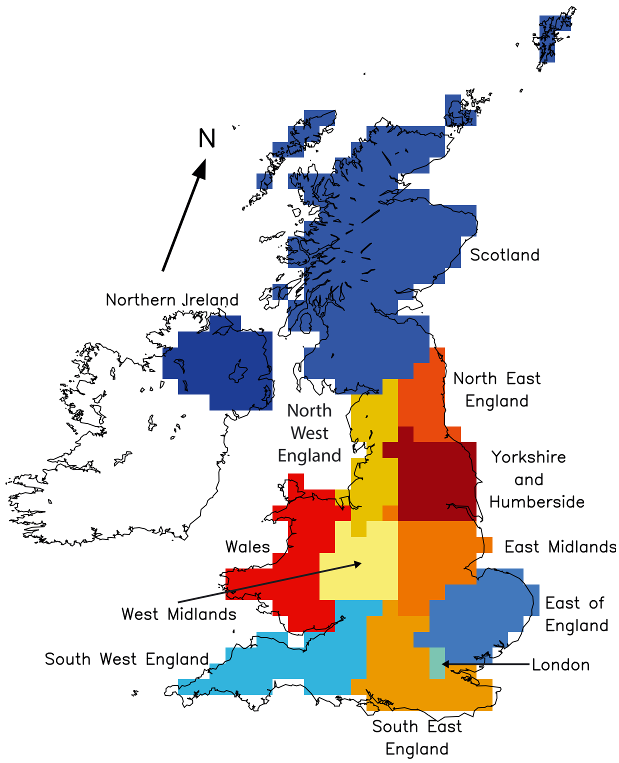

Fig. 1. Administrative regions of the United Kingdom at the same 25 km resolution used by the regional climate model. Under the United Kingdom Climate Projections 2009 (UKCP09), Scotland had been divided into 3 parts; in the present study, Scotland is treated as a single region. The Isle of Man and the Channel Islands are too small to be properly resolved by the regional climate model and so were not included in the present study

Table 2. Maximum and minimum temperature thresholds used to define a heat wave. These thresholds are defined in the Heat Wave Plan published by Public Health England (2015). Scotland, Wales and Northern Ireland do not have a heat wave plan. The lowest thresholds (for North East England) were selected for Scotland. For Wales, the thresholds for the West Midlands were used. The thresholds for North West England were selected for Northern Ireland, owing to their close proximity (see Fig. 1)

Region	Threshold (°C) Max	Min
Scotland	28	15
North West England	30	15
North East England	28	15
Yorkshire and Humberside	29	15
West Midlands	30	15
East Midlands	30	15
Wales	30	15
London	32	18
East of England	30	15
South West England	30	15
South East England	31	16
Northern Ireland	30	15

which lay within that 25 km grid box. For a small number of the 5 km points, 1 or 2 additional heat waves were identified. In almost all of these instances, either the daily maximum or daily minimum temperatures on the 25 km grid exceeded the PHE threshold but the other did not. Occasionally, both temperatures on the 25 km grid were below their respective thresholds when heat waves were identified at a few of the 5 km points. There was no systematic difference in the amount by which temperatures on the 25 km grid were below the PHE thresholds, or which variable (daily maximum or minimum temperatures) was below its threshold. It was concluded that there was no justification for adjusting the PHE temperature thresholds for use at the scale of the RCM (25 km). However, the number of heat waves identified at the 25 km scale would probably be slightly smaller than at the 5 km scale.

2.5. Analysis of heat waves

Heat waves were identified over the period 1970–2089 for each RCM ensemble member, where observed temperatures were used for 1970–1989, and bias-corrected model data for 1990–2089. The minimum, median and maximum numbers of heat waves in each 20 yr period and administrative region are shown in Table S1 in the Supplement. These numbers were calculated after pooling heat wave numbers from all 11 RCM simulations.

Trends in the number of heat wave days per year were calculated using a non-parametric method (Sen 1968) which is robust against outliers in the data and non-normal distributions. Trends were calculated separately for each RCM ensemble member and model grid box, and then the maximum and minimum trends in each grid box were identified. If there were <3 yr with heat waves, a trend was not calculated. Mean trends were found by first calculating the ensemble-average number of heat wave days in each grid box and then calculating the trend using the averaged data. The mean trends therefore represent the trend in the mean numbers of heat wave days in each grid box.

The length of the heat wave season, approximated as the number of whole months between the first and last heat wave in any given year was determined. Distributions of the maximum lengths of heat waves and the total number of heat wave days were examined to further understand how the climate change signal is manifested. Land fractions of the UK affected by heat waves were also calculated.

3. RESULTS

3.1. Changes in summer average daily maximum and daily minimum temperatures

Average summer temperatures in England, Scotland, Northern Ireland and Wales were calculated over the 20 yr periods listed in Table 1, where summer is defined as June, July and August. Daily maximum temperatures are projected to increase at a slightly higher rate than daily minimum temperatures during the twenty-first century. These increases are consistent with an analysis of surface observations by Makowski et al. (2008), who found that trends in the diurnal temperature range (DTR) in the UK changed from negative to positive around 1965. A positive trend in DTR means that daily maximum temperatures must be increasing at a higher rate than daily minimum temperatures. The highest increases in maximum temperatures are projected over England (0.49°C decade^{-1}) and Wales (0.47°C decade^{-1}), and about 0.40°C decade^{-1} in the other 3 regions. The largest increases in summer minimum temperatures are projected for England, Scotland and Wales, where the trends are about 0.40°C decade^{-1}. Trends over Northern Ireland were smaller, at about 0.33°C decade^{-1}.

3.2. Trends in heat wave days

Trends in the number of heat wave days in each year are shown in Fig. 2 for the period 1970–2089. Unshaded grid boxes are where there were either no heat wave days or the trend was not significant at the 5% level. The largest trends are seen over southern and eastern England and western Scotland, and all trends were positive.

The number of heat wave days is projected to increase throughout the study period, although the rate of increase varies considerably across the RCM ensemble. The smallest trends lie between 0.1 and 0.5 d decade^{-1} (Fig. 2a), whereas the largest trends, seen in central and eastern England, are 1.5–2.0 d decade^{-1} (Fig. 2b). The highest trends over South East England and western Scotland were mostly produced by 2 of the ensemble members. In contrast, the lowest trends across the UK were distributed across 9 of the RCM ensemble members. No single parameter perturbation within the RCM (Section 2.2) is responsible for the large temperature increases in 2 of the models. The inclusion (or not) of the response of stomatal conductance to increasing carbon dioxide lev-

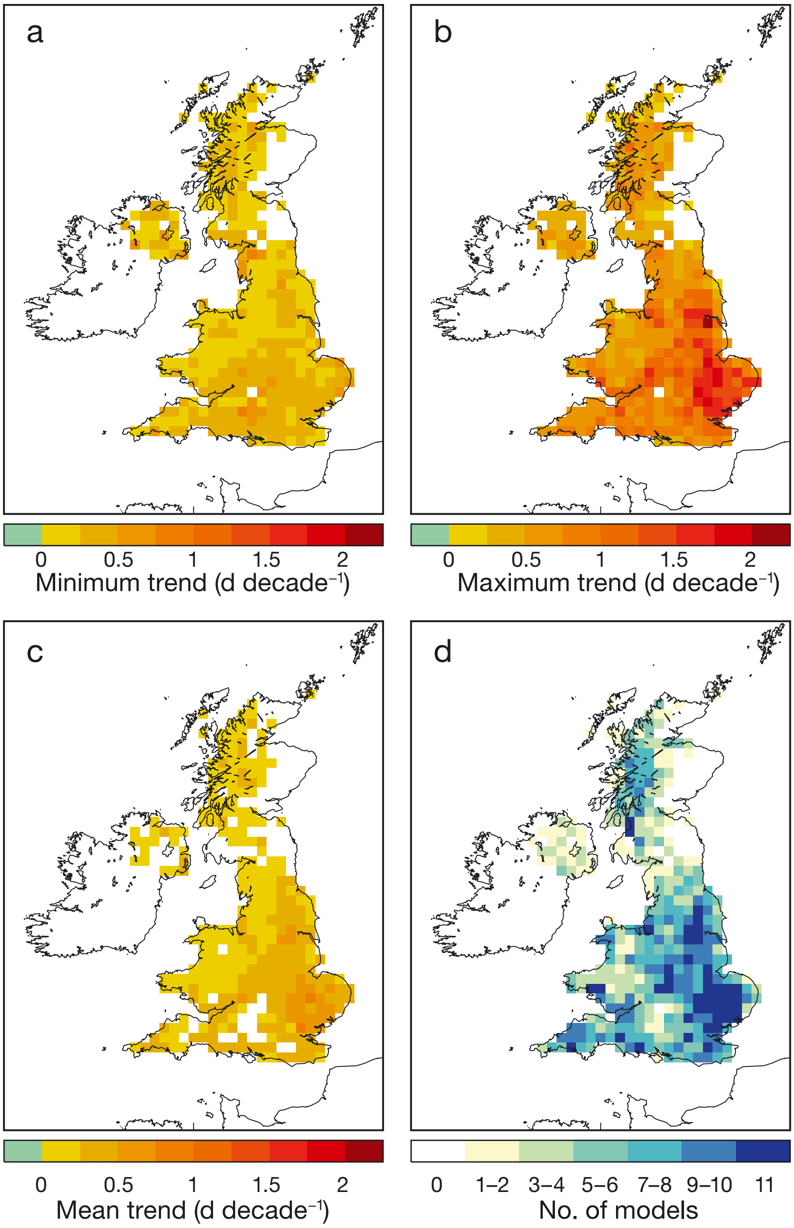

Fig. 2. Trends in the number of heat wave days over the period 1970–2089. The minimum and maximum trends are shown in (a) and (b) respectively; the mean trends (c) represent the trend in the mean numbers of heat wave days in each grid box; (d) shows the number of models from which a significant trend was found for each grid box in (a) and (b)

els, and changes to the conversion rate of cloud droplets to rain appear to be important. Other parameter changes which are also relevant are the number of soil levels available for evapotranspiration and the threshold of relative humidity for cloud formation.

The trends in the mean numbers of heat wave days, calculated as described in Section 2.5, lie between 0.2 and 0.7 d decade^{-1} over eastern England and between 0.02 and 0.2 over the rest of the UK (Fig. 2c). These mean trends are closer in value to the minimum than the maximum trends. The parameter perturbations used to create the 11 versions of the RCM mean that some variants project higher amounts of warming in response to a given emission of greenhouse gases than others. Trends from 3 of the ensemble members are generally larger than those from the remaining members, so that the distributions of trend values in many grid boxes are positively skewed.

The number of ensemble members from which significant trends in numbers of heat wave days were found is shown in Fig. 2d. The largest numbers of members (9–11) are seen over England and southern Wales, where the projected increases in temperature are the largest, and so the highest trends are also found there. The results for England, Western Scotland and southern Wales are the most robust. Significant trends were only found from a small number of members over Scotland and Northern Ireland. Positive trends were calculated from additional members in these regions, but the trends were not significant at the 5% level.

The trend values shown in Fig. 2 were found using heat wave days over the period 1970–2089. Climate variability acted to enhance or reduce the trends over shorter periods. For example, in some years during the 2080s the numbers of heat wave days in parts of South East England were higher than would be predicted using the maximum trend values shown in Fig. 2b. Climate variability may also have amplified the increase in heat wave days in some ensemble members, leading to the largest trends shown in Fig. 2b.

3.3. Distributions of longest heat wave lengths

Distributions of the lengths of the longest heat waves in each year for the UK regions are shown in Fig. 3, using lengths pooled from all model grid boxes within each region and all RCM ensemble members. For clarity, only heat waves up to 20 d in

