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Cold-related mortality vs heat-related mortality in a changing climate: a case study in Vilnius (Lithuania)

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Abstract

Introduction: Direct health effects of extreme temperatures are a significant environmental health problem in Lithuania, and could worsen further under climate change. This paper attempts to describe the change in environmental temperature conditions that the urban population of Vilnius could experience under climate change, and the effects such change could have on excess heat-related and cold-related mortality in two future periods within the 21st century.

Methods: We modelled the urban climate of Vilnius for the summer and winter seasons during a sample period (2009–2015) and projected summertime and wintertime daily temperatures for two prospective periods, one in the near (2030–2045) and one in the far future (2085–2100), under the Representative Concentration Pathway (RCP) 8.5. We then analysed the historical relationship between temperature and mortality for the period 2009–2015, and estimated the projected mortality in the near future and far future periods under a changing climate and population, assuming alternatively no acclimatization and acclimatization to heat and cold based on a constant-percentile threshold temperature.

Results: During the sample period 2009–2015 in summertime we observed an increase in daily mortality from a maximum daily temperature of 30°C (the 96th percentile of the series), with an average of around 7 deaths per year. Under a no acclimatization scenario, annual average heat-related mortality would rise to 24 deaths/year (95 % CI: 8.4–38.4) in the near future and to 46 deaths/year (95 % CI: 16.4–74.4) in the far future. Under a heat acclimatization scenario, mortality would not increase significantly in the near or in the far future. Regarding wintertime cold-related mortality in the sample period 2009–2015, we observed increased mortality on days on which the minimum daily temperature fell below -12°C (the 7th percentile of the series), with an average of around 10 deaths a year. Keeping the threshold temperature constant, annual average cold-related mortality would decrease markedly in the near future, to 5 deaths/year (95 % CI: 0.8–7.9) and even more in the far future, down to 0.44 deaths/year (95 % C: 0.1–0.8). Assuming a “middle ground” between the acclimatization and non-acclimatization scenarios, the decrease in cold-related mortality will not compensate the increase in heat-related mortality.

Conclusion: Thermal extremes, both heat and cold, constitute a serious public health threat in Vilnius, and in a changing climate the decrease in mortality attributable to cold will not compensate for the increase in mortality attributable to heat. Study results reinforce the notion that public health prevention against thermal extremes should be designed as a dynamic, adaptive process from the inception.

Keywords: Vilnius; Heat-related mortality; Cold-related mortality; Climate change

1. Background

Fewer studies focus on cold-related mortality than on heat-related mortality. Probable reasons include a longer delay between exposure to cold and effect (Alberdi *et al.*, 1998; Anderson and Bell 2009; Díaz *et al.*, 2005) as well as an overlap in time of concomitant infectious diseases (Carmona *et al.*, 2016; Rocklov *et al.*, 2014; Ryti *et al.*, 2016). In addition, while heat waves are increasing in frequency, duration and intensity, cold spells are decreasing. This trend is likely to continue (IPCC, 2013; Melillo *et al.*, 2014), despite some evidence suggesting a prospective increase in cold waves in medium latitudes (Cohen *et al.*, 2014; Zhang *et al.*, 2016). However, a reduction in the frequency, duration or intensity of cold waves may not necessarily translate into a decrease in cold-related mortality. Various studies in multiple locations suggest that while heat-related mortality is in decline due to various adaptative processes (Gasparrini *et al.*, 2015; Mirón *et al.* 2015; Díaz *et al.* 2015a; Ha and Kim 2013; Petkova *et al.*, 2014), cold-related mortality has either remained constant or increased (Gasparrini *et al.* 2015; Díaz *et al.* 2015a; Linares *et al.*, 2016).

Consistently, studies on future impacts of thermal extremes on health focus mostly on heat and its effects on mortality. Most researchers assume that neither the “heat wave” threshold temperature nor the effect of temperature increase itself will change in time, so projections of mortality attributable to heat in far future horizons tend to be quite high (Peng *et al.*, 2011; Wu *et al.*, 2014; Martinez *et al.*, 2016; Roldán *et al.* 2016). Others, however, assume a heat acclimatisation process (Martinez *et al.*, 2018). Very few studies analyse projected impacts of cold, and all assume no changes in the impacts of cold on mortality across time (Wang *et al.*, 2016).

The evidence base on health and temperature extremes (particularly heat, as mentioned) is relatively well established in several European countries. However, research in this field is still scarce in Baltic countries. In the context of the technical assistance of the WHO Regional Office for Europe to its Member States in the area of climate change and health, we set out to contribute to addressing this gap in Lithuania, where various studies suggest a significant impact of thermal extremes on health and wellbeing (Liukaityte, 2011; Styra *et al.*, 2009; Vaičiulis *et al.*, 2014). However, no study had comprehensively analysed the impacts of heat and cold on mortality in urban settings in the country.

This study has various objectives: first, to analyse retrospectively the impact of heat and cold on daily short-term mortality in Vilnius, determining threshold temperatures for both. Second, to estimate the projected impact of heat and cold in a near future period (2030-2045) and a far future one (2085-2100), under Representative Concentration Pathway (RCP) 8.5. For the projected impacts, we considered two hypotheses: 1) constant thresholds for heat waves and cold waves, and 2) thresholds for heat waves and cold waves varying over time. In addition, we compare projected heat and cold impacts, to determine whether lower cold-related mortality (Kinney *et al.*, 2015; Staddon *et al.*, 2014) will compensate an increase in heat-related deaths.

The results of this study show the change in environmental temperature conditions that the urban population of Vilnius could experience under climate change, and the effects such change could have on excess heat-related and cold-related mortality in two future periods within the 21st century. These results can inform both current-day prevention efforts and relevant urban health adaptation policies.

