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RESEARCH ARTICLE

Urban–rural differences in mortality during the 2010 heatwave in European Russia

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ABSTRACT The 2010 summer heatwave in European Russia led to a notable increase in mortality due to extreme heat and associated wildfires. However, the diverse settlement patterns and the uneven impact of the heatwave in European Russia have left many geographical aspects of this event unexplored. For instance, the variations in excess mortality between major cities and smaller urban and rural areas remain unclear. According to our findings, during the 27–33 weeks of 2010, the total number of excess deaths was estimated at 56.0, with nearly 20% of them concentrated in Moscow. The age-standardized mortality rate in cities with more than one million inhabitants exceeded the expected values by 52% during the heatwave, while the excess mortality rate in rural areas was only 17%. The geographical area experiencing the highest excess mortality rate aligned with the zone of the greatest heatwave extent, as indicated by deviations from the climatic norm in temperatures and other measures of thermal stress. The risk of death from this increase in thermal stress more accurately represented by the Heat Index was found to be substantially higher in larger cities of 500,000 or more inhabitants, with the risk of death being especially high in major cities. Notably, air pollution was not found to be a significant modifier of excess mortality. It is important to note that the results obtained may have been influenced by the use of raster-based data from climate reanalysis, which may be expected to underrepresent local urban heat island effects, and consequently to underestimate risk exposure in urban areas.

KEYWORDS Heatwaves • Climate change • Excess mortality • Rural-urban disparity

Introduction

Ongoing climate change is affecting populations across various regions and climate zones. While residents of urban areas are experiencing accelerated warming, rural populations are also affected by rising temperatures (IPCC, 2023). The impact of climate change on human

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well-being is extensive and multifaceted, with elevated exposure to extreme weather events, particularly heatwaves, being just one example of its consequences. As the frequency and the severity of heatwaves are projected to increase, numerous scholars have been focusing on the health effects of heatwaves (Boeckmann and Rohn, 2014; Arbuthnott et al., 2016). Mortality and morbidity associated with extreme heat have been the subjects of multiple studies. As a result of this research, various patterns and effects of these events, including age and cause specificity, are currently well understood.

For instance, air pollution has been identified as a substantial confounder of heat-related mortality (Basu, 2009). A substantial body of literature has focused on the combined effects of temperature and air pollution on heat-related risks (Katsouyanni et al., 1993; Analitis et al., 2014; Analitis et al., 2018; Tait et al., 2018; Stafoggia et al., 2023). Multiple air pollutants have been associated with increased mortality during heatwaves, with ground-level ozone and particulate matter being among the most extensively studied. There is also evidence that carbon monoxide and sulphur dioxide are significant modifying factors of heat-related mortality. Furthermore, nitrogen oxides and volatile organic compounds (VOCs), which act as precursors of tropospheric ozone due to photochemical transformations, have been linked to elevated mortality risks during heatwaves.

However, various factors, such as the geographic variance in heatwave effects, continue to be discussed. Several studies conducted in the United States (Curriero, 2002; Spangler and Wellenius, 2021; Heutel et al., 2021) have found that the populations of southern cities, despite being exposed to higher heat levels, tend to experience lower excess mortality than their northern counterparts. Similar observations have been made in East Asia (Ma et al., 2015; Chung et al., 2015). Furthermore, Revich (2019) suggested that the largest increases in death rates occur in cities with moderately continental climate conditions. This finding was supported by the results of a study based on the Global Burden of Disease (Zhao et al., 2021), which indicated that Eastern Europe is the region with the highest mortality attributed to nonoptimal heat. The spatial disparity in the severity of heat-related risks depends on a range of factors, including the adaptive capacity at the individual and community levels, behavioural patterns and the adoption of heat-preventing measures (Hajat and Kosatky, 2010).

Spatial inequality in heat-related risks is influenced not only by climatic conditions, but also by settlement patterns. Extreme heat is experienced much more severely in densely populated and highly urbanized areas, which are known as urban heat islands. This, phenomenon, which was first studied in detail more than 50 years ago (Buechley et al., 1972), can be partially explained by the heat retention of built-up areas and the stagnation of polluted air due to decreased wind velocity. Furthermore, the resilience of urban populations to extreme heat is altered by a variety of factors that influence temperature-related risks both within and between cities, including urban planning and levels of greenness, access to healthcare, housing conditions and levels of social deprivation and exclusion (Semenza et al., 1996).

As the impact of urban heat islands is more pronounced in the largest cities, the majority of studies on heat-related mortality are focused solely on the most populated urban areas. Furthermore, the limited number of deaths in smaller cities often constrains the analytical capabilities of these methods. Therefore, city-level studies are usually limited to urban

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areas with more than 200,000 inhabitants (Zhou et al., 2014; Kuchcik, 2021). Below this threshold, the results are rarely found to be statistically significant (Shaposhnikov and Revich, 2016), unless they not considered in an aggregate form or through pooled analysis.

While assessments of risks related to extreme heat have also been conducted in rural areas, the results for these areas are ambiguous when compared to those for cities. Moreover, although numerous papers have investigated urban-rural differences in the impact of extreme temperature on human health, they have not provided consistent results.

A clear urban-rural divide, with cities having higher mortality, was identified in China (Wang et al., 2018). An increased risk of death during heatwaves was found in both urban areas and rural surroundings in Brandenburg (Gabriel and Endlicher, 2011), Czechia (Urban et al., 2014) and North Carolina (Choi et al., 2021).

However, studies conducted in British Columbia (Henderson et al., 2013), China (Ma et al., 2015), New South Wales (Jegasothy et al., 2017) and Queensland (Xu et al., 2019) found a substantial increase in heat-related risks in urban areas, with the results for rural districts not reaching statistical significance. Moreover, the variance in temperature-related mortality between urban, suburban and rural areas in Ohio was found to be insignificant (Sheridan and Dolney, 2003).

By contrast, studies conducted in North Carolina (Kovach et al., 2015), Illinois (Jagai et al., 2017), Jiangsu (Chen et al., 2016) and Zhejiang (Hu et al., 2019) found that rural populations had higher heat-related risks than urban populations. Uneven U-shaped patterns in the relationship to population density at the district level were found in South Korea, indicating that mortality was higher in both remote areas and highly urbanized territories (Lee et al., 2022).

Multiple factors have been proposed to explain the differences in mortality between urban and rural areas. Intercity variance is most often attributed to differences in air pollution levels, population density and urban design patterns (Sera et al., 2019; De Schrijver et al., 2023). Inequalities between rural districts are usually associated with socio-economic factors, such as educational attainment (Chen et al., 2016), access to healthcare, age (Kovach et al., 2015) and occupational risk (López-Bueno et al., 2022; Zeng et al., 2022).

Moreover, the size of a settlement, which is an indicator of heat island effects and the level of urbanicity of the local population, has rarely been considered. For instance, while a positive association between city size and increasing heat-related risks was found for two regions of Poland, this relationship was not shown to be consistent across time or territory (Graczyk et al., 2022).

Despite the increasing frequency of heatwaves and the associated concerns (Meehl and Tebaldi, 2004), studies on heat-related mortality in Russia are lacking. Numerous estimates of the burden of heatwaves have been utilized at the regional level (Revich, 2011; Otrachshenko et al., 2017; Otrachshenko et al., 2018), as most demographic data are presented by regions. However, this scope is too broad for comprehensive studies. City-level comparisons have been made in only a small number of locations. For instance, studies have been conducted in various parts of Russia, including in the European North

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(Shaposhnikov and Revich, 2016; Shartova et al., 2019), the South (Revich et al., 2015), Siberia (Revich and Shaposhnikov, 2010; Revich and Shaposhnikov, 2017; Chernykh and Taseiko, 2018), and the Far East (Grigorieva, 2020). However, the majority of these studies focused on only one or a few cities. Meanwhile, less is known about heat-related mortality in rural areas of Russia.

The 2010 summer heatwave in European Russia, which was attributed to a blocking anticyclone, resulted in record-breaking temperatures from July to early August. The impact of the heat was compounded by widespread forest fires in areas exceeding one million hectares (Barriopedro et al., 2011). The combined effects of extreme heat and air pollution (Shaposhnikov et al., 2014) contributed to more than 50,000 deaths (Revich, 2011), which made the impact of the 2010 heatwave comparable to that of a similar event that occurred in Europe in the summer of 2003 (Robine et al., 2008). The regions with the highest levels of excess mortality were Moscow city (which experienced 11,000 additional deaths in July and August 2010 compared to the same period in 2009) and the regions southeast of Moscow, including the territory extending to the Volga River. This geographical area coincided with the maximum extent of the heatwave in August 2010.

This study aimed to examine the differences in excess mortality during the 2010 heatwave between different areas of Russia based on the type and the size of the settlement. First, spatial and hierarchical variations in the risk of death were evaluated. Subsequently, an analysis of the associations of specific risk factors (thermal stress and air pollution) with excess mortality, categorized by the type of settlement, was conducted to identify urban heat island effects.

