A tale of two temperature extremes: exploring how exposure to extreme heat or cold affects mental health and wellbeing in the UK

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Abstract

Background and Objective: The UK's climate change vulnerability to extreme temperatures, hotter summers and milder winters, and emerging evidence on climate change and mental health require further empirical research. Therefore, this study aims to investigate the relationship between exposure to extreme temperatures and mental health and wellbeing outcomes across the UK. We also examined whether this relationship is modified by a range of factors such as sex, age, education, and social support.

Materials and Methods: We linked geographical data on daily temperatures to 10 waves of the UK Household Longitudinal Survey (2009-2019) based on residence location at each wave. Individual exposure was defined as experiencing extreme heat or extreme cold for 4+ days in the preceding four weeks. Outcomes included mental health and subjective wellbeing (SWB). Mixed-effects models were fitted, and effect modification analysis was conducted to unpack factors moderating the association with heat/cold.

Results: Exposure to extreme heat during the previous month was associated with increased risk of poor mental health (AOR (95% CI): 1.12 (1.06-1.17)) and risk of poor SWB (1.08 (1.02-1.14)) compared to those who were unexposed. However, exposure to extreme cold was associated with decreased risk of poor mental health (0.82 (0.77-0.87)). There was limited evidence for effect modification, which was inconsistent between outcomes and heat/cold exposure. Association between extreme heat and poor mental health and SWB was weaker amongst individuals with high social support and high levels of pro-environmental behaviours practised, respectively, suggesting they operate as protective factors.

Conclusion: These findings underscore the need for developing targeted interventions to enhance adaptive capacity against extreme heat. The positive association between extreme cold and mental health was unexpected and warrants further exploration. This study lends weight to indications that fostering social support and pro-environmental behaviours may help build community mental health resilience to extreme temperatures.

Keywords: Climate change, UK, extreme heat, extreme cold, mental health, wellbeing, longitudinal data, UKHLS, risk and protective factors

Introduction

In July 2023, the World Health Organisation (WHO) Europe Regional Office declared the climate crisis and associated extreme weather events a public health emergency for the first time [1, 2]. Approximately 3.6 billion people currently reside in regions that are particularly vulnerable to climate change, with an estimated 250,000 additional deaths due to climate change predicted annually between 2030 and 2050 [3]. Since the 1950s, the frequency and intensity of hot extremes have increased, and those of cold extremes have decreased globally [4]. Although the polar regions are warming rapidly and the frequency of extreme cold events is declining, their intensity does not seem to be declining in tandem [5]. Both temperature extremes - heat and cold pose significant multifaceted health risks. Some of the extreme heat-related risks include suicide ideation, increased mortality due to heatstroke, cardiovascular and respiratory causes, and renal impacts [6]. Extreme cold conditions can cause a) veins and arteries to constrict and blood to become more viscous, therefore generating many of the same circulatory stressors as heat and increasing cardiac effort [7] and b) the body to lose heat more rapidly than it generates, draining stored energy and raising the danger of hypothermia, a disorder marked by a core temperature below 35°C [8]. However, many negative physical health impacts mediated by climate change are causally and reciprocally related to mental health directly, indirectly or via multiple interconnected diverse pathways [6, 9-12]. Direct impact of climate change on mental health often arises from first-hand experiences of climate events, such as a) an increased rate of post-traumatic stress disorder and depression following a flood or b) worsening of the symptoms in individuals with pre-existing mental health conditions, such as bipolar disorder or anxiety, due to a heatwave. On the other hand, indirect impacts on mental health can occur as a result of awareness or bearing witness to changes caused by the climate crisis or as a result of compounding mental health impacts of socio-economic factors such as poverty or unemployment [12]. For instance, during the period of extreme cold, the added financial distress associated with keeping homes warm may exacerbate the stress among those unemployed or from lower socio-economic status [13]. The amount of time people spend outside can also be adversely affected by cold weather, resulting in reduced social interactions with people outside of the home [14], which can worsen mental health conditions and feelings of loneliness [15, 16]. Additionally, in recent years, due to the growing awareness of climate-driven psychological distress, new terms for climate-specific mental health conditions have also emerged, such as eco-anxiety, climate anxiety, solastalgia, and eco-grief [17-19].

Climate change and mental health are both significant issues for the UK. The UK's temperate maritime climate is being affected by climate change and is vulnerable to extreme temperatures, both hot and cold [20, 21]. According to the Met Office projections, by 2070, the summer will become 1-6°C warmer, up to 60% drier, and winter will become 1 - 4.5°C warmer and 30% wetter [22]. These statistics highlight the increasing and compounding burden of climate change on the health system. UK cities are vulnerable to climate change because of dense infrastructure, rapid urbanisation, social inequality, and the urban heat island (UHI) effect [23]. UHI effect is a significant concern in UK cities, where urban areas can be several degrees warmer than their rural surroundings – an effect intensified by building density and lack of vegetation [23, 24]. These factors increase mental health risks from high temperatures for those living in urban areas, especially vulnerable groups such as homeless people, slum dwellers, migrants, and young children under the age of 5 [25, 26]. Furthermore, while newer, energy-efficient homes may be more prone to overheating because their airtight and well-insulated design can restrict heat loss when ventilation is inadequate, older and heritage buildings face different challenges [27]. Traditional building designs and retrofit measures may not be well suited to increasingly frequent heatwaves and hotter summers, potentially increasing thermal discomfort and associated health risks for occupants [28]. This is particularly important in the UK, where people spend substantial time indoors [27]. According to the English Housing Survey (EHS) 2021–2022, 52% of households in England reported using fans, and 3% used air conditioning to keep cool during summer, with reliance on these cooling measures expected to increase [29].

Population sub-groups that are likely to be affected disproportionately by climate change-related mental health and wellbeing issues include adolescents and younger people, women, economically disadvantaged people, less educated, unmarried adults, ethnic minorities, those living alone, and people living with pre-existing health conditions [30-32]. People over age 75 years, though highly vulnerable to heat and cold due to diminished thermoregulatory capacity and the prevalence of chronic health conditions, often don't perceive themselves at risk [33, 34]. However, there is currently limited empirical evidence on how experiences of extreme temperature exposure differ across sociodemographic groups, and how these differences are associated with mental health and wellbeing outcomes in nationally representative populations [35]. It is also important to underscore that the cross-cutting nature of inequalities discussed above heightens and compounds the threats of extreme temperatures for at-risk population subgroups.

Considering the risks discussed above, it is imperative to study the factors influencing improved mental health and wellbeing in the context of climate change-associated exposures. Practising pro-environmental behaviours (PEBs), such as using public transport, recycling, and taking fewer flights, provides individuals with a sense of control and agency against climate change, thus promoting positive mental health and wellbeing [36]. A study conducted among 16+ year olds using the UK Household Longitudinal Study (UKHLS) dataset that examined climate concern, PEBs, satisfaction with PEBs, and the association between PEBs and wellbeing outcomes, found that individuals who were happy with their environmental efforts reported higher levels of wellbeing [35]. There is strong empirical evidence that social support, in the form of family, friends, neighbourhood ties, and community networks, serves as an environmental and social resource that positively affects wellbeing [9, 37-42]. The same is true during or after the experience of climate change-induced extreme weather events (EWEs). Following exposure to EWEs, strong social networks are associated with reduced rates of anxiety and depression as well as improved recovery [37, 41, 43-45]. Even though the reviews and theoretical literature on climate change and mental health have identified population subgroups at higher risk, questions about the individual and community-level risk and modifiable protective factors that influence extreme temperature-related mental health outcomes remain unanswered through empirical research, especially in the UK context.

Few studies have effectively explored the role of potential protective factors in modifying the effect of extreme temperature impacts on mental health. Using a cross-sectional analysis of one wave of UKHLS, the study by Olsen et al (2025) found that people who felt good about their PEBs reported higher wellbeing; however, this relationship was not explored in the context of EWE exposure [35]. Our study builds further on this work and other literature by using 10 waves of the UKHLS data, and relevant confounders and effect modifiers. To address the gaps discussed and identified above, we utilised a robust methodology to define extreme heat and cold based on daily weather data and linked it with self-reported mental health and wellbeing from waves 1 - 10 of UKHLS data. By undertaking a longitudinal analysis of mental health and wellbeing data linked with real-time exposure to extreme temperatures, this research seeks to explore a) how does the exposure and repeat exposure to extreme temperature, i.e. extreme heat and cold, impact mental health and subjective wellbeing (SWB) in the UK, and b) is this association modified by a range of factors such as age, sex, education, social support and PEBs?

Methods

Data

This study used two sources of data that were linked to measure the effect of extreme temperature exposure on mental health and wellbeing: (1) UK meteorological data and (2) UKHLS data

Meteorological Data

To define extreme temperature exposure, we used 5x5 km gridded daily minimum (t_{min}) and daily maximum temperature (t_{max}) (in degrees Celsius) HadUK-Grid data available from The Centre for Environmental Data Analysis (CEDA), which runs and hosts the UK's national data centre for atmospheric and earth observation research [46]. For this research, we chose 30 years, 1971-2000, as a baseline following WMO guidelines to define the temperature extremes for the study period 2009-2020 [47]. This choice of baseline period is recommended to avoid inhomogeneity in the defined measures, ensuring that extreme events in newer years can be compared to those in older years consistently [48, 49]. The study period was restricted to end in February 2020 to avoid potential confounding effects of the COVID-19 pandemic on the outcomes.

UKHLS

UK Household Longitudinal Study (UKHLS), also known as the Understanding Society, is funded by the Economic and Social Research Council and various Government Departments, with scientific leadership by the Institute for Social and Economic Research, University of Essex [50]. The research data are distributed by the UK Data Service. We chose the UKHLS as it collects longitudinal information on socioeconomic characteristics, health behaviours, and attitudes from individuals aged 16+, and is representative of the UK population. Beginning in 2009- 2010 (Wave 1), the households selected using a stratified clustered random sample have been visited every year since then to capture changes in circumstances over time [51]. Interviews are carried out face-to-face in respondents' homes or through an online self-completion survey. Everyone in the household is surveyed, and transitions out of the household and into the household are tracked. To conduct geo-spatial mapping of respondents' neighbourhoods with the temperature data, we requested access to lower-super output area (LSOA) levels, a special-licensed (SL) version of the dataset from the UK Data Service [52]. The SL version contains census 2011-defined LSOASs for England and Wales households, Super Output Areas (SOA) for Northern Ireland and Data Zones (DZ) for Scotland (approximately equivalent census geographies in each part of the UK). For the rest of this paper, all country-specific geographic identifiers, i.e. LSOA, DZ, and SOA, will be referred to as LSOA. Typically, LSOAs are small geographic areas with 400–1,200 households and typically 1,000–3,000 residents [53]. More information on the statistical and geographical unit of analysis can be found elsewhere [53, 54].

Linking temperature data with outcomes

According to the World Meteorological Organisation (WMO), a heatwave is defined as 'a period of marked and unusually hot weather persisting for at least two consecutive days', and a cold wave as 'marked and unusually cold weather, which can be associated with a sharp and significant drop of air temperatures near the Earth's surface and persisting for at least two consecutive days' [55]. Despite extensive use and intuitive comprehension of these terms, there isn't a single, accepted quantified measure of heatwave or cold wave either in the UK or globally due to variations in climate, population vulnerability, and data availability [56]. While some definitions follow relative thresholds, like the 90th or 95th percentile of historical temperature distributions [48, 57], others use fixed temperature thresholds, which are frequently used by national weather services [56, 58]. Although fixed thresholds are straightforward to explain, they are not transferable to different climates; for example, what is considered a heatwave in the UK might be normal in Southern Europe. On the other hand, percentile-based definitions are more adaptable and sensitive to regional differences; however, they require long-term data [59]. Similarly, definitions of cold waves include either the number of days below the 5th percentile of the daily mean temperature that persist for several days or fixed values such as ≤ 0°C [60]. To account for regional adaptation and variability, the WMO recommends using locally relevant thresholds based on long-term climate normal [61] – an approach this research used.

LSOA-level shapefile for the UK was used for layering with temperature data to compute LSOA-level daily t_{min} and t_{max} data. LSOA-level data on temperature was then used for the period January 1971- December 2000 to compute the 95th percentile for t_{max} and 5th percentile for t_{min} baseline thresholds (detailed definition given in measures section below). The second subset of LSOA-level daily temp data (t_{min} and t_{max}) from December 2008 to February 2020, corresponding to the study period, was used to create the exposure dataset. 30-year threshold baselines were used to compare and determine whether the daily temperature at the LSOA level was above or below the t_{max} and t_{min} thresholds, respectively. If true, the said date was flagged as an extreme heat/cold event. Using the continuous date-wise data, we then defined exposure, i.e., experiencing an extreme heat/cold in the four weeks preceding the current date. The time frame of "four weeks preceding the survey" was chosen to make sure that the exposure measure and the self-reported mental health were consistent, as respondents were asked to describe how they had felt over the previous four weeks. Using the same reference period let us look at the link between exposure and mental health in a comparable timeframe. Once the exposure data was created at the LSOA level, it was then merged with the UKHLS data using LSOA and date of interview as the unique identifier. Fig 1 describes the analytical sample selection. To measure the effect of extreme temperatures, the unbalanced panel sample was limited to individuals who participated in the survey at least twice for each exposure. For example, for the heat model, only those who participated in the survey for at least two summers (June-September) were considered; for the cold model, those who participated in at least two winters (November-February). The choice of months for defining summer and winter reflects the months during which the Office issues heat and cold health alerts. S2 Table in the Supporting information file provides the comparison of the distribution of characteristics between the complete data and analytic sample. The distributions were found to be highly similar across the two samples.

Fig 1: Analytical sample selection using the UKHLS dataset, Wave 1-Wave 10, merged with the Met data on exposure

Measures

Exposure

Using the Met data on t_{max} and t_{min} in degrees Celsius, we defined the exposure for this study as:

Heat exposure: No. of days experienced extreme heat in the 4 weeks preceding the interview

Cold exposure: No. of days experienced extreme cold in the 4 weeks preceding the interview

No. of days experienced extreme heat/cold was broken down into three groups: None, 1-3 days, and 4+ days.

It is important to note that temperature conditions are spatially variable across the UK; therefore, what is an extreme temperature in one region may not be in another [48, 62]. Utilising LSOA-specific percentiles relative to the baseline period temperatures for the same LSOA instead of a national fixed value acknowledges these regional variations [63]. Based on the guidelines regarding the definition and monitoring of extreme weather and climate events by the World Meteorological Organisation (WMO) and as applied by other global studies [47, 61, 63], extreme temperature events for this study were defined as:

Extreme heat: $TX_{ijk} > TX_{in95k}$

TX_{ijk}: daily maximum temperature on day i in period j within LSOA k (December 2008- February 2020)

TX_{in95k}: calendar day 95th percentile centred on a 5-day window for the base period 1971-2000 for LSOA k

Extreme cold: $TN_{ijk} < TN_{in5k}$

TN_{ijk}: daily minimum temperature on day i in period j within LSOA k (December 2008- February 2020)

TN_{in5k}: calendar day 5th percentile centred on a 5-day window for the base period 1971-2000 for LSOA k

Outcomes

Mental health

In the self-completion module of UKHLS, a module on Short Form-12 (SF-12) is administered in every survey wave. The SF-12's Mental Component Summary (MCS) is used extensively for evaluating psychological distress [64, 65]. The SF-12 has been validated for reliability and validity in assessing mental health, as it shows notable relationships with depression and anxiety scales [66]. The MCS score is available in the UKHLS data as a continuous variable on a range of 0 (low functioning) to 100 (high functioning). The methodology for computing the score is given in detail elsewhere [65, 67]. To create the categorical variable for mental health, we used the MCS score <50 as the cut-off per the recommended screening criteria to check for any mental health condition [68]. Respondents with the MCS score <= 50 were defined to have poor mental health, whereas those with the MCS score of 50+ were defined to have good mental health.

Subjective wellbeing (SWB)

As per other global studies, we defined an individual's SWB using the measure of self-reported overall satisfaction with life [69-76]. Response to the question: "Please choose the number which you feel best describes how dissatisfied or satisfied you are with your life overall" captures responses on a scale from 1 to 7, where 1 denotes 'completely dissatisfied' and 7 denotes 'completely satisfied'. To create the dichotomous variable, those who responded to the question in the range of 5-7, i.e. somewhat, mostly and completely satisfied, were defined to have good SWB, whereas those who responded in the range of 1-4 were defined to have poor SWB.

Confounders and potential effect modifiers

All potential effect modifiers were considered as potential confounders in fully adjusted models. Socio-economic and demographic confounders included in the analyses were: age (15-19, 20-35, 36-50, 51-65, 66-80), sex (female, male), highest qualification (no qualification, degree/other higher degree, A-level, GCSE, other qualification), employment status (unemployed, employed, retired, student), current marital status (married/civil partner/couple, widowed/divorced/separated, never married), net equivalised monthly household income (quintiles), household family structure (lone person, lone person with children, couple with no children, couple with children, 2 or more persons household (HH) with/out children, long-term health conditions including disability or impairment (yes, no), migrant (yes, no), ethnicity (White British, other white, mixed, Asian, Black, any other), area type (urban/rural), social support-level (low, high), level of PEBs practiced (low, high), and home ownership. Net equivalised monthly household income was calculated by dividing the household's net monthly income by the modified OECD equivalency scale. The resultant value was then divided into quintiles to assess the variations. Controlling for these variables allowed us to better isolate the relationship between extreme temperatures and mental health or SWB, and to identify potential pathways through which these effects may occur. Additionally, our controls improve the generalisability of our findings across various population subgroups.

Social support: We used Buckner's score on neighbourhood social cohesion as the proximate measure to define social support [77]. The module captured Likert-responses on eight questions, such as respondent a) belongs to the neighbourhood, b) plans to stay in the neighbourhood, c) willing to improve the neighbourhood, d) similar to others in the neighbourhood, e) talks regularly to neighbours, f) could go to someone for advice in the neighbourhood, g) friendships and associations with others in neighbourhood means a lot, and h) could borrow things and exchange favours with neighbours. Buckner's module on neighbourhood social cohesion was administered in a self-completion questionnaire during waves 1,3,6,9, and 12 [77]. The score was measured as an average of the reverse-coded responses to eight questions and ranged between 1-5, with higher values indicating greater cohesion. Using a median split of 3.6 to avoid skewness [78], we created the binary measure on social support – low (≤ 3.6) and high (> 3.6).

Pro-environmental behaviours (PEBs) practised: In the self-completed module, 11 questions on PEBs were asked during survey waves 1,4, and 10. These questions captured how frequently respondents a) left TV on standby at night, b) switched off lights in rooms that aren't being used, c) kept the tap running while brushing teeth, d) put more clothes on rather than turning on the heater, e) didn't buy something because of too much packaging, f) bought recycled paper products such as toilet paper or tissues, g) took own shopping bag when shopping, h) used public transport, i) walked or cycled for short journeys, j) shared car with others, and k) took fewer flights. Like other studies, we reverse-coded individual responses on a scale of 1-6 and then calculated the sum to generate an overall score, with a higher score denoting higher levels of PEBs practised by the individual [35, 79, 80]. We used a median split to avoid skewness for creating the categorical variable on the level of PEBs practised: low (score ≤39) and high (> 39).