2. Methods

2.1. Retrospective study of the impact of thermal extremes on short-term daily mortality

A) Data sources

Environmental variables:

- Air temperature data: Air temperature measurements for the years 2009 to 2015 were obtained from the Lithuanian Hydrometeorological Services under the Ministry of Environment. Only daytime temperatures with a 3h frequency were made available for the current study. Measurements took place daily at 9h, 12h, 15h and 18h. We have used the measurement at 9h as a proxy for the minimum daily temperature, and the measurement at 12h as proxy for the maximum daily temperature.
- Relative humidity: Data were also available on relative humidity (rH) at 9h, 12h, 15h and 18h for the same period; we worked with mean relative humidity obtained as the average of the relative humidity readings recorded at the above-mentioned times of day.
- Chemical air pollution: daily data were available on $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$, PM_{10} , SO_2 , NO_2 and O_3 for the same period, recorded at four monitoring stations, and received from the Environmental Protection Agency in Lithuania. We worked with the daily means obtained based on the values furnished by these four stations.

Health variables:

We calculated the daily crude mortality rate of Vilnius based on the following two variables:

- Daily mortality: The geographical area under study comprises the Municipality of Vilnius, for which we collected from the Institute of Hygiene the daily mortality series corresponding to the period 01-01-2009 to 31-12-2015 for all-cause mortality (International Classification of Diseases, 10th Revision (ICD-10:A00-R99)).
- Population: Population data for the city of Vilnius were obtained from Statistical Office of Lithuania (DoS, 2018) for the period 2009-2015.

B) Statistical methodology

Determination of cold wave and heat wave threshold temperatures

Some definitions of heat wave or cold wave require that the threshold temperature is exceeded two or more days for the series to qualify as either (Guo et al., 2017). However, from the health impact standpoint, mortality increases can be observed already when the threshold value is exceeded only by a single day, an observation confirmed in several studies analyzing the impact of heat and cold on mortality (Díaz et al. 2002, Montero et al. 2012, Mirón et al. 2015, Díaz et al. 2015, Carmona et al. 2016, Sanchez-Martínez et al. 2018, Gasparrini et al. 2017, Wang et al. 2016). However, acknowledging that there is no consensus on what constitutes a heat wave or a cold wave, we considered impacts in this study on the basis of an operational definition, following previous studies

(see for instance Martinez *et al.*, 2018). Thus, we defined “hot days” as days with mortality attributable to heat, and “cold days” as days with mortality attributable to cold.

The extent of the retrospective analysis was limited by the availability of daily mortality data, corresponding to the period 2009-2015, hereon referred to as the “sample period”. Impact of heat was studied for summertime (June-September) and impact of cold for wintertime (November-March). In both cases, we aimed at determining a threshold temperature. For heat, it was defined as the maximum daily temperature beyond which mortality significantly increases (T_{max}-threshold) (Díaz *et al.*, 2002; Díaz *et al.*, 2015b). For cold, it was defined as the minimum daily temperature below which mortality increases significantly (T_{min}-threshold) (Carmona *et al.*, 2016). These threshold temperatures were ascertained from the scatterplot diagrams of pre-cleaned mortality rate time series (Box *et al.*, 1994) against the corresponding temperature series. In these diagrams, T_{max}-threshold and T_{min}-threshold are associated to the corresponding temperature in the daily T_{max} series for summertime and the daily T_{min} series for wintertime, respectively. A “hot day” (i.e. a day in which heat-related mortality occurs) is then based on the value of T_{max}-threshold through a newly created variable thusly defined (Díaz *et al.*, 2006; Díaz *et al.*, 2015b; Carmona *et al.*, 2016; Martinez *et al.*, 2018):

$$\begin{aligned} T_{\text{heat}} &= 0 & \text{si } T_{\text{max}} < T_{\text{max-threshold}} \\ T_{\text{heat}} &= T_{\text{max}} - T_{\text{max-threshold}} & \text{si } T_{\text{max}} > T_{\text{max-threshold}} \end{aligned}$$

Since the effect of heat on mortality may not be immediate, the following lagged variables will also be calculated: T_{heat1} (lag 1), which accounts for the effect of the temperature of a day “d” on the mortality the next day “d+1”; T_{heat2} (lag 2), which accounts for the effect of the temperature of a day “d” on the mortality two days later “d+2”; and so on. The number of lags is based on the existing literature, which shows that heat effects happen mostly in the short term (Theat: lags 1-4) (Alberdi *et al.*, 1998).

Similarly, we shall define the occurrence of a “cold day” (i.e. a day in which cold-related mortality occurs) when:

$$\begin{aligned} T_{\text{cold}} &= T_{\text{min-threshold}} - T_{\text{min}} & \text{si } T_{\text{min}} < T_{\text{min-threshold}} \\ T_{\text{cold}} &= 0 & \text{si } T_{\text{min}} > T_{\text{min-threshold}} \end{aligned}$$

The effect of cold on mortality is not immediate either, so for this exposure we also defined lagged variables. The existing literature shows that cold has effects both in the short and the medium term (T_{cold}: lags 1-13) (Alberdi *et al.*, 1998).

Calculation of the impact of “hot days” and “cold days” on daily mortality

To determine the values of the Relative Risks (RR) attributable to hot days and cold days respectively, we used a Generalized Linear Models (GLM) methodology linked with a Poisson regression. We ascertained the significant variables in the model to calculate the RRs through a “Stepwise backward” methodology. This method starts with an initial model including all explanatory variables, and gradually eliminates those that are individually least statistically significant. The process is repeated until all remaining variables are significant at p<0.05. We went through this process for all wintertime (November through March) and summertime (June through September) periods.