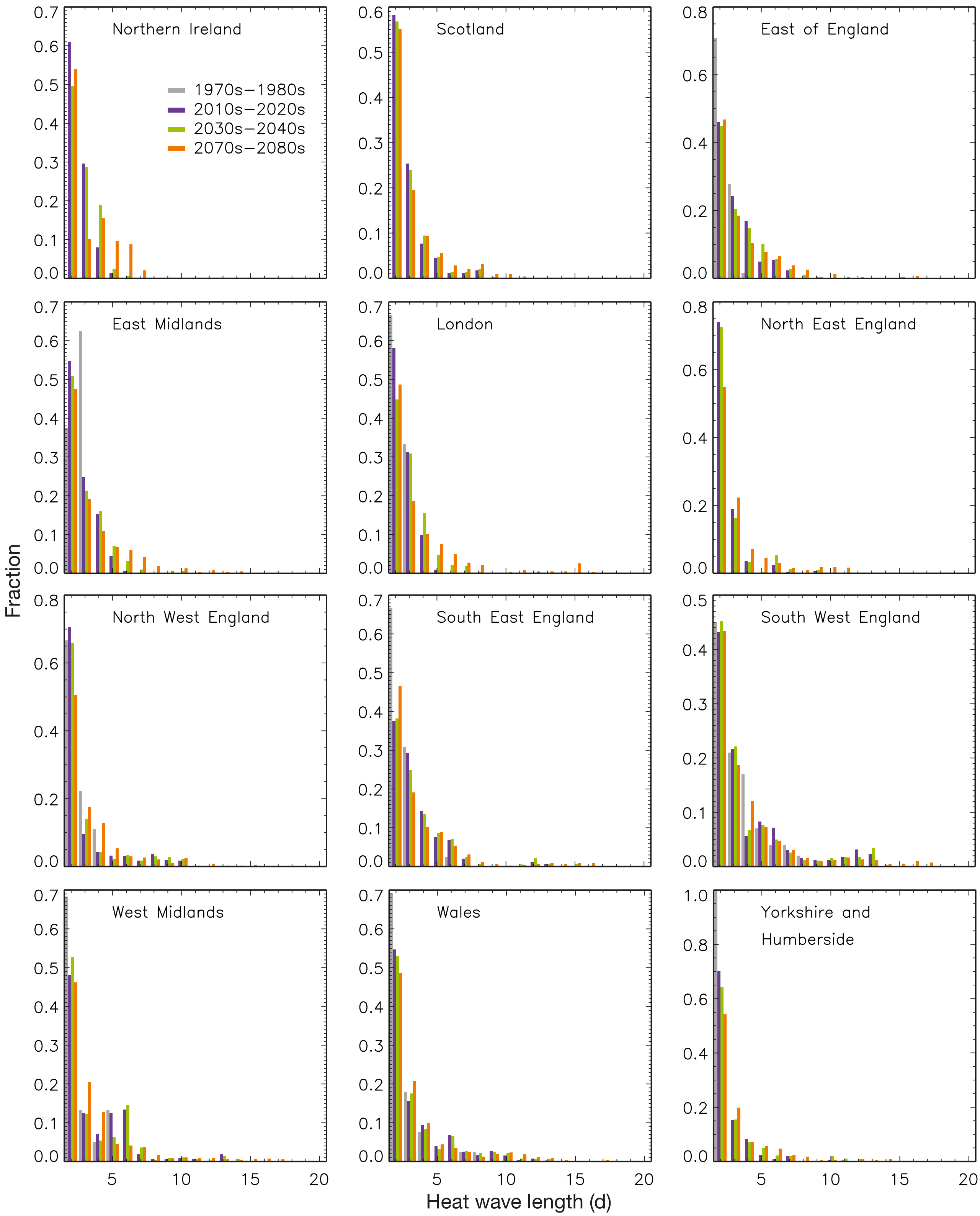

Fig. 3. Maximum heat wave lengths in the administrative regions. The maximum lengths derived from all regional model simulations were pooled and used to calculate the fractions, which sum to 1 for each time period. For clarity, only heat waves up to 20 d long are shown. In some regions (for example, East of England and South East England) heat waves up to 28 d in length were identified. Note the different *y*-axis scales

Table 3. Comparison of heat wave metrics for the UK with previous studies. The present study and Fischer & Schär (2010) used climate projections under the Special Report on Emissions Scenarios (SRES) A1B scenario. Scenarios used in the other studies are listed next to the heat wave metrics. The data in the upper half of the table are the minimum and maximum values (given as ranges) across all UK land points. In the lower half, the area-averaged values are shown as these quantities were listed by Fischer & Schär (2010). (–) Data values not quoted (present study) or unavailable (other studies)