Statistical analysis

Depending on the analytical need, we used various statistical and geospatial software for data curation, management and analysis. We used QGIS for creating a custom UK shapefile using Census 2011 information on LSOAs, and RStudio to generate zonal statistics for daily t_{max} and t_{min} at the LSOA level. We used Stata 18 (StataCorp, TX) for data cleaning, merging, and analysis of the temperature and UKHLS data. A multiple imputation technique with the missing at random assumption was used to impute the individual responses for social support and PEB measures within the survey waves in which these modules were asked [81]. Assuming that the response for these modules is unlikely to change drastically between waves, we used the data from the intermittent wave to populate missing values in the analytical sample for the adjacent wave in which the modules weren't administered. This study used a longitudinal design to explore the relationship between extreme heat and cold and study outcomes over 10 survey waves. We conducted bivariate analysis using Chi-square tests for categorical variables, explanatory variables, and exposure. Multilevel mixed-effect logistic regression models were fitted for longitudinal data to estimate the unadjusted and adjusted association between the number of times exposed to the extreme temperatures and change in mental health and SWB over time, wherein we added the individual as a random intercept effect with survey wave as the slope to adjust for within-participant clustering. Because both exposure and outcome vary over time, we included the survey wave as a random slope. This approach helps avoid over-controlling for time and ensures that temporal variation relevant to the outcome is not entirely absorbed by the model [82, 83]. A mixed-effects approach was selected as it offers multilevel modelling for observations with non-independence or variance due to cluster effects, allowing for more accurate model selection. The study also explored the interaction between exposure and potential effect-modifier variables on the outcomes. Interactions of effect modifiers with the exposure were determined by the Wald test. Although the Wald test for the interaction between exposure and modifier was statistically insignificant for many effect modifiers, we conducted exploratory effect modification analyses across all hypothesised modifiers by presenting stratum-specific AORs. The stratified analysis for all potential effect modifiers allowed for the exploration of potential variations across subgroups, which is critical in the development of our understanding of how extreme temperature exposures may impact mental health and SWB amongst different population groups. Furthermore, interaction tests can be underpowered and meaningful differences in effect sizes may exist even in the absence of statistically significant interaction terms [84-86]. The supporting information file provides a detailed sensitivity analysis, which showed minimal differences in the key findings. The sensitivity of longitudinal models was tested using different thresholds – 90th and 99th percentile cut-offs for extreme heat and 10th and 1st percentile cut-offs for extreme cold and constructing both exposure indicators within the past 14 days.

Ethical considerations

All data collection on the UKHLS study waves has been approved by the University of Essex Ethics Committee, which also requested consent for all data linkages other than those involving medical records [87]. This low-risk project was also granted exemption from human research ethics approval

in 2023 by the University of Queensland.

Role of the funding source

This study's funding sources were not involved in the article's planning, designing, analysing, interpreting, or writing.

Results

Sample characteristics

The final longitudinal sample consisted of 28,099 individuals over 131,942 observations for the extreme heat model and 28,284 individuals over 131,846 observations for the extreme cold model (Fig 1 above). Table 1 presents the characteristics of these individuals during wave 1 and wave 10 for both models. For extreme heat model - during wave 1, a higher proportion of individuals were aged 36-50 years (29.2%); between 10 waves, the proportion of people with degree increased by almost 8 percentage points (pp), unemployment decreased by 5 pp, living in rural areas increased by ~3 pp, social support decreased by ~ 5 pp and prevalence of PEBs practiced increased by ~11 pp. Similar changes in individual characteristics over time were noted for the extreme cold analytical sample.

Prevalence of extreme temperature events, mental health, and SWB

Met data analysis found that compared to the baseline, mean t_{max} and t_{min} steadily increased over the study period (S3-S4 Tables, S1-S2 Figs), translating into a higher prevalence of extreme heat and lower prevalence of extreme cold over time (S3 Fig). Between wave 1 and wave 10, the proportion exposed to extreme heat increased by 31 pp, and those who experienced extreme heat for 4+ days increased by 24 pp (Table 1). For extreme cold, the proportion exposed decreased by 27pp between wave 1 and wave 10, resulting in a decline of those who experienced extreme cold for 4+ days from 29.5% in wave 1 to 5.5% in wave 10. Among outcomes, poor mental health increased by ~ 13 pp in both models, and poor SWB increased by ~3 pp and ~4 pp in the extreme heat and cold models over time, respectively. Supporting information provides more details on the change over time in mental health and SWB by exposure to both temperature extremes.

Table 1: Characteristics of survey respondents from the unbalanced longitudinal sample at wave 1 and wave 10, the UKHLS survey, Wave 1-Wave 10

	Extreme heat model		Extreme cold model	
	Wave 1	Wave 10	Wave 1	Wave 10
	N = 12,809	N = 9,989	N = 12,734	N = 9,982
Exposed to extreme heat/cold in the past 4 weeks	%	%	%	%
Unexposed	46.40	15.18	30.65	58.04
Exposed	53.60	84.82	69.35	41.96
No. of times experienced an extreme heat/cold day in the past 4 weeks				
None	46.40	15.18	30.65	58.04
1-3	39.70	46.84	39.83	36.47
4+	13.90	37.98	29.52	5.49
Mental health using the SF-12 module				
Good mental health	61.76	48.71	60.02	46.60
Poor mental health	38.24	51.29	39.98	53.40
Subjective wellbeing (Overall satisfaction with life)				
Good SWB	76.82	73.42	76.70	72.29
Poor SWB	23.18	26.58	23.30	27.71
Age categories				
15-19	6.62	3.58	5.92	3.44
20-35	23.37	19.82	24.43	18.66
36-50	29.18	24.91	29.13	25.67
51-65	23.64	27.33	24.16	27.19
66-80	14.28	19.45	13.60	20.07
80+	2.90	4.91	2.75	4.98
Sex				
Female	55.53	55.72	55.10	55.25
Male	44.47	44.28	44.90	44.75
Highest qualification				
No qualification	17.23	9.89	17.32	10.28
Degree/other higher degree	32.69	41.14	32.76	40.78
A-level	18.51	20.99	18.92	21.11
GCSE	21.05	18.89	20.92	19.25
Other qualification	10.52	9.09	10.08	8.58
Employment status				
Employed	54.19	56.36	54.58	56.21
Retired	21.06	26.73	20.80	27.33
Student	6.42	4.20	6.49	4.10
Unemployed	18.33	12.71	18.14	12.36
Net equivalised monthly HH income (in quintiles)				
1st quintile (lowest)	31.73	13.49	31.97	13.58
2nd quintile	21.74	15.50	20.94	15.36
3rd quintile	17.20	20.54	17.21	19.81
4th quintile	15.42	22.82	15.92	22.81
5th quintile (highest)	13.92	27.65	13.96	28.45
De facto marital status				
Married/Civil partner/couple	63.55	63.72	64.89	64.90
Widowed/divorced/separated	14.99	14.89	14.21	14.76
Never married	21.45	21.40	20.90	20.34
Household family structure type				
Lone person	14.64	16.39	14.58	16.43
Lone person with children	5.75	3.12	5.54	2.59
Couple with no children	28.44	28.43	29.10	28.95
Couple with children	25.01	19.75	25.15	20.52

2 or more persons HH with/out children	26.16	32.31	25.63	31.51
Migrant				
No	83.33	85.85	82.84	84.91
Yes	16.67	14.15	17.16	15.09
Ethnicity				
White British	77.28	78.36	77.14	77.49
Other white	4.14	4.70	4.14	4.81
Mixed	1.74	1.92	1.94	1.94
Asian	11.44	11.13	11.28	11.67
Black	5.00	3.66	5.00	3.82
Any other	0.40	0.23	0.51	0.27
Type of area				
Rural	22.82	25.61	20.07	23.48
Urban	77.18	74.39	79.93	76.52
Home ownership				
Rented	30.30	26.09	30.95	25.41
Own house	69.33	73.73	68.65	74.25
Other	0.37	0.18	0.40	0.34
Has central heating				
No			7.39	10.84
Yes			92.61	89.16
Social support using Buckner's Neighbourhood Cohesion				
Low	50.16	55.46	51.20	55.40
High	49.84	44.54	48.80	44.60
Level of PEBs				
Low	51.12	39.66	53.78	42.57
High	48.88	60.34	46.22	57.43
Has a long-standing illness or disability				
No	63.54	63.80	64.23	62.99
Yes	36.46	36.20	35.77	37.01

Effect of extreme heat and extreme cold on mental health and SWB

Exposure to extreme heat was associated with mental health and SWB after controlling for socio-demographic characteristics and other confounders. For example, exposure to extreme heat for 4+ days was associated with increased risk of poor mental health by 12% and poor SWB by 8% compared to those unexposed (Table 2). However, upon exposure to extreme cold, the risk of poor mental health decreased significantly. Compared to those unexposed, extreme cold exposure for 4+ days decreased the risk of poor mental health by 18%. Extreme cold was found not to be associated with SWB in either unadjusted or adjusted models. Sensitivity analysis with a) alternative percentile criteria for defining exposure, and b) calculating exposure in the past two weeks with the 95th/5th percentile threshold supports the findings for mental health due to extreme heat and cold (S8-S13 Tables).

Table 2: Unadjusted and adjusted mixed-effects logistic models for extreme heat and extreme cold exposure in the past 4 weeks, the UKHLS survey, Wave 1-Wave 10

	Extreme heat model							
	Mental Health				**SWB**			
Experienced extreme heat in the past 4 weeks	OR [95% CI]	p-value	AOR [95% CI]	p-value	OR [95% CI]	p-value	AOR [95% CI]	p-value
1-3 days	1.04 [1.00,1.08]	0.060	1.03 [0.99,1.07]	0.155	0.99 [0.95,1.03]	0.488	1.00 [0.96,1.04]	0.935
4+ days	1.09 [1.04,1.14]	0.001	1.12 [1.06,1.17]	p<0.001	1.04 [0.99,1.10]	0.131	1.08 [1.02,1.14]	0.010
	Extreme cold model							
	Mental Health				**SWB**			
Experienced extreme cold in the past 4 weeks:	OR [95% CI]	p-value	AOR [95% CI]	p-value	OR [95% CI]	p-value	AOR [95% CI]	p-value
1-3 days	1.00 [0.96,1.04]	0.950	0.99 [0.95,1.03]	0.724	1.03 [0.98,1.07]	0.225	1.01 [0.96,1.05]	0.831
4+ days	0.84 [0.79,0.88]	p<0.001	0.82 [0.77,0.87]	p<0.001	0.97 [0.92,1.04]	0.402	0.98 [0.92,1.05]	0.451

Adjusted for age, sex, highest qualification, employment status, monthly HH income, HH type, marital status, migration status, ethnicity, type of area, home ownership, social support level, and level of good environmental habits practised. In addition to all these confounders, the extreme cold model was also adjusted for the availability of central heating.