We used generalized linear models with the Poisson regression to calculate the coefficients that allow determining the value of the RR. The following covariables were included in the analysis, in order to control for the trend and seasonalities of the series, as well as the lags in the T_{heat} and T_{cold} mentioned before:

- Sine and Cosine functions of 365, 180 and 120 days to account for annual, six-monthly and four month periodicities.
- The trend of the series, using a counter (n_1), equal to 1 for the first day of the series, 2 for the second day, and so on, successively.
- Autoregressive character of the series by introducing a first order autoregressive process (AR1).
- The modeling process was carried out in reverse order manually, eliminating the variables in a stepwise procedure until $P < 0.05$

The explanatory variables include not only the effect of the previously defined T_{heat} and T_{cold} , but also that of other environmental variables known to act synergistically with temperature in aggravating mortality. In terms of meteorological variables, for instance, the role of relative humidity (RH) has been studied during hot days and cold days (Díaz *et al.*, 2015b; Carmona *et al.*, 2016), and we have considered it in this study too. The RH variable was established as linearly related to mortality and its effect considered until lag 14 (Alberdi *et al.*, 1998; Díaz *et al.*, 2015b). Similarly, multicentre and cross-over studies have shown the synergistic effect of high temperatures on inhalable particles (Staffoglia *et al.*, 2008; Stieb *et al.*, 2009), as well as on ozone (Zmirou *et al.*, 1998; Díaz *et al.*, 2002). Strong interactions have also been reported between chemical air pollution and low temperature, so the available chemical air pollution data were also introduced in the model as control variables. Methodologically, based on previous studies (Linares *et al.*, 2006; Jiménez *et al.*, 2009), the relationship between PM_{10} , $\text{PM}_{2.5}$, NO_2 and SO_2 and mortality is assumed to be linear, with an effect until lag 4. Therefore, we created the corresponding lagged variables in the same way as we did for temperature. For Ozone, we included until lag 8 (Díaz *et al.*, 1999).

We calculated the increases in RR corresponding to the unit increases of each independent variable:

- T_{heat} : increase for each 1°C increase beyond the established threshold temperature ($T_{\text{max-threshold}}$)
- T_{cold} : increase for each 1°C decrease below the established threshold temperature ($T_{\text{min-threshold}}$)
- Chemical air pollution: increase for each increase of $10 \mu\text{g}/\text{m}^3$ in measured daily concentration of every pollutant
- Relative humidity: increase for each 1% increase in relative humidity

Based on the RR we calculated the Population Attributable Fraction (PAF) associated to those increases, through the following equation:

$$\text{PAF} = (\text{RR} - 1 / \text{RR}) * 100$$

Heat and Cold Attributable deaths during the sample period (2009–2015)

To calculate attributable mortality, we used the methodology of a previous study (Martinez *et al.*, 2018). First, we calculated the excess or deficit in temperature beyond (heat) or below (cold) the daily threshold temperature with the following equation:

$$\begin{aligned}\text{Excess } ^\circ\text{C during hot day} &= \Sigma T_{\text{max}} - T_{\text{max-threshold}} \\ \text{Deficit } ^\circ\text{C during cold day} &= \Sigma T_{\text{min-threshold}} - T_{\text{min}}.\end{aligned}$$

The Σ extends to all days in which daily maximum temperature goes beyond the hot day temperature threshold and those were daily minimum temperature goes below the cold day temperature threshold. Since we have calculated the % increase in mortality per $^\circ\text{C}$ through the AR, the total percentage of mortality for the whole excess of degrees for the sample period (2009-2015) is:

$$\% \text{mortality attributable to heat} = \text{AR} \times \text{Excess } ^\circ\text{C}$$

We can then calculate the daily mortality by also taking into account the average daily mortality in Vilnius during hot days:

$$\begin{aligned}\text{Mortality attributable to heat} &= (\% \text{ mortality attributable to hot days} \times \text{average mortality}) / 100 \\ \text{Daily mortality attributable to heat} &= \text{mortality attributable to hot days} / \text{number of hot days}\end{aligned}$$

For the case of cold, the procedure was similarly applied to $^\circ\text{C}$ below the threshold temperature

2.2. Prospective climate assessment

A) Data sources

To calculate the impact of thermal extremes in future years, we compiled time series of projected temperatures using a statistical method. The methodology relies on two steps:

- In a first step, we compose monthly rescaling functions describing the change of the percentiles of the daily minimum and maximum temperatures in the GCM-output. For instance, for each month, we determine how the 75th percentile of the daily minimal temperature changes between the current-day (2000 – 2015) and the future periods (2030-2045 and 2085-2100). This analysis is based on the output of a representative set of GCMs contained in the archives of the Coupled Model Intercomparison Project (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC) (Rity *et al.* 2015).
- In a second step, the rescaling functions are applied on the Vilnius measurements to compose yearlong daily minimum and maximum temperatures for the two periods under consideration. In this way, the methodology takes into account both the seasonal pattern of climate change, and the increase in the frequency and severity of hot days. The methodology has been used for the Representative Concentration Pathway 8.5 (RCP8.5), representing a weak mitigation strategy (Rity *et al.* 2015).

Population projections for the periods 2030-2045 and 2085-2100 were based on the United Nations World Population Prospects (WPP) forecasts for Lithuania, “Medium Variant” (UNDESA 2008; UNDESA 2013). Vilnius is the largest city in the country in terms of population. In the late 2000s,

Vilnius saw years of declines in its population, dropping from its peak 559,234 in 2009 to 534,348 in 2011. However, since 2011, the city has seen population increases of less than 1%, indicating that the city may continue to see slow growth in the years ahead (DoS, 2018). Taking as reference the population data for the Vilnius agglomeration in the year 2015, we calculated the proportion it represented from the total national population. Thereafter, that proportion was assumed constant, whereby the population of Vilnius would behave like that of Lithuania as a whole.