Reference	Time period	Heat wave metric					
		No. yr^{-1} [d]		Longest heat wave (d)		Heat wave days	
		Mean	Range	Mean	Range	Mean	Range
This study[a]	1970–1989	–	1–2	–	2–8	–	2–10
	2030–2049	–	1–6	–	2–16	–	2–28
	2070–2089	–	1–13	–	2–28	–	2–54
Koffi & Koffi (2008)[b]	1971–2000	–	–	–	–	–	5.6–7.3
	2071–2100	–	–	–	–	–	1–10 (B2)
						–	20–30 (A2)
Russo et al. (2014)[b]	2022–2054	–	1–2 (all scenarios)	–	–	–	–
	2068–2100	–	1–2 (RCP2.6)	–	–	–	–
		–	1–3 (RCP4.5)	–	–	–	–
		–	6–15 (RCP8.5)	–	–	–	–
This study[c]	1970–1989	1.0	1.1–1.2	2.5	2.1–3.1	2.7	2.1–3.7
	2030–2049	1.0	1.2–2.2	2.9	2.0–6.8	3.4	2.0–8.5
	2070–2089	1.0	1.8–4.4	3.7	2.0–10.0	5.8	2.0– 20.3
Fischer & Schär (2010)[c]	1961–1990	0.2	0.2–0.3	7.8	7.4–8.3	1.9	1.7–2.2
	2021–2050	0.7	0.5–1.0	9.4	8.8–10.1	6.1	4.7–9.2
	2071–2100	1.6	0.9–3.0	8.5	11.9–19.9	16.6	7.3–38.1

[a]The ranges of the metrics were calculated by pooling values across all UK land points and model variants for the time periods shown

[b]The numbers quoted for these studies were estimated from figures in the original papers

[c]Area-averaged values of the metrics were calculated across all UK land points for each year. The numbers listed are the mean values, with the minimum and maximum given as ranges

[d]Numbers of heat waves in the UK administrative regions for all time periods from the present study are listed in Table S1 in the Supplement at www.int-res.com/articles/suppl/c071p063_supp.pdf

length are shown; in parts of Wales and southern and eastern England, a small number of extremely long heat waves (20–28 d in length) were simulated during the 2060s and 2080s. The longest heat waves in Northern Ireland were projected to increase in both number and length throughout the twenty-first century, although overall heat wave lengths remained shorter than those simulated over the rest of the UK.

The projected changes in the longest heat wave lengths appear to differ between western and eastern regions of the UK. In many western areas, the distributions of projected heat wave lengths do not change much during the twenty-first century, and the climate signal mainly acts to increase their numbers (see Table S1 in the Supplement at www.int-res.com/articles/suppl/c071p063_supp.pdf). In some areas (for example, Yorkshire and Humberside), the modelled changes were fairly consistent across the different versions of the RCM. All of the models projected heat waves up to 13–14 d long by the 2080s. In other regions, the maximum lengths varied across the RCM ensemble. In eastern parts of England, the tails of the distributions of the heat wave lengths were projected to increase as the climate warmed. Three of the ensemble members projected extremely long heat waves (between 20–28 d in length) during the 2060s and 2080s.

3.4. Comparison with previous studies

The results from the present study are compared with previous work in Table 3. Only a qualitative comparison is possible owing to the different heat wave definitions, climate models and emissions scenarios used. The metrics cited also differ; Fischer & Schär (2010) tabulated their metrics as averages over all land points in the British Isles, whereas Koffi &

Koffi (2008) and Russo et al. (2014) provided figures showing the values of the metrics at each model grid point over land. Jacob et al. (2014) showed changes in metrics only, so their results were not included.

All studies project a general increase in the numbers and lengths of heat waves as the climate warms (Table 3). The ranges of numbers and lengths are wider under high emissions scenarios (A2, RCP8.5) than lower emissions scenarios (B2, RCP2.6, RCP4.5). The projected numbers of heat waves in the present study are similar to those of Russo et al. (2014) for the 2080s. Larger numbers of heat wave days are projected in the present study than Koffi & Koffi (2008). Both Fischer & Schär (2010) and the present study project that the numbers of heat wave days will increase as the climate warms, with large increases projected by the 2080s. The distributions of both the longest heat waves and the numbers of heat wave days widen as the climate warms, and become more positively skewed.

