Public Health 236 (2024) 261–267

Contents lists available at ScienceDirect

Public Health

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

Original Research

The impact of climate and demographic changes on future mortality in Brussels, Belgium

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ARTICLE INFO

Article history:
Received 22 May 2024
Received in revised form
12 July 2024
Accepted 28 July 2024

Keywords:
Attributable mortality
Climate change
Demographic changes
Mortality projections

ABSTRACT

Objectives: City populations are particularly vulnerable to climate change, but it is difficult to reliably estimate the impact on health due to the lack of high-resolution data. We used recently developed regional climate model projections at kilometre resolution combined with demographic projections to estimate the future mortality burden associated with temperatures in the region of Brussels, Belgium.
Study design: The study incorporated a time-series analysis.
Methods: Based on quasi-Poisson regression with distributed-lag non-linear models for the historical temperature–mortality relationship, we derive the mortality burden for the near (2020–2044) and mid (2045–2069) future and disaggregated the contributions of demographic and climate changes.
Results: The cold-related attributable fraction of deaths is expected to decrease from 6.22% (95% empirical confidence interval: 1.76%; 10.52%) in 1994–2019 to 5.17% (1.08%; 9.09%) in 2045–2069, whereas for heat, this fraction will increase from 1.02% (0.59%; 1.47%) to 1.83% (0.82%; 2.96%), with contributions of both climate and demographic changes. In stratified analyses by age, we found that because of demographic changes, the number of cold-attributable deaths will increase for people aged above 85 years, with 6815 (95% empirical confidence interval: 1424; 12,003) deaths expected in 2045–2069 compared to 5245 (1462; 8867) deaths in 1994–2019. For people aged below 65 years, on the other hand, the number of heat-related deaths will decrease from 456 (265; 658) to 344 (154; 561) deaths.
Conclusions: Public health policies that especially target the elderly and the summer-time period are needed to limit the impact of climate change on health.
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Introduction

The impact of temperature on mortality is now well established,[1,2] but the magnitude may strongly depend on the location. Cities are generally warmer than rural surroundings due to the urban heat island and heat stress will be exacerbated by climate change.[3,4] Nowadays, more than half of the world's population lives in a city or an urban area, and this number is expected to rise in the next decades.[3,5] The assessment of the impact of climate change in cities is therefore a public health priority and is required to be informed to policymakers to protect current and future populations.[6,7] To this aim, studies based on local data in a specific city are well adapted to the needs of local authorities and policymakers in the design of better-localised intervention strategies and provide more tailored answers.

Belgium is a densely populated and highly urbanised country,[8] and its population is therefore subject to a strong and increasing degree of heat stress.[9] The capital of Belgium, Brussels, is by far the most densely populated region with 7642 inhabitants/km^2.[10] While temperature–mortality relationships have already been estimated for Brussels,[11–13] the projected impact of future temperatures under climate change was only integrated in a large Europe-wide study that used coarse temperature observations.[14] Fine-scale spatial resolutions, however, are key to capture local aspects of climate variability and change, especially within cities. For Brussels, an ensemble of 10 specific urban-climate simulations was recently

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https://doi.org/10.1016/j.puhe.2024.07.028
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developed under the Representative Concentration Pathway 8.5 (RCP 8.5).[15]

Demographic changes, adaptability, urbanