Temporal changes of heat-attributable mortality in Prague, Czech Republic, over 1982–2019

Urban Climate 44 (2022) 101197

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Temporal changes of heat-attributable mortality in Prague, Czech Republic, over 1982–2019

Aleš Urban [a,b,*], Osvaldo Fonseca-Rodríguez [a,c,d], Claudia Di Napoli [e,f], Eva Plavcová [b]

[a] Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic
[b] Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czech Republic
[c] Department of Epidemiology and Global Health, Umeå University, Umeå, Sweden
[d] Centre for Demographic and Ageing Research, Umeå University, Umeå, Sweden
[e] School of Agriculture, Policy and Development, University of Reading, Reading, United Kingdom
[f] Department of Geography and Environmental Science, University of Reading, Reading, United Kingdom

A R T I C L E I N F O

Keywords:
Heat-attributable deaths
Heat-attributable fraction
Temporal changes
Trend reversal

A B S T R A C T

While previous research on historical changes in heat-related mortality observed decreasing trends over the recent decades, future projections suggest increasing impact of heat on mortality in most regions of the world. This study aimed to analyse temporal changes in temperature-mortality relationships in Prague, Czech Republic in the warm season (May–September), using a daily mortality time series from 1982 to 2019. To investigate possible effect of adaptation to increasing temperature, we divided the study period into four decades (1980s–2010s). We used conditional Poisson regression models to identify decade-specific relative risk of heat-related mortality and to calculate the annual number of heat-attributable deaths and the heat-attributable fraction of total warm season deaths. We estimated their trends over the whole study period by a generalized additive model with non-parametric smoothing spline. Our results showed that the unprecedentedly hot 2010s was associated with approximately twice as large relative risk of heat-related mortality than in previous decades. This resulted in the reversal of the trend in heat-attributable mortality in the 1990s and its increase during the last two decades. Our findings highlight the importance of further improvement of adaptation measures such as heat-and-health warning systems to protect the heat-susceptible population.

1. Introduction

In association with climate change, increased frequency and magnitude of heatwaves are projected in Europe for the 21st century (e.g., Lau and Nath, 2014; Molina et al., 2020; IPCC, 2021). Hot summers, such as those in 2015 (Russo et al., 2015; Hoy et al., 2016), 2018 (Hoy et al., 2020) and 2019 (Sousa et al., 2020), may be examples of the 'shape of things to come' as to summer weather in a future Central-European climate (Lhotka et al., 2017). Increases in heat-related mortality have been projected under future climate change scenarios (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018b; Lee et al., 2019) and the impact of climate change on human health is detectable already today. A recent study analysing data from 735 locations in 43 countries (including Prague) suggests that

* Corresponding author at: Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic.
E-mail address: urban@ufa.cas.cz (A. Urban).

https://doi.org/10.1016/j.uclim.2022.101197
Received 3 January 2022; Received in revised form 17 April 2022; Accepted 25 May 2022
Available online 9 June 2022

every third heat-related death during 1990–2015 was attributable to climate change (Vicedo-Cabrera et al., 2021). These findings are seemingly in contrast to the declining vulnerability to extremely high temperatures in recent decades reported mainly in developed countries of North America, Europe, and East Asia (Sheridan and Allen, 2018; Vicedo-Cabrera et al., 2018a; Achebak et al., 2019; Lay et al., 2021).

Although most studies projecting the impact of climate change on heat-related mortality simply extrapolate the current temperature–mortality relationship into the future (e.g., Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018b; Martínez-Solanas et al., 2021), empirical studies have demonstrated that the non-optimal temperature range associated with increased mortality risk depends upon the temperature distribution in a given geographical location (Tobías et al., 2017; Tobías et al., 2021). Similarly, the effect of adaptation to changing temperature distribution (i.e., acclimatization) over time has been documented (Chung et al., 2018; Vicedo-Cabrera et al., 2018a). It is therefore important to consider variations in temperature characteristics when long-term changes in temperature-related mortality are investigated.

In the Czech Republic, earlier studies reported significant decline in heat-related mortality between the 1980s and 2000s associated with positive socioeconomic development after the political transition in Central and Eastern Europe around 1990 (Kyselý and Kříž, 2008; Kyselý and Plavcová, 2012). Nevertheless, an abatement of this decline, possibly related to increased frequency and intensity of heatwaves and changes in the population age structure, has been documented recently (Urban et al., 2017; Urban et al., 2020). This has been supported by studies from other Central-European regions that reported significant impact of recent heatwaves on mortality in Germany (Muthers et al., 2017), Slovakia (Výberči et al., 2018), small Czech cities (Arsenović et al., 2019a) and Serbia (Arsenović et al., 2019b). Central-European cities, including Prague, the Czech Republic's capital, have recently been identified as cities with the largest increases in daily maximum temperatures by the end of the century under the high impact (RCP8.5) climate change scenario (Guerreiro et al., 2018). Within this context, understanding how exposure to heat and associated mortality have changed in Prague in the recent past can serve as a platform for future projections of heat-related mortality within the whole region.

The goal of the present study was to analyse historical changes in the effect of heat on mortality in Prague. For the first time, we consider the effect of acclimatization to increasing temperatures over the study period. More specifically, using the longest daily mortality time series available to date, covering the period 1982–2019 (38 years), we investigated the association between mortality and temperature in the warm season (May–September) separately in four decades (1980s–2010s). Applying the distributed lag non-linear model framework (Gasparrini et al., 2010; Gasparrini and Leone, 2014) and based upon decade-specific exposure-response functions, we estimated heat-attributable mortality in each year of the study period. The overall trend of heat-attributable mortality was estimated using a generalized additive model (GAM) with non-parametric smoothing spline (Wood, 2006).

2. Data and methods

2.1. Data

We used daily number of deaths in Prague, Czech Republic during 1982–2019. Because before 1994, additional information about sex, age, cause of death was not available, we considered all-cause deaths. The data were collected by the Czech Statistical Office and the Institute of Health Information and Statistics of the Czech Republic. Prague is the largest urban area in the Czech Republic and one of the major metropolitan areas in Central Europe. Its average population count over the study period was 1.2 million inhabitants and the total number of deaths analysed in the period May–September 1982–2019 was 213,313.

To analyse temperature characteristics, we used daily mean air temperature from the Prague–Ruzyně meteorological station provided by the Czech Hydrometeorological Institute.

2.2. Methods

Since the aim of this study was to analyse temporal changes in heat-related mortality, the study was restricted to the warm season (May–September). In order to take into account, the effect of acclimatization to increasing temperature, the 38-year study period (1982–2019) was divided into four decades. Specifically, decade 1 (1980s) comprised the years 1982–1989, decade 2 (1990s) the years 1990–1999, decade 3 (2000s) the years 2000–2009, and decade 4 (2010s) the years 2010–2019. Because the available mortality datasets in the Czech Republic start in 1982, it was not possible to extend the first decade back to 1980.

