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Projected risks associated with heat stress in the UK Climate Projections (UKCP18)

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Abstract

Summer heat extremes in the UK pose a risk to health (amongst other sectors) and this is exacerbated by localised socio-economic factors that contribute to vulnerability. Here, regional climate model simulations from the UK Climate Projections are used to assess how different elements of extreme heat will vary across the UK in the future under global mean surface temperature warming levels of +1.5 °C, +2.0 °C and +3.0 °C above pre-industrial. Heat stress metrics incorporating daily maximum and minimum temperature, temperature variability and vapour pressure are included. These show qualitatively similar spatial patterns for the recent past, with the most pronounced heat hazards found in south-eastern regions of the UK. Projected heat hazard changes across the UK are not homogeneous, with southern regions (e.g. Greater London, South East) showing greater increases in maximum temperatures and northern regions (e.g. Scotland and Northern Ireland) showing greater increases in humidity. With +3.0 °C warming, the relative change in combined heat hazards is found to be greatest in the south-western UK, however, in absolute terms, south-eastern regions will still experience the greatest hazards. When combined with socio-economic factors, hotspots of high heat stress risk emerge in parts of London, the Midlands and eastern England along with southern and eastern coastal regions. Weighting of different heat risk factors is subjective and to this end we have developed and made available an interactive app which allows users to assess sensitivities and uncertainties in the projected UK heat risk.

1. Introduction

In recent years, the UK has experienced significant regional increases in mortality in response to high temperatures during summer heatwaves (Public Health England 2019b, Kovats and Brisley 2021). Projected future warming is expected to increase the occurrence of heat hazards across the world (Andrews *et al* 2018, Vicedo-Cabrera *et al* 2018, Wang *et al* 2020), including the UK (Mitchell *et al* 2016, Christidis *et al* 2020, Slingo 2021). Furthermore, within the UK there will be individuals in society whose health and well-being are particularly vulnerable to heat hazards due to socio-economic, environmental and demographic factors such as deprivation, age, air pollution, access to green space, quality of accommodation and underlying health issues (Lindley *et al* 2011, Bennett *et al* 2014, Paavola 2017, Sera *et al* 2019, Ellena *et al* 2020). To implement adequate mitigation measures, urgent research using the latest data is needed to assess how these risk factors related to heat extremes interact across the UK (Brimicombe *et al* 2021).

Currently, there is evidence that excess heat related mortality in the UK is first detectable above an absolute temperature threshold of ∼24.5 °C (Public Health England 2019a). However, as the population adapts and acclimatises to higher temperatures this threshold could change. Similar absolute temperature thresholds above which the risk of heat-related mortality increases have increased over time in France (Todd and Valleron 2015) and Sweden (Åström *et al* 2016), for example. An alternative approach to using absolute thresholds is to use relative percentile-based thresholds based on observation (Armstrong *et al* 2011, Gasparrini *et al* 2015). These percentile-based thresholds may hold better into the future and implicitly incorporate any long-term changes in climatic baseline, however Åström *et al* (2016) also observed an increase in a percentile-based threshold over time.

Besides climatic factors which affect the magnitude of the hazard associated with heat extremes, there are a wide range of socio-economic factors that could increase vulnerability and exacerbate impacts. For example, older age is a commonly cited contributor to heat vulnerability (Kovats and Hajat 2008, Benzie *et al* 2011, Paavola 2017, Public Health England 2019a). Many other factors have been identified by various studies, including underlying health conditions, housing quality, income, employment and inability to adapt behaviour (Benzie *et al* 2011, Ellena *et al* 2020). Many of these factors are identified in the Heatwave Plan for England (Public Health England 2019a) and align with broader social deprivation indicators (Paavola 2017). However, the balance of how these factors contribute to vulnerability and risk is not trivial: risk is 'driven by a still undefined combination of sub-systems' (Ellena *et al* 2020, p 2), requiring multiple datasets and exploratory methods (for instance principal component analysis [PCA]; e.g. Lindley *et al* 2011).

The UK Climate Projections (UKCP18) (Lowe *et al* 2018, Kendon *et al* 2019, Murphy *et al* 2019) provide the opportunity to assess changing heat stress this century under the representative concentration pathway 8.5 (RCP8.5) scenario. Climate projections are available at a range of spatial scales, ranging from global (∼60 km resolution) down to local scale (∼2.2 km resolution). Building upon an extensive review of UKCP18 simulated past heat stress variability over the UK (Kennedy-Asser *et al* 2021), here UKCP18 projections are combined with socio-economic data to drive an interactive heat risk app. This research has similar objectives to previous projects, such as Climate Just (2017), however the updated, higher resolution UKCP data and greater detail regarding climate extremes means that this research is complementary to previous work. Here, we investigate the following questions:

- How do different aspects of extreme heat (heat hazards) vary spatially across the UK at different warming levels?
- Which areas of the UK are most at risk due to interacting heat hazards and selected socio-economic vulnerability factors?

Section 2 outlines the methods, data, hazard and vulnerability metrics used in the analysis and app development. Section 3 shows key results of changing heat hazards spatially across the UK as well as risk projections from the app. Section 4 discusses these results, including important caveats and highlighting the main conclusions.

2. Methods

2.1. Climate and socio-economic data

Climate data used in this study comes primarily from the 12 km spatial resolution regional climate model (RCM) subset of UKCP18, a perturbed parameter ensemble of 12 regional simulations nested within the global model HadGEM3-GC3.05 (Murphy *et al* 2019). These RCM simulations are atmosphere only, using sea surface temperature and sea ice conditions from the driving global model (Murphy *et al* 2019). While this lack of two-way coupling with the ocean could introduce errors in, for example, internal variability, it likely does not preclude the model's ability to reproduce the majority of large climate signals found in fully coupled simulations (He and Soden 2016). All simulations were run from 1981 to 2080 using the RCP8.5 forcing from 2005 onwards and the Coupled Model Intercomparison Project phase 5 (CMIP5) historical climate forcing before then. A time slice approach is used here to assess 30 year periods that represent the recent past (1990–2019) and a mean annual global warming of +1.5 °C, +2.0 °C and +3.0 °C above pre-industrial levels. The years at which these warming levels are reached are provided in supplementary table 1 (available online at stacks.iop.org/ERL/17/034024/mmedia). Warming levels are calculated for the corresponding global model simulation in which each RCM simulation is nested.

Bias correction of UKCP18 data has been carried out using ERA5 reanalysis data (Hersbach *et al* 2020) following the Inter-Sectoral Impact Model Intercomparison Project 2b bias correction method (Hempel *et al* 2013, Frieler *et al* 2017, Lange 2018). ERA5 data (Hersbach *et al* 2020), obtained at 0.25° horizontal resolution, is interpolated to the resolution of the HadGEM3-GC3.05 and RCM simulations using nearest neighbour interpolation, with no specific treatment for coastal points. All data was obtained and assessed at daily temporal resolution with the summer period taken as 1st June to 15th September, consistent with the period over which the heatwave

Table 1. Heat hazard and socio-economic vulnerability metrics used in the risk analysis.

Risk metric	Brief description	Example of use in previous research
$T_{max\text{-}95+}$	Extreme mean (days exceeding 95th percentile) of summer T_{max}	Fischer and Knutti (2013), Zhao *et al* (2015)
VP_{95+}	Mean vapour pressure on days exceeding the 95th percentile of summer mean T_{max}	Zhao *et al* (2015)
$T_{min\text{-}95+}$	Mean daily minimum temperature on days exceeding the 95th percentile of summer mean T_{max}	Public Health England (2019a), Wang *et al* (2020)
DD_{66}	Degree days exceeding the 66th percentile-based T_{mean} threshold during the climatology period	
PopDens	Number of people living per km^2	Wolf and McGregor (2013)
Pop > 65	Proportion of population aged 65 or older	Wolf and McGregor (2013)
IMD	Adjusted indices of multiple deprivation Abel *et al* (2016)	Rey *et al* (2009)

plan for England is active (Public Health England 2019a).

Three socio-economic variables were selected to explore the spatial variation in some of the non-climatic factors influencing heat mortality risk (table 1). Estimates of the population density (people per km^2) and proportion of individuals over 65 were derived from publicly available current population estimates from the Office for National Statistics (2020a), Northern Ireland Statistics and Research Agency (2020) and the National Records of Scotland (2020). These datasets are for home residence and not place of work, so it is possible that some commuting would occur and potentially increase the risk of exposure in urban areas. Deprivation was parameterised as Abel *et al*'s (2016) adjusted indices of multiple deprivation (IMD) to allow valid comparisons between UK countries. For the main analysis, these socio-economic data are assumed constant over the simulated period, however we include quantitative estimates of future population density and proportion of individuals over 65 from the UK-SSP5 (Pedde *et al* 2021) for supplementary analysis.

2.2. Defining heat hazards

Four heat hazard metrics are used in this study, summarised in table 1, presented both in terms of their spatial distribution for a given time period and their change between time periods.

The first metric is the mean of extreme summer daily maximum temperature (T_{max}), that is, the mean T_{max} on all days exceeding the 95th percentile of summer T_{max} for a given location (Fischer and Knutti 2013). Corresponding means were also calculated for vapour pressure (VP, a key component of many humid heat stress metrics; Zhao *et al* 2015) and daily minimum temperature (T_{min}, a variable used by Public Health England for issuing heatwave warnings; Public Health England 2019a) on days exceeding the 95th percentile of summer T_{max}.

Finally, a degree day metric (DD_{66}) captures temperature variability, calculated by summing the number of days and °C exceeding the 66th percentile of summer daily mean temperature (T_{mean}) at a given location. The summer 66th percentile threshold was chosen as it gives approximate agreement with the annual (∼90th) percentile minimum mortality threshold identified for the UK in previous research (Gasparrini *et al* 2015). For the UK, there is an upward curve in the baseline mortality associated with increasing temperatures above this threshold (Armstrong *et al* 2011, Gasparrini *et al* 2015), however the exact shape of heat-mortality curves varies spatiotemporally and depending on the data used in calibration. We use the simplified degree day approach for its general applicability to the future when both the climate and society may have diverged from the present.

2.3. Categorising combined hazards and risk

In this study we also present an interactive methodological framework for examining the relative risk associated with spatially varying heat hazard and socio-economic vulnerability factors. When combining multiple risk factors, the weight applied to each factor is critically important in constructing relative risk (e.g. Lindley *et al* 2011). The framework presented here—a Shiny App built in *R* (Chang *et al* 2021), shown in figure 1—provides user friendly graphical exploration of uncertainties in these weights. Spatially standardised climate and socio-economic risk factors are provided as inputs for a user-specified weight profile. The app linearly combines the multiple indicators into two dimensions (socio-economic vulnerability and heat hazard), then constructs a bivariate plot of spatial variation. We encourage readers to test the app and modify the risk illustration according to their own priors.

The app's default weightings are derived from a common single factor variance decomposition of indicators from the recent past (common factor analysis; CFA). CFA and PCA present similar but critically distinct approaches to dimensionality reduction. PCA constructs components to summarise maximal variance in the manifest observed variables. By contrast, CFA assumes the observed indicators (in this

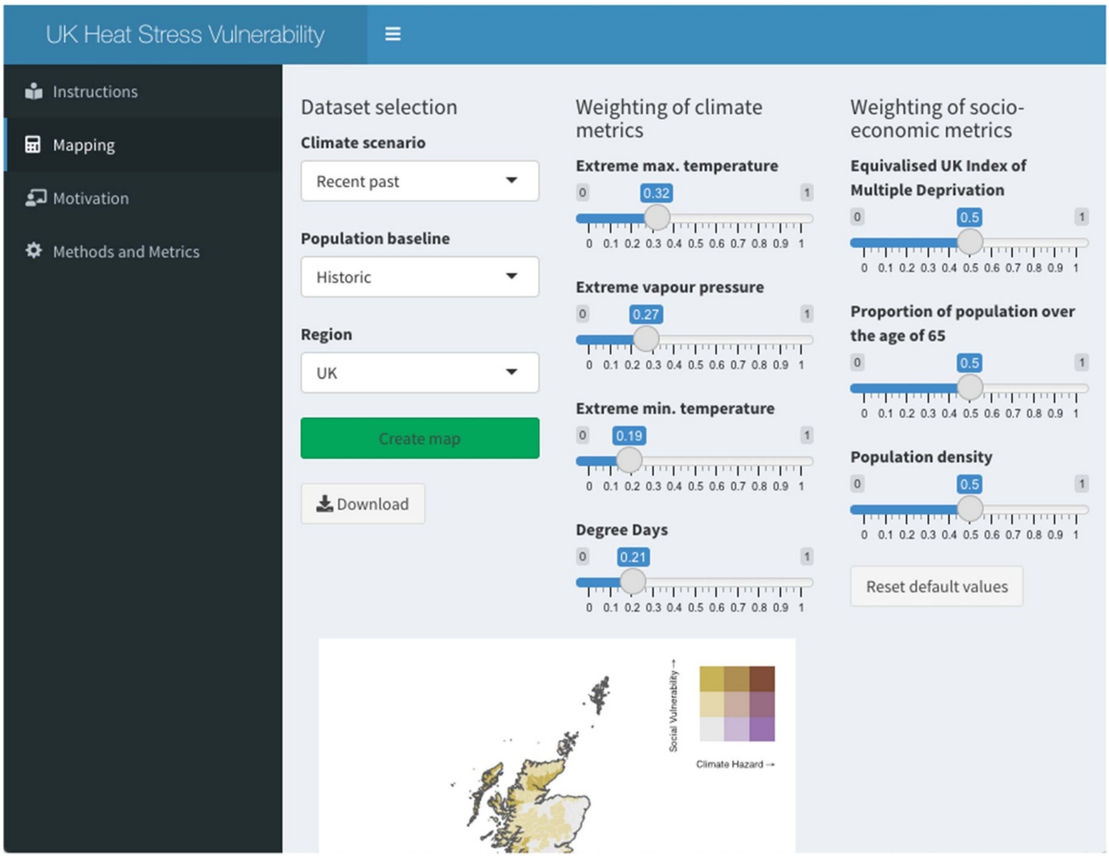

Figure 1. Main screen and default heat risk map produced by UK Heat Stress Vulnerability Shiny App (https://akaresearch.shinyapps.io/heatstressvulnerability/) that accompanies this paper (Griffith and Kennedy-Asser 2022). Reproduced with permission from https://akaresearch.shinyapps.io/heatstressvulnerability/.

case the heat hazard metrics) are imperfect indicators of an underlying latent variable (in this case 'heat risk'), so partitions indicator variation into common factor and indicator-specific variance (Conway and Huffcutt 2003, Office for National Statistics 2020b).

We present CFA results here as we consider climate models as an imperfect representation of an immensely complex reality. However, we note that climate models might also be considered perfectly measured representations of a simplified reality, in which case PCA could be appropriate. Weights are then constructed from factor loadings, which indicate the degree to which each heat hazard metric contributes to the underlying common factor of 'heat risk', without over-representing effects expressed in the more correlated heat hazard metrics. The risk mapping carried out here is solely descriptive, and necessarily sensitive to the specification and weighting of the various risk factors that are used to calculate it. The default weightings are derived as shown in equations (1)–(3).

First, the CFA derived hazard metric weights for the recent past are adjusted to sum to 1:

$$W_x = \frac{w_x}{\sum w_x} \tag{1}$$

where w_x is the CFA derived weighting for each hazard metric x and W_x is the adjusted weighting. For the change in risk between the +3.0 °C and recent past scenarios, the weight applied to each metric is adjusted by the metric's spatial mean change and spatially weighted standard deviation over the recent past:

$$\Delta w_x = \frac{W_x\left(\overline{x_{3.0}} - \overline{x_{\text{past}}}\right)}{\sigma_x^2} \tag{2}$$

where $\overline{x_{3.0}}$ and $\overline{x_{\text{past}}}$ are the spatial means of metric x in the +3.0 °C and recent past scenarios respectively, and σ_x^2 is the spatial standard deviation of each metric for the recent past. This functionally upweights metrics that change more dramatically relative to their previous spatial variability as we want to express change relative to between-area differences which will have likely driven past policy prioritisation. Again, as for the weighting for the recent past, Δw_x is adjusted to sum to 1:

$$\Delta W_x = \frac{\Delta w_x}{\Delta w_x}. \tag{3}$$

These derivations are shown in supplementary table 2. The magnitude of each heat hazard metric is then multiplied by its respective weighting before being linearly combined to give a combined risk score for the recent past or between the +3.0 °C and recent past scenarios (r or Δr) as in equations (4) and (5) respectively:

$$r = \sum x W_x \tag{4}$$

$$\Delta r = \sum \Delta x \Delta W_x \tag{5}$$

where x (Δx) is the magnitude (of change) of each heat hazard metric, expressed as z-scores.

3. Results

3.1. Spatial variability in heat hazards

Regional changes in heat hazard metrics for the recent past (1990–2019) and at three warming levels above pre-industrial level from the UKCP18 RCM subset are shown in figure 2. Figure 2(a) shows the variation in regional mean $T_{\text{max-95+}}$ and VP_{95+}, with grey shading showing isolines of the heat stress metric, simplified wet bulb globe temperature (sWBGT; calculated following Zhao *et al* 2015). There are spatial differences across the UK, with southern and eastern regions (Greater London, East of England, South East, East and West Midlands) showing the highest T_{max} values and largest increases with projected warming. Inland regions (East and West Midlands) generally have the smallest increase in VP, while north westerly regions (Scotland, Northern Ireland, North East and North West) have the lowest absolute T_{max} values but show large increases in VP. In terms of heat stress metrics (here, sWBGT), the greater projected increases in humidity in cooler regions partially compensate for the greater temperatures experienced in warmer parts of the UK, meaning spatial differences in heat stress are less pronounced. On days when T_{max} exceeds the 95th percentile, between the recent past and +3.0 °C warming level, all regions show an increase in sWBGT of between 2.49 and 2.77, whereas regional $T_{\text{max-95+}}$ increases vary between 3.16 and 4.14 °C.

At +1.5 °C warming, Greater London lies just below the 'slight' sWBGT heat stress threshold (sWBGT > 28; Zhao *et al* 2015). By +2.0 °C, Greater London and the South East both exceed this threshold and by +3.0 °C the majority of England (Greater London, South East, East of England, South West, East and West Midlands) exceeds this threshold. Not only that, under +3.0 °C global mean warming, $T_{\text{max-95+}}$ in Greater London, South East, East and West Midlands regularly approaches 33 °C, currently noted as a trigger temperature for infrastructure disruption when tarmac may begin to melt (Public Health England 2019a).

Figure 2(b) shows how $T_{\text{min-95+}}$ varies with $T_{\text{max-95+}}$. These variables are strongly correlated and display less regional variation in warming trends across the UK. Figure 2(c) shows how the variability of daily temperatures (DD_{66}) varies between UK regions relative to the 66th percentile of T_{mean}. Of all metrics assessed here, DD_{66} shows the least linear increase with warming. For most regions, DD_{66} is similar for the recent past, +1.5 °C and +2.0 °C scenarios but shows a larger increase at +3.0 °C. Increases in this metric are most pronounced in Wales and the South West and smallest in Greater London and the East of England.

Figure 3 shows maps of the spatial variability in these heat hazard metrics for the recent past and their relative change between the +3.0 °C warming and the recent past. All of the metrics have been converted into z-scores, so they are normalised relative to the magnitude of their mean and spatial variability. For the recent past, all of the metrics show qualitatively similar spatial distributions across the UK (figures 3(a)–(d)). The highest heat hazards (positive z-scores) are found over England, particularly towards the southeast, and the lowest hazards (negative z-scores) are found over Scotland and Northern Ireland. There are some subtle differences, for example VP_{95+} and $T_{\text{min-95+}}$ are greatest closer to the southeast coast of England, while $T_{\text{max-95+}}$ and DD_{66} are greater inland in England.

Although the absolute spatial distribution of heat hazards remains similar with future warming (i.e. higher risk in the southeast compared to the northwest, as shown in supplementary figures 1(a)–(h)), projected changes in each hazard metric show regional differences across the UK (figures 3(e)–(h)). In absolute terms, all metrics increase for all regions across the UK (supplementary figures 1(i)–(l)). $T_{\text{max-95+}}$ increases under global mean warming with a broadly similar spatial pattern to its recent past absolute values (figure 3(e)). However, VP_{95+} shows the largest projected increase in the north of the UK and some coastal regions (figure 3(f)), consistent with the regional results in figure 2. $T_{\text{min-95+}}$ and DD_{66} (figures 3(g) and (h)) show broadly similar patterns with western and southwestern parts of the UK (particularly southern Wales and the South West) showing the largest increases and the eastern coast of England showing the smallest increases.

Using the CFA derived weightings for each metric shown in table 2, the resultant combined hazard map shows again the highest combined heat hazard for the recent past in the southeast of the UK (figure 3(i)). This is in qualitative agreement with the regions that have historically experienced the greatest impacts from heatwaves in terms of mortality (Public Health England 2018a, 2018b, 2019b). In terms of the projected change for +3.0 °C global mean warming (figure 3(j)), there is less variability in the spatial distribution of relative heat hazards across the UK, with only subtly larger increases particularly in South West England, Wales and to a lesser extent the West Midlands and North West.

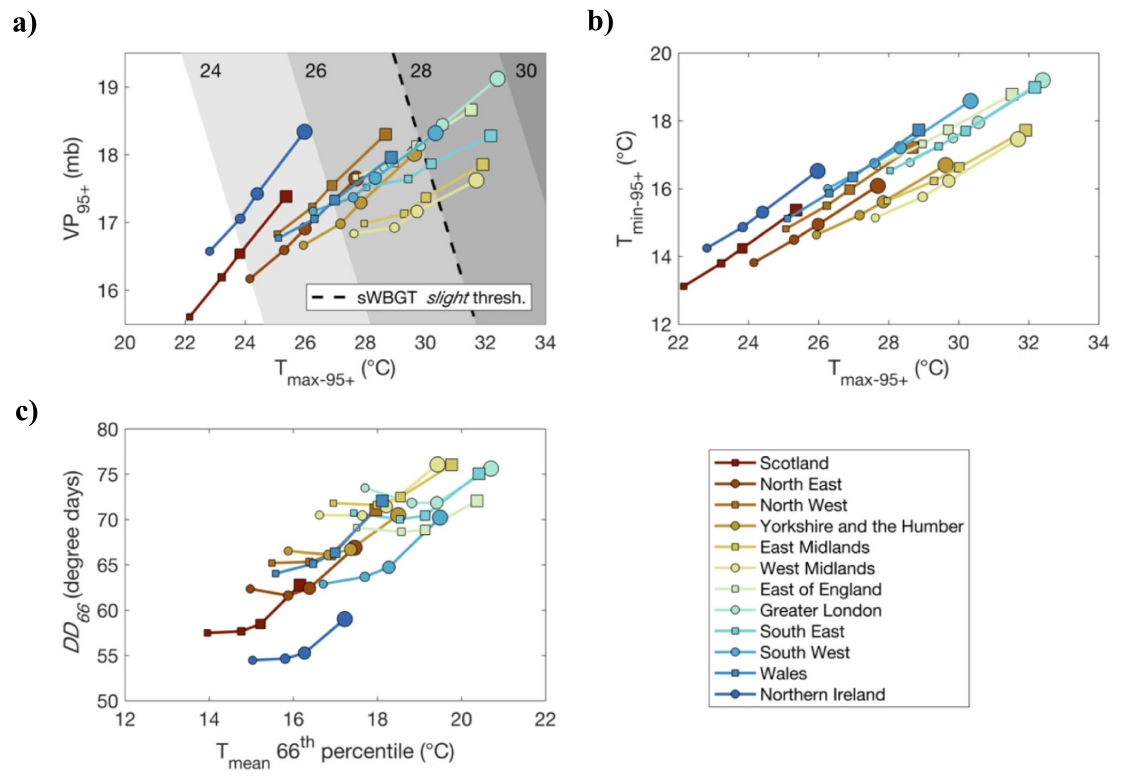

Figure 2. (a) Projected UK regional $T_{max\text{-}95+}$ and VP_{95+} for the four warming levels from the UKCP18 RCM subset, with grey shading showing isolines of sWBGT (Zhao *et al* 2015 'slight' threshold marked). (b) Projected regional $T_{max\text{-}95+}$ and $T_{min\text{-}95+}$ for the four warming levels. (c) Projected regional summer T_{mean} 66th percentile and DD_{66} for the four warming levels. For each region, the marker size increases from the past (smallest) through to the +1.5 °C, +2.0 °C and +3.0 °C warming levels (largest).

3.2. Mapping heat risk

Figure 4 illustrates a UK risk map combining climate hazard metrics from figure 3 with the socio-economic factors (IMD, proportion of population aged >65 and population density) at medium super output area scale. The weighting of hazard metrics is the same as presented in figures 3(i) and (j) and the socio-economic variables are equally weighted. For visualisation purposes, the colour scheme divides the metrics into three bins in each dimension (climate hazard and socio-economic vulnerability), representing the upper, middle and lower tertiles of the combined values.

Figure 4(a) shows for the recent past that the localities with higher heat hazards, higher levels of socio-economic vulnerability and therefore higher heat risk are in London, eastern England, particularly East Anglia and around The Wash, and coastal regions along the southern coasts of England from Kent to the Isle of Wight. Figure 4(b) shows that when socio-economic factors are considered in combination with the potential future change in climate hazards, localities with the greatest increase in risk lie in the South West, multiple parts of Wales and western Scotland along with some areas of the West Midlands, northern and north western England and London. Although these regions show the greatest relative increase in climate risk, in absolute terms the southeast of the UK will still remain at the highest risk as shown in supplementary figures 2(a)–(c).

Three examples of alternative weighting schemes are shown in supplementary figures 3–5, showing the effect of leaving out hazard metrics VP_{95+}, $T_{min\text{-}95+}$ and DD_{66} respectively on risk map for the recent past. In each of these cases, the CFA weightings have been recalculated, as listed in supplementary table 3. Excluding VP_{95+} (supplementary figure 3) has the effect of shifting the area of greatest climate risk inland and away from southern and eastern coasts of England. Coastal areas of Kent and around the Isle of Wight no longer appear as being at the highest risk, while areas of the West Midlands around Birmingham instead appear at highest risk. Excluding $T_{min\text{-}95+}$ (supplementary figure 4) has a similar effect, but the shift of risk inland is not as pronounced. By contrast, excluding DD_{66} (supplementary figure 5) results in the areas of greatest risk mostly shifting southwards and eastwards into coastal regions, from the coasts of East Anglia through to Dorset.

These results assume unchanging socio-economic conditions in the future. However, future heat exposure and heat-related mortality can be underestimated when population growth and demographic change is not included (Rohat *et al* 2019, Chen *et al* 2020). In supplementary figures 2(d)–(f) we show risk maps at the different future warming levels assuming a

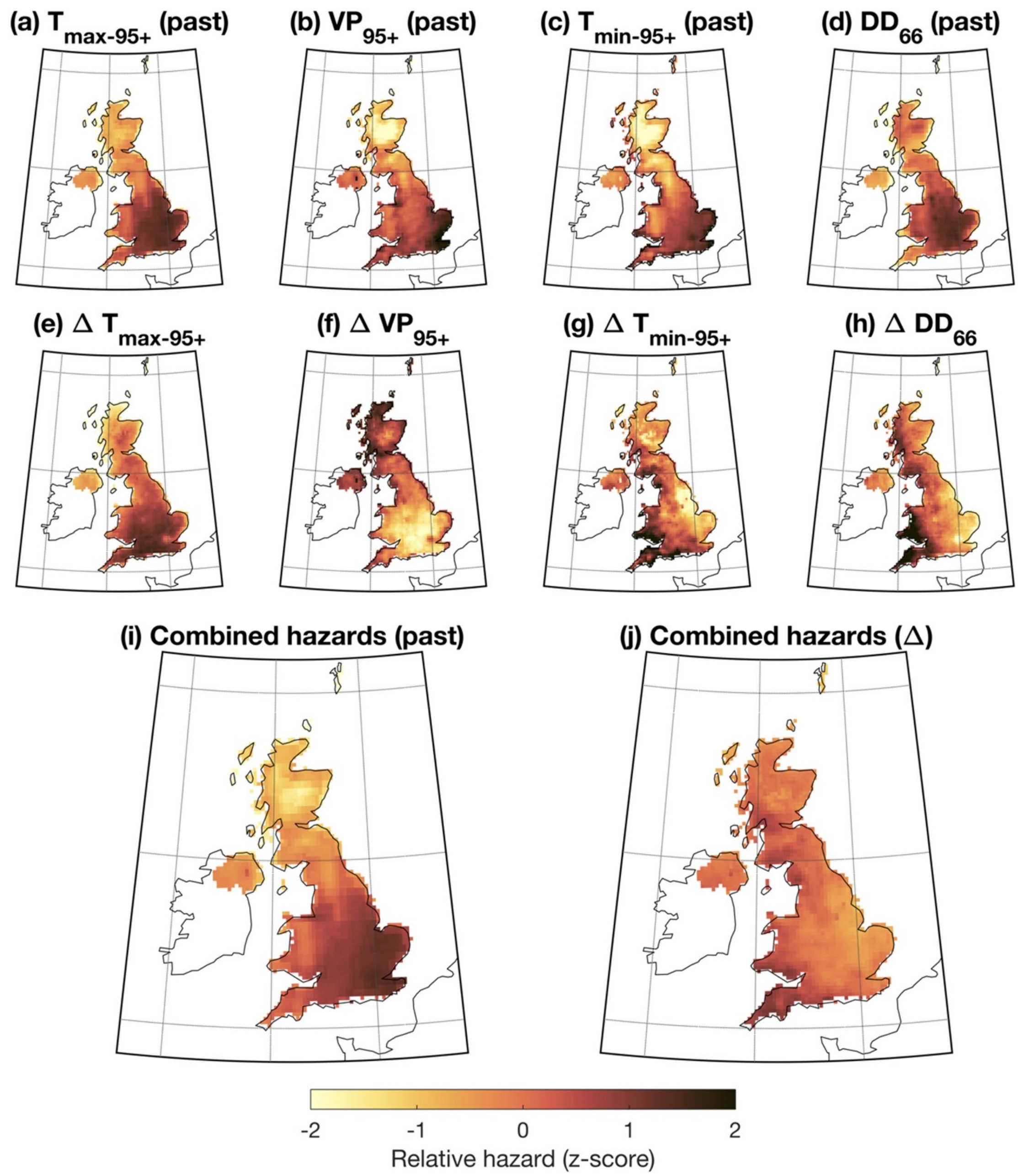

Figure 3. (a)–(d) *z*-scores of relative spatial distribution in heat hazard for the recent past (1990–2019) for each of the metrics outlined in table 1. (e)–(h) Projected changes in heat hazard metrics between +3.0 °C global mean warming and recent past. Linear combination of the four heat hazard factors for the recent past (i) and between the +3.0 °C global mean warming level and recent past (j) using the weightings outlined in table 2.

future population change as described by UK-SSP5 in 2050 (Pedde *et al* 2021). This changes the population density and proportion of people aged >65, not the IMD (which remains the same as for the recent past). This change in population structure sees a widespread increase of risk across the south coast of England and in East Anglia. This is only a single realisation of a future population, but it gives an indication of the magnitude of effect these changes might have. To explore these different scenarios fully, however, will require an additional study.

Although the weighting of climate and socio-economic risk metrics does impact the resulting spatial distribution, the differences are relatively minor due to the high degree of multicollinearity and spatial autocorrelation between the metrics—particularly the heat hazard metrics. We provide the associated Shiny app to demonstrate this more comprehensively (https://akaresearch.shinyapps.io/heatstressvulnerability/) (Griffith and Kennedy-Asser 2022). The app also allows figures to be downloaded in PDF format for higher

Table 2. Summary of weightings applied to each heat hazard metric in the combination presented in figure 3. Weightings are derived as described in equations (1)–(3), detailed further in supplementary table 2.

Metric	Weighting	Method
	Recent past	
$T_{\text{max-95+}}$	0.32	Factor analysis (1 factor), adjusted as in equation (1)
VP_{95+}	0.27	Factor analysis (1 factor), adjusted as in equation (1)
$T_{\text{min-95+}}$	0.19	Factor analysis (1 factor), adjusted as in equation (1)
DD_{66}	0.21	Factor analysis (1 factor), adjusted as in equation (1)
	Δ (+3.0 °C—recent past)	
$T_{\text{max-95+}}$	0.31	Factor analysis (1 factor), adjusted as in equations (2) and (3)
VP_{95+}	0.37	Factor analysis (1 factor), adjusted as in equations (2) and (3)
$T_{\text{min-95+}}$	0.21	Factor analysis (1 factor), adjusted as in equations (2) and (3)
DD_{66}	0.10	Factor analysis (1 factor), adjusted as in equations (2) and (3)

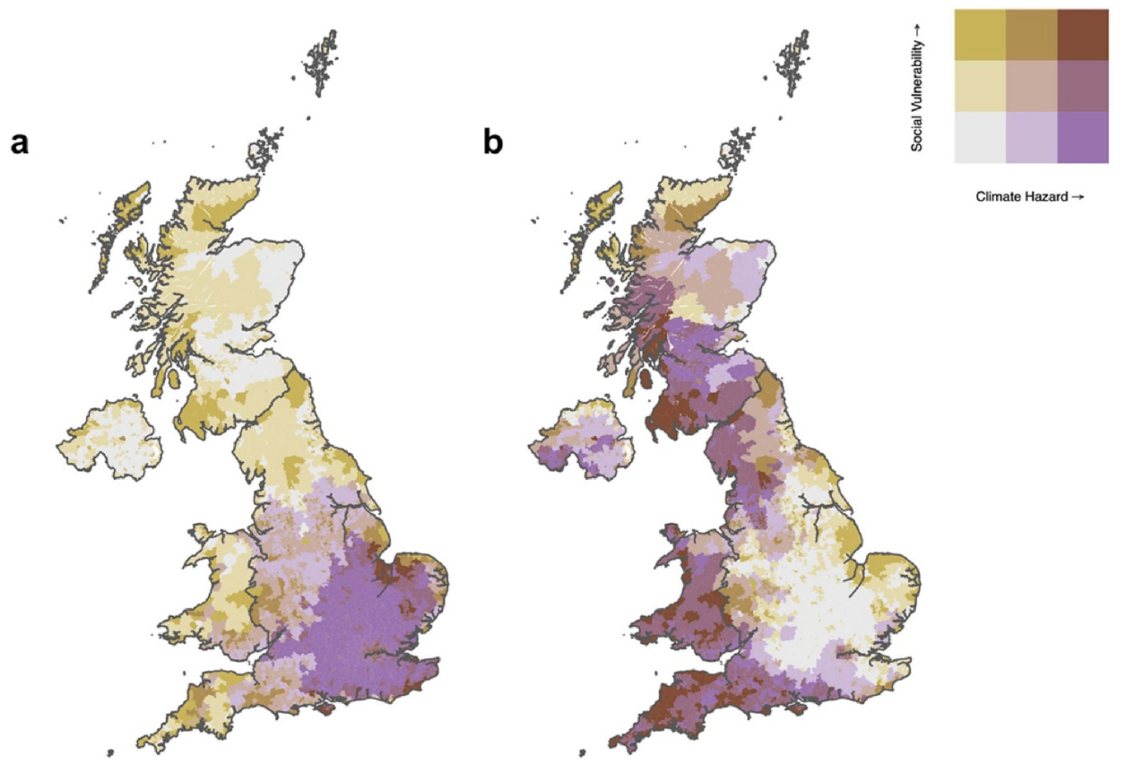

Figure 4. Relative risk (in terms of climate hazards and socio-economic vulnerability) across the UK for (a) the recent past (1990–2019) and (b) for the projected change between recent past and +3.0 °C warming. The weighting of climate hazard metrics is as used in figures 3(i) and (j) respectively. Socio-economic factors remain stationary in time

resolution plotting. For further consideration of spatial variability in results, see the supplementary information, including supplementary figures 6–9 which use a further range of different weighting schemes.

4. Discussion and conclusions

This work has presented (a) a novel analysis of changing heat hazards for the UK using UKCP18 data and (b) a methodology for assessing at-risk areas which could be applied to other countries that have comparable climate and socioeconomic data available. We have highlighted how aspects of risk relating to heat extremes are unevenly distributed across the UK and how these aspects of risk could change under a range of warming levels in the RCM subset of UKCP18. Our interactive methodology for visualising uncertainty, in the form of a Shiny App, could prove valuable for future climate impacts and risk research where multiple complex and interacting factors need consideration.

4.1. Caveats

There are several important caveats to the results presented here. Firstly, we have used hazard metrics and not linked fully through to impacts data, such as historic morbidity or mortality during past heatwaves (e.g. Public Health England 2019b). To date, we have carried out a detailed evaluation of this model's representation of UK summer climate using observational and reanalysis climate data (Kennedy-Asser *et al* 2021), however, we do not have access to comparable risk data to evaluate the performance of the model or methods in this regard. A particular focus of this research was on providing an interactive and open framework for the descriptive exploration of relative risk factors and their uncertainty, and we do not aim to produce absolute predictions of increased mortality under certain warming levels. Although it would be possible to regress the constructed weightings and associated risk maps against datasets of observed heat impacts over the recent past, this is non-trivial (Skrondal and Laake 2001) and would require data products beyond the scope of the study. The unidimensional common factor weighting used here should not be interpreted as showing which factors are most important for mortality—the weighting simply provides a parsimonious summary of an underlying, latent driver of common variability across heat hazard metrics, so this common variability is not over-represented when combining metrics (Office for National Statistics 2020b). Further work could integrate some of the spatial mapping methods here with a more thorough analysis of the drivers of mortality (Gasparrini *et al* 2015, Sera *et al* 2019).

Although a range of important climate and socio-economic factors have been used here, these are not expected to be exhaustive. Other socio-economic groups which have been noted in previous research and reports to be at elevated risk from extreme heat include babies and infants, those with drug and alcohol dependencies, homeless people, those with illnesses that affect thermoregulation and those who are unable to adapt their behaviour (Public Health England 2015). The metrics we have used were selected based primarily upon data availability, however they have been consistently highlighted in previous literature (Lindley *et al* 2011, Arbuthnott and Hajat 2017) and are likely to continue to remain relevant in the future: for example, the population aged over 65 is much larger than the population aged under 5 and is expected to expand. However, additional risk factors should be considered in future work.

This research has taken a UK-wide regional focus. Higher population density is accounted for and will increase the vulnerability and associated risk in urban areas. However, heat hazards may be less accurate climatically for urban areas than other modelling products, such as the UKCP18 local projections at 2.2 km resolution which has both higher resolution and an improved urban modelling scheme (Keat *et al* 2021). However, these simulations are currently not available for the full continuous time period required to select the warming levels that were used here.

Regarding the use of thresholds such as the sWBGT threshold used in figure 2(a) or the choice of the 66th percentile for the degree day metric, it is important to consider that many different historic heatwaves in the UK have been associated with significant mortality increases over the past two decades (Green *et al* 2016, Public Health England 2020). These events had varying climatic characteristics as well as context specific social factors that contributed to their impact (Public Health England 2020). The imposition of thresholds (whether in absolute or relative terms) implies an artificial binary of 'hazardous' or 'not hazardous'. This is a necessary simplification, but it should be noted that other possible thresholds could be equally valid. Other heat stress metrics, such as Humidex or Apparent Temperature (e.g. as used in Zhao *et al* 2015) could be used in the definition of heat stress thresholds. Examples of alternative 'slight' heat stress thresholds for these metrics are shown in supplementary figure 10 for comparison.

It is known that HadGEM3-GC3.05 has a relatively high climate sensitivity compared to other models (e.g. those in CMIP5; Murphy *et al* 2019). Sensitivity analysis of the non-bias corrected HadGEM3-GC3.05 simulations (which drove the RCM used here) compared to other CMIP5 models is included in supplementary figure 10. Because of the time sampling approach used here, with the climate only taken for 30 year periods corresponding to given warming levels, HadGEM3-GC3.05 does not show a particularly extreme climate, with projected changes in $T_{\text{max-95+}}$ and VP_{95+} for UK regions that are broadly consistent with CMIP5 GCMs (supplementary figure 10): it simply reaches these warming levels earlier than other models. There are some differences between the behaviour of the CMIP5 models compared to HadGEM3-GC305, with several showing their highest values of VP_{95+} for the recent past. The UKCP18 GCM and RCM simulations are particularly well suited for analysing summer heat stress variables for the UK compared to these other CMIP5 models (Kennedy-Asser *et al* 2021), however other modelling products (e.g. EURO-CORDEX; Jacob *et al* 2014) or bias correction techniques could be used and these could potentially produce different results.

Finally, the use of the extreme RCP8.5 forcing scenario (Hausfather and Peters 2020) means that warming trends are particularly steep in these simulations. As a result, the climatology periods used for +1.5 °C and +2.0 °C occur very early in the model projections (between 2021–2025 and 2031–2037 respectively). The time sampling approach is limited because there may be considerable overlap between these climatology periods and it may not be capturing the true equilibrium climate response (King *et al* 2020). For this reason, time sampled global mean warming levels should be treated as approximations and absolute values may be less robust than spatial variability in relative risk across the UK. Currently, RCP8.5 is the only forcing scenario available at this resolution of UKCP18. Future implementation of research for policy planning should consider using additional warming scenarios and models to ensure that these uncertainties are adequately captured.

4.2. Conclusions

The heat hazard analysis used four metrics that plausibly contribute to the health impacts associated with extreme heat. Regions in the southeast of the UK that have recently been exposed to the greatest heat extremes (Public Health England 2019b) will continue to be most exposed in the future. However, other regions, particularly in the west and southwest show slightly greater projected increases in heat hazard metrics, particularly those relating to night time temperatures (T_{min}) and temperature variability (DD_{66}). The relative importance of these various heat hazard metrics and their causal contribution to health impacts is currently unclear, however these different factors require consideration as adaptation methods could vary for each of the metrics. For example, adaptation to increased T_{max} extremes could require adaptation of workplaces (Surminski 2021) whereas increased T_{min} extremes would primarily affect people in their homes (Kovats and Brisley 2021).

Heat hazards were combined with socio-economic metrics that contribute to the vulnerability of populations to impacts from heat extremes (population density, proportion of the population >65 and IMD), highlighting risk hotspots across the UK, primarily around London and coastal regions of southern and eastern England for the recent past, while various western regions show the largest increase in risk with +3.0 °C global warming. Although this paper has focussed on heat risk during the summer season, it is likely that other climate hazards (including winter cold) share similar vulnerability factors (e.g. older people will also be at greater risk from winter cold Hajat *et al* 2014). As a result, adaptations to reduce the risk associated with one hazard could benefit or exacerbate another: for example, increased insulation in housing to reduce winter cold risk can lead to increased overheating risk in summer (Jones *et al* 2016, Ozarisoy and Elsharkawy 2019). It is important therefore to consider assessing multiple climate risk factors in tandem in future research.

Projected changes in UK heat extremes are still less than those currently experienced in other regions of the world (Vicedo-Cabrera *et al* 2021). The UK has an opportunity to target adaptation and management of risk factors to minimise future impacts and suffering associated with extreme heat. The general distribution of heat extremes across the country will remain qualitatively similar in the future, with the southeast exposed to more extreme heat than the northwest. However, the results shown here suggest the changes in different heat hazard factors subtly vary across the country. Additionally, due to the spatial autocorrelation of socio-economic vulnerability factors, morbidity and mortality risk associated with heat extremes will likely be concentrated in areas which experience compound climate and socio-economic risk factors (Mitchell 2021). It is important that adaptation strategies are sensitive to this, explicitly targeting interventions at vulnerable regions and ensuring that those in society who are least capable of coping with rapid change are not left to combat the negative health impacts of heat stress unaided.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/Zimbabwelsh/HeatStressVulnerability.

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