Given that urban heat island effects are most pronounced in densely populated urban areas, it was anticipated that the largest increases in death rates would be observed in the largest cities and their surrounding agglomerations. Conversely, "core-periphery" inequalities, which have been linked to substantial spatial disparities in life expectancy, particularly in Russia by the end of the first decade of the 21st century (Shchur, 2019; Shchur et al., 2021), might have reversed the expected outcomes. During that period, rapid advancements in public health and health-conscious behavioural changes in Russia primarily occurred in the most populated urban areas, and had limited impacts on peripheral cities and rural areas. The increasing polarization in Russia could challenge the conventional assumptions about heatwave mortality, revealing a "double burden" due to the combined effects of urban heat islands and limited access to healthcare in second-tier or even medium-sized and small-sized cities.

Data and methods

Temporal scope of the research

During the summer of 2010, the territories of European Russia and neighbouring countries experienced record-breaking temperature anomalies. The area of the blocking high was established over the vast territory in July, and had dissipated by mid-August. However,

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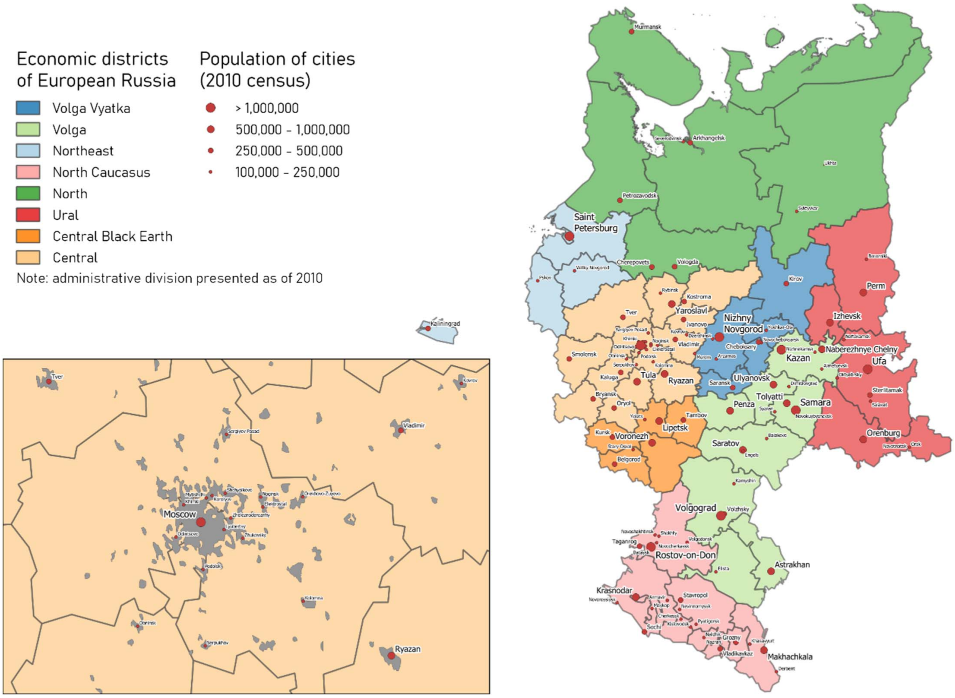
the development of anticyclones was uneven, leading to temperature anomalies occurring at different times in various regions. Extreme heat was initially observed at the end of June at a latitude of Moscow, and spread to the Central, Central Black Earth and Volga-Vyatka districts in July. Peak temperatures were recorded in early August, and the heatwave abruptly subsided in the middle of that month. Therefore, to capture the entire progress of the heatwave and its impact on excess mortality, a long time frame of 27–33 weeks in 2010 (05.07–22.08) was chosen for the study.

Area of the study

The study covered the entire territory of European Russia, which spans almost four million square kilometres and consists of 55 regions (with the cities of Moscow and Saint Petersburg considered distinct regions) grouped into eight economic districts (Figure 1). Due to the substantial heterogeneity of climatic conditions in European Russia, several of these territories, such as the Arctic North and the North Caucasus, did not experience extreme heat during the 2010 heatwave.

Figure 1 Regions and cities with more than 100,000 inhabitants in European Russia as of 2010



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Populated places in Russia were categorized into rural settlements and urban-type settlements (*posyolok gorodskogo tipa*) and cities. In the past, the threshold populations for inclusion in the latter categories were 3,000 and 12,000, respectively, and these thresholds were accompanied by a requirement that the settlement have a non-agricultural occupational structure. However, as of 2010, no strict criteria were applied, and the status of the settlement was generally determined by its role in the hierarchy of municipal subdivisions. All the computations were undertaken in an aggregate form for different groups of settlements divided by their size and type. This approach not only allowed us to account for settlement patterns, it also helped us to mitigate the limitations caused by the small population sizes.

The following classification of settlements was utilized: rural settlements; urban settlements (both city and urban-type settlements) with fewer than 100,000 inhabitants; and cities with 100,000–249,999, 250,000–499,999, 500,000–999,999 or 1,000,000+ inhabitants.

Data sources

We obtained individual-level microdata on mortality for the 2005–2010 period from the Federal State Statistics Service of Russia (Rosstat). The data were aggregated by five-year age group, territory and date of death (by week according to the International Organization for Standardization (ISO) standard). Additionally, the age and the sex composition of the rural and the urban populations by region were sourced from the Russian Fertility and Mortality Database (http://demogr.nes.ru/index.php/en/demogr_indicat/data), while city-level population data were obtained from unpublished statistical tables provided by Rosstat.

To assess heatwave exposure, we acquired raster data from climate reanalysis to aggregate thermal stress and air pollution levels, which are considered the primary risk factors for heat-related mortality, at the regional level. Climate reanalysis integrates ground observations and remote sensing data into a model, providing continuous numerical estimates of various atmospheric parameters. Since the excess mortality was calculated at the regional level, the raster data were extracted for the centroids of municipalities and weighted by their population as of the 2010 census for the region-level estimates (Spangler et al., 2019). This helped to mitigate the disturbances caused by the large areas of the regions. Climate reanalysis, despite being limited by spatial resolution, is often consistent with in situ observations from ground stations, and appears to be applicable in the absence of data (Urban et al., 2021; Mistry et al., 2022).

Meteorological data for the study were computed on the basis of the ERA-Interim reanalysis by the North Eurasian Thermal Comfort Indices Dataset (NETCID) team (Konstantinov et al., 2022) at a 0.75-degree resolution. The dataset included three-hour raster calculations of the main biometeorological indices: the Heat Index (HI), Humidex (HUM), Physiologically Equivalent Temperature (PET) and the Universal Thermal Comfort Index (UTCI). Biometeorological indices were used to assess perceived temperatures, while taking into account additional factors.

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The selection of the optimal indicator of thermal stress has been the subject of debate, with various studies providing different results (Barnett et al., 2010; Morabito et al., 2014; Shartova et al., 2019). Therefore, in addition to two-meter air temperatures (t2m), we obtained data on all of the biometeorological indices. Subsequently, for each week during the study period, we computed the deviation of the mean daily temperature from the 30-year average for July and August.

Air pollution data were also acquired from gridded datasets based on climate reanalysis (Lee et al., 2016). Data on concentrations of carbon monoxide (CO), ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and VOCs were obtained from the Copernicus Atmosphere Monitoring Service (CAMS) global reanalysis (EAC4) (Inness et al., 2019). The data were accessed via the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/) at a 0.75-degree resolution, averaged weekly and reweighted by the population of municipalities. The vertical resolution of the reanalysis dataset comprised 60 layers, each representing different air pressure conditions.

Particulate matter concentrations (PM1, PM2.5 and PM10) were provided in kg/m^3. For other air pollutants, concentrations were provided in mass mixing ratios (kg/kg) and further converted to parts per billion (ppbv). Formaldehyde (HCHO) is often used to represent volatile organic compounds (VOCs) that are emitted from forest fires during heatwaves and generated through photochemical transformation (Sitnov, 2011). The concentrations of all air pollutants were extracted from the lowest model level, reflecting the conditions at the surface.

Excess mortality estimation

Mortality was assessed in both absolute terms (total number of deaths) and relative terms (death rate standardized by the 2013 European population standard) during the 27–33 ISO weeks of 2010. Excess mortality was estimated based on the differences between the observed values and the expected values calculated from the model using the 2005–2009 reference period. This process was performed for each aggregated group of settlements at the regional level.

Interrupted time-series analysis is considered the gold standard in environmental epidemiology, but the applicability of many convenient approaches is limited due to the aggregation of data at the weekly level. For example, the inclusion of the day of the week and other independent variables, as well as the use of distributed lags, can become impractical. Moreover, regression models incorporating only time variables are applicable when weekly data are used.