Effect modification

Effect modification analysis was conducted to identify whether the association between extreme heat and cold with mental health and SWB varied by selected socio-economic and demographic factors. Where the interaction p-value was <0.05, we considered it to be strong statistical evidence of effect modification; whereas the interaction p-value was ≥0.05, we considered patterns of association across sub-groups to be indicative of conducting effect modification analysis. Despite weaker statistical evidence for the interaction testing for some modifiers (S7 Table), stratified analyses are presented in Tables 3 and 4 for all potential modifiers to examine differences in associations across levels of modifiers, given the relevance of these variables in the context of our study objectives.

A statistically significant interaction between extreme heat exposure and household structure was observed with mental health (S7 Table); specifically, lone-person HHs and two- or more-person HHs experienced a stronger adverse association compared to couples (Table 3). Even though evidence for effect modification by age and highest educational qualification in the association between extreme heat and mental health was statistically weak, exploratory stratified analyses suggested some patterns. The detrimental association between extreme heat exposure and poor mental health was highest among people aged 15-35-years, which declined with age. A similar pattern was observed across qualification levels, with the strongest associations seen among those with a degree or higher qualification, and weaker associations among those with lower and no qualifications (Table 3).

Similarly, the differential effects were examined for the risk of poor SWB following the heat exposure. Even though the risk of poor mental health associated with exposure to extreme cold decreased, the subgroups for which these associations were discernible were older people, retired/students, and lone-person households (Table 4). Patterns of association across potential effect modifiers were mixed and variable by outcome.

Table 3: Comparison of mental health and SWB among those who experienced exposure to extreme heat by select factors, the UKHLS survey, Wave 1-Wave 10

	Extreme heat model							
	Mental Health				Subjective Wellbeing			
	1-3 days		4+ days		1-3 days		4+ days	
	AOR [95% CI]	p-value	AOR [95% CI]	p-value	AOR [95% CI]	p-value	AOR [95% CI]	p-value
Age								
15-35	1.07 [0.99,1.16]	0.070	1.24 [1.12,1.37]	p<0.001	1.03 [0.95,1.13]	0.459	1.08 [0.96,1.21]	0.209
36-65	1.02 [0.97,1.08]	0.406	1.11 [1.03,1.19]	0.004	1.01 [0.95,1.07]	0.743	1.12 [1.04,1.20]	0.004
66+	0.99 [0.90,1.08]	0.777	0.98 [0.88,1.10]	0.759	0.93 [0.84,1.02]	0.143	0.97 [0.85,1.09]	0.576
Sex								
Female	1.06 [1.00,1.11]	0.037	1.14 [1.07,1.22]	p<0.001	1.01 [0.96,1.07]	0.617	1.04 [0.96,1.12]	0.316
Male	0.99 [0.93,1.06]	0.821	1.08 [0.99,1.17]	0.068	0.98 [0.91,1.04]	0.477	1.12 [1.03,1.22]	0.007
Highest qualification								
No qualification	1.05 [0.94,1.17]	0.404	0.90 [0.78,1.04]	0.145	0.90 [0.80,1.01]	0.068	0.91 [0.78,1.05]	0.199
Degree/other higher degree/other qualification	1.04 [0.99,1.11]	0.141	1.16 [1.08,1.25]	p<0.001	1.07 [1.00,1.14]	0.040	1.18 [1.08,1.28]	p<0.001
A-level/GCSE	1.00 [0.94,1.07]	0.938	1.13 [1.04,1.23]	0.003	0.96 [0.90,1.03]	0.248	1.03 [0.94,1.12]	0.546
Employment status								
Unemployed	0.99 [0.88,1.11]	0.880	1.09 [0.94,1.27]	0.238	0.95 [0.85,1.06]	0.365	1.07 [0.93,1.23]	0.350
Employed	1.04 [0.98,1.09]	0.170	1.16 [1.08,1.24]	p<0.001	1.02 [0.96,1.08]	0.467	1.13 [1.05,1.22]	0.001
Retired/Student	1.03 [0.95,1.11]	0.463	1.05 [0.96,1.16]	0.292	0.99 [0.91,1.08]	0.783	0.98 [0.87,1.09]	0.657
Net equivalised monthly household income								
1st quintile	1.02 [0.93,1.12]	0.642	1.08 [0.95,1.23]	0.218	0.97 [0.89,1.07]	0.579	1.00 [0.89,1.13]	0.976
2nd quintile	1.04 [0.95,1.14]	0.435	1.16 [1.03,1.31]	0.016	0.98 [0.89,1.09]	0.758	1.13 [0.99,1.28]	0.066
3rd quintile	1.05 [0.95,1.15]	0.325	1.20 [1.06,1.35]	0.004	1.05 [0.95,1.16]	0.363	1.17 [1.03,1.33]	0.015
4th quintile	1.02 [0.93,1.12]	0.661	1.11 [0.99,1.26]	0.085	1.03 [0.93,1.15]	0.549	1.17 [1.02,1.34]	0.021
5th quintile	1.03 [0.94,1.13]	0.559	1.09 [0.97,1.22]	0.141	1.02 [0.91,1.14]	0.718	1.10 [0.96,1.26]	0.162
De facto marital status								
Married/Civil partner/couple	1.00 [0.95,1.05]	0.969	1.10 [1.03,1.17]	0.004	1.01 [0.96,1.07]	0.700	1.09 [1.02,1.18]	0.013
Widowed/divorced/separated	1.03 [0.93,1.14]	0.542	1.02 [0.90,1.16]	0.729	0.93 [0.84,1.04]	0.207	0.98 [0.85,1.12]	0.739
Never married	1.12 [1.02,1.23]	0.014	1.24 [1.10,1.39]	p<0.001	1.02 [0.93,1.13]	0.665	1.12 [0.99,1.26]	0.077
Household family structure type								
Lone person with/out children	1.06 [0.97,1.16]	0.193	1.14 [1.02,1.28]	0.022	0.96 [0.88,1.06]	0.411	1.04 [0.93,1.18]	0.469
Couple with/out children	0.99 [0.94,1.05]	0.849	1.07 [1.00,1.16]	0.051	1.05 [0.99,1.12]	0.105	1.13 [1.04,1.23]	0.003
2 or more person HH with/out children	1.07 [0.99,1.15]	0.103	1.15 [1.04,1.27]	0.006	0.94 [0.86,1.02]	0.128	1.03 [0.93,1.15]	0.536
Migrant								
No	1.03 [0.98,1.07]	0.226	1.14 [1.08,1.20]	p<0.001	0.99 [0.95,1.04]	0.682	1.07 [1.01,1.14]	0.026
Yes	1.04 [0.94,1.16]	0.441	0.99 [0.86,1.14]	0.920	1.06 [0.94,1.19]	0.350	1.11 [0.95,1.29]	0.196
Ethnicity								
White British	1.02 [0.98,1.07]	0.351	1.13 [1.06,1.19]	p<0.001	0.99 [0.94,1.04]	0.596	1.06 [1.00,1.13]	0.065

	Extreme heat model							
	Mental Health				Subjective Wellbeing			
	1-3 days		4+ days		1-3 days		4+ days	
	AOR [95% CI]	**p-value**	**AOR [95% CI]**	**p-value**	**AOR [95% CI]**	**p-value**	**AOR [95% CI]**	**p-value**
Other white	1.21 [0.99,1.48]	0.063	1.23 [0.95,1.57]	0.111	1.07 [0.86,1.34]	0.548	1.35 [1.03,1.78]	0.029
Mixed	1.11 [0.82,1.51]	0.496	1.21 [0.81,1.81]	0.341	1.14 [0.81,1.61]	0.465	1.08 [0.68,1.71]	0.746
Asian	1.00 [0.89,1.14]	0.950	1.00 [0.85,1.18]	0.976	1.06 [0.92,1.21]	0.427	1.16 [0.97,1.38]	0.106
Black	1.04 [0.85,1.28]	0.680	1.01 [0.78,1.32]	0.925	1.01 [0.81,1.26]	0.923	1.02 [0.77,1.34]	0.915
Type of area								
Rural	0.97 [0.90,1.06]	0.526	1.07 [0.96,1.18]	0.234	1.00 [0.91,1.09]	0.924	1.00 [0.89,1.12]	0.986
Urban	1.05 [1.00,1.10]	0.046	1.13 [1.07,1.20]	p<0.001	1.00 [0.95,1.05]	0.937	1.10 [1.03,1.17]	0.003
Social support								
Low	1.03 [0.97,1.09]	0.352	1.18 [1.09,1.26]	p<0.001	0.99 [0.93,1.05]	0.668	1.06 [0.98,1.14]	0.167
High	1.02 [0.97,1.09]	0.410	1.05 [0.97,1.13]	0.213	1.00 [0.94,1.07]	0.899	1.09 [1.01,1.19]	0.037
Level of PEBs								
Low	1.01 [0.95,1.07]	0.787	1.10 [1.02,1.18]	0.014	1.01 [0.95,1.07]	0.782	1.10 [1.02,1.19]	0.018
High	1.06 [1.00,1.12]	0.039	1.14 [1.05,1.22]	0.001	0.99 [0.93,1.05]	0.694	1.06 [0.98,1.15]	0.160
Has a long-standing illness or disability								
No	1.04 [0.99,1.09]	0.129	1.13 [1.06,1.20]	p<0.001	1.02 [0.97,1.08]	0.433	1.09 [1.02,1.17]	0.018
Yes	1.03 [0.97,1.11]	0.338	1.12 [1.02,1.22]	0.014	0.97 [0.91,1.04]	0.434	1.05 [0.96,1.15]	0.269

Table 4: Comparison of mental health and SWB among those who experienced exposure to extreme cold by select factors, the UKHLS survey, Wave 1-Wave 10