2.2.1. Analysis of temperature characteristics

In the first stage of the study, we analysed temporal variations in the temperature characteristics of individual decades. For this purpose, one single temperature threshold was used across the entire study period. A hot day was defined as a day with daily mean temperature higher than the 95th percentile of its May–September distribution (23.1 °C). Although there is no universally accepted definition in public health studies, the 95th percentile of a temperature distribution is generally understood as a threshold of a heatwave according to the WHO and WMO Guidance on Warning-System Development (McGregor et al., 2015). We used daily mean temperature threshold to define heat in the present study because it represents the whole-day heat exposure better than does a single temperature extreme and excludes days with cold nights. A heatwave was defined as a period of at least 2 consecutive hot days according to the recommendation by Robinson (2001). We found this definition useful also in previous studies (Kyselý et al., 2011; Urban et al., 2020) because the events lasting at least 2 days were associated with much larger and more significant mortality impacts than were single isolated days. The differences between 3-day and 2-day events, on the other hand, were minor. To quantify the overall intensity of heatwaves in each year, we calculated the Heat Wave Index (HWI) as the sum of temperature deviations (in °C) above the

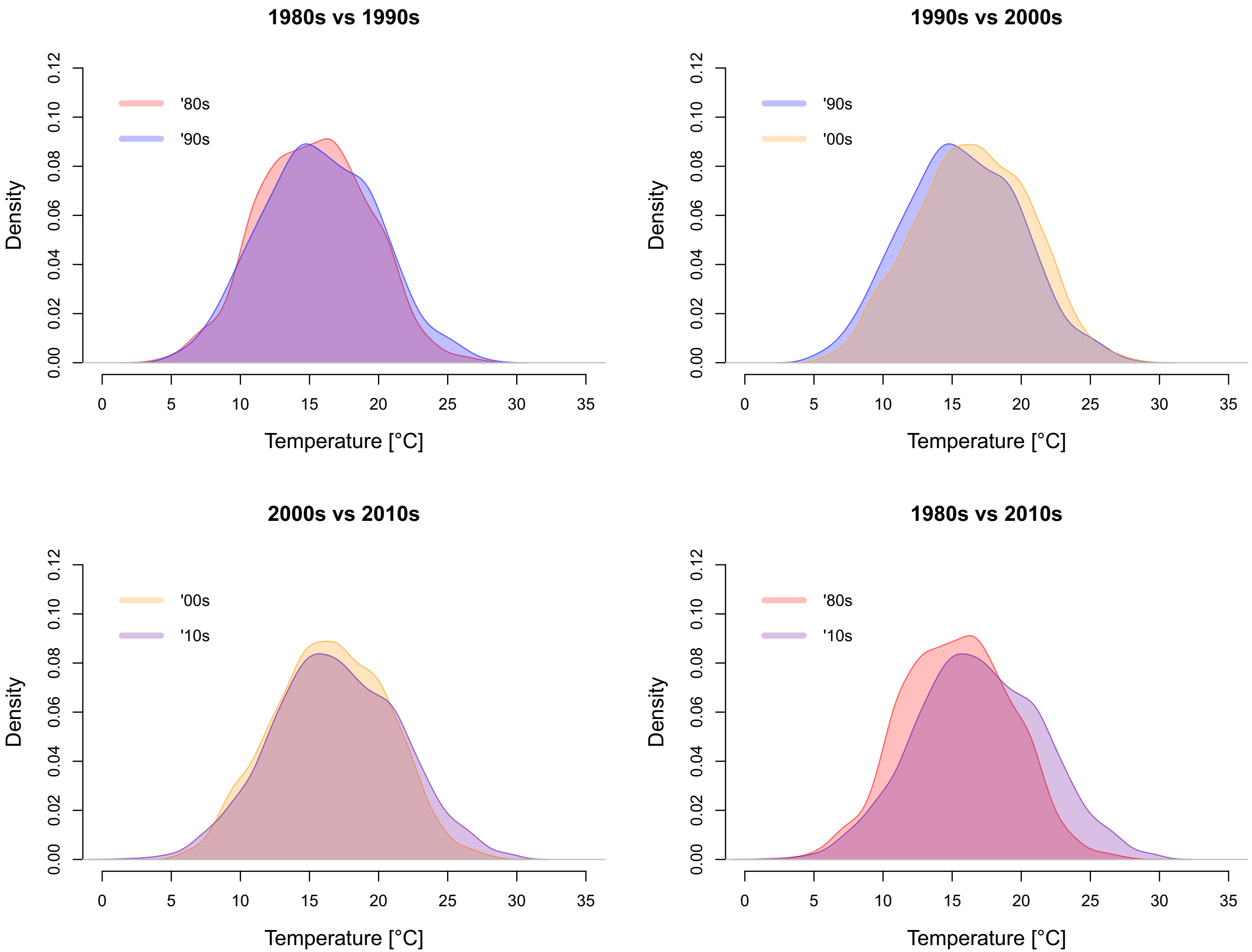

Fig. 1. Changes of the decade-specific temperature distributions in Prague, May–September 1982–2019.

95th percentile of the daily mean temperature distribution on heatwave days for each year. This index characterizes the combined effect of heatwaves' duration and temperature anomalies.

2.2.2. *Analysis of exposure-response relationships between temperature and mortality*

When assessing temporal changes in the effect of heat on mortality over a longer period, potential acclimatization to increasing temperatures needs to be considered. In order to derive decade-specific temperature–mortality associations, conditional Poisson regression models were run separately in each decade. A stratum indicator variable composed of year, month, and day of the week was used to control for long-term and seasonal trends (following Armstrong et al., 2014, Fonseca-Rodríguez et al., 2020). Temperature was introduced into the models as a cross-basis function describing the non-linear and delayed effect of temperature. Specifically, we applied distributed lag non-linear models (DLNM) to estimate a common exposure-response function using a quadratic B-spline with one internal knot placed at the 75th percentile of the decade-specific warm season (May–September) daily mean temperature distribution (hereinafter referred to as "decade-specific temperature distribution") and a lag-response function using a natural cubic spline with two equally spaced internal knots on the log-scale (Gasparrini et al., 2010, the R package *dlnm*). A maximum lag of 10 days was used to account for the lagged heat effect and short-term harvesting. Modelling choices were tested in a sensitivity analysis changing the type of spline, as well as the position and number of knots, and extending the lag windows up to 14 days to consider longer delays in the effect of heat. Sensitivity analyses confirmed selection of the main model.

The relative risks (RRs) of temperature-related mortality were calculated separately for each decade with the reference value at the 50th percentile of the decade-specific temperature distribution. Values of RRs at the 99th percentile are presented in results. In addition, the attributable number of deaths (AD) and the attributable fraction (AF in %) of total warm season deaths on days above the 95th percentile of the decade-specific temperature distribution were calculated for each year and decade. The attributable measures were estimated using the methodology developed by Gasparrini and Leone (2014) within the DLNM framework (function *attrdl* from the R package *FluMoDL*), which takes into account the additional temporal dimension of the temperature–mortality association when providing risk estimates. For each day, the AF of mortality due to temperature was estimated by combining the risks on the given and previous days according to the predefined lag window (0–10 days). The daily AD was calculated by multiplying the daily AF by the daily number of total deaths. The total AD was given by the sum of the AD for all the days above the 95th percentile of the decade-specific temperature distribution.

The statistical significance of the difference between the decade-specific RRs was evaluated by an interaction test according to Altman and Bland (2003, 2011), using the following formula:

$$Z = \frac{E1 - E2}{\sqrt{SE1^2 + SE2^2}}$$

where Z is the *Z*-test, E_1 and E_2 are the effect estimates for two periods (decades), and SE_1 and SE_2 are their respective standard errors.