The baseline mortality level during the heatwave was estimated using a regression model incorporating both long-term changes in mortality and seasonality. Linear and quadratic yearly trends represent long-term changes in mortality (Comas-García and Erdely, 2023), while two pairs of sine and cosine functions with periods of 52 and 26 weeks are employed for seasonal patterns (Nepomuceno et al., 2022). Weekly baseline mortality estimates for each week of 2010 were retrospectively projected using data from the reference period. The resulting formula was stated as follows:

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$$\log(E(d_{ij})) = \beta_0 + \beta_1 i + \beta_2 i^2 + \beta_3 \sin\left(\frac{2\pi}{52}j\right) + \beta_4 \cos\left(\frac{2\pi}{52}j\right) + \beta_5 \sin\left(\frac{2\pi}{26}j\right) + \beta_6 \cos\left(\frac{2\pi}{26}j\right),$$

where $E(d_{ij})$ is the expected mortality during the jth week of year i. 95% confidence intervals were also calculated for all the estimates using bootstrapping. All the data extraction and processing, calculations and analyses were performed in R 3.6.2.

Regression analysis

We employed regression analysis to quantitatively evaluate the impact of settlement type and size on heat-related mortality. Two distinct model types were considered: the first included the category of settlement size as a categorical variable, while the second incorporated interactions between settlement characteristics and thermal stress indicators. The first approach allowed us to investigate the differences in excess mortality between cities of varying sizes and rural areas during heatwaves while controlling for external heatwave effects. The latter approach provided an assessment of the "heat slope", revealing the varying risk-exposure relationships based on the size and the type of settlement.

The first approach can be expressed as:

$$\log(Y_{ijk}) = \beta_0 + \beta_1 k + \beta_2 X + \beta_3 Z$$

where Y_{ijk} represents the relative excess of the observed week-specific age-standardized death rate over the expected values in region i and category of settlements k during the jth week, X is the measurement of thermal stress and Z denotes the vector of air pollution variables. Since k is the factor variable, β_1 is a set of coefficients, each representing the change in the age-standardized death rate during the heatwave associated with a specific type of settlement. Thermal stress and air pollution variables from the available parameters described above were analysed, and the most effective models were selected based on information criteria (AIC and BIC) and their performance.

To demonstrate the consistency of the estimates of the coefficients β_1 indicating the association between excess mortality and the type of settlement, we also assessed models that included the observed X_j in conjunction with a one-week lag X_{j-1}. This decision was motivated by the persistent lag effects observed in multiple studies.

The second model can be defined as:

$$\log(Y_{ijk}) = \beta_0 + \beta_1 k + \beta_2 k * X + \beta_3 Z$$

Here, the settlement category k interacts with the heat stress X, providing the "heat slope" steepness, which denotes the varying associations between heat stress and excess mortality based on the type and the size of the settlement. All the descriptive statistics of the variables used in the regression analysis are presented in Table 1.

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Table 1 Descriptive statistics of the independent variables

	N.obs	Mean	SD	Min	Max	25%	75%
Deviations from 30-year summer averages							
t2m	1295	5.85	3.56	−5.18	12.37	3.55	8.28
PET	1295	7.23	4.63	−6.69	14.88	4.16	10.53
UTCI	1295	6.58	4.67	−9.25	14.21	3.66	10.05
HI	1295	1.93	1.52	−1.63	5.34	0.70	2.88
HUM	1295	2.53	2.20	−4.77	8.09	1.06	3.85
Air pollution							
PM1, μg/m^3	1295	31.40	53.88	1.80	553.73	10.38	27.80
PM2.5, μg/m^3	1295	38.78	63.05	3.91	648.12	13.69	34.55
PM10, μg/m^3	1295	54.08	88.38	6.07	913.01	18.95	47.76
CO, ppbv	1295	676.23	2360.40	95.57	31820.19	157.83	336.85
HCHO, ppbv	1295	5.85	12.47	0.18	154.38	2.77	4.44
SO_2, ppbv	1295	1.57	1.93	0.17	16.40	0.79	1.64
O_3, ppbv	1295	35.66	6.33	23.60	69.34	32.34	36.92
NO_2, ppbv	1295	3.94	5.52	0.48	75.86	1.87	3.98

Results

Estimates of excess mortality

During the 27–33 weeks of 2010, the total number of excess deaths, compared to the baseline calculated from the 2005–2009 reference period, was estimated at 56.0 (95% confidence interval (CI): 48.9–62.9) thousand individuals. The distribution of casualties was not uniform, with 10.7 (CI: 10.3–11.0) thousand excess deaths occurring in Moscow. The excess mortality in the Central economic district, excluding Moscow, amounted to 11.3 (CI: 9.8–12.7) thousand cases. The Central Black Earth and Volga districts, which were also among the most severely affected by the heatwave experienced during this period, had 5.7 (CI: 5.1–6.3) and 12.0 (CI: 10.7–13.2) thousand excess deaths, respectively.

The impact of the heatwave was uneven across different types and sizes of settlements (Table 2). Rural areas, which accounted for 26.8% of the total population in European Russia, experienced an estimated 10.0 (CI: 7.8–12.2) thousand excess deaths. Simultaneously, in cities with populations of more than a million (excluding Moscow and Saint Petersburg) the number of excess deaths was 5.5 (CI: 5.1–5.9) thousand, corresponding to 6.4% of the population as of the 2010 census.

Throughout the study period, excess mortality was observed within all weeks, with the impact starting earlier and being relatively modest in Saint Petersburg (Figure 2). In most areas, the peak was observed at 31–32 weeks (02.08–15.08). However, a compensatory

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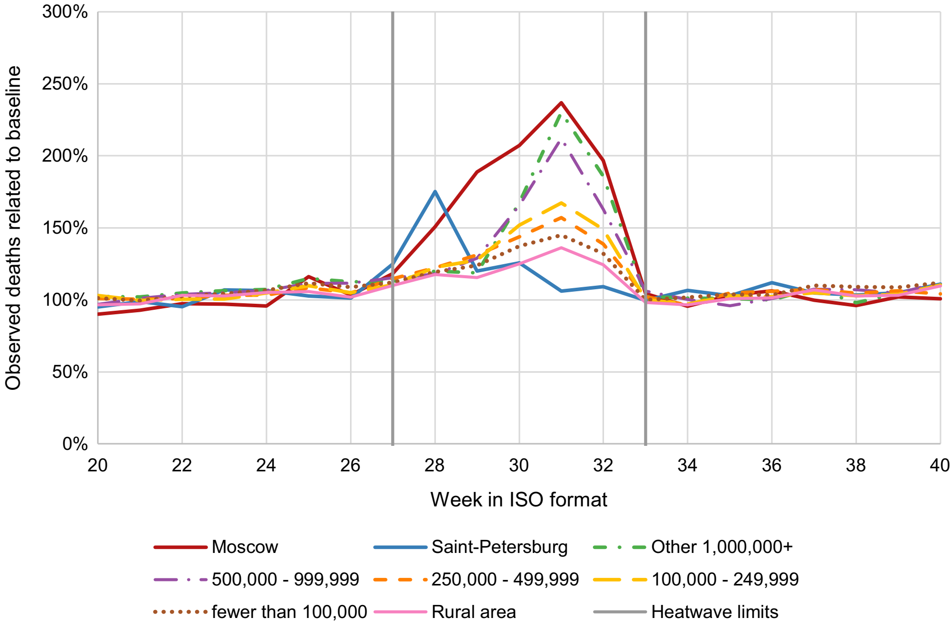
Table 2 Contribution of the studied settlement categories to the total population size according to the 2010 census and excess deaths during the heatwave

	Total population (mil.)		Excess deaths (thousands)	
Total	105.2	100.0%	56.0 (CI: 48.9–62.9)	100.0%
Moscow	11.5	10.9%	10.7 (CI: 10.3–11)	19.1%
Saint Petersburg	4.9	4.6%	1.8 (CI: 1.7–2)	3.2%
Other 1,000,000+	6.7	6.4%	5.5 (CI: 5.1–5.9)	9.8%
500,000–999,999	10.2	9.7%	6.9 (CI: 6.3–7.5)	12.3%
250,000–499,999	9.2	8.7%	4.4 (CI: 3.7–5.1)	7.9%
100,000–249,999	9.2	8.7%	5.1 (CI: 4.4–5.8)	9.2%
Fewer than 100,000	25.5	24.2%	11.5 (CI: 9.6–13.3)	20.6%
Rural area	28.2	26.8%	10.0 (CI: 7.8–12.2)	17.9%

Note: The two largest cities are presented individually.

Figure 2 Observed number of deaths related to the baseline level by week and settlement category



Note: The two largest cities are presented individually.

decline in excess mortality (also known as a “harvesting effect”) after the end of the heatwave was not identified.

The observed age-standardized death rate during the 2010 heatwave in European Russia was estimated to be 13.9 per 1,000, exceeding the baseline by 3.1 (CI: 2.6–3.5).

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Interestingly, the initial variations in death rates led to decreased differences in cities of different sizes during the heatwave. The baseline age-standardized death rates ranged between 10.4 and 12.0 per 1,000 in the largest cities (over 1,000,000) and the smallest urban areas (fewer than 100,000), respectively, while the observed death rates were 15.2 and 14.5 per 1,000, respectively.