	Extreme cold model							
	Mental Health				Subjective Wellbeing			
	1-3 days		4+ days		1-3 days		4+ days	
	AOR [95% CI]	p-value	AOR [95% CI]	p-value	AOR [95% CI]	p-value	AOR [95% CI]	p-value
Age								
15-35	1.05 [0.97,1.14]	0.205	0.71 [0.63,0.80]	p<0.001	1.07 [0.97,1.17]	0.168	0.98 [0.86,1.13]	0.808
36-65	0.97 [0.92,1.02]	0.235	0.84 [0.77,0.91]	p<0.001	0.99 [0.93,1.04]	0.613	0.98 [0.90,1.07]	0.687
66+	1.00 [0.92,1.09]	0.982	0.97 [0.84,1.11]	0.614	1.01 [0.91,1.11]	0.904	0.98 [0.83,1.15]	0.782
Sex								
Female	1.02 [0.96,1.07]	0.537	0.83 [0.77,0.90]	p<0.001	0.99 [0.93,1.04]	0.632	0.96 [0.88,1.05]	0.357
Male	0.96 [0.91,1.02]	0.226	0.81 [0.74,0.88]	p<0.001	1.03 [0.97,1.10]	0.329	1.00 [0.91,1.11]	0.932
Highest qualification								
No qualification	0.93 [0.83,1.04]	0.180	0.86 [0.73,1.01]	0.065	0.91 [0.81,1.03]	0.124	0.91 [0.77,1.07]	0.253
Degree/other higher degree/other qualification	1.00 [0.95,1.06]	0.992	0.84 [0.77,0.92]	p<0.001	1.02 [0.96,1.09]	0.494	0.96 [0.87,1.07]	0.482
A-level/GCSE	1.01 [0.95,1.08]	0.775	0.79 [0.71,0.87]	p<0.001	1.02 [0.95,1.09]	0.571	1.02 [0.92,1.13]	0.702
Employment status								
Unemployed	1.00 [0.89,1.12]	0.998	0.76 [0.65,0.90]	0.002	0.93 [0.83,1.04]	0.212	0.86 [0.73,1.01]	0.062
Employed	1.00 [0.95,1.05]	0.988	0.82 [0.76,0.89]	p<0.001	1.04 [0.98,1.10]	0.212	1.01 [0.93,1.11]	0.765
Retired/Student	0.97 [0.90,1.05]	0.470	0.86 [0.76,0.97]	0.011	0.97 [0.89,1.06]	0.533	0.98 [0.86,1.13]	0.816
Net equivalised monthly household income								
1st quintile	0.91 [0.83,1.00]	0.051	0.80 [0.70,0.91]	0.001	0.98 [0.89,1.08]	0.672	0.98 [0.85,1.12]	0.741
2nd quintile	0.99 [0.90,1.08]	0.762	0.78 [0.68,0.89]	p<0.001	0.94 [0.85,1.04]	0.236	0.95 [0.82,1.10]	0.513
3rd quintile	0.92 [0.83,1.01]	0.069	0.73 [0.63,0.84]	p<0.001	0.94 [0.85,1.04]	0.230	0.97 [0.83,1.14]	0.725
4th quintile	1.07 [0.98,1.18]	0.131	0.81 [0.70,0.94]	0.006	1.08 [0.98,1.20]	0.113	0.92 [0.78,1.08]	0.298
5th quintile	1.04 [0.95,1.14]	0.355	0.93 [0.80,1.07]	0.292	1.03 [0.93,1.14]	0.624	0.82 [0.69,0.99]	0.036
De facto marital status								
Married/Civil partner/couple	0.98 [0.93,1.03]	0.405	0.81 [0.75,0.88]	p<0.001	1.00 [0.95,1.06]	0.981	0.95 [0.87,1.03]	0.207
Widowed/divorced/separated	0.94 [0.85,1.04]	0.237	0.98 [0.84,1.14]	0.783	0.96 [0.86,1.06]	0.420	0.98 [0.83,1.15]	0.769
Never married	1.09 [0.99,1.19]	0.084	0.75 [0.65,0.86]	p<0.001	1.07 [0.97,1.18]	0.160	1.06 [0.92,1.24]	0.418
Household family structure type								
Lone person with/out children	1.00 [0.91,1.09]	0.980	0.88 [0.77,1.00]	0.053	0.99 [0.90,1.09]	0.886	0.96 [0.83,1.10]	0.525
Couple with/out children	0.96 [0.91,1.02]	0.161	0.82 [0.75,0.89]	p<0.001	0.97 [0.91,1.04]	0.377	0.97 [0.88,1.07]	0.489
2 or more person HH with/out children	1.05 [0.97,1.14]	0.215	0.78 [0.69,0.88]	p<0.001	1.07 [0.99,1.17]	0.080	1.02 [0.89,1.16]	0.785
Migrant								
No	0.99 [0.95,1.03]	0.662	0.82 [0.77,0.88]	p<0.001	1.00 [0.95,1.05]	0.918	0.97 [0.90,1.04]	0.360
Yes	1.01 [0.91,1.12]	0.893	0.82 [0.71,0.96]	0.014	1.06 [0.94,1.18]	0.343	1.06 [0.89,1.26]	0.533
Ethnicity								
White British	0.98 [0.94,1.03]	0.422	0.82 [0.76,0.88]	p<0.001	0.99 [0.95,1.04]	0.821	0.95 [0.88,1.03]	0.199

	Extreme cold model							
	Mental Health				**Subjective Wellbeing**			
	1-3 days		**4+ days**		**1-3 days**		**4+ days**	
	AOR [95% CI]	**p-value**	**AOR [95% CI]**	**p-value**	**AOR [95% CI]**	**p-value**	**AOR [95% CI]**	**p-value**
Other white	1.02 [0.84,1.22]	0.867	0.86 [0.64,1.14]	0.294	1.08 [0.88,1.32]	0.487	0.85 [0.61,1.19]	0.352
Mixed	0.91 [0.67,1.23]	0.551	0.75 [0.47,1.20]	0.227	1.18 [0.87,1.60]	0.287	1.66 [1.04,2.65]	0.032
Asian	1.06 [0.93,1.20]	0.375	0.79 [0.65,0.96]	0.016	0.97 [0.85,1.11]	0.655	1.08 [0.88,1.33]	0.470
Black	1.10 [0.90,1.34]	0.358	1.09 [0.80,1.48]	0.575	1.15 [0.94,1.42]	0.171	1.10 [0.80,1.51]	0.576
Type of area								
Rural	1.01 [0.93,1.10]	0.832	0.78 [0.68,0.89]	p<0.001	1.04 [0.95,1.1.4]	0.375	1.01 [0.87,1.17]	0.883
Urban	0.99 [0.95,1.04]	0.664	0.83 [0.78,0.89]	p<0.001	0.99 [0.95,1.04]	0.802	0.97 [0.90,1.04]	0.406
Social support								
Low	1.02 [0.96,1.08]	0.576	0.76 [0.70,0.83]	p<0.001	1.00 [0.94,1.06]	0.908	0.93 [0.85,1.02]	0.126
High	0.98 [0.92,1.03]	0.406	0.90 [0.83,0.98]	0.021	1.01 [0.95,1.08]	0.660	1.03 [0.93,1.14]	0.530
Level of PEBs								
Low	0.98 [0.93,1.04]	0.510	0.84 [0.77,0.91]	p<0.001	1.03 [0.97,1.09]	0.347	1.01 [0.92,1.10]	0.884
High	1.01 [0.95,1.07]	0.810	0.80 [0.73,0.88]	p<0.001	0.99 [0.92,1.05]	0.678	0.95 [0.86,1.05]	0.280
Has a long-standing illness or disability								
No	0.99 [0.94,1.04]	0.689	0.82 [0.76,0.88]	p<0.001	0.99 [0.94,1.05]	0.733	0.95 [0.87,1.04]	0.285
Yes	0.99 [0.92,1.06]	0.692	0.80 [0.72,0.89]	p<0.001	1.01 [0.95,1.09]	0.688	1.00 [0.90,1.12]	0.976
Has central heating								
No	0.90 [0.77,1.05]	0.187	0.70 [0.55,0.89]	0.004	1.11 [0.93,1.32]	0.266	0.76 [0.57,1.01]	0.058
Yes	1.00 [0.96,1.04]	0.970	0.83 [0.77,0.88]	p<0.001	1.00 [0.95,1.04]	0.916	0.99 [0.93,1.06]	0.825

Discussion

The daily temperature data analysis evidence from this study aligns with the steady increase in the warming effects attributed to climate change in the UK. Compared to 1971-2000, there has been a notable rise in the mean t_{max} and mean t_{min} over the 11-year study period (S3-S4 Tables). Consequently, we observed an increase in the number of extreme heat events and a decrease in the number of extreme cold events over the years. By linking extreme temperature events defined using Met data with the individual-level data from 10 survey waves of the UKHLS, we found that multiple exposures to extreme heat were significantly associated with poor mental health and SWB. However, in the case of exposure to extreme cold, we noted the opposite pattern, i.e., over time, exposures to extreme cold were associated with better mental health. This finding is unexpected, since it is well established that extreme cold can adversely affect individuals [88, 89]. However, we found no significant association between extreme cold and SWB in the unadjusted and fully adjusted models. In the adjusted extreme heat and cold models, all confounders were typically associated with mental health and SWB as expected (S6 Table). Short-term exposure to either of the extreme temperatures, i.e. for 1-3 days, was not significantly associated with poor mental health and SWB. However, when the threshold for the extreme heat model was raised from the 95th to the 99th percentile during sensitivity analysis, we observed an increased risk of poor mental health associated with short-term exposure (S8-S13 Tables). These findings thus underscore the heightened risk of poor mental health resulting from the ongoing rise in temperatures, with a suggestion of greater risk at higher temperatures or longer durations.