Finally, the trends in AD and AF over the study period were estimated by GAMs with non-parametric smoothing splines to describe non-linear relationships (Wood, 2006, the R package *mgcv*). The final model's choice was made automatically by minimizing the generalized cross-validation (GCV) score. The GCV score is a measure of goodness of fit in GAMs that takes into account the effective degrees of freedom of the model (Wood, 2006). This approach allowed us to estimate a trend function without assuming any specific shape. The resulting trend was less sensitive to outliers compared to traditional ordinary least square regression.

3. Results

3.1. *Temperature characteristics of the four decades*

Fig. 1 represents the decade-specific temperature distributions in Prague. The results are in line with the globally observed trend of increasing mean and variance of the temperature distribution with a change in asymmetry toward the upper tail of the distribution (IPCC, 2021). This appears especially when comparing the distributions from the 1980s and 2010s (Table 1). The mean temperature (standard deviation) was 15.3 (3.9) °C in the 1980s, compared to 16.9 (4.5) °C in the 2010s. The change in the temperature distribution was associated with increase in both heatwave duration and intensity (Table 1; Fig. 2). While the average number of heatwave days was 3 per year in the 1980s (with a peak of 10 days in 1983), it increased to 11 days per year in the 2010s. The maximum of 25 days was recorded in 2015, which also was the year with the largest total number of heatwave days during the study period, followed by 2018 (21 days), 1994 (20 days) and 2019 (17 days). The average length of a heatwave was 2.2 days in the 1980s but 3.3 days in the 2010s

Table 1

Temperature and heatwave (HW) characteristics of warm seasons (May–September) in the four decades from 1982 to 2019 in Prague, Czech Republic.

	Tmean (SD)[a] (°C)	Mean number of HW days per year	Mean HW length per year (days)	Mean HW number per year	HWI[b] per year (°C)
1980s	15.3 (3.9)	2.6	2.2	1.3	3.8
1990s	15.7 (4.2)	4.9	2.4	1.9	9.0
2000s	16.5 (4.1)	5.1	2.6	1.9	9.2
2010s	16.9 (4.5)	11.0	3.3	3.3	24.6

[a] Mean warm season (May–September) temperature in a given decade and its standard deviation.

[b] Heat Wave Index.

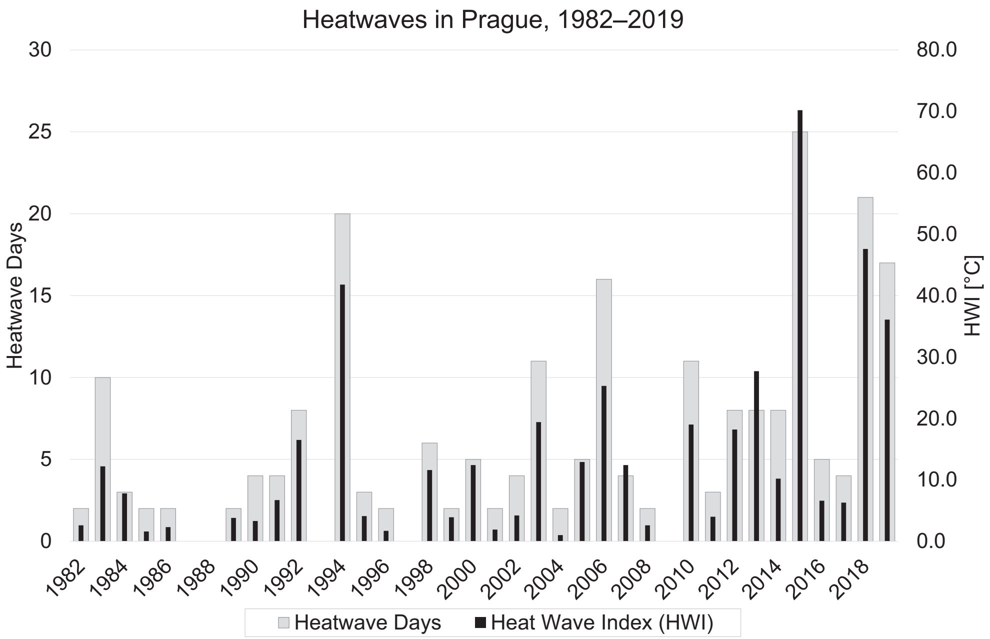

Fig. 2. Duration (Heatwave Days) and intensity of heatwaves (Heat Wave Index) in Prague, 1982–2019.

(Table 1). The mean intensity of heatwaves per year in the 2010s, as represented by the HWI, was more than six times that in the 1980s (24.6 °C in 2010s vs 3.8 °C in 1980s).

3.2. Relationships between temperature and relative mortality risk

Fig. 3 compares cumulative (over the 10-day lag) temperature–mortality associations in the four decades. The record-breaking intensity and frequency of heatwaves in the last decade documented that our results were in accordance with the increased risk of mortality (RR) due to high temperatures in Prague. A visual comparison of the exposure-response curves reveals a reduced RR associated with the extremely high temperatures in the 1990s and 2000s compared to the 1980s and also that RR increased again in the last decade.

Table 2 illustrates temperature characteristics of days above the decade-specific thresholds and related mortality characteristics. While in the first three decades, the cumulative RR of death at the 99th percentile of the decade-specific temperature distribution was about 20% higher than at the 50th percentile (1.22, 1.19, and 1.24 in the 1980s, 1990s, and 2000s, respectively), it more than doubled in the 2010s (1.50). The differences in RR between the 1980s, 1990s, and 2000s were negligible and statistically insignificant, whereas the RR was significantly larger in the 2010s ($p = 0.06$, 0.04, and 0.08, respectively; Table 3). In terms of the total number of heat-attributable deaths, the burden increased from approximately 50 deaths per year (61, 43, and 53 deaths per warm season in the 1980s, 1990s, and 2000s, respectively) to almost 90 heat-attributable deaths per year in the 2010s. This corresponds to the fraction of 0.90, 0.73, 1.03, and 1.75%, respectively, of the total number of deaths in the warm season.

3.3. Trends in heat-attributable deaths

The GAM analysis of trends in heat-attributable deaths (AD) and fraction (AF) of the total warm season deaths in individual years revealed a U- (AD) and J- (AF) shaped trend, respectively, with minimum AD and AF in the 1990s and maximum in the 2010s (Fig. 4). The smoothed trend estimate for AF was statistically significant at $p < 0.1$. Fig. 4 shows that although 1994 was the year with the third-largest impact on heat-related mortality over the four decades, the impacts of other years in the 1990s were relatively weak. In the 2010s, on the other hand, we observed four out of eight years with AD larger than 100 deaths. The year 2015 was record-breaking year regarding AD (271 deaths) and AF (5.4%), followed by 2018 and 1994.

4. Discussion

Most epidemiological studies on this subject have documented decline in heat-related mortality in developed countries during the second half of the 20th century and its abatement in the late 1990s and/or 2000s (Hondula et al., 2015; Arbuthnott et al., 2016; Sheridan and Allen, 2018; Vicedo-Cabrera et al., 2018b; Achebak et al., 2019). Accordingly, Kyselý and Plavcová (2012) reported a significant decline in heat-related mortality in the Czech Republic between 1986 and 2009. Positive socioeconomic development following the collapse of communism in Central and Eastern Europe in 1989 and better public awareness of heat-related risks were

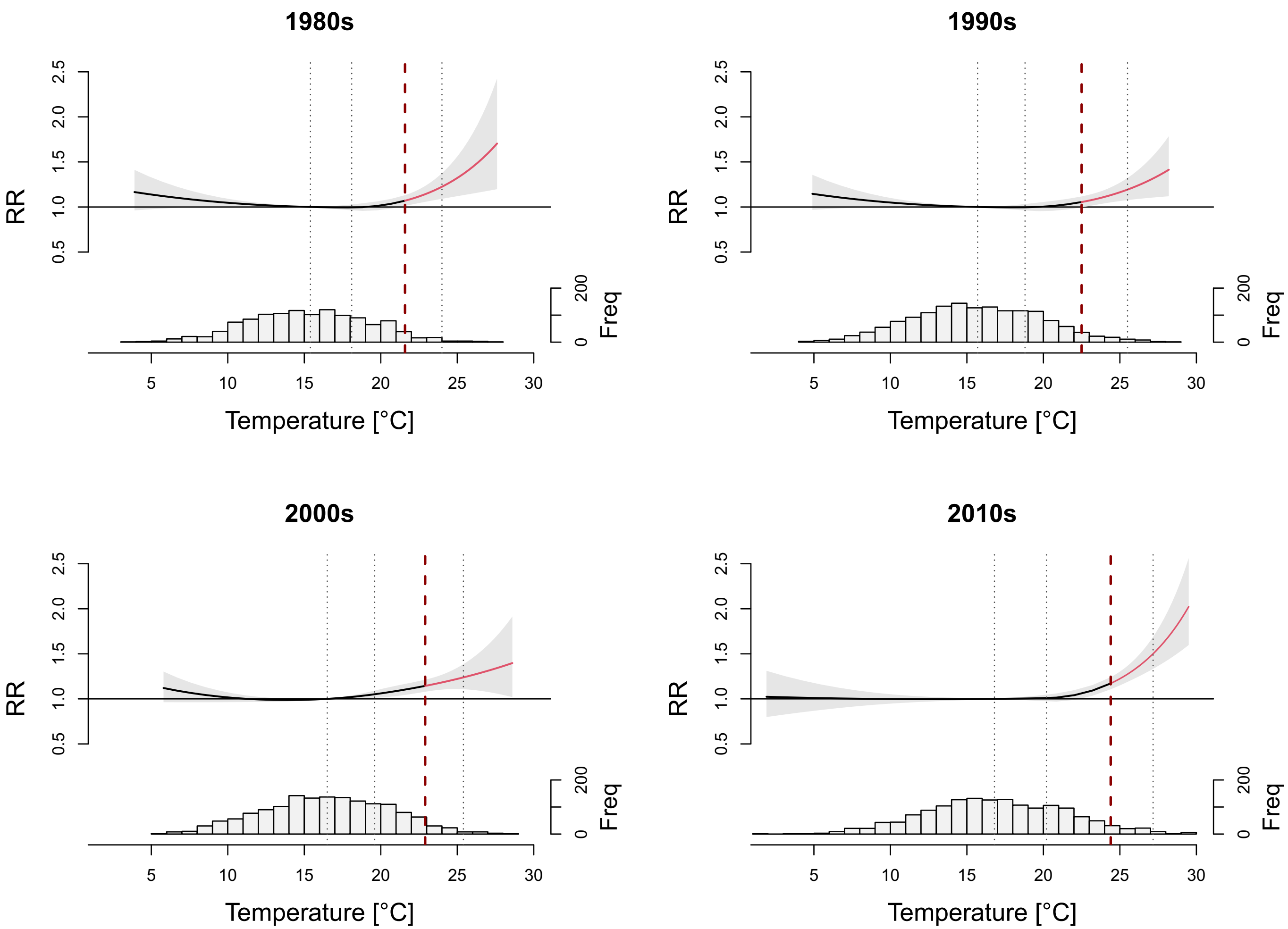

Fig. 3. Cumulative (lags of 0–10 days) exposure-response associations between relative mortality risk (RR, centred at the 50th percentile of the decade-specific temperature distribution) and daily mean temperature during May–September in four decades between 1982 and 2019. Histograms represent the daily mean temperature distribution in each decade. Grey (dark red) vertical lines denote the 50th, 75th, and 99th (95th) percentiles of the decade-specific temperature distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Temperature and heat-related mortality characteristics on days above the 95th percentile in the four decades during 1982–2019 in Prague.

	T (°C)[a]	RR (Q99)[b]	AD per year[c]	AF (%)[d]
1980s	23.1	1.22 (1.09, 1.37)	61 (32, 89)	0.90 (0.46, 1.34)
1990s	24.3	1.19 (1.08, 1.32)	43 (20,65)	0.73 (0.37,1.10)
2000s	24.4	1.24 (1.11, 1.39)	53 (29,74)	1.03 (0.58,1.47)
2010s	25.8	1.50 (1.33, 1.69)	86 (64,107)	1.75 (1.32,2.19)

Note: Values in parentheses show 95% empirical confidence intervals.
[a] Average daily temperature on days above decade-specific 95th percentile.
[b] Cumulative (lags of 0–10 days) relative mortality risk (RR) at 99th percentile of decade-specific temperature distribution.
[c] Mean attributable deaths per warm season (May–September).
[d] Attributable fraction (%) of heat-related deaths related to total number of deaths in warm season in each decade.

Table 3
Significance (*P*-values) of differences between relative mortality risk values for individual decades.

Decades	**1990s**	**2000s**	**2010s**
1980s	0.83	0.80	*0.06*
1990s	–	0.55	**0.04**
2000s		–	*0.08*

Note: Values in bold and italic represent significant differences at $p < 0.05$ and $p < 0.1$, respectively.

claimed as the primary causes of the decreasing trend. This observation was confirmed also by Urban et al. (2020), who analysed temporal changes between 1994 and 2017. The decline observed in the latter study was less steep (3% decrease per decade in mean heatwave-related mortality vs 5% in Kyselý and Plavcová, 2012), however, and the trend appeared to be inconclusive if harvesting effect was taken into consideration.

4.1. *Reversal in heat-related mortality trend*

In the present study, we used the longest possible daily all-cause mortality data for Prague (1982–2019) to analyse non-linear trends in heat-attributable mortality over the past four decades. Our study highlights the extraordinarily hot last decade (2010s) in Central Europe with its unprecedented frequency and intensity of heatwaves (Hoy et al., 2020; Brás et al., 2021; Sulikowska and Wypych, 2021; Wibig, 2021). Despite considering the effect of acclimatization to increasing temperatures, the extreme heat exposure in the 2010s resulted in the largest RR of heat-related mortality, largest heat-attributable deaths (AD) and largest heat-attributable fraction of warm-season deaths (AF in %) in Prague since the 1980s. Using a non-parametric smoothing technique (GAMs), we revealed an increasing trend in AD and AF (the latter significant at $p < 0.1$) during the last two decades.

Although some studies have documented abatement of the decreasing heat-related mortality risk in the late 1990s and/or 2000s (Sheridan and Allen, 2018), only a few of them reported significant increase in heat-related mortality. This has been observed mostly in Australia (Gasparrini et al., 2015; Vicedo-Cabrera et al., 2018a). The reversal in the heat-related mortality trend in our results is in line with future projections (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018b). The major limitation of such studies, however, is that they do not consider the role of adaptation (acclimatization) and demographic changes in future. Because these factors may substantially modify the burden of heat-related health risks in a warming climate (Rai et al., 2019; Chen et al., 2020), it is important to focus on further investigating factors defining these past changes in heat susceptibility (Vicedo-Cabrera et al., 2018a; Sera et al., 2020). Doing so may lead to more precise estimation of temperature-related mortality in future (Vanos et al., 2020).

4.1.1. *Role of heat adaptation*

In addition to meteorological factors, a lack of adaptation to and readiness for extreme heat (e.g. the absence of heat-health warning systems) in the Czech Republic may be reasons contributing to the increasing heat-related mortality during the last two decades in Prague. Patterns similar to that seen in Prague, with significantly larger RR of heat-related mortality after 2003 than appeared prior (i.e., 2004–2010 vs 1996–2002, respectively), was observed also in other Central (Budapest) and Northern (Helsinki, Stockholm) European cities (de Donato et al., 2015). These are located in regions that experienced no extraordinary impact of the 2003 heatwave on mortality (e.g., Sardon, 2007; Kyselý and Kříž, 2008). The lack of experience with a harsh heatwave's impact led to a delayed or non-existent implementation of heat-health warning systems (HHWSs) and action plans in Northern-European cities by the time of de'Donato's et al study (2015).

Since HHWSs have been regarded as effective tools to reduce heat-related morbidity and mortality (Pascal et al., 2006; Fouillet et al., 2008; Morabito et al., 2012; de Donato et al., 2018), their absence in some countries might have contributed to the increasing trend in heat-related mortality risk due to increased heat exposure. However, the beneficial effects of HHWSs have not been consistent across different cities and regions (de Donato et al., 2015; Weinberger et al., 2021). Martínez-Solanas and Basagaña (2019) suggest that any beneficial effect depends upon complexity of the HHWS and actions following the heat alerts. Any causality between implementation of HHWSs and reduced mortality remains inconclusive due to the limited number of evaluating studies and the nature of

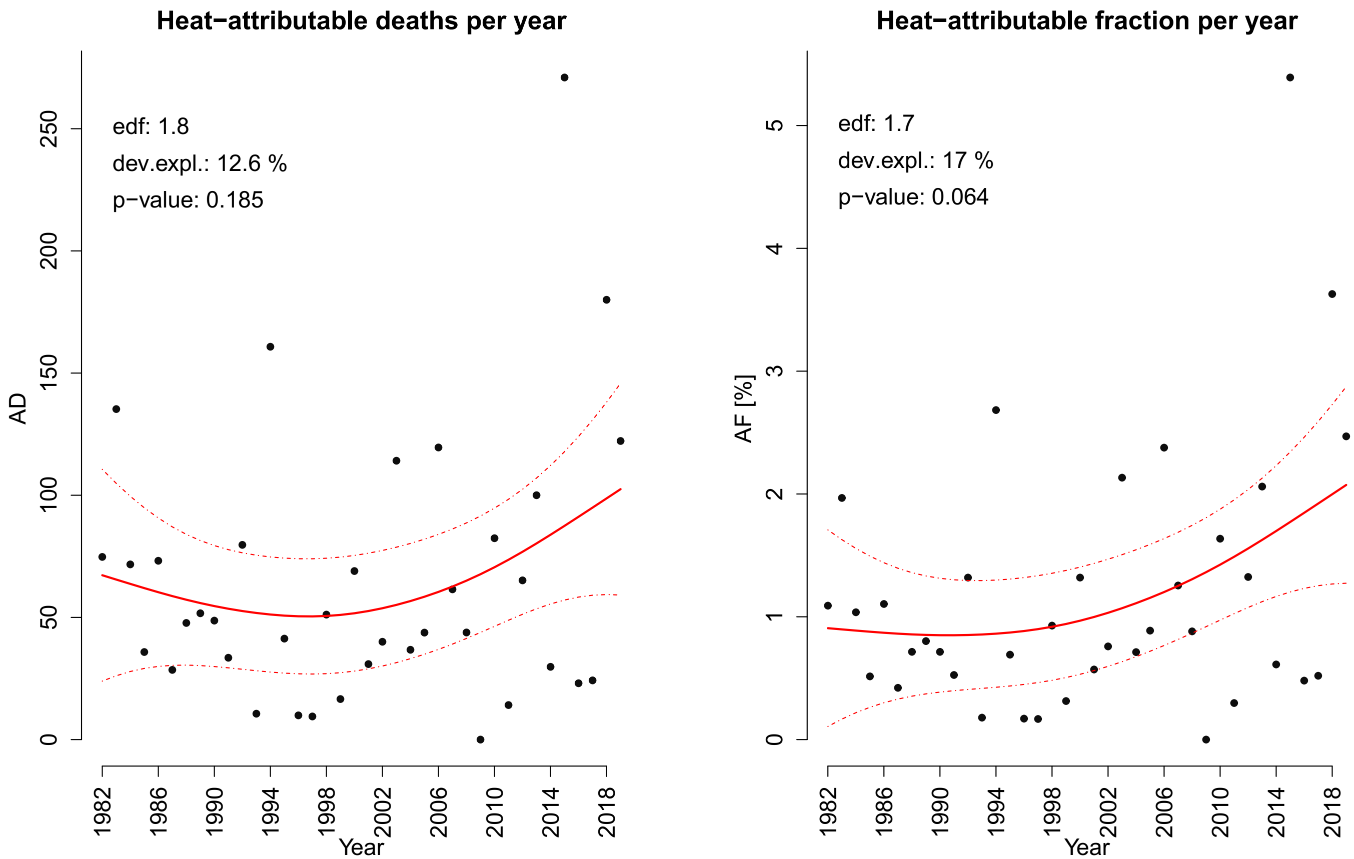

Fig. 4. Smoothed (generalized additive model) trend estimations of seasonal heat-attributable deaths (left) and fraction of total deaths (right), respectively, during May–September 1982–2019. *Edf:* shows estimated degrees of freedom for the smoothed trend. *Dev. expl.*: indicates proportion of the null deviance explained by the model. *P-value*: indicates significance of the smoothed trend estimate.

HHWS design (Toloo et al., 2013; Casanueva et al., 2019). As improving and developing HHWSs are among the priorities of the World Meteorological and World Health organizations (McGregor et al., 2015; WHO, 2021), further research is needed to understand the (cost-)efficiency and ability of heat-adaptation measures to prevent heat-related mortality (Bobb et al., 2014, Boeckmann and Rohn, 2014,Ng et al., 2016, Kotharkar and Ghosh, 2021).

4.1.2. Role of demography

Another important aspect that very likely contributed to the largest heat-related mortality in the last decade in Prague was population ageing (i.e., the increasing proportion of the elderly within the population – Kačerová et al., 2012). Previous studies in the Czech Republic have documented that while the immediate effect of heat on the healthy, middle-aged population decreased between 1994 and 2015, the most heat-vulnerable population group shifted toward older age (70+ years for males and 75+ years for females) (Urban et al., 2017; Urban et al., 2020). Accordingly, the 2020 Lancet Countdown report estimated that the global annual heat-related mortality for populations 65+ years of age almost doubled between 2000 and 2019 (Watts et al., 2021). These findings highlight the fact that even though the heat-vulnerability of the general population might have been decreasing over the decades, the demand for heat-protection measures such as HHWS remains acute due to the growing numbers in the elderly population and their increasing exposure to heat (Pascal et al., 2021).

4.2. Strength and limitations

Although 30 years has been considered a minimal period for determining trends in climatology, studies analysing mortality time series in Europe rarely reach this time span (cf. Výberči et al., 2018; Ragettli et al., 2017; Vicedo-Cabrera et al., 2018a; Huber et al., 2020; Graczyk et al., 2022). Thanks to long-time collaboration with the Czech National Public Health Institute, we were able to collect a time series of daily mortality in Prague spanning 38 years, making it one of the longest study periods used in studies of this kind (cf. Achebak et al., 2019; Sheridan et al., 2021; Madaniyazi et al., 2021). Such a long time series enabled us to split the full study period into four sub-periods and analyse the temperature–mortality relationship relevant to decade-specific temperature distributions. Thus, we were able to consider the effect of acclimatization to increasing temperatures in accordance with the state-of-the-art in research (e.g., Chen et al., 2020).

Even considering acclimatization, heat's impact on mortality in the 2010s was significantly greater than in previous decades. These findings raise the questions as to how representative is the observed increasing trend in heat-attributable deaths and fractions of total warm season deaths and can that be extrapolated into the future. First, the intensity and duration of heatwaves varies considerably between years and decades in association with short- and mid-term atmospheric circulation patterns (Ghosh et al., 2017). Moreover, non-meteorological factors play an important role in year-to-year fluctuation of the health burden associated with extreme temperatures (Putnam et al., 2018). In addition to long-term changes in socioeconomic and demographic factors and general adaptation to heat, the magnitude of the mortality peak in the preceding winter season is an important non-meteorological factor affecting the vulnerability of populations to heat in the following summer (Rocklöv et al., 2009). Considering these factors, one needs to interpret any trends of heat-related mortality with caution because their extrapolation even into the near future may be very uncertain.

5. Conclusions

In the present study, we used a daily mortality time series for Prague 38 years long (1982–2019) to analyse temporal changes in temperature–mortality associations during the warm season (May–September). Conditional Poisson regression coupled with distributed lag non-linear models was run separately in each decade (1980s–2010s) to derive decade-specific temperature–mortality associations while considering the effect of acclimatization to increasing temperature. Trends in annual heat-attributable deaths and heat-attributable fraction of total warm season deaths were estimated by non-parametric smoothing splines in generalized additive models (GAM). The main results observed in our study were as follow:

- The 2010s was the hottest decade in Prague since at least the 1980s as measured by the duration and intensity of heatwaves.
- Despite taking into account the effect of acclimatization, we observed significant increase in the relative risk of heat-related mortality in the 2010s compared to previous decades.
- The GAM analysis revealed a non-linear trend of heat-attributable deaths and heat-attributable fraction, respectively, with a minimum in the 1990s and maximum in the 2010s.
- These findings suggest a reversal of the trend in heat-related mortality in Prague, which was increasing in the last two decades.

While many studies analysing historical changes in heat-related mortality have observed decreasing trends over recent decades, future projections suggest increasing impact of heat on mortality in most regions of the world. The timing of the trend reversal depends upon how well humans can adapt to ongoing climate change. Our findings suggest that the heat-attributable mortality trend reversal has already occurred in Prague, Czech Republic. This highlights the importance of i) further investigating trends in heat-related mortality in other regions while using data as recent as possible; and ii) further evaluating, developing, and implementing efficient adaptation strategies to protect the heat-susceptible population.

Declaration of Competing Interest

The authors declare they have no actual or potential competing financial interests.

Acknowledgment

We would like to thank all the national data providers for supplying meteorological as well as health data. Special thanks go to Bohumír Křříž (in memoriam) and Jan Kynčl, National Institute of Public Health, for collecting mortality datasets as well as for useful discussions concerning their interpretation. We thank Jan Kyselý, Institute of Atmospheric Physics CAS, for critically reviewing the manuscript. The study was supported by the Czech Science Foundation [22-24920S]. CDN was supported by a Wellcome Trust grant [209734/Z/17/Z].