3.5. Length of heat wave season

In this section, the length of the heat wave season (the number of whole months between the first and last months in which a heat wave has occurred) is analysed. To the best of the authors' knowledge, this metric has not been used in previous studies of heat waves. Heat waves need not occur in all months of the season. Historically, most heat waves in the late nineteenth, twentieth and early twenty-first centuries occurred in one or both of July and August (Burt 2004), so the baseline heat wave season only lasts 1 or 2 mo. By the 2040s, heat waves were projected to be fairly common in June, July and August, and 1 or 2 heat waves were simulated in May and September. The heat wave season has therefore expanded to 3 mo, and occasionally 5 mo in some years. By the 2080s, heat waves were projected to occur every year between June and August, and about every other year in May and September. One or 2 heat waves were simulated as early as April and as late as October. The heat wave season could last as long as 7 mo during the 2080s. This expansion of the heat wave season could have serious implications for excess mortality. The mortality risk associated with the first heat wave of summer was found to be higher than the risk from subsequent heat waves in cities in the USA (Anderson & Bell 2011). A heat wave early in the summer means the population has had less time to adapt to the warmer temperatures and so is more vulnerable.

3.6. Administrative regions and land fractions affected by heat waves

The numbers of administrative regions (Fig. 1, Table 2) affected by heat waves were calculated, which gives an idea of the spatial extent of the heat waves. Very few published studies have examined projected changes in the land areas or land fractions affected by heat waves. Historically, the largest numbers of administrative regions affected were 7 (1976), 8 (1990) and 9 (1995). Similar numbers of regions were projected in some years in the 2020s. By the 2060s and 2080s, heat waves were projected to affect at least half of the administrative regions every year, and all regions were affected simultaneously, on average, once every 4 or 5 yr.

Extreme heat waves, defined as those which occur simultaneously in all 12 UK regions (Table 2), were searched for in the projections. Four day heat waves affecting between 55 and 75% of the UK land area were projected to occur between 1 and 3 times during the 2080s. In the most extreme projection, between 62 and 85% of the UK land area would be under heat wave conditions for 8 consecutive days.

4. DISCUSSION AND CONCLUSIONS

Heat waves are known to cause excess mortality, mostly amongst the very young and very old. Here, characteristics of projected heat waves in the UK were studied using a set of 11 RCM simulations. These models were created using combinations of parameter perturbations which were chosen to cover a range of climate sensitivity whilst retaining skill in reproducing the present day climate. The models produce different rates and patterns of warming over the UK, so allow some of the uncertainty in the projections to be included. The RCM simulations were created using the SRES A1B emissions scenario (IPCC 2000). Equivalent simulations using scenarios with higher or lower emissions of greenhouse gases were not available, but if they were, they would be expected to produce larger or smaller increases in heat wave numbers and lengths respectively.

The use of a different baseline period could change some of the details of the results, but the overall conclusions would be expected to be very similar. Amengual et al. (2012) created 1000 different baselines using bootstrap sampling, and found that changing the baseline years had only a small effect on the errors in their corrected data. The regression model used to create the gridded surface temperatures includes an estimate of the urban heat island effect, but may underestimate its actual value. The RCM does not include a representation of urban areas, and so might underestimate future temperatures in large urban areas.

Heat waves were defined as ≥2 d when daily maximum and minimum temperatures exceeded thresholds associated with a 15–20% increase in mortality risk (PHE 2015). Heat waves in all members of the RCM ensemble were projected to become more common and last longer. An analysis of changes in the distributions of the longest heat wave lengths suggested different behaviour between some western and eastern regions. In the western areas, the warming climate mainly acted to increase the number of heat waves with little effect on the shape of the distribution. In eastern areas, the lengths of the heat waves increased as the climate warmed and very long heat waves of 20 d or more were simulated. It is not clear what is driving this difference between eastern and western regions. Changes in wind speeds and directions projected by the RCM ensemble are small (Brown et al. 2009), so that the predominant wind direction over the UK remains westerly to south-westerly.

Historically, heat waves are rare events in the UK and most have occurred during July or August. By the 2040s, heat waves were projected to be fairly common in June, July and August, and 1 or 2 heat waves were simulated in May and September. By the 2080s, heat waves occurred every year between June and August, and about every other year in May and September. One or 2 heat waves were simulated as early as April and as late as October during the 2080s.

The UK land area affected by heat waves was projected to increase as the climate warmed. By the 2060s and 2080s, heat waves would be experienced by some parts of the UK every year. Extreme heat waves were defined in terms of their spatial extent, as events which affect all of the UK administrative regions simultaneously. These extreme heat waves first appear in the 2060s, and could occur, on average, every 4 yr and last for 4 d. In the most extreme case, between 62 and 85% of the UK land area could be affected by a heat wave over 8 consecutive days. These projected changes in heat waves represent a significant threat to public health unless suitable adaptation measures are put into place.

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