The highest standardized death rate, 16.2 per 1,000, was observed in the Volga-Vyatka economic district, which was partially attributable to this district having one of the highest baseline levels of mortality (12.0 per 1,000 during the corresponding period). Furthermore, the most substantial increases in age-standardized death rates, exceeding 4.0 per 1,000 people, occurred in the Volga, Volga-Vyatka and Central Black Earth districts (Figure 3).

The relative increase in terms of age-standardized death rates was 28.4% (CI: 23.2%–33.8%) for the entire population of European Russia (Figure 4). The increased risk of death during the heatwave was 16.8% (11.9%–22.0%) in rural areas, while it was estimated at 46.6% (CI: 41.5%–51.8%) in cities with a population exceeding one million (excluding capital cities). In Moscow and Saint Petersburg, age-standardized death rates increased by 67.1% (CI: 63.4%–70.7%) and 22.5% (CI: 20.0%–25.3%), respectively. Overall, cities with more than 500,000 inhabitants experienced significantly greater excess mortality during the heatwave, as these urban areas had the largest increases in death rates compared to the total population (as presented in Table S.1 in the Supplementary material, available online at https://doi.org/10.1553/p-42de-zc5p).

Figure 3 Composition of the observed age-standardized death rates in regions of European Russia, weeks 27–33 of 2010

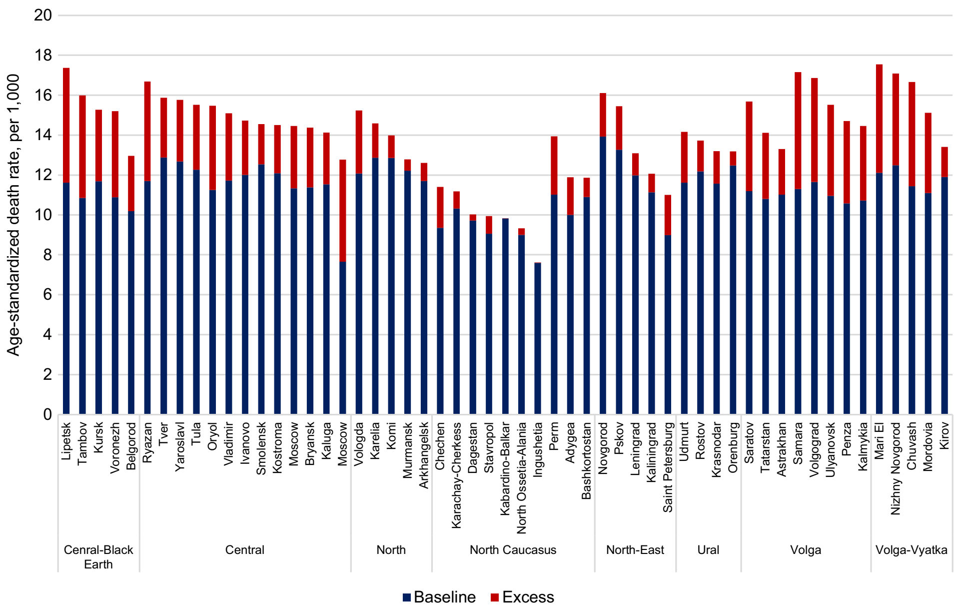
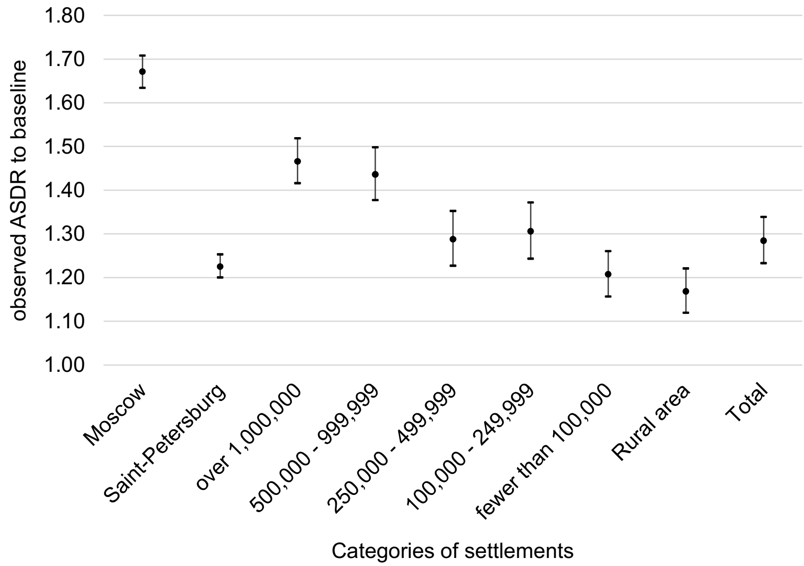


Figure 4 Age-standardized death rates observed relative to baseline by settlement category, weeks 27–33 of 2010



Note: The two largest cities are presented individually.

Spatial disparities in heatwave mortality were also observed between the different districts. In the Central, Central Black Earth and Volga economic districts, age-standardized death rates exceeded the baseline by more than 35% (Figure 5). However, the Northeast, North Caucasus and Ural districts did not experience increases of more than 15% (Table S.2, Supplementary material). The geographic variations in excess mortality reflect the patterns of the heatwave, with the most affected regions being located within the area where the extent of the heatwave was the greatest.

Regression analysis

The regression analysis revealed substantial variations in the risk of death during the heatwave associated with the type of settlement. According to all the models with various variables included, excess mortality was higher in the largest cities, with a significant increase in risk being detected in cities with more than 500,000 inhabitants. For instance, cities belonging to the largest population groups (500,000–999,999 and 1,000,000+) experienced an increase in the age-standardized death rate that was 19.5% (CI: 13.4%–25.9%) and 21.3% (CI: 13.2%–29.9%) higher, respectively, than that in rural areas. In contrast, in cities and urban settlements with fewer than 100,000 inhabitants, the relative excess over the baseline was much lower, at only 4.0% (CI: 0.4%–7.7%).

The urban-rural dipartites in excess mortality persisted after adjusting for extreme heat, as shown in Table S.3 (Supplementary material). In the analysis, thermal stress, as assessed

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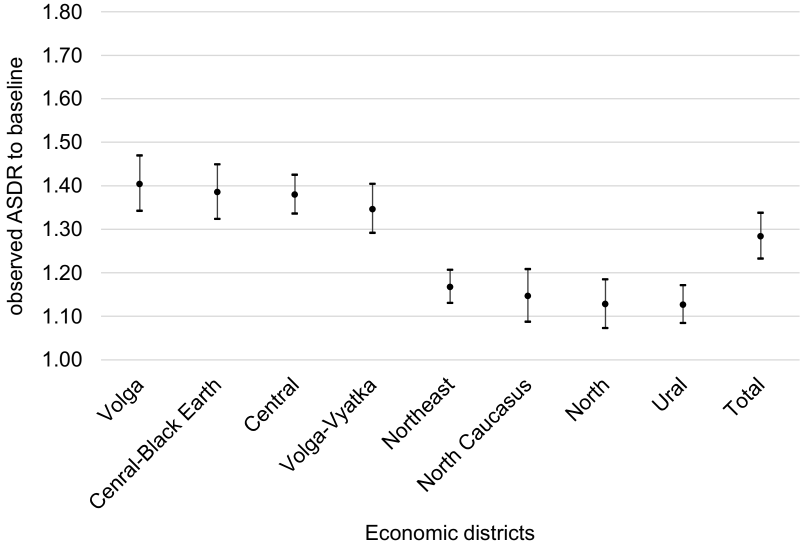
Figure 5 Age-standardized death rates observed relative to baseline by economic district, weeks 27–33 of 2010



by any of the metrics, whether with or without one-week lags, was found to be a statistically significant control variable for assessing the differences based on the size of the settlement. While the findings were consistent across all models, the models including the Heat Index demonstrated the best fit and were more appropriate based on information criteria (AIC and BIC). Thus, a one-degree increase in the deviation of mean Heat Index values from 30-year summer averages was associated with a 10.4% (CI: 9.7%–11.2%) increase in the risk of death during the specific week.

The inclusion of variables representing air pollution did not lead to a significant improvement in the model. Their impact was only modest in the presence of thermal stress, and none of the variables provided statistically significant coefficients (as shown in Table S.4, Supplementary material). Models assuming lag effects did not alter the results, with the increases in death rates in cities of different sizes compared to those in rural areas being similar in all cases (as indicated in Table S.5, Supplementary material).

“Heat slopes” and interaction models

The models that considered the varying associations of extreme heat with excess mortality by the size of the settlement provided additional insights. Comparable temperature extremes led to significantly higher death risks in larger cities. Once more, the Heat Index provided the best fit (as shown in Table S.6, Supplementary material).

A one-degree increase in the weekly Heat Index anomaly was associated with a 17.1% (CI: 14.3%–20.1%) and a 18.4% (CI: 14.3%–22.6%) greater risk of death in the two

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most populous city categories (500,000–999,999 and 1,000,000+, respectively). In the smallest cities and in rural areas, the “heat slope” was less steep, amounting to 9.3% (CI: 8.0%–10.7%) and 6.5% (5.2%–7.9%), respectively. The impact of air pollution was found to be limited, with minimal changes in the observed associations (Table S.7, Supplementary material).

Discussion

In this study, we investigated the excess mortality during the 2010 summer heatwave in Russia, emphasizing the variations by settlement type. Our findings align with those of prior studies on this event. The estimated total number of excess deaths was close to the preliminary assessments by Revich (2011), who reported values of 54,000 for the entire country and 11,000 for Moscow. Furthermore, Shaposhnikov et al. (2014) found similar results for excess mortality in Moscow, indicating that an increase in the risk of nonaccidental deaths accounted for 90% of excess mortality (CI: 84%–97%). Although the evidence of spatial differences in excess mortality was limited, the list of the most affected regions was consistent with that in other studies (Revich, 2011).

The variations in excess mortality by settlement size

We examined the relationships between the risk of death during the heatwave and the size and the type of settlement. The results of regression analysis supported the empirical findings, particularly when accounting for environmental factors. We found evidence of the influence of urban heat island effects on mortality rates, with a more significant impact being observed in the largest cities with populations exceeding 500,000. A study conducted in Poland (Graczyk et al., 2022) provided a comparable population threshold for heat-related mortality effects in urban areas.

The impact of urban heat islands tends to be more pronounced in areas characterized by high population density, reduced urban greenery and densely built-up zones (Sera et al., 2019; Choi et al., 2022; Lee et al., 2022). These factors are likely to be important contributors to the observed differences in excess mortality.

In Russia, there is a positive correlation between the proportion of residents living in urban environments and multi-story buildings and the size of the settlement. Consequently, many residents in small towns live in low-rise, “rural” built-up areas (Kolosov and Nefedova, 2014), which experience less pronounced urban heat island effects.

Furthermore, the prevalence of air conditioning is considered one of the most important contributors to the decline in heat-related mortality in many countries (Sera et al., 2020). Since a significant portion of households in Russia were not equipped with air conditioners in 2010, the importance of air conditioning as a mitigating factor during the studied heatwave was diminished (Shaposhnikov et al., 2014; Otrachshenko et al., 2017). However, due to the absence of statistical data at the local level, we were unable to confirm these associations.

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The study period was characterized by a significant decline in mortality. Life expectancy began to gradually increase from the mid-2000s onwards, initially in the capital and in the largest cities (Shchur, 2019; Shchur et al., 2021). As a result, a substantial geographic and hierarchical disparity in mortality had emerged by 2010 (Timonin et al., 2020). While mortality during the heatwave, as measured by excess age-standardized death rates, was nearly uniform across various settlement categories, the relative increase in mortality was considerably greater in the largest cities. Due to this disparity, it is reasonable to compare relative figures only when assessing heatwave effects.

The preceding rapid decline in mortality was largely attributed to a decrease in deaths from external causes at working ages, which were closely linked to alcohol consumption (Shkolnikov et al., 2013; Grigoriev et al., 2014; Timonin et al., 2017). Simultaneously, heat-related mortality in Russia, like elsewhere, tends to be mainly concentrated in older age groups (Shaposhnikov et al., 2014; Grigorieva and Revich, 2021). Thus, we cannot assume that recent mortality trends had a direct influence on the results, although they might have altered the calculation of the baseline, potentially impacting the outcomes. Therefore, the regression coefficients for the dummy variables representing city size in the interaction models may partially reflect the imprecise estimation of the baseline. However, none of these coefficients were found to be statistically significant.

Thermal stress as the factor influencing excess mortality

Excess mortality during heatwaves is generally attributed to extreme heat stress, which affects individuals in various ways, including by increasing the occurrence of heat-related illnesses and by worsening pre-existing health conditions. While air temperature is often regarded as the primary determinant of thermal stress, a number of studies have employed alternative parameters, such as biometeorological indices, to represent the perceived heat, which may be influenced by multiple additional factors.

In our analysis, we incorporated multiple biometeorological indices in addition to two-meter air temperatures to more accurately represent the impact of thermal stress on heat-related mortality. Although all of these parameters significantly explained spatial differences in excess mortality during the heatwave, formal statistical tests revealed that the Heat Index was the most comprehensive predictor in our study. The selection of the exact indicator of thermal stress is not governed by a universal rule, but rather depends on data accessibility, convenience and model fit (Barnett et al., 2010; Vaneckova et al., 2011; Lo et al., 2023).

The region with the highest observed risk of death coincided with the area that was most affected by the heatwave, and that experienced the highest level of heat stress. In other parts of European Russia, including in the North and Northeast, Ural and North Caucasus regions, there were slight increases in death rates. Thus, in these areas there were only minor urban-rural differences in excess mortality.

An investigation of the temperature-mortality relationship using interaction models revealed a steeper increase in the risk of death in the largest cities. However, due to the relatively coarse spatial resolution of the gridded datasets from which temperatures and

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air pollution were extracted, the measurements used in the regression analysis might only represent the "background" conditions, while disregarding the influence of the local microclimate. Therefore, it is likely that the observed relationship reflects the variations in urban heat island effects in cities of different sizes rather than variations in heat-related mortality risks for other reasons. Thus, it may be assumed that the urban heat island effects were much more pronounced in cities with more than 500,000 inhabitants, though they also occurred in smaller cities.

As demonstrated by Spangler et al. (2019), gridded datasets based on extrapolations provide more accurate measurements of temperature-mortality relationships in remote and rural areas, while underestimating them in large metropolitan areas. This discrepancy could be attributable to the failure to account for local conditions, which are also prevalent when using data from in situ observations, as most ground stations are situated at airports outside the urban environment.

Impact of air pollution

The 2010 summer heatwave in European Russia was accompanied by widespread forest fires, which generated smog and the associated health problems (Shaposhnikov et al., 2014). The burning of forests leads to elevated concentrations of various pollutants and suspended microparticles in the air. In addition to forest fires, air pollution during the heatwave was attributed to air stagnation and photochemical transformations. However, distinguishing the specific influences of these factors can be complex.

Although CAMS considered both anthropogenic emissions and pollution from fires based on data retrieved from satellite observations, the association between air pollutant concentrations and the risk of death during the heatwave was found to be weak when accounting for thermal stress. None of the tested air pollutants could be identified as the primary modifier of heat-related mortality, as their inclusion did not substantially improve the model. The inclusion of formaldehyde, which is typically not considered an outdoor air pollutant, produced comparable outcomes. Previous studies have associated outdoor formaldehyde concentrations with nonaccidental mortality (Ban et al., 2022), and there is evidence that these concentrations increased during the 2010 summer heatwave (Sitnov, 2011).

The strong correlation between air pollutant concentrations complicates the separation of their effects and the identification of the most significant of these concentrations. While this challenge could be addressed through the use of reanalysis data, which provide approximate estimates based on modelling, this approach cannot precisely represent local conditions (Cobelo et al., 2023). This highlights the importance of considering local-level microclimate characteristics when assessing heat-related death risks and estimating the effects of urban heat islands (Analitis et al., 2012).

Problems and limitations

Several additional limitations of the study should be acknowledged. The aggregation of all the data on a weekly basis may have provided a temporal scale that was too coarse

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for heat-related mortality analysis. Consequently, peak and extreme observations were not captured due to averaging by weeks. Therefore, despite the prolonged duration of the 2010 heatwave, many short-term effects were not identified in our study. The influence of lagging in assessments of the effects of temperature and air pollution on excess mortality has been well documented and discussed in previous research (Anderson and Bell, 2009). However, since strong lag effects are observed within several days, lagging did not substantially alter our week-specific estimates.

Due to the aggregation of our data at the regional level, numerous local patterns could be overlooked. The coarse spatial resolution of gridded datasets limited our ability to identify local conditions, which was particularly critical in urban areas due to the improper consideration of urban heat islands. Since the regions of European Russia often cover significant areas, the weather and climate within them might vary. To mitigate this problem, we reweighted the observations by the population of municipalities; however, it is important to acknowledge that some inconsistencies may still persist. Furthermore, numerous studies have found evidence of a link between heat-related mortality and abrupt changes in temperature (Cao et al., 2009; Lin et al., 2013; Vicedo-Cabrera et al., 2016), which could not be identified within the scope of our study.

Despite the relatively high level of aggregation in both spatial and temporal scopes, the total number of deaths in specific regions was insufficient to provide reliable estimates. Shaposhnikov and Revich (2016) argued that in territories with fewer than 200,000 inhabitants, the confidence intervals for mortality are excessively wide. Of the 184 groups of settlements by region that we examined in our study, 27 had a population size under than this threshold. The problem of small sample sizes was partially mitigated by grouping by weeks. However, in certain regions, particularly in rural areas, the estimates of excess mortality were not statistically significant.

The uneven distribution of population within regions may have resulted in specific settlement patterns being overlooked when reweighting gridded data for the total population. This issue was especially significant for the largest urban agglomerations, which also included the surrounding areas of large cities affected by urban heat islands. This may have distorted the results, especially in the Moscow region, where a substantial share of the population resides within the area of continuous urban development around Moscow.

Summary

It was estimated that during the 2010 heatwave in European Russia, there were 56,000 excess deaths, which were strongly associated with thermal stress. The relative increase in the death rate was 28.4% (CI: 23.2%–33.8%) for the entire population. Specifically, the death rate increased by 16.8% (11.9%–22.0%) in rural areas and by 46.6% (CI: 41.5%–51.8%) in the largest cities.

The impact of thermal stress was significantly more pronounced in cities, particularly in the largest cities (with 500,000 inhabitants as the threshold value), reflecting urban-rural disparities in excess mortality due to the heatwave. For example, the increase in the standardized death rate in cities with a population of more than one million was estimated

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to be 18.7% (CI: 12.4%–25.4%) larger than that in rural areas when controlling for thermal stress. The modification effects of air pollution were not found to be statistically significant.

Furthermore, the strength of the association between excess mortality and thermal stress increased with city size. The steepness of the "heat slopes" might indicate the varying responses to extreme heat based on the type and the size of the settlement. However, given the coarse spatial resolution of climate reanalysis, local conditions might have been disregarded, which may have resulted in the underestimation of urban heat island effects and unmeasured exposure to thermal stress and air pollution in the largest cities.

Supplementary material

Available online at https://doi.org/10.1553/p-42de-zc5p
Supplementary file 1. Tables S.1–S.7.

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References

Analitis, A., De' Donato, F., Scortichini, M., Lanki, T., Basagana, X., Ballester, F., Astrom, C., Paldy, A., Pascal, M., Gasparrini, A., Michelozzi, P., and Katsouyanni, K. (2018). Synergistic effects of ambient temperature and air pollution on health in Europe: Results from the PHASE project. *International Journal of Environmental Research and Public Health*, *15*(9), 1856. https://doi.org/10.3390/ijerph15091856

Analitis, A., Georgiadis, I., and Katsouyanni, K. (2012). Forest fires are associated with elevated mortality in a dense urban setting. *Occupational and Environmental Medicine*, *69*(3), 158–162. https://doi.org/10.1136/oem.2010.064238

Analitis, A., Michelozzi, P., D'Ippoliti, D., de'Donato, F., Menne, B., Matthies, F., Atkinson, R. W., Iñiguez, C., Basagaña, X., Schneider, A., Lefranc, A., Paldy, A., Bisanti, L., and Katsouyanni, K. (2014). Effects of heat waves on mortality: Effect modification and confounding by air pollutants. *Epidemiology*, *25*(1), 15–22. https://doi.org/10.1097/EDE.0b013e31828ac01b

Anderson, B. G., and Bell, M. L. (2009). Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States. *Epidemiology*, *20*(2), 205–213. https://doi.org/10.1097/EDE.0b013e318190ee08

Arbuthnott, K., Hajat, S., Heaviside, C., and Vardoulakis, S. (2016). Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. *Environmental Health*, *15*(S1), S33. https://doi.org/10.1186/s12940-016-0102-7

Ban, J., Su, W., Zhong, Y., Liu, C., and Li, T. (2022). Ambient formaldehyde and mortality: A time series analysis in China. *Science Advances*, *8*(26), eabm4097. https://doi.org/10.1126/sciadv.abm4097

Barnett, A. G., Tong, S., and Clements, A. C. A. (2010). What measure of temperature is the best predictor of mortality? *Environmental Research*, *110*(6), 604–611. https://doi.org/10.1016/j.envres.2010.05.006

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., and García-Herrera, R. (2011). The hot summer of 2010: Redrawing the temperature record map of Europe. *Science*, *332*(6026), 220–224. https://doi.org/10.1126/science.1201224

https://doi.org/10.1553/p-42de-zc5p

Basu, R. (2009). High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environmental Health*, *8*(1), 40. https://doi.org/10.1186/1476-069X-8-40

Boeckmann, M., and Rohn, I. (2014). Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. *BMC Public Health*, *14*(1), 1112. https://doi.org/10.1186/1471-2458-14-1112

Buechley, R. W., Van Bruggen, J., and Truppi, L. E. (1972). Heat island = death island? *Environmental Research*, *5*(1), 85–92. https://doi.org/10.1016/0013-9351(72)90022-9

Cao, J., Cheng, Y., Zhao, N., Song, W., Jiang, C., Chen, R., and Kan, H. (2009). Diurnal temperature range is a risk factor for coronary heart disease death. *Journal of Epidemiology*, *19*(6), 328–332. https://doi.org/10.2188/jea.JE20080074

Chen, K., Zhou, L., Chen, X., Ma, Z., Liu, Y., Huang, L., Bi, J., and Kinney, P. L. (2016). Urbanization level and vulnerability to heat-related mortality in Jiangsu Province, China. *Environmental Health Perspectives*, *124*(12), 1863–1869. https://doi.org/10.1289/EHP204

Chernykh, D. A., and Taseiko, O. V. (2018). Assessment of the risk mortality from thermal waves in Krasnoyarsk city. *Human Ecology*, *2*, 3–8. https://doi.org/10.33396/1728-0869-2018-2-3-8

Choi, H. M., Chen, C., Son, J.-Y., and Bell, M. L. (2021). Temperature-mortality relationship in North Carolina, USA: Regional and urban-rural differences. *Science of The Total Environment*, *787*, 147672. https://doi.org/10.1016/j.scitotenv.2021.147672

Choi, H. M., Lee, W., Heo, S., Urban, A., Entezari, A., Vicedo-Cabrera, A., Zanobetti, A., Analitis, A., Gasparrini, A., Tobias, A., Armstrong, B., Forsberg, B., Íñiguez, C., Åström, C., Roye, D., Indermitte, E., Lavigne, E., Mayvaneh, F., Acquaotta, F., … Bell, M. L. (2022). Effect modification of greenness on the association between heat and mortality: A multi-city multi-country study. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4064658

Chung, Y., Lim, Y.-H., Honda, Y., Guo, Y.-L. L., Hashizume, M., Bell, M. L., Chen, B.-Y., and Kim, H. (2015). Mortality related to extreme temperature for 15 cities in northeast Asia: *Epidemiology*, *26*(2), 255–262. https://doi.org/10.1097/EDE.0000000000000229

Cobelo, I., Castelhano, F. J., Borge, R., Roig, H. L., Adams, M., Amini, H., Koutrakis, P., and Réquia, W. J. (2023). The impact of wildfires on air pollution and health across land use categories in Brazil over a 16-year period. *Environmental Research*, *224*, 115522. https://doi.org/10.1016/j.envres.2023.115522

Comas-García, A., and Erdely, A. (2023). *A polynomial regression model for excess mortality in Mexico 2020-2022 due to the COVID-19 pandemic*. ArXiv. https://doi.org/10.48550/ARXIV.2311.15483

Curriero, F. C. (2002). Temperature and mortality in 11 cities of the eastern United States. *American Journal of Epidemiology*, *155*(1), 80–87. https://doi.org/10.1093/aje/155.1.80

De Schrijver, E., Royé, D., Gasparrini, A., Franco, O. H., and Vicedo-Cabrera, A. M. (2023). Exploring vulnerability to heat and cold across urban and rural populations in Switzerland. *Environmental Research: Health*, *1*(2), 025003. https://doi.org/10.1088/2752-5309/acab78

Gabriel, K. M. A., and Endlicher, W. R. (2011). Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environmental Pollution*, *159*(8–9), 2044–2050. https://doi.org/10.1016/j.envpol.2011.01.016

Graczyk, D., Pi skwar, I., and Chory ski, A. (2022). Heat-related mortality in two regions of Poland: Focus on urban and rural areas during the most severe and long-lasting heatwaves. *Atmosphere*, *13*(3), 390. https://doi.org/10.3390/atmos13030390

Grigoriev, P., Meslé, F., Shkolnikov, V. M., Andreev, E., Fihel, A., Pechholdova, M., and Vallin, J. (2014). The recent mortality decline in Russia: Beginning of the cardiovascular revolution? *Population and Development Review*, *40*(1), 107–129. https://doi.org/10.1111/j.1728-4457.2014.00652.x

Grigorieva, E. A. (2020). Heat and cold waves at the south of the Russian Far East in 1999-2017. *IOP Conference Series: Earth and Environmental Science*, *606*(1), 012016. https://doi.org/10.1088/1755-1315/606/1/012016

Grigorieva, E. A., and Revich, B. A. (2021). Health risks to the Russian population from temperature extremes at the beginning of the XXI century. *Atmosphere*, *12*(10), 1331. https://doi.org/10.3390/atmos12101331

Hajat, S., and Kosatky, T. (2010). Heat-related mortality: a review and exploration of heterogeneity. *Journal of Epidemiology and Community Health*, *64*(9), 753–760. https://doi.org/10.1136/jech.2009.087999