References

Achebak, H., Devolder, D., Ballester, J., 2019. Trends in temperature-related age-specific and sex-specific mortality from cardiovascular diseases in Spain: a national time-series analysis. Lancet Planet Health 3, e297–e306. https://doi.org/10.1016/S2542-5196(19)30090-7.
Altman, D.G., Bland, J.M., 2003. Interaction revisited: the difference between two estimates. BMJ 326, 219. https://doi.org/10.1136/bmj.326.7382.219.
Altman, D.G., Bland, J.M., 2011. How to obtain the P value from a confidence interval. BMJ 343, 1–2. https://doi.org/10.1136/bmj.d2304.
Arbuthnott, K., Hajat, S., Heaviside, C., Vardoulakis, S., 2016. Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. Environ. Health 15, 33. https://doi.org/10.1186/s12940-016-0102-7.
Armstrong, B.G., Gasparrini, A., Tobias, A., 2014. Conditional Poisson models: a flexible alternative to conditional logistic case cross-over analysis. BMC Med. Res. Methodol. 14, 1–6. https://doi.org/10.1186/1471-2288-14-122.
Arsenović, D., Lehnert, M., Fiedor, D., et al., 2019a. Heat-waves and mortality in Czech cities: a case study for the summers of 2015 and 2016. Geogr. Pannonica 23, 162–172. https://doi.org/10.5937/gp23-22853.
Arsenović, D., Savić, S., Lužanin, Z., et al., 2019b. Heat-related mortality as an indicator of population vulnerability in a mid-sized Central European city (Novi Sad, Serbia, summer 2015). Geogr. Pannonica 23, 204–215. https://doi.org/10.5937/gp23-22680.
Bobb, J.F., Peng, R.D., Bell, M.L., Dominici, F., 2014. Heat-related mortality and adaptation to heat in the United States. Environ. Health Perspect. 122, 811–816. https://doi.org/10.1289/ehp.1307392.
Boeckmann, M., Rohn, I., 2014. Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. BMC Public Health 14, 1112. https://doi.org/10.1186/1471-2458-14-1112.
Brás, T.A., Seixas, J., Carvalhais, N., Jägermeyr, J., 2021. Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abf004.
Casanueva, A., Burgstall, A., Kotlarski, S., et al., 2019. Overview of existing heat-health warning systems in Europe. Int. J. Environ. Res. Public Health 16, 2657. https://doi.org/10.3390/ijerph16152657.
Chen, K., Vicedo-Cabrera, A.M., Dubrow, R., 2020. Projections of ambient temperature- and air pollution-related mortality burden under combined climate change and population aging scenarios: a review. Curr. Environ. Health Reports 7, 243–255. https://doi.org/10.1007/s40572-020-00281-6.
Chung, Y., Yang, D., Gasparrini, A., et al., 2018. Changing susceptibility to non-optimum temperatures in Japan, 1972-2012: the role of climate, demographic, and socioeconomic factors. Environ. Health Perspect. 126, 057002-1–057002–8. https://doi.org/10.1289/EHP2546.
de Donato, F., Leone, M., Scortichini, M., et al., 2015. Changes in the effect of heat on mortality in the last 20 years in nine European cities. Results from the PHASE project. Int. J. Environ. Res. Public Health 12, 15567–15583. https://doi.org/10.3390/ijerph121215006.
de Donato, F., Scortichini, M., De Sario, M., et al., 2018. Temporal variation in the effect of heat and the role of the Italian heat prevention plan. Public Health 161, 154–162. https://doi.org/10.1016/j.puhe.2018.03.030.
Fonseca-Rodríguez, O., Sheridan, S.C., Lundevaller, E.H., Schumann, B., 2020. Hot and cold weather based on the spatial synoptic classification and cause-specific mortality in Sweden: a time-stratified case-crossover study. Int. J. Biometeorol. 64, 1435–1449. https://doi.org/10.1007/s00484-020-01921-0.
Fouillet, A., Rey, G., Wagner, V., et al., 2008. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. Int. J. Epidemiol. 37, 309–317. https://doi.org/10.1093/ije/dym253.
Gasparrini, A., Leone, M., 2014. Attributable risk from distributed lag models. BMC Med. Res. Methodol. 14, 55. https://doi.org/10.1186/1471-2288-14-55.
Gasparrini, A., Armstrong, B., Kenward, M.G., 2010. Distributed lag non-linear models. Stat. Med. 29 (21), 2224–2234.
Gasparrini, A., Guo, Y., Hashizume, M., et al., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386, 369–375. https://doi.org/10.1016/S0140-6736(14)62114-0.
Gasparrini, A., Guo, Y., Sera, F., et al., 2017. Projections of temperature-related excess mortality under climate change scenarios. Lancet Planet Health 1, e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0.
Ghosh, R., Müller, W.A., Baehr, J., Bader, J., 2017. Impact of observed North Atlantic multidecadal variations to European summer climate: a linear baroclinic response to surface heating. Clim. Dyn. 48, 3547–3563. https://doi.org/10.1007/s00382-016-3283-4.
Graczyk, D., Pińskwar, I., Choryński, 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. https://doi.org/10.3390/atmos13030390.
Guerreiro, S.B., Dawson, R.J., Kilsby, C., et al., 2018. Future heatwaves, droughts and floods in 571 European cities. Environ. Res. Lett. 13, 034009 https://doi.org/10.1088/1748-9326/aaaad3.
Hondula, D.M., Balling, R.C., Vanos, J.K., Georgescu, M., 2015. Rising temperatures, human health, and the role of adaptation. Curr. Clim. Chang. Rep. 1, 144–154. https://doi.org/10.1007/s40641-015-0016-4.
Hoy, A., Hänsel, S., Skalak, P., et al., 2016. The extreme European summer of 2015 in a long-term perspective. Int. J. Climatol. 37, 943–962. https://doi.org/10.1002/joc.4751.
Hoy, A., Hänsel, S., Maugeri, M., 2020. An endless summer: 2018 heat episodes in Europe in the context of secular temperature variability and change. Int. J. Climatol. 40, 6315–6336. https://doi.org/10.1002/joc.6582.
Huber, V., Krummenauer, L., Peña-Ortiz, C., et al., 2020. Temperature-related excess mortality in German cities at 2 °C and higher degrees of global warming. Environ. Res. 186, 109447 https://doi.org/10.1016/j.envres.2020.109447.
IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press (In Press).
Kačerová, M., Ondačková, J., Mládek, J., 2012. A comparison of population ageing in the Czech Republic and the Slovak Republic based on generation support and exchange. Morav. Geogr. Rep. 20 (4), 26–38.
Kotharkar, R., Ghosh, A., 2021. Progress in extreme heat management and warning systems: a systematic review of heat-health action plans (1995-2020). Sustain. Cities Soc. 103487 https://doi.org/10.1016/j.scs.2021.103487.
Kyselý, J., Kříž, B., 2008. Decreased impacts of the 2003 heat waves on mortality in the Czech Republic: an improved response? Int. J. Biometeorol. 52, 733–745. https://doi.org/10.1007/s00484-008-0166-3.

Kyselý, J., Plavcová, E., 2012. Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? Clim. Chang. 113, 437–453. https://doi.org/10.1007/s10584-011-0358-4.

Kyselý, J., Plavcová, E., Davídkovová, H., Kynčl, J., 2011. Comparison of hot and cold spell effects on cardiovascular mortality in individual population groups in the Czech Republic. Clim. Res. 49 (2), 113–129. https://doi.org/10.3354/cr01014.

Lau, N.C., Nath, M.J., 2014. Model simulation and projection of European heat waves in present-day and future climates. J. Clim. 27, 3713–3730. https://doi.org/10.1175/JCLI-D-13-00284.1.

Lay, C.R., Sarofim, M.C., Vodonos Zilberg, A., et al., 2021. City-level vulnerability to temperature-related mortality in the USA and future projections: a geographically clustered meta-regression. Lancet Planet Health 5, e338–e346. https://doi.org/10.1016/S2542-5196(21)00058-9.

Lee, J.Y., Kim, H., Gasparrini, A., et al., 2019. Predicted temperature-increase-induced global health burden and its regional variability. Environ. Int. 131, 105027 https://doi.org/10.1016/j.envint.2019.105027.

Lhotka, O., Kyselý, J., Farda, A., 2017. Climate change scenarios of heat waves in Central Europe and their uncertainties. Theor. Appl. Climatol. https://doi.org/10.1007/s00704-016-2031-3.

Madaniyazi, L., Chung, Y., Kim, Y., et al., 2021. Seasonality of mortality under a changing climate: a time-series analysis of mortality in Japan between 1972 and 2015. Environ. Health Prev. Med. 26, 69. https://doi.org/10.1186/s12199-021-00992-8.

Martínez-Solanas, È., Basagaña, X., 2019. Temporal changes in temperature-related mortality in Spain and effect of the implementation of a heat health prevention plan. Environ. Res. 169, 102–113. https://doi.org/10.1016/j.envres.2018.11.006.

Martínez-Solanas, È., Quijal-Zamorano, M., Achebak, H., et al., 2021. Projections of temperature attributable mortality in Europe: a 1 time series analysis in 147 contiguous regions. Lancet Planet Health 1–17. https://doi.org/10.1016/S2542-5196(21)00150-9.

McGregor, G., Basemoulin, P., Ebi, K., Menne, B., et al., 2015. Heatwaves and Health: Guidance on Warning–System Development; WMO-No. 1142; World Meteorological Organization and World Health Organization: Geneva, Switzerland (ISBN 978-92-63-11142-5).

Molina, M.O., Sánchez, E., Gutiérrez, C., 2020. Future heat waves over the Mediterranean from an Euro-CORDEX regional climate model ensemble. Sci. Rep. 10, 1–10. https://doi.org/10.1038/s41598-020-65663-0.

Morabito, M., Profili, F., Crisci, A., et al., 2012. Heat-related mortality in the Florentine area (Italy) before and after the exceptional 2003 heat wave in Europe: an improved public health response? Int. J. Biometeorol. 56, 801–810. https://doi.org/10.1007/s00484-011-0481-y.

Muthers, S., Laschewski, G., Matzarakis, A., 2017. The summers 2003 and 2015 in south-West Germany: heat waves and heat-related mortality in the context of climate change. Atmosphere 8 (11), 224. https://doi.org/10.3390/atmos8110224.

Ng, F.C.S., Boeckmann, M., Ueda, K., et al., 2016. Heat-relatedmortality: effect modification and adaptation in Japan from 1972 to 2010. Glob. Environ. Chang. 39, 234–243. https://doi.org/10.1016/j.gloenvcha.2016.05.006.

Pascal, M., Laaidi, K., Ledrans, M., et al., 2006. France's heat health watch warning system. Int. J. Biometeorol. 50, 144–153. https://doi.org/10.1007/s00484-005-0003-x.

Pascal, M., Lagarrigue, R., Tabai, A., et al., 2021. Evolving heat waves characteristics challenge heat warning systems and prevention plans. Int. J. Biometeorol. 65, 1683–1694. https://doi.org/10.1007/s00484-021-02123-y.

Putnam, H., Hondula, D.M., Urban, A., et al., 2018. It's not the heat, it's the vulnerability: attribution of the 2016 spike in heat-associated deaths in Maricopa County, Arizona. Environ. Res. Lett. 13, 094022 https://doi.org/10.1088/1748-9326/aadb44.

Ragettli, M.S., Vicedo-Cabrera, A.M., Schindler, C., Röösli, M., 2017. Exploring the association between heat and mortality in Switzerland between 1995 and 2013. Environ. Res. 158, 703–709. https://doi.org/10.1016/j.envres.2017.07.021.

Rai, M., Breitner, S., Wolf, K., et al., 2019. Impact of climate and population change on temperature-related mortality burden in Bavaria, Germany. Environ. Res. Lett. 14, 124080 https://doi.org/10.1088/1748-9326/ab5ca6.

Robinson, P.J., 2001. On the definition of a heat wave. J. Appl. Meteorol. 40, 762–775. https://doi.org/10.1175/1520-0450(2001)040<0762:OTDOAH>2.0.CO;2.

Rocklöv, J., Forsberg, B., Meister, K., 2009. Winter mortality modifies the heat-mortality association the following summer. Eur. Respir. J. 33, 245–251. https://doi.org/10.1183/09031936.00037808.

Russo, S., Sillmann, J., Fischer, E.M., 2015. Top ten European heatwaves since 1950 and their occur- rence in the future. Environ. Res. Lett. 10, 124003 https://doi.org/10.1088/1748-9326/10/12/124003.

Sardon, J.-P., 2007. The 2003 heat wave. Eur. Surveill. 12 (3), 694. https://doi.org/10.2807/esm.12.03.00694-en.

Sera, F., Hashizume, M., Honda, Y., et al., 2020. Air conditioning and heat-related mortality: a multi-country longitudinal study. Epidemiology 31, 779–787. https://doi.org/10.1097/EDE.0000000000001241.

Sheridan, S., Allen, M., 2018. Temporal trends in human vulnerability to excessive heat. Environ. Res. Lett. 13, 043001 https://doi.org/10.1088/1748-9326/aab214.

Sheridan, S.C., Grady Dixon, P., Kalkstein, A.J., Allen, M.J., 2021. Recent trends in heat-related mortality in the United States: an update through 2018. Weather Clim. Soc. 13, 95–106. https://doi.org/10.1175/WCAS-D-20-0083.1.

Sousa, P.M., Barriopedro, D., García-Herrera, R., et al., 2020. Distinct influences of large-scale circulation and regional feedbacks in two exceptional 2019 European heatwaves. Commun. Earth Environ. 1, 1–13. https://doi.org/10.1038/s43247-020-00048-9.

Sulikowska, A., Wypych, A., 2021. Seasonal variability of trends in regional hot and warm temperature extremes in Europe. Atmosphere 12, 612. https://doi.org/10.3390/atmos12050612.

Tobías, A., Armstrong, B., Gasparrini, A., 2017. Brief report: investigating uncertainty in the minimum mortality temperature. Epidemiology 28, 72–76. https://doi.org/10.1097/EDE.0000000000000567.

Tobías, A., Hashizume, M., Honda, Y., et al., 2021. Geographical variations of the minimum mortality temperature at a global scale. Environ. Epidemiol. 5, e169 https://doi.org/10.1097/ee9.0000000000000169.

Toloo, G.S., Fitzgerald, G., Aitken, P., et al., 2013. Are heat warning systems effective? Environ. Health 12, 27. https://doi.org/10.1186/1476-069X-12-27.

Urban, A., Hanzlíková, H., Kyselý, J., Plavcová, E., 2017. Impacts of the 2015 heat waves on mortality in the Czech Republic—a comparison with previous heat waves. Int. J. Environ. Res. Public Health 14, 1562. https://doi.org/10.3390/ijerph14121562.

Urban, A., Kyselý, J., Plavcová, E., et al., 2020. Temporal changes in years of life lost associated with heat waves in the Czech Republic. Sci. Total Environ. 716, 137093 https://doi.org/10.1016/J.SCITOTENV.2020.137093.

Vanos, J.K., Baldwin, J.W., Jay, O., Ebi, K.L., 2020. Simplicity lacks robustness when projecting heat-health outcomes in a changing climate. Nat. Commun. 11, 10–14. https://doi.org/10.1038/s41467-020-19994-1.

Vicedo-Cabrera, A.M., Sera, F., Guo, Y., et al., 2018a. A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. Environ. Int. 111, 239–246. https://doi.org/10.1016/j.envint.2017.11.006.

Vicedo-Cabrera, A.M., Sera, F., Heaviside, C., et al., 2018b. Temperature-related mortality impacts under and beyond Paris agreement climate change scenarios. Clim. Chang. 150, 391–402. https://doi.org/10.1007/s10584-018-2274-3.

Vicedo-Cabrera, A.M., Scovronick, N., Sera, F., et al., 2021. The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Chang. 11, 492–500. https://doi.org/10.1038/s41558-021-01058-x.

Výberči, D., Labudová, L., Eštóková, M., et al., 2018. Human mortality impacts of the 2015 summer heat spells in Slovakia. Theor. Appl. Clim. 133, 925–936. https://doi.org/10.1007/s00704-017-2224-4.

Watts, N., Amann, M., Arnell, N., et al., 2021. The 2020 report of the lancet countdown on health and climate change: responding to converging crises. Lancet 397, 129–170. https://doi.org/10.1016/S0140-6736(20)32290-X.

Weinberger, K.R., Wu, X., Sun, S., et al., 2021. Heat warnings, mortality, and hospital admissions among older adults in the United States. Environ. Int. 157, 106834 https://doi.org/10.1016/j.envint.2021.106834.

WHO, 2021. Heat and Health in the WHO European Region: Updated Evidence for Effective Prevention. WHO Regional Office for Europe, Copenhagen (ISBN 978 92 890 5540 6).
Wibig, J., 2021. Hot days and heat waves in Poland in the period 1951-2019 and the circulation factors favoring the most extreme of them. Atmosphere 12, 340. https://doi.org/10.3390/atmos12030340.
Wood, S., 2006. Generalized Additive Models: An Introduction with R. Chapman & Hall/CRC (ISBN 978 13 153 7027 9).