The findings from our study on the association between exposure to extreme heat and mental health and SWB are comparable with other studies that have also found the negative effects of extreme heat on mental health [90, 91]. For example, using daily meteorological data and self-reported information on mental health difficulties from around two million randomly selected US citizens between 2002 and 2012, the study by Obradovich et al., 2018 found that exposure to higher temperatures deteriorates mental health. They estimated that a) increasing monthly temperatures from the 25-30°C range to above 30°C was associated with a 0.5 percentage-point rise in the likelihood of mental health difficulties, and b) a 1°C increase in five-year average temperatures was associated with a 2 percentage-point increase in the prevalence of mental health problems [90]. A retrospective study using the Taiwanese nationwide Longitudinal Health Insurance Database followed a cohort from year 2003 to 2013 to evaluate the association between long-term exposure to temperature and the incidence of major depressive disorder (MDD) and found that the risk for MDD incidence was higher among those who lived in regions with an average temperature of> 23 °C, with a 7% increase in MDD incidence per 1 °C increment (Chen et al., 2019). Our findings on the association between extreme temperatures and mental health conditions are also to an extent corroborated by another US study that examined linkages between ambient temperature and mental health outcomes using daily temperature data from 1960-2016 [92]. Although the US study did not specifically focus on periods of extreme temperature exposure and defined the number of days within a given month during which a county experienced average temperatures within each specified range, they found that cold temperatures reduce negative mental health outcomes while hot temperatures increase them [92]. Another study of interest on extreme temperatures is by Baylis, 2020 that uses a novel approach, combining more than one billion geolocated Twitter posts (the social media platform now known as X) with natural language processing to measure daily expressed sentiment, including a measure of SWB, and linking these data with local weather conditions in the US. The study found a) an inverted U-shaped relationship between temperature and expressed sentiment, i.e., when temperature becomes very hot or very cold, the language people use on Twitter tends to become less positive/more negative, and b) the decline in sentiment was more pronounced at higher temperatures, suggesting that extreme heat may have a stronger effect on short-term emotional state than extreme cold [93]. The study also found regional and seasonal differences, with people in colder regions responding more negatively to warmer temperatures and those in warmer regions responding more negatively to colder temperatures, suggesting adaptation to local climatic conditions [93]. Even though the study measures expressed sentiment from Twitter rather than clinical mental health or life satisfaction, they provide unique insights into short-term expressed emotional state, echoing the findings from our study on exposure to extreme heat and SWB in the UK.

Previous research on the relationship between winter conditions and mental health has produced mixed findings. In the literature, increases in anxiety and depressive symptoms during winter have been attributed partly to seasonal affective disorder and reduced daylight exposure [94]. There is limited but growing evidence that while extreme cold can present challenges, it also has positive psychological effects associated with winter, holidays, and the festive season. A study on wintertime mindset and wellbeing in Norway suggests that adopting a positive mindset towards winter can be associated with increased wellbeing [95]. This involves appreciating the unique aspects of the season, such as opportunities for cosy activities, celebrations, and enjoying the landscapes [96]. Furthermore, even short exposure to daylight during the winter months is associated with a lower likelihood of depressive symptoms and seasonal affective disorder compared to no exposure at all [97, 98]. Virk et al. found that untreated patients with seasonal affective disorder tested during the winter season experienced immediate improvements in mood following light therapy, with benefits observed after as little as 20 minutes of exposure; 40 minutes was as effective as 60 minutes. Similarly, Raza et al. 2024 found that Swedish individuals exposed to at least one hour of daylight during winter were less likely to report depressive symptoms than those with less than one hour of exposure. These papers therefore lend support to the idea that, in our study, extreme cold days with sunlight may also be perceived more favourably than mild winter days without sunlight. People may find these crisp, sunny winter days, despite the cold, more pleasant and psychologically uplifting than gloomy, grey conditions on a mild winter day. Our findings also align with an international study of 67 countries that examined the differences in self-reported levels of happiness with temperature change. The study found that countries where the coldest month was relatively warm were, on average, happier than countries where the coldest month was relatively cold (Rehdanz & Maddison, 2005). Some of the other factors that might explain why some individuals feel better in extreme cold compared to extreme heat include acclimatisation and thermoregulation. Populations living in colder climates, such as those in the UK, may be better acclimatised to cold temperatures due to generations of adaptation and thermoregulation. The human body has various mechanisms to maintain its core temperature. In cold conditions, the body can generate heat through shivering and vasoconstriction, i.e. narrowing of blood vessels to conserve heat [99]. However, in extreme heat, the body relies on sweating to dissipate heat [100], which can lead to dehydration and heat stress if not managed properly. Moreover, it's generally easier to protect oneself from the cold by wearing layers of clothing, drinking hot beverages, and seeking shelter inside heated buildings. In contrast, it can be more challenging to escape extreme heat, especially for those without access to air conditioning. Additionally, the UK is better adapted to manage extreme cold through central heating, insulation, and double glazing [101]. Taken together, the mixed evidence suggests that the relationship between extreme cold conditions and mental health or wellbeing is unlikely to be explained by temperature or season alone. Rather, its effects may depend on how environmental conditions interact with individual vulnerabilities, social circumstances, exposure to wintertime daylight, and the capacity to adapt to seasonal and climatic conditions.

Despite the weaker statistical evidence for interaction effects in the case of some effect modifiers, we also conducted exploratory stratified analysis to understand how the association between exposure to heat and cold with mental health and SWB varied by selected socio-economic and demographic factors. The pattern for the differences by effect modifiers is mixed across both outcomes and exposures, with some differences being more comparable and pronounced than others (Tables 3-4). To highlight the severity, we focus only on the 4+ days of exposure compared to no exposure prior to the survey between the sub-groups in this section. Effect modification analysis by age indicated that the risk of poor mental health and SWB due to extreme heat exposure was greater among people aged 15-35 years and 35-65 years. However, the risk of poor mental health due to extreme cold was higher among people aged 65 years and older. While some studies have noted aggravated effects on children and youth, others have highlighted the increased risks for older people [33, 38, 102]. By developing a "cohort" perspective, researchers estimate that children born in 2020 will experience a two-to-sevenfold increase in extreme events, particularly heat waves, compared to people born in 1960 [103]. These findings highlight the severe threat to the safety of young generations due to intergenerational inequities in exposure to climate extremes, i.e., young people are more at risk and likely to experience more exposure to extreme events in their lifetimes compared with previous generations. It has also been documented that older people often do not take any preventive measures for heat and cold risks, as they do not believe these risks to be personal [33, 104]. As the UK has an ageing population, despite these varied differences in risk by age groups, the vulnerability of older adults to the mental health impacts of extreme temperatures needs to be acknowledged [20].

Due to exposure to extreme heat, the findings from exploratory stratified analysis suggest that females are at increased risk of poor mental health, whereas males are at increased risk of poor SWB, thus highlighting that gender differences may vary depending on the dimension of mental health and wellbeing being considered. This apparent difference perhaps could be due to the fact that SWB and mental health capture different aspects of psychological experience. Previous research has similarly identified a gender life satisfaction - depression paradox, whereby women may report higher life satisfaction while also experiencing greater levels of depression, potentially reflecting differences in emotional responses to life events, resilience, social expectations and other gendered experiences [105, 106]. Since our findings complement previous research showing that women may face a greater risk of adverse mental health outcomes in response to extreme temperatures, reflecting a combination of biological, social and economic factors [107-110], to reduce mental health risks from climate change, it is important to create policies that focus on the specific ways women are more vulnerable to extreme temperatures. Similar to our findings, using three waves of nationally representative panel data linked to high-resolution climate measures, a study from Tanzania found that even a one-degree

Fahrenheit increase in the monthly average heat index was associated with a lower likelihood of reporting higher life satisfaction, with these effects more pronounced among men [111]. On the other hand, men are more prone to conceal mental health conditions or use coping mechanisms such as substance use or social withdrawal [112] and are overrepresented in outdoor and manual labour occupations such as construction, agriculture, and transportation, which increases their physical exposure to both heat and cold [111, 113, 114]. These factors make men uniquely susceptible to temperature-related physical stress, which can have cumulative mental health effects [113, 115]. Therefore, even though women demonstrate greater mental health risks in varied circumstances, knowing men's exposure and mental health outcomes will help to design comprehensive, inclusive, and effective public health interventions that address the spectrum of climate-related risks. Our longitudinal findings on gendered differences in mental health and SWB sex in the context of their exposure to EWEs also present an opportunity for future studies to examine how self-reporting on mental health and SWB is influenced by climate change.

The findings from the stratified analysis by the highest qualification revealed higher odds of poor mental health due to extreme heat and cold, and poor SWB due to extreme heat exposure among those with a degree/ higher degree qualifications. A higher level of education is often associated with increased awareness of climate change and its potential mental health impacts, as individuals with higher educational attainment may be more informed about climate-related risks [12, 104]. Supporting our findings, several studies have established the link between increased awareness of the associated risks and increased engagement in climate change issues, which may result in heightened climate anxiety, especially among University students [116-118]. In our study, employed individuals showed a higher risk of poor mental health and poor SWB from extreme heat, and of poor mental health from extreme cold, compared to those who were unemployed. A scoping review that examined research on climate change, mental health, and indicators of workplace behaviour noted a dearth of studies on the subject [119]. In support of our findings, this review found that the psychological effects of extreme events may result in heightened workplace hostility, increased job tension, and higher intentions to leave. Furthermore, for occupations in which employees are exposed to adverse temperature conditions, such as construction site workers, a review identified 21 challenges associated with hot weather conditions, including heat stroke, kidney disease, heat cramps, anxiety, and depression, as well as 20 challenges related to cold weather conditions, such as asthma, frostbite, musculoskeletal disorders, and hallucinations [113]. Our findings thereby highlight the need for workplace safety management that considers local conditions and enables workers to manage their exposure to extreme weather.