Henderson, S. B., Wan, V., and Kosatsky, T. (2013). Differences in heat-related mortality across four ecological regions with diverse urban, rural, and remote populations in British Columbia, Canada. *Health and Place*, *23*, 48–53. https://doi.org/10.1016/j.healthplace.2013.04.005

Heutel, G., Miller, N. H., and Molitor, D. (2021). Adaptation and the mortality effects of temperature across U.S. climate regions. *The Review of Economics and Statistics*, 1–14. https://doi.org/10.1162/rest_a_00936

Hu, K., Guo, Y., Hochrainer-Stigler, S., Liu, W., See, L., Yang, X., Zhong, J., Fei, F., Chen, F., Zhang, Y., Zhao, Q., Chen, G., Chen, Q., Zhang, Y., Ye, T., Ma, L., Li, S., and Qi, J. (2019). Evidence for urban–rural disparity in temperature–mortality relationships in Zhejiang Province, China. *Environmental Health Perspectives*, *127*(3), 037001. https://doi.org/10.1289/EHP3556

Inness, A., Ades, M., Agustí-Panareda, A., Barré, J., Benedictow, A., Blechschmidt, A.-M., Dominguez, J. J., Engelen, R., Eskes, H., Flemming, J., Huijnen, V., Jones, L., Kipling, Z., Massart, S., Parrington, M., Peuch, V.-H., Razinger, M., Remy, S., Schulz, M., and Suttie, M. (2019). The CAMS reanalysis of atmospheric composition. *Atmospheric Chemistry and Physics*, *19*(6), 3515–3556. https://doi.org/10.5194/acp-19-3515-2019

IPCC. (2023). *Climate Change 2022 – Impacts, adaptation and vulnerability: Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Jagai, J. S., Grossman, E., Navon, L., Sambanis, A., and Dorevitch, S. (2017). Hospitalizations for heat-stress illness varies between rural and urban areas: an analysis of Illinois data, 1987–2014. *Environmental Health*, *16*(1), 38. https://doi.org/10.1186/s12940-017-0245-1

Jegasothy, E., McGuire, R., Nairn, J., Fawcett, R., and Scalley, B. (2017). Extreme climatic conditions and health service utilisation across rural and metropolitan New South Wales. *International Journal of Biometeorology*, *61*(8), 1359–1370. https://doi.org/10.1007/s00484-017-1313-5

Katsouyanni, K., Pantazopoulou, A., Touloumi, G., Tselepidaki, I., Moustris, K., Asimakopoulos, D., Poulopoulou, G., and Trichopoulos, D. (1993). Evidence for interaction between air pollution and high temperature in the causation of excess mortality. *Archives of Environmental Health: An International Journal*, *48*(4), 235–242. https://doi.org/10.1080/00039896.1993.9940365

Kolosov, V. A., and Nefedova, T. G. (2014). Cities, rural areas and urbanization: Russia and the world. *Regional Research of Russia*, *4*(2), 68–75. https://doi.org/10.1134/S2079970514020099

Konstantinov, P. I., Varentsov, M. I., and Shartova, N. V. (2022). North Eurasian thermal comfort indices dataset (NETCID): new gridded database for the biometeorological studies. *Environmental Research Letters*, *17*(8), 085006. https://doi.org/10.1088/1748-9326/ac7fa9

Kovach, M. M., Konrad, C. E., and Fuhrmann, C. M. (2015). Area-level risk factors for heat-related illness in rural and urban locations across North Carolina, USA. *Applied Geography*, *60*, 175–183. https://doi.org/10.1016/j.apgeog.2015.03.012

Kuchcik, M. (2021). Mortality and thermal environment (UTCI) in Poland—long-term, multi-city study. *International Journal of Biometeorology*, *65*(9), 1529–1541. https://doi.org/10.1007/s00484-020-01995-w

Lee, M., Shi, L., Zanobetti, A., and Schwartz, J. D. (2016). Study on the association between ambient temperature and mortality using spatially resolved exposure data. *Environmental Research*, *151*, 610–617. https://doi.org/10.1016/j.envres.2016.08.029

Lee, W., Choi, M., Bell, M. L., Kang, C., Jang, J., Song, I., Kim, Y.-O., Ebi, K., and Kim, H. (2022). Effects of urbanization on vulnerability to heat-related mortality in urban and rural areas in South Korea: a nationwide district-level time-series study. *International Journal of Epidemiology*, *51*(1), 111–121. https://doi.org/10.1093/ije/dyab148

Lin, H., Zhang, Y., Xu, Y., Xu, X., Liu, T., Luo, Y., Xiao, J., Wu, W., and Ma, W. (2013). Temperature changes between neighboring days and mortality in summer: A distributed lag non-linear time series analysis. *PLoS ONE*, *8*(6), e66403. https://doi.org/10.1371/journal.pone.0066403

Lo, Y. T. E., Mitchell, D. M., Buzan, J. R., Zscheischler, J., Schneider, R., Mistry, M. N., Kyselý, J., Lavigne, É., Da Silva, S. P., Royé, D., Urban, A., Armstrong, B., Multi Country Multi City (MCC) Collaborative Research Network, Gasparrini, A., and Vicedo Cabrera, A. M. (2023). Optimal heat stress metric for modelling heat related mortality varies from country to country. *International Journal of Climatology*, *43*(12), 5553–5568. https://doi.org/10.1002/joc.8160

López-Bueno, J. A., Navas-Martín, M. A., Díaz, J., Mirón, I. J., Luna, M. Y., Sánchez-Martínez, G., Culqui, D., and Linares, C. (2022). Analysis of vulnerability to heat in rural and urban areas in Spain: What factors explain heat's geographic behavior? *Environmental Research*, *207*, 112213. https://doi.org/10.1016/j.envres.2021.112213

Ma, W., Zeng, W., Zhou, M., Wang, L., Rutherford, S., Lin, H., Liu, T., Zhang, Y., Xiao, J., Zhang, Y., Wang, X., Gu, X., and Chu, C. (2015). The short-term effect of heat waves on mortality and its modifiers in China: An analysis from 66 communities. *Environment International*, *75*, 103–109. https://doi.org/10.1016/j.envint.2014.11.004

Meehl, G. A., and Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, *305*(5686), 994–997. https://doi.org/10.1126/science.1098704

Mistry, M. N., Schneider, R., Masselot, P., Royé, D., Armstrong, B., Kyselý, J., Orru, H., Sera, F., Tong, S., Lavigne, É., Urban, A., Madureira, J., García-León, D., Ibarreta, D., Ciscar, J.-C., Feyen, L., de Schrijver, E., de Sousa Zanotti Stagliorio Coelho, M., Pascal, M., … Gasparrini, A. (2022). Comparison of weather station and climate reanalysis data for modelling temperature-related mortality. *Scientific Reports*, *12*(1), 5178. https://doi.org/10.1038/s41598-022-09049-4

Morabito, M., Crisci, A., Messeri, A., Capecchi, V., Modesti, P. A., Gensini, G. F., and Orlandini, S. (2014). Environmental temperature and thermal indices: What is the most effective predictor of heat-related mortality in different geographical contexts? *The Scientific World Journal*, *2014*, 1–15. https://doi.org/10.1155/2014/961750

Nepomuceno, M. R., Klimkin, I., Jdanov, D. A., Alustiza Galarza, A., and Shkolnikov, V. M. (2022). Sensitivity Analysis of Excess Mortality due to the COVID 19 Pandemic. *Population and Development Review*, *48*(2), 279–302. https://doi.org/10.1111/padr.12475

Otrachshenko, V., Popova, O., and Solomin, P. (2017). Health consequences of the Russian weather. *Ecological Economics*, *132*, 290–306. https://doi.org/10.1016/j.ecolecon.2016.10.021

Otrachshenko, V., Popova, O., and Solomin, P. (2018). Misfortunes never come singly: Consecutive weather shocks and mortality in Russia. *Economics and Human Biology*, *31*, 249–258. https://doi.org/10.1016/j.ehb.2018.08.008

Revich, B.A. (2011). Volny zhary, kachestvo atmosfernogo vozduha i smertnost' naseleniya Evropejskoj chasti Rossii letom 2010 goda: rezul'taty predvaritel'noj ocenki [Heatwaves, air quality anf mortality in European part of Russia on summer 2010: the results of preliminary esimates]. *Ecologiya cheloveka*, *7*, 3–9.

Revich, B. A. (2019). Heat-waves in metropolises and thresholds of their impact on public health. *Hygiene and Sanitation*, *96*(11), 1073–1078. https://doi.org/10.18821/0016-9900-2017-96-11-1073-1078

Revich, B. A., and Shaposhnikov, D. A. (2010). Extreme temperature episodes and mortality in Yakutsk, East Siberia. *Rural and Remote Health*, *10*(2), 1338.