B) Statistical methodology

Heat- and Cold-related mortality for 2030-2045 and 2085-2100

To calculate the impact of cold days and hot days on mortality under the projected scenarios, we considered two hypotheses:

- Hypothesis 1: the threshold temperature of hot days and cold days does not change over time. That is, there is no acclimatisation to either heat or cold.
- Hypothesis 2: there is a process or acclimatisation to both heat and cold whereby the threshold temperature changes, but the percentile corresponding to that threshold in the baseline series remains constant.

In both cases, we assumed that AR remains constant and equal to the one calculated for the sample period 2009-2015

3. Results

3.1. Heat- and Cold–mortality relationship during the sample period: 2009–2015

The descriptive statistics of the independent and dependent variables are shown in **Table 1**.

Table 1. Descriptive statistics of the analyzed variables, sample period: 2009-2015.

	N	Minimum	Maximum	Mean	Std. Dev.
Total_Mortality	2556	3	30	15.79	4.05
Tmin (°C)	2556	-24.00	32.30	8.53	10.37
Tmax (°C)	2556	-19.30	33.80	10.08	10.44
Humidity (%)	2554	22.50	100.00	71.39	18.24
PM _{2.5} (µg/m ³)	2496	1.70	107.03	18.68	11.80
PM ₁₀ (µg/m ³)	2556	3.70	137.34	25.84	14.14
O ₃ (µg/m ³)	2525	1.05	105.45	36.96	16.80
NO ₂ (µg/m ³)	2556	3.59	71.93	21.26	8.75
SO ₂ (µg/m ³)	2556	.00	39.17	2.29	2.62

Determination of cold day and hot day threshold temperatures

Figure 1 shows the relevant scatterplot diagrams. The Y-axis represents the pre-cleaned mortality series, and the X-axis the maximum (1a) and minimum (1b) daily temperatures. In the case of hot days, heat-related mortality begins to rise statistically significantly from a maximum daily temperature of 30°C upwards (Figure 1a), a threshold which coincides with the 96th percentile of the maximum daily temperature series for the summer months (June to September) across the period considered.

We therefore consider that a hot day occurs in this context when the daily maximum temperature rises above 30°C (T_{max}-Threshold).

Conversely, cold-related mortality in the sample period starts to statistically significantly increase when minimum daily temperatures drop below -12°C (Figure 1b). This value (T_{min}-threshold) coincides with the 7th percentile of the maximum daily temperature series for the winter months (November to March).

Figure 1. Relationship between daily mortality and maximum daily temperature during the summer months (a) and relationship between mortality and minimum daily temperature during the winter months (b)

Calculation of the impact of heat and cold on daily mortality

Table 2 shows the results of the Poisson model, in which only heat at lag 1 and PM₁₀ at lag 0 are associated with summertime mortality. An increase of 1°C in daily maximum temperature above 30°C results in an increase in the risk of daily all-cause mortality of 7.1%. The table also shows the impact of cold days during the sample period. The effect of cold is associated with all-cause mortality at lag 1. That is, mortality rises one day after the minimum temperature drops below -12°C. Relative humidity is statistically significant at lag 2, and positive, implying that higher relative humidity increases mortality on the two days after the minimum temperature drops below -12°C. Among the pollutants, PM_{2.5} is significantly associated at lag 2 and SO₂ at lag 1. Values of daily minimum temperature under -12°C translate into an increase in all-cause mortality risk of 1.6%.

Table 2. Relative Risks (RR) and Population Attributable Fractions (PAF) for Theat (for each degree when T_{max} exceeds 30°C (June-September)) and for T_{cold} (for each degree when T_{min} falls below -12°C (November–March)), and for increases of 10 µg/m³ in PM₁₀, PM_{2.5} and SO₂ concentrations. Relative Humidity (RH)

Vilnius 2009-2015	Variable	RR (95%CI)	PAF (95%CI)
Total Mortality (June-September)	T _{heat} (lag 1)	1.076 (1.025-1.129)	7.1 (2.52-11.46)
	PM ₁₀ (lag 0)	1.027 (1.006-1.048)	2.6 (0.63-4.59)
Total Mortality (November-March)	T _{cold} (lag 1)	1.016 (1.003-1.029)	1.6 (0.29-2.81)
	PM _{2.5} (lag 2)	1.017 (1.006-1.028)	1.7 (0.59-2.73)
	SO ₂ (lag 1)	1.070 (1.016-1.127)	6.5 (1.57-11.26)
	RH (lag 2)	1.002 (1.000-1.003)	0.2 (0.01-0.39)

Heat and cold attributable deaths during the sample period (2009–2015)

We calculated the mortality attributable to heat and cold during the sample period in Vilnius according to our established methodology. Results are listed in **Table 3**.

Across the period 2009-2015, there were 29 days on which the maximum daily temperature rose above 30°C. The aggregate heat-related mortality in this period was 52 persons (95% CI: 19-84), which translates as an annual mortality of 7.4 persons (95% CI: 2.7-12), i.e., for each day on which there is a daily maximum temperature above 30°C, there is a total heat-related mortality of 1.80 persons (95% CI: 0.63-2.90).

For cold days, across the period 2009-2015, there were 71 days on which the minimum daily temperature fell below -12°C. Cold-related mortality in this period totalled 70 persons (95% CI: 13-124) which translates as an annual mortality of 10 persons (95% CI: 1.9 -17.7), i.e., for each day on which there is a daily minimum temperature below -12 °C, there is a total cold-related mortality of 1 person (95% CI: 0.2-1.7).

Table 3. Heat and Cold Attributable deaths during the sample period (2009–2015).

Vilnius (2009-2015)	Total Attributable Mortality (95%CI)	Annual Mortality
T _{max} >30°C	52 (19-84)	7.4 (2.7-12)
Every day (N= 29days)	1.8(0.6-2.9)	
T _{min} <-12°C	70 (13-124)	10 (1.9-17.7)
Every day (N= 71 days)	1.0(0.2-1.7)	

3.2. Health impact assessment for 2030-2045 and 2085-2100

Heat –related mortality for 2030-2045 and 2085-2100

Under our first hypothesis, that is, a constant T_{max}-threshold (i.e. a maximum daily temperature of 30°C fixed), there would be 142 “hot days” in Vilnius during the period 2030-2045 under RCP8.5, reaching 8.9 “hot days”/year versus the sample period figure of 4.1 days. Attributable mortality across the 2030-2045 period would be 381 persons (CI95% 135-614), with a mean heat-related mortality of 24 deaths per year (CI95%: 8-38). This value is 3.2 times that calculated for the sample period 2009-2015. In the “far future” period 2085-2100, the yearly number of “hot days” would increase further, to 20 a year. The total attributable mortality for the entire period would be 738 deaths (CI95% 262-1190), with a mean heat-related mortality of 46 deaths per year (CI95%: 16-74). On a yearly basis, this would represent an increase in attributable mortality by a factor of 6.2 compared with the sample period 2009-2015.

Under the second hypothesis, that is, a variable T_{max} threshold (i.e. a “hot day” is defined as one with T_{max}>p96), there would be 77 “hot days” in Vilnius during the period 2030-2045 under RCP8.5, with 4.8 “hot days”/year versus the current figure of 4.1 days, a 20% increase respect 2009-2015. Attributable mortality across this entire period would be 162 persons (CI95% 57-261), with a mean heat-related mortality of 10 deaths per year (CI%: 4-17). This value is 1.4 times that calculated for the retrospective period 2009-2015. In the “far future” period 2085-2100, the yearly number of “hot days” would stay at 4.8, and the total attributable mortality for the entire period would be 96 deaths (CI95% 31-155). On a yearly basis, this would represent a decrease in attributable mortality by about 20% compared with the baseline period 2009-2015. These results are listed in **Table 4**, disaggregated by five-year periods.

Table 4. Projected mortality attributable to hot days (i.e. with heat-related mortality) during the periods: 2030-2045 and 2085-2100, with reference to the established hypotheses.

Hypothesis 1: Maximum daily temperature fixed at 30°C constant					
Period	Days with heat-related mortality	Total Attributable Mortality	Daily Total Attributable Mortality	Total Attributable Mortality (every year)	
2030-2034	42	94.69 (33.61-152.84)	2.25 (0.80-3.64)	18.94 (6.72-30.57)	
2035-2039	29	70.82 (25.14-114.31)	2.44 (0.87-3.94)	14.16 (5.03-22.86)	
2040-2045	71	215.11 (16.35-347.20)	3.03 (1.08-4.89)	35.85 (2.73-57.87)	
2085-2089	109	224.70 (79.75-362.68)	2.06 (0.73-3.33)	44.94 (15.95-72.54)	
2090-2094	83	164.88 (58.52-266.13)	1.99 (0.71-3.21)	32.98 (11.70-53.23)	
2095-2100	128	347.95 (123.50-561.62)	2.72 (0.97-4.39)	57.99 (20.58-93.60)	
Hypothesis 2: Percentile 96 of maximum daily temperature fixed					
Period	Tmax Threshold (p96)	Days with heat-related mortality	Total Attributable Mortality	Daily Total Attributable Mortality	Total Attributable Mortality (every year)
2030-2034	30.90	24	57.32 (20.35-92.53)	2.39 (0.85-3.86)	11.46 (4.07-18.51)
2035-2039	30.20	24	63.33 (22.48-102.23)	2.64 (0.94-4.26)	12.67 (4.50-20.45)
2040-2045	32.80	29	41.09 (14.58-66.33)	1.42 (0.50-2.29)	6.85 (2.43-11.06)
2085-2089	33.49	24	31.04 (11.02-50.09)	1.29 (0.46-2.09)	6.21 (2.20-10.02)
2090-2094	32.87	24	36.29 (12.88-58.58)	1.51 (0.54-2.44)	7.26 (2.58-11.72)
2095-2100	35.25	29	28.53 (10.12-46.04)	0.98 (0.35-1.59)	4.76 (1.69-7.67)

Cold –related mortality for 2030-2045 and 2085-2100

On the basis of the fixed threshold under the first hypothesis (i.e. a “cold day” is defined as one in which minimum daily temperature drops below -12°C), there would be 71 “cold days” in Vilnius during the period 2030-2045 under RCP8.5, with 4.4 “cold days”/year versus the current figure of 10.1 days, a 56% decrease. Attributable mortality across this entire period would be 72 persons (CI95% 13.13-127.21), with a mean cold related mortality of approximately 5 persons per year. This value is 54% lower than that calculated for the sample period 2009-2015.

In the “far future” period 2085-2100, the yearly number of “cold days” would decrease by 93%, and the total attributable mortality for the entire period would be 7 deaths (CI95% 1.25-12.13). On a yearly basis, this would represent a decrease in attributable mortality by 96% compared with the sample period 2009-2015.