While effect modification results are tentative, our findings were suggestive of an increased risk of poor mental health due to extreme heat and cold, and poor SWB due to extreme heat exposure among individuals living in urban areas compared with those in rural areas. This could be explained by the fact that in urban settings, characteristics such as high population density, increased exposure to the UHI effect, housing costs, less social cohesion and social inequality may drive the mental health impacts of climate change, which can be more pronounced among the homeless, migrants, and young people [12, 25, 120, 121]. Urban greening can play an important role in reducing the UHI effect, as trees and other vegetation provide shade and cooling through evapotranspiration [122]. This is particularly relevant for neighbourhoods with limited access to well-shaded green spaces, where greater exposure to urban heat may increase vulnerability to heat-related health impacts. Evidence suggests that urban parks and green spaces can be cooler than surrounding built-up areas, with one systematic review finding that parks were, on average, around 0.94°C cooler during the day than surrounding urban areas [123]. More importantly, green spaces can enhance mental health by reducing heat exposure, promoting physical activity, fostering social interactions, and offering restorative opportunities [124, 125]. Our findings thus suggest that urban greening should be considered an important component of climate adaptation and public health policy, particularly in areas where access to shade and cooler green spaces is limited. On the other hand, it can be argued that even though rural areas may face different vulnerabilities such as limited resources, restricted access to services, and communication barriers, strong social cohesion in rural settings can enhance mental health resilience [126]. The findings from exploratory effect modification analysis underscore that the mental health impacts of climate change are not experienced uniformly but are shaped by the interplay of intersecting social and economic inequalities. Factors such as young or old age, urban residence, sex, higher educational attainment, and employment status can amplify risk by influencing levels of exposure, sensitivity, and adaptive capacity. Therefore, understanding how these cross-cutting dimensions interact is key to developing equitable and targeted interventions that address the mental health burden of climate change across diverse population groups.

In light of the above-discussed factors by which the risks of adverse mental health and SWB due to extreme temperature exposure vary, it is crucial to identify factors that can buffer against these adverse mental health effects. While effect modification results are tentative, given the results of interaction tests, this study found that higher levels of social support and PEBs may be key to promoting mental health and SWB, as both are modifiable and can be strengthened through targeted awareness and engagement strategies. Our findings highlight an increased risk of poor mental health among people with low levels of social support due to exposure to extreme heat. The results concur with other global studies that have recognised social support and community connections as vital in reducing climate change-related mental health impacts [37, 43, 127-129]. Social structures, such as family, neighbourhood, and organisations, play an important role in providing emotional support, which can help mitigate mental health impacts related to climate change [36]. In our study, due to extreme heat exposure, the risk of poor mental health was higher among people practising high levels of PEBs, whereas the risk of poor SWB was lower among those practising high levels of PEBs. This is because engaging in PEBs has a dual relationship with mental health outcomes. On the one hand, because of their increased awareness of the climate crisis, people who are deeply committed to environmental values may be more susceptible to psychological distress, such as eco-anxiety, guilt, or grief [130-133]. This increased sensitivity may cause feelings of responsibility or helplessness. On the other hand, engaging in PEBs can also act as a protective factor by enhancing wellbeing through a sense of purpose, agency, and collective efficacy, factors known to buffer climate-related stress [133-135]. We believe the strategy of promoting social support and advocating for PEBs may have the potential to create emotionally secure environments and improve mental wellbeing amidst ongoing climate challenges.

Practical implications and policy recommendations

While the adverse effects of extreme temperatures on physical health, including mortality, are well established, emerging evidence on their impact on mental health and SWB, such as from our study, strengthens the case for targeted adaptation strategies and highlights population subgroups that may be at increased risk. Addressing the challenges posed by extreme heat and cold requires a multisectoral approach at individual, community, and systemic levels that requires building upon knowledge, awareness, risk perception, adaptation and preparedness, sustainable cooling/warming strategies, urban planning, integrating mental health services in emergency services and public health interventions, among other possible strategies [34, 136-138]. Firstly, there is a need to create awareness around the extreme temperatures and their impacts on not just physical health but also mental health and their interdependence [139]. The latest Adverse Weather and Health Plan (AWHP) report by the UKHSA discusses early weather-health alerting system mechanisms in place that have been developed jointly by the UKHSA and the Met Office for extreme heat and cold [140]. Despite such provisions, following heat protection behaviours among UK residents, including those at higher risk, such as people over the age of 75 and UK tourists in international locations, is low, as they may not perceive themselves as vulnerable to the risk [33, 34, 141]. Some of the ways of promoting awareness and preparedness could comprise of a) involving local media in promoting awareness about climate change and the associated risks positively, b) incorporating the topic of mental health effects of climate change in medical school curriculums to encourage research at local, regional, and global levels, and c) public education campaigns that enhance risk perception to promote improved self-protective behaviours and preparedness [139, 142]. Behaviour change interventions informed by research in psychology and climate communication have proven effective in turning public awareness into tangible actions, leading to improved perceptions and preparedness, particularly when developed collaboratively with local communities [143, 144].

The sharp contrast between the mental health and wellbeing outcomes associated with both extreme temperatures from our study highlights the importance of adaptive capacity in the UK to battle with an increasingly warming climate. Historically, the UK, as a predominantly colder country, has developed relatively strong adaptive measures against extreme cold weather, but now needs strategies in place to improve adaptive capacity to extreme heat. Community-led research is defined as projects initiated and guided by community members who play an active role in identifying local needs and contributing to the research process, based on their lived experience and local insights to help develop relevant solutions [145, 146]. Culturally appropriate, community-led research that integrates information, technology, and training, including the use of digital tools, has been found to strengthen coping and adaptation strategies, encourage adaptive behaviours, and improve health outcomes [145, 147]. Moreover, via these initiatives, communities not only take steps to increase individual and community capacity to drive social, economic, and environmental change but also promote social cohesion and cooperation [148, 149]. In the UK, Natural England's Green Infrastructure Framework has helped communities co-design nature-based solutions in areas where they are needed most, by using mapping tools to target health inequalities, boost climate resilience, and foster community connections [150]. The Highlands and Islands Climate Change Community Grant, funded by UK Research and Innovation (UKRI) and delivered by the British Science Association and Science Ceilidh, supported communities in Scotland to collaborate with researchers on local climate challenges. The initiative funded nine community-led projects that enabled underrepresented groups to lead research partnerships, design projects, select researchers, and manage funding [151]. Despite the beneficial nature of these projects, gaps exist in their sustainability, ability to bring about long-lasting change, generating momentum at the local level, and assessing their efficacy via evaluation [152]. These gaps highlight further opportunities for stakeholders and policymakers to design community-led initiatives aimed at enhancing adaptive capacity to extreme temperatures.

The latest WHO European Region report on nature-based solutions (NbS) and health highlighted that NbS aimed at climate change mitigation or adaptation also bring important health and wellbeing benefits directly or indirectly [125]. For example, urban greening initiatives, such as the planting of trees, can ease the UHI effect and lower the risk of heat-related deaths. Importantly, engaging in PEB activities such as community tree planting, conservation volunteering, citizen science and other green initiatives may offer additional benefits for mental wellbeing by fostering social connection, a sense of purpose and engagement with nature [153-155]. This suggests that urban greening could be designed not only as a means of reducing heat exposure, but also as a form of community-based PEB that strengthens social capital and psychological responses to climate change. Additionally, providing cooling green spaces supports mental health and enhances overall wellbeing [156]. Therefore, integrating green spaces into urban planning could be a key strategy for strengthening climate resilience and improving public health. To reduce heat-related risks in urban areas, cities should also focus on passive cooling methods that don't require energy such as a) switching to designs that promotes natural cooling and ventilation, for instance thoughtful building layouts can lower energy demand and enhance resilience to rising temperatures, b) using heat-reflective, low-absorption construction materials can further reduce indoor heat buildup, c) expanding vegetative cover across cities can provides multiple benefits, including cooler outdoor temperatures, reduced pollution, lower energy use for cooling, and increased carbon sequestration [101, 136, 157, 158]. The implementation of these approaches can help promote more sustainable, heat-resilient urban environments.

While the negative effects of cold on health and mental health are declining, they remain a public health concern in the UK. This might worsen due to a future ageing population and potential rises in fuel prices [89]. Fuel poverty, exacerbated by the current cost-of-living crisis and energy price surges, and cold homes can contribute to mental distress [13]. Beyond the physical discomfort of cold homes, the difficult choice between heating and eating, and the consequences of that decision, can negatively impact both physical and mental health, especially among young children, older people, and people with pre-existing health conditions [159-161]. Therefore, policies could concentrate efforts to bridge the affordability gap by improving household insulation, offering targeted subsidies, and eliminating policies that penalise low-income people [13, 162]. The UK's Energy Company Obligation (ECO) scheme and similar efforts, such as Warm Home Discount, may also be evaluated and scaled to protect low-income cold homes [163, 164].

Lastly, the government and local authorities can increase resilience, lessen inequality, and better protect the communities at increased risk from the effects of climate change by incorporating mental health considerations into emergency planning and national and local adaptation strategies [138]. Per the recent AWHP report, there is also a need to train staff working with patients on the impact of adverse weather events on bodily functions and to be alert to physical as well as mental health signs [UKHSA, 140]. For developing effective strategies to mitigate the health impacts of extreme temperatures, policymakers might want to examine the intricate interplay between environmental factors, socioeconomic determinants, and individual characteristics closely and take that into consideration. Understanding which individuals and neighbourhoods are most vulnerable can help guide local adaptation efforts [165]. Vulnerability maps are one such tool that can enable health officials and policymakers to identify hotspots within cities and target interventions to places and people most in need [157]. These maps can serve as a helpful guiding tool for medical professionals and legislators to identify high-risk areas inside urban centres and focus their efforts on the individuals and locations that require them most.

Strengths and limitations

To the best of our knowledge, this is the only empirical study that has utilised longitudinal data for 10 waves and linked it with real-time exposure using data on extreme temperatures to investigate their effects on mental health outcomes in the UK. One of the strengths of this study lies in its comprehensive approach, as it examined not only exposure but also its severity by considering the number of days respondents experienced extreme heat or cold in the last four weeks. Our findings underscored that, along with exposure, its severity and frequency also affect mental health and SWB. Furthermore, mapping daily temperatures at granular spatial resolution, such as the LSOA/DZ/SOA, enabled us to estimate changes in exposure to both temperature extremes at a small geographic unit, thereby contributing to the accuracy of exposure estimation. The application of established methodology for measuring extreme thresholds using a 5-day centred window based on the day of the year enhances the robustness of our exposure definition. Moreover, historically, almost no study in the UK has used the period from 1971 to 2000 to define baseline normal, as the period from 1961 to 1999 is commonly relied upon. Additionally, our sensitivity analyses explored alternative thresholds and exposure durations. The study also benefits from utilising the UKHLS data, which has surveyed over 40,000 households across the UK, facilitating robust generalisation and subgroup analyses across socio-demographic and economic characteristics. The longitudinal design of the study, with repeated annual data collection since 2009, has enabled us to examine trends in validated mental health measures over time. The availability of geographic identifiers within the specially licensed version of the dataset has allowed us to link outcomes with exposures. Moreover, the richness of UKHLS data has enabled us to control for a variety of individual and household-level confounders related to demographic, socioeconomic, employment, and family data, thus enhancing our analysis of mental health outcomes. Oversampling of ethnic minority and immigrant populations permitted our research into interactions with mental health and climate vulnerability.

Despite its merit, the study has limitations that warrant cautious interpretation of its findings. Since measures on mental health and SWB are self-reported, they may be subject to bias due to stigma or mood at the time of response. Although the SF-12 is a strong instrument for evaluating mental health and is helpful in large-scale studies, its brevity may not fully reflect the complexity of mental health problems. Creating a balanced panel of individuals repeatedly exposed to extreme temperatures proved challenging. In a longitudinal study like the UKHLS, it is difficult to interview the same person during the same season over the years, making it impossible to establish a balanced panel of those consistently exposed to extreme heat or cold for all 10 survey waves. To create exposure data, we included individuals who completed surveys ≥ 2 times and filtered them based on season, specifically those interviewed during the summer ≥ 2 times. Only the observations from their summer interviews were retained for the extreme heat model, and vice versa for the extreme cold model. Furthermore, the module on environmental habits and social support, measured using neighbourhood social cohesion, was not administered in every wave, which may have diluted the strength of these protective factors in our analysis. Although we employed imputation for within-wave missingness and used proxy measures from intermittent waves for waves in which the modules weren't administered, several observations were missing as participants entered and exited the panel at various points. Similarly, information on dwelling type, which couldn't be considered as it was available starting in 2015, would have been interesting to explore how buildings substantially modified the studied associations. Lastly, even though the findings from effect modifications have been instrumental in highlighting the varied differences between population sub-groups supporting the study objective, they need to be interpreted with caution due to the weaker statistical evidence for some of the interactions.

We propose that future research prioritise understanding individuals' lived experiences of increasing extreme heat and decreasing extreme cold to inform the development of interventions that enhance coping, preparedness, and long-term adaptation strategies. In particular, there is a need to design and validate scales that specifically capture the mental health and wellbeing impacts of extreme temperatures. While our study found that exposure to cold waves improved mental health, it would be interesting to investigate whether the overall shifting trends and baseline patterns of minimum temperatures during winters alleviate conditions such as seasonal affective disorder and other cold-related mental health issues among the UK population. It is also important to examine how the adaptive capacity of UK nationals has evolved in response to changing climatic conditions. We suggest that existing large-scale UK-wide longitudinal surveys should be leveraged to include annual modules on lived experiences of EWEs, such as extreme heat, extreme cold, and floods, to develop a better understanding of the cumulative effects of extreme weather stressors on mental health and wellbeing. Such data would be instrumental in guiding policymakers to develop evidence-based, targeted interventions that enhance population resilience.

Conclusion

By linking temperature data with the UKHLS data, we found associations between multiple exposure to extreme heat and cold and their effects on mental health and wellbeing in the representative sample of the UK population over 11 years. While exposures to extreme heat were significantly associated with poor mental health and SWB, for exposures to extreme cold, the opposite pattern was observed; i.e., over time, exposures to extreme cold were associated with better mental health. Subgroups of the population likely to be at higher risk of adverse mental health effects due to extreme temperatures include younger and older people, females, people with a degree/ higher degree qualifications, people living in urban areas, and those employed. This study identified that robust social support and pro-environmental behaviours can be key to enhancing mental health and wellbeing, since both are modifiable and can be strengthened through focused awareness and engagement. Future research on the subject may want to prioritise understanding individuals' lived experiences to enhance coping, preparedness, and long-term adaptation. Strategies to mitigate the negative impacts of extreme temperatures on mental health necessitate a multisectoral approach at the individual, community, and systemic levels. This could include enhancing knowledge and awareness, risk perception, adaptation and preparedness, designing and providing sustainable cooling/warming strategies with a focus on the urban landscape, and integrating mental health services in emergency services and public health interventions.

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Declaration of interests

The authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

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Supporting information

S1 Fig: Average tmax at LSOA level for the baseline period 1971-2000 and study period 2009-2019, Met Data, UK

S2 Fig: Average tmin at LSOA level for the baseline period 1971-2000 and study period 2009-2019, Met Data, UK

S3 Fig: Change over time in the % of extreme heat and % of extreme cold events experienced every year from 2009 to 2019, Met Office data, UK

S2 Table: Comparison of the characteristics of survey respondents with complete data and the eligible sample in Wave 1, UKHLS

S3 Table: Mean tmax during 2009-2019 compared to baseline normal 1971-2000, Met Data, UK

S4 Table: Mean tmin during 2009-2019 compared to baseline normal 1971-2000, Met Data, UK

S6 Table: Adjusted mixed-effects models with all confounders for extreme heat and extreme cold exposure in the past 4 weeks, UKHLS survey, Wave 1-Wave 10

S7 Table: Results of interaction test for extreme heat and extreme cold exposure vs. effect modifiers

S8 Table: Adjusted mixed effects models using the number of days experienced extreme heat in the past 2 weeks and 95th percentile threshold

S9 Table: Adjusted mixed effects models using the number of days experienced a cold day in the past 2 weeks, and a 5th percentile threshold

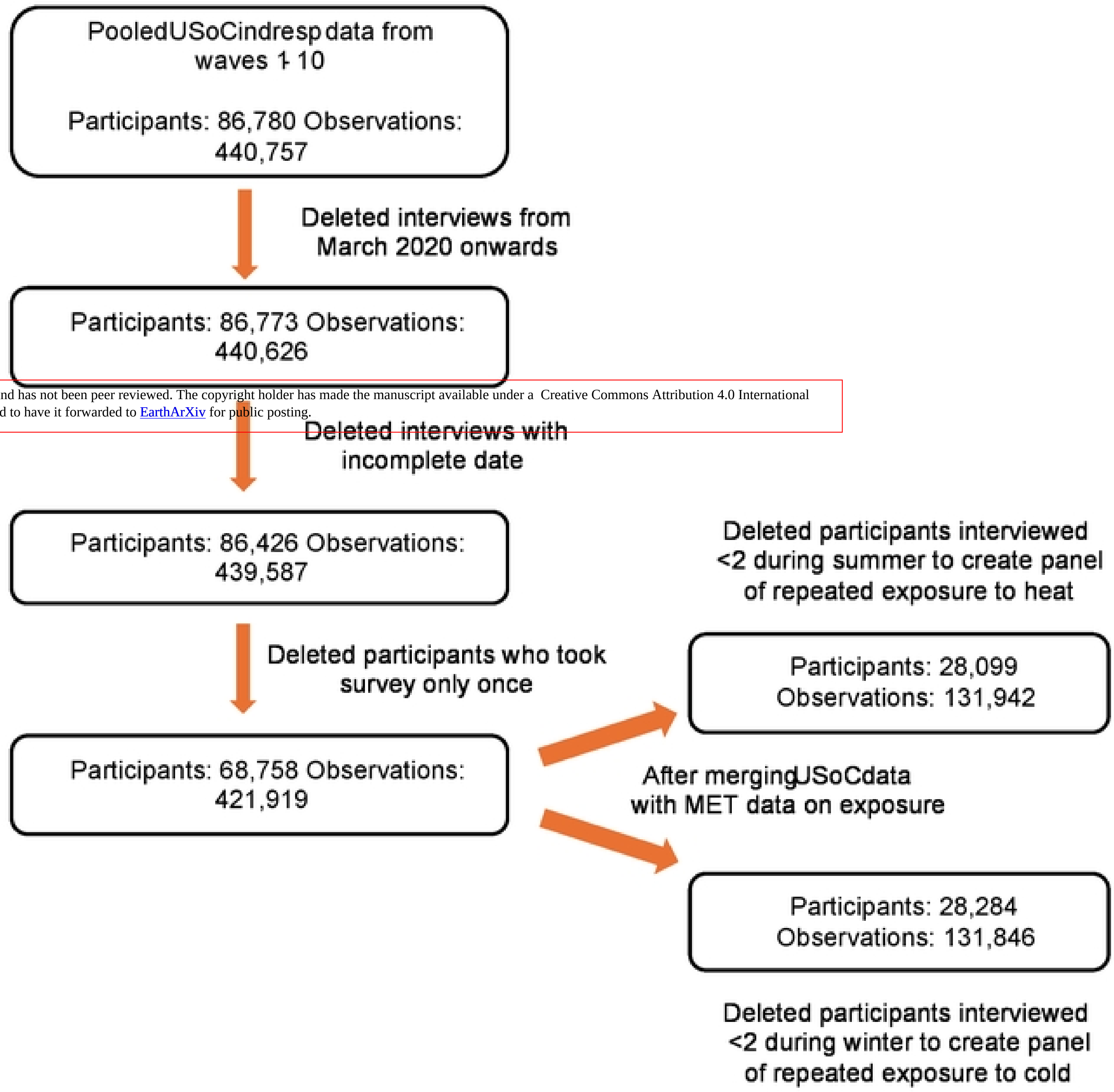
S10 Table: Adjusted mixed effects models using the number of days experienced an extreme heat day in the past 4 weeks and a 90th percentile threshold

S11 Table: Adjusted mixed effects model using the number of days experienced a cold day in the past 4 weeks and the 10th percentile threshold

S12 Table: Adjusted mixed effects model using the number of days experienced an extreme heat day in the past 4 weeks and the 99th percentile threshold

S13 Table: Adjusted mixed effects model using the number of days experienced a cold day in the past 4 weeks and 1st percentile threshold

Fig 1: Analytical sample selection using the UKHLS dataset, Wave 1-Wave 10, merged with the Met data on exposure



Figure