Revich, B. A., and Shaposhnikov, D. A. (2017). Influence features of cold and heat waves to the population mortality – the city with sharply continental climate. *Siberian Medical Review*, *2*, 84–90. https://doi.org/10.20333/2500136-2017-2-84-90

Revich, B. A., Shaposhnikov, D. A., Podol'naya, M. A., Khor'kova, T. L., and Kvasha, E. A. (2015). Heat waves in southern cities of European Russia as a risk factor for premature mortality. *Studies on Russian Economic Development*, *26*(2), 142–150. https://doi.org/10.1134/S1075700715020100

Robine, J.-M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P., and Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies*, *331*(2), 171–178. https://doi.org/10.1016/j.crvi.2007.12.001

Semenza, J. C., Rubin, C. H., Falter, K. H., Selanikio, J. D., Flanders, W. D., Howe, H. L., and Wilhelm, J. L. (1996). Heat-related deaths during the July 1995 heat wave in Chicago. *New England Journal of Medicine*, *335*(2), 84–90. https://doi.org/10.1056/NEJM199607113350203

Sera, F., Armstrong, B., Tobias, A., Vicedo-Cabrera, A. M., Åström, C., Bell, M. L., Chen, B.-Y., De Sousa Zanotti Stagliorio Coelho, M., Matus Correa, P., Cruz, J. C., Dang, T. N., Hurtado-Diaz, M., Do Van, D., Forsberg, B., Guo, Y. L., Guo, Y., Hashizume, M., Honda, Y., Iñiguez, C., … Gasparrini, A. (2019). How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. *International Journal of Epidemiology*, *48*(4), 1101–1112. https://doi.org/10.1093/ije/dyz008

https://doi.org/10.1553/p-42de-zc5p

Sera, F., Hashizume, M., Honda, Y., Lavigne, E., Schwartz, J., Zanobetti, A., Tobias, A., Iñiguez, C., Vicedo-Cabrera, A. M., Blangiardo, M., Armstrong, B., and Gasparrini, A. (2020). Air conditioning and heat-related mortality: A multi-country longitudinal study. *Epidemiology*, *31*(6), 779–787. https://doi.org/10.1097/EDE.0000000000001241

Shaposhnikov, D., and Revich, B. (2016). Toward meta-analysis of impacts of heat and cold waves on mortality in Russian north. *Urban Climate*, *15*, 16–24. https://doi.org/10.1016/j.uclim.2015.11.007

Shaposhnikov, D., Revich, B., Bellander, T., Bedada, G. B., Bottai, M., Kharkova, T., Kvasha, E., Lezina, E., Lind, T., Semutnikova, E., and Pershagen, G. (2014). Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. *Epidemiology (Cambridge, Mass.)*, *25*(3), 359–364. https://doi.org/10.1097/EDE.0000000000000090

Shartova, N. V., Shaposhnikov, D. A., Konstantinov, P. I., and Revich, B. A. (2019). Universal thermal climate index (UTCI) applied to determine thresholds for temperature-related mortality. *Health Risk Analysis*, *3*, 83–93. https://doi.org/10.21668/health.risk/2019.3.10.eng

Shchur, A. (2019). Cities of over a million people on the mortality map of Russia. *Demographic Review*, 64–84. https://doi.org/10.17323/demreview.v5i5.10179

Shchur, A., Shkolnikov, V. M., Timonin, S., Andreev, E., and Leon, D. A. (2021). Where do people live longer in Russia in the 21st century? Life expectancy across urban and rural areas. *Population and Development Review*, *47*(4), 1049–1074. https://doi.org/10.1111/padr.12437

Sheridan, S., and Dolney, T. (2003). Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, USA. *Climate Research*, *24*, 255–265. https://doi.org/10.3354/cr024255

Shkolnikov, V. M., Andreev, E. M., McKee, M., and Leon, D. A. (2013). Components and possible determinants of decrease in Russian mortality in 2004-2010. *Demographic Research*, *28*, 917–950. https://doi.org/10.4054/DemRes.2013.28.32

Sitnov, S. A. (2011). Satellite monitoring of atmospheric gaseous species and optical characteristics of atmospheric aerosol over the European part of Russia in April–September 2010. *Doklady Earth Sciences*, *437*(1), 368–373. https://doi.org/10.1134/S1028334X11030081

Spangler, K. R., Weinberger, K. R., and Wellenius, G. A. (2019). Suitability of gridded climate datasets for use in environmental epidemiology. *Journal of Exposure Science and Environmental Epidemiology*, *29*(6), 777–789. https://doi.org/10.1038/s41370-018-0105-2

Spangler, K. R., and Wellenius, G. A. (2021). Spatial and intraseasonal variation in changing susceptibility to extreme heat in the United States. *Environmental Epidemiology*, *5*(2), e136. https://doi.org/10.1097/EE9.0000000000000136

Stafoggia, M., Michelozzi, P., Schneider, A., Armstrong, B., Scortichini, M., Rai, M., Achilleos, S., Alahmad, B., Analitis, A., Åström, C., Bell, M. L., Calleja, N., Krage Carlsen, H., Carrasco, G., Paul Cauchi, J., Dszs Coelho, M., Correa, P. M., Diaz, M. H., Entezari, A., … De' Donato, F. K. (2023). Joint effect of heat and air pollution on mortality in 620 cities of 36 countries. *Environment International*, *181*, 108258. https://doi.org/10.1016/j.envint.2023.108258

Tait, P. W., Allan, S., and Katelaris, A. L. (2018). Preventing heat-related disease in general practice. *Australian Journal of General Practice*, *47*(12), 835–840. https://doi.org/10.31128/AJGP-07-18-4658

Timonin, S., Danilova, I., Andreev, E., and Shkolnikov, V. M. (2017). Recent mortality trend reversal in Russia: Are regions following the same tempo? *European Journal of Population*, *33*(5), 733–763. https://doi.org/10.1007/s10680-017-9451-3

Timonin, S., Jasilionis, D., Shkolnikov, V. M., and Andreev, E. (2020). New perspective on geographical mortality divide in Russia: a district-level cross-sectional analysis, 2008–2012. *Journal of Epidemiology and Community Health*, *74*(2), 144–150. https://doi.org/10.1136/jech-2019-213239

Urban, A., Davídkovová, H., and Kyselý, J. (2014). Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. *International Journal of Biometeorology*, *58*(6), 1057–1068. https://doi.org/10.1007/s00484-013-0693-4

Urban, A., Di Napoli, C., Cloke, H. L., Kyselý, J., Pappenberger, F., Sera, F., Schneider, R., Vicedo-Cabrera, A. M., Acquaotta, F., Ragettli, M. S., Íñiguez, C., Tobias, A., Indermitte, E., Orru, H., Jaakkola, J. J. K., Ryti, N. R. I., Pascal, M., Huber, V., Schneider, A., … Gasparrini, A. (2021). Evaluation of the ERA5 reanalysis-based Universal Thermal Climate Index on mortality data in Europe. *Environmental Research*, *198*, 111227. https://doi.org/10.1016/j.envres.2021.111227

Vaneckova, P., Neville, G., Tippett, V., Aitken, P., FitzGerald, G., and Tong, S. (2011). Do biometeorological indices improve modelling outcomes of heat-related mortality? *Journal of Applied Meteorology and Climatology*, *50*(6), 1165–1176. https://doi.org/10.1175/2011JAMC2632.1

Vicedo-Cabrera, A. M., Forsberg, B., Tobias, A., Zanobetti, A., Schwartz, J., Armstrong, B., and Gasparrini, A. (2016). Associations of inter- and intraday temperature change with mortality. *American Journal of Epidemiology*, *183*(4), 286–293. https://doi.org/10.1093/aje/kwv205

Wang, C., Zhang, Z., Zhou, M., Wang, P., Yin, P., Ye, W., and Zhang, L. (2018). Different response of human mortality to extreme temperatures (MoET) between rural and urban areas: A multiscale study across China. *Health and Place*, *50*, 119–129. https://doi.org/10.1016/j.healthplace.2018.01.011

Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., and Tong, S. (2019). Assessing heatwave impacts on cause-specific emergency department visits in urban and rural communities of Queensland, Australia. *Environmental Research*, *168*, 414–419. https://doi.org/10.1016/j.envres.2018.10.013

Zeng, P., Sun, F., Liu, Y., Chen, C., Tian, T., Dong, Q., and Che, Y. (2022). Significant social inequalities exist between hot and cold extremes along urban-rural gradients. *Sustainable Cities and Society*, *82*, 103899. https://doi.org/10.1016/j.scs.2022.103899

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A. M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S.-C., . . . Li, S. (2021). Global, regional, and national burden of mortality associated with nonoptimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *The Lancet Planetary Health*, *5*(7), e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4

Zhou, M. G., Wang, L. J., Liu, T., Zhang, Y. H., Lin, H. L., Luo, Y., Xiao, J. P., Zeng, W. L., Zhang, Y. W., Wang, X. F., Gu, X., Rutherford, S., Chu, C., and Ma, W. J. (2014). Health impact of the 2008 cold spell on mortality in subtropical China: the climate and health impact national assessment study (CHINAs). *Environmental Health*, *13*(1), 60. https://doi.org/10.1186/1476-069X-13-60

https://doi.org/10.1553/p-42de-zc5p