Under the threshold definition for the second hypothesis (i.e. a “cold day” is defined as one with $T_{min} < \text{percentile } 7$), there would be 167 “cold days” in Vilnius during the period 2030-2045 under RCP8.5, with 10.4 “cold days”/year versus the current figure of 10.1 days, that is, a negligible change. Attributable mortality across this entire period would be 200 persons (CI95% 37-352), with a mean cold-related mortality of 12.5 persons per year. This value is 1.3 times that calculated for the retrospective period 2009-2015. In the “far future” period 2085-2100, the yearly number of “cold days” would remain virtually unchanged at 10.6, and the total attributable mortality for the entire period would be 105 deaths (CI95% 19-184). On a yearly basis, this would represent a decrease in attributable mortality by about 35% compared with the baseline period 2009-2015. Results are shown in **Table 5**.

Table 5. Projected mortality attributable to cold days (i.e. with cold-related mortality) during the periods: 2030-2045 and 2085-2100, with reference to the established hypotheses

Hypothesis 1: Minimum daily temperature fixed at -12°C constant					
Period	Days with cold-related mortality	Total Attributable Mortality	Daily Total Attributable Mortality	Total Attributable Mortality (every year)	
2030-2034	20	20.27 (3.70-35.84)	1.01 (0.18-1.79)	4.05 (0.74-7.17)	
2035-2039	17	19.90 (3.60-34.94)	1.17 (0.21-2.06)	3.98 (0.72-6.99)	
2040-2045	34	32.25 (5.85-56.63)	0.95 (0.17-1.66)	5.37 (0.98-9.43)	
2085-2089	3	1.77 (0.32-3.11)	0.59 (0.10-1.04)	0.35 (0.06-0.62)	
2090-2094	4	1.62 (0.29-2.85)	0.41 (0.07-0.71)	0.33 (0.06-0.57)	
2095-2100	5	3.48 (0.63-6.11)	0.69 (0.12-1.22)	0.58 (0.10-1.02)	
Hypothesis 2: Percentile 7 of minimum daily temperature fixed					
Period	Tmin Threshold (p7)	Days with cold-related mortality	Total Attributable Mortality	Daily Total Attributable Mortality	Total Attributable Mortality (every year)
2030-2034	-7.79	52	70.08 (12.70-123.07)	1.35 (0.24-2.37)	14.02 (2.54-24.62)
2035-2039	-8.56	52	60.45 (10.96-106.17)	1.16 (0.21-2.04)	12.09 (2.19-21.22)
2040-2045	-9.52	63	69.96 (12.67-122.86)	1.10 (0.20-1.95)	11.65 (2.11-20.48)
2085-2089	-2.56	53	40.36 (7.31-70.89)	0.76 (0.14-1.33)	8.07 (1.46-14.18)
2090-2094	-4.08	53	29.32 (5.34-51.72)	0.55 (0.10-0.98)	5.89 (1.07-10.35)
2095-2100	-4.37	63	35.14 (6.37-61.71)	0.53 (0.10-0.98)	5.85 (1.06-10.29)

4. Discussion

On heat and mortality in Vilnius, currently

The heat-related mortality threshold temperature, corresponding to a daily maximum of 30°C (96th percentile of the maximum temperature series of the summer months), indicates that days with mortality attributable to heat are currently infrequent in Vilnius. This threshold temperature is in line with the climatic characteristics to which the Vilnius population is subjected (Curriero *et al.*, 2002; Kovats *et al.*, 2006) characterised by mild summers. However, several factors other than climate influence heat-related mortality, including the population pyramid, and the over-65 age group in particular (Díaz *et al.*, 2002; Montero *et al.* 2012) as well as socio-economic factors, such as access to air conditioning, and the existence or absence of infrastructures adapted to heat (Abrahamson *et al.*, 2009; Montero *et al.* 2012; Vandetorren *et al.*, 2006). The fact that the association between high temperatures and mortality is established at lag 1 (an extremely short-term effect) is in line with the biological mechanisms implicated (Alberdi *et al.*, 1998; Havenit., 2002; Díaz *et al.*, 2015b). Quantitatively, the AR is higher than those of more temperate climates (e.g. Antwerp, see Martinez *et al.*, 2018) and lower than those of southern Europe (e.g. Spain, see Díaz *et al.*, 2015b).

On heat and mortality in Vilnius in the near and far future

Under a “no acclimatisation to heat” scenario, the current annual average figure of “hot day” would more than double in Vilnius by the period 2030-2045, and rise almost five-fold in the most distant time horizon 2085-2100. This increase in hot days is compatible with IPCC predictions (IPCC, 2013) which indicate that hot days will become increasingly frequent in Europe. In terms of health impacts, heat-related mortality would more than triple by 2030-2045, and increase more than 6-fold in 2085-2100 in relation to the current reference period.

The “no acclimatisation to heat” hypothesis may be taken as an upper limit, for a number of reasons. Demographic and socio-economic factors might account in part for the trend in minimum mortality temperatures (Mirón *et al.*, 2008). Studies conducted in different parts of the world conclude that the impact of heat on mortality is decreasing over time (Schifano *et al.*, 2012), particularly in cardiovascular-cause mortality (Ha and Kim 2013), while in the case of respiratory-cause mortality the effect remains practically constant (Mirón *et al.*, 2015). This trend seems to be linked to improvements in health services, socio-economic improvements, better built environments and a degree of acclimatisation of the population to heat (Konkel *et al.*, 2014).

Modelling the heat-acclimatisation process as a rise in the hot day threshold temperature, by keeping the percentile of future temperature series constant, may serve as a benchmark to test whether adaptive processes currently being implemented are adequate to the task. For instance, in order for heat-related mortality not to rise in Vilnius despite the increase in daily temperatures, the threshold temperature at the 2045 horizon should be 32.8 °C and 35.2 °C at 2100. Furthermore, it should also be borne in mind that annual mortality will gradually rise over time, something we have not taken into account, with the result that heat-related mortality, affected by this demographic factor, will increase accordingly.

On cold and health in Vilnius, currently

A systematic review conducted up to 2013 (Ryti *et al.* 2015) indicated that in most studies cold days were statistically defined on the basis of the frequency distribution of the set of days with extreme temperatures. The percentiles in those studies were between 1st and 3rd. The relatively high percentile value (7th percentile of the minimum temperatures of the winter months) in Vilnius may be related to cold acclimatisation factors and socio-economic conditions (Linares *et al.*, 2016; Carmona *et al.*, 2016). In general, cold-related mortality is associated with an increase in respiratory-cause mortality, though a relationship has been reported between low temperatures and circulatory-cause morbidity and mortality (Chau *et al.*, 2014). Low temperatures are associated with a higher incidence of respiratory tract infections (Makinen *et al.*, 2009), respiratory diseases (Monteiro *et al.*, 2013), and excess mortality and morbidity due to cardiovascular diseases (Davidkovova *et al.*, 2014). Multi-country global observational study found that moderate temperatures, rather than extreme temperatures, represented most of the total health burden (Gasparrini *et al.*, 2015). The adverse health effects of cold temperatures are more pronounced in warmer climates (Ballester *et al.*, 2011).

These results for Vilnius (significant at lag 1) suggest that most cold-related mortality is due to circulatory rather than respiratory causes. Cold-related mortality typically has a bimodal distribution, with a first peak of circulatory mortality between days 1-4 and a second peak in days 7-14 due to a higher degree to respiratory causes. This phenomenon is linked to the underlying biological mechanisms (Ryti *et al.*, 2016). The AR obtained for this city in relation to cold is 1.6% for each degree that the minimum daily temperature falls below -12°C. According to a meta-analysis which addressed the impact of cold on mortality (Ryti *et al.* 2016), the AR of cold on all-cause mortality would be around 10% per degree, a value similar to that of circulatory causes (11%) and far higher than that of respiratory causes (20%). The low value found for Vilnius supports the notion that the population of Vilnius is well adapted to low temperatures. Residents of hot regions are known to show less physical, social and behavioural adaptation to low temperatures (Lin *et al.*, 2013), with the effects of cold being more significant in such regions (Langford *et al.* 1995; Wang *et al.*, 2012) or in areas with moderate winter climates (Conlon *et al.*, 2011).

The fact that daily mortality attributable to hot days is almost twice that due to cold, underscores the pressing need for the implementation of heat wave prevention plans in Vilnius. However, the data

also clearly show a need for effective cold wave prevention plans in Vilnius, where the overall effect of cold on mortality is 20-fold that of heat (Gasparrini *et al.*, 2015). Moreover, the recent trend of heat-related mortality is a decreasing one, whereas cold-related mortality is increasing (Díaz *et al.*, 2015a).

On cold and health in Vilnius in the near and far future

“Cold days” would continue to occur under RCP8.5 in Vilnius, albeit falling to less than half the current number in the 2030-2045 and decreasing by over 90% by the end of the century, a finding in line with other studies (Kodra *et al.*, 2011). Similarly, annual mortality attributable to cold is projected to fall, to a value around 2.5 times lower by 2030-2045 and by a factor of 20 in 2085-2100 in relation to the current values. This decline in cold-related mortality is also in line with the results reported by other studies (Gasparrini *et al.* 2015). Mortality estimates obtained until the year 2050 with 20 climate models in 209 cities of the USA (Wang *et al.*, 2016) suggest that future mortality associated with cold days and prolonged cold waves (i.e., those occurring less than seven days after the end of the preceding one) will decline over time by 0% to -2.1%, values close to those obtained in another study (1.59%) undertaken in the USA (Medina- Ramon 2007). Yet, other studies based on a meta-analysis (Ryti *et al.* 2016) performed until February 2013, which included studies from China, The Netherlands and Yakutsk, reported rises in mortality of the order of 10%.

Will the decrease in cold-related mortality compensate the increase in heat-related mortality?

In the case of heat, with a constant threshold there is a strong increase in heat-related mortality, due to the increase in the number of hot day episodes. However, if we assume a process of acclimatisation (the temperature series percentile remains constant but as climate warms that percentile corresponds to higher temperatures), heat-related mortality increases until the year 2035 and decreases thereafter due to the evolution in the mortality rate. Evidently, such a sharp rate of acclimatisation is unlikely, but some degree of heat acclimatisation is clearly happening (Gasparrini *et al.*, 2015; Mirón *et al.* 2015; Díaz *et al.* 2015a; Ha and Kim 2013; Petkova *et al.*, 2014). Therefore, we may assume that expected mortality by the year 2100 may be somewhere between both hypotheses. How close to one or the other will depend on the impact of the adaptation processes, whether natural or institutionally driven.

The steep decrease in cold-related mortality is caused by the combination of a constant threshold definition and a reduction in the number of cold days under a warming climate. Put simply, less cold episodes would qualify as “cold days” under that assumption. However, if such threshold temperature increases (i.e. populations become used to less cold) and the number of cold days remains practically constant in time, the mortality reduction would be less pronounced, as can be seen in Figure 2. In addition, since we have assumed the cold and heat AR to be constant, we have not captured a possible increase of the impact of cold on daily mortality (Díaz *et al.*, 2015a; Gasparrini *et al.*, 2015).

Overall, if we assume no acclimatisation for either heat or cold, the increase in heat-related mortality would clearly outweigh reductions in cold-related mortality. **Figure 2** shows the yearly evolution of the difference between heat-related and cold-related mortality (i.e. yearly heat-related mortality minus yearly cold-related mortality), assuming either a constant threshold definition temperature, or a changing one. If we assume that future cold-attributable mortality may be somewhere between both scenarios, the decrease in cold day mortality (due to fewer cold days) will generally not compensate the increase in hot day mortality (due to more hot days) (Staddon *et al.*, 2014). Thus, the benefits of a warmer climate may be quite limited from the standpoint of direct effects of temperature on mortality (Kinney *et al.*, 2015)

Figure 2. Time trend of the annual mortality attributable to heat and cold, according the different periods and hypothesis

Limitations and biases

Several limitations of this study should be mentioned: firstly, with reference to the quality and consistency of the data analysed, 3-hourly daytime temperatures were used as proxies for daily maximum and daily minimum temperature. Regarding the minimum daily temperature used to define cold days, it is worth noting that sunrise in the middle of our wintertime period (i.e. December 31st) happens at 8:39AM (Sunrisesunset, 2018). Since minimum daily temperatures are typically reached one hour after sunrise, using 9AM measurements is not a far-off proxy. Similarly, sunrise in Vilnius on 21 June happens at 04:39AM, so that by noon, the sun has had about 7 and a half hours to increase temperatures (Sunrisesunset, 2018). Climatological series indicate an average of daily maximum temperatures for Vilnius of 10.46 °C (Climate-data, 2018), a very close value to the one in this study, of 0.08 °C. Furthermore, using measurements at 12h as maximum daily temperature (in the absence of complete hourly series) seems justifiable in this case since the average 12h temperature series was higher than that of the 15h temperature series.

Another possible limitation of this study is the potential misclassification of the cause of mortality. However, since we only considered natural causes excluding accidental deaths and suicides, the potential for this type of bias is limited. In relation to the lack of data on environmental variables, and pollution in particular and meteorology to a lesser extent, led to the use of statistical methods to fill the gaps, with the resulting errors.

With respect to methodological limitations, essentially two should be highlighted: 1) the shortcomings inherent in a statistical method that works with a high number of variables at a 95% confidence level; and 2) this is an ecological study, which means that inferences cannot be made at an individual level. It is only possible to show the existence of a statistical association between the variables analysed. Factors favouring the existence of a real -as opposed to a spurious- relationship, are the high correlation index, increasing dose-response relationship, absence of temporal ambiguity, biological plausibility of the effect shown in clinical studies, and consistency of results obtained by previous studies.

Furthermore, in the case of estimates of the impact of temperatures on mortality, various hypotheses were postulated, including the assumption of mortality being constant over time, the related population attributable fraction remaining similarly constant, as well as the mortality threshold temperature associated with the extreme temperatures. Although these aspects have been addressed in the Discussion section, it is evident that their use might lead to biases in the results obtained in this study.

Implications for prevention

Cold-related mortality in Vilnius is, unsurprisingly, currently a greater public health problem than heat-related mortality in absolute terms; it is more than twice as frequent, and more people are killed by cold on a yearly basis than by heat. However, daily heat-related mortality in Vilnius currently practically doubles that attributable to cold. Moreover, heat is set to become a greater public health problem in Vilnius due to climate change and demographics. That suggests a high vulnerability and points to an urgent need to design and implement adequate measures within a coherent heat-health action plan. Those measures need to take into account this changing landscape, and be calibrated on the existing epidemiological evidence (E.g. the very short lag time between high temperatures and mortality). In the case of Lithuania, institutional efforts are currently underway to address these public health factors (in fact, this study was partly intended to support such efforts in terms of evidence base). Given these results, implementation should be urgent, and incorporate climate change considerations from the inception, making an explicit link with adaptation activities, both general and specific to the health sector, and on a multi-level governance framework with clear roles also for authorities at the local level.

5. Conclusions

Thermal extremes, both heat and cold, constitute a serious public health threat in Vilnius. Cold causes currently more premature deaths than heat in Vilnius, and effective public health preventive action is needed locally in cold-health prevention. However, efforts in heat-health prevention are also warranted in this case. High temperatures are comparatively deadlier in an unacclimatised population, and they are set to become more extreme and more frequent under climate change. Moreover, the decrease in mortality attributable to cold will not compensate for the increase in mortality attributable to heat in Vilnius. Our results reinforce the notion that public health prevention against thermal extremes should be understood as a dynamic, adaptive process from the inception.

List of abbreviations

AD: attributable deaths
AF: attributable fraction
ARIMA: autoregressive integrated moving average
CI: confidence interval
CMIP5: Coupled Model Intercomparison Project 5
DTU: Technical University of Denmark
GCMs: global climate models
ICD: International Classification of Diseases
IHD: ischemic heart disease
IPCC: Intergovernmental Panel on Climate Change
ISCH: Institute of Health Carlos III
PAF: Population Attributable Fraction
PM₁₀: particulate matter less than 10 micrometers in diameter
PM_{2.5}: particulate matter less than 2.5 micrometers in diameter
RAMSES: Reconciling Adaptation, Mitigation and Sustainable Development for Cities
RCP8.5: Representative Concentration Pathway scenario 8.5
RR: relative risks
SMLPC: Centre for Health Education and Diseases Prevention
VITO: Flemish Institute for Technological Research
WHO: World Health Organization
WPP: World Population Prospects

Declarations

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Consent for publication

Not applicable

Competing interests

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Authors' contributions

GSM designed and coordinated the study, and drafted this article; JD coordinated and supervised the epidemiological analysis, which was carried out by CL, RC and CO. HH and DL collaboratively carried out the urban climate and climate change modelling, with the supervision and collaboration of KDR. VK provided inputs and context for the discussion and introduction sections. DA collected and analysed population data, formatted the draft and references, and managed the peer review coordination among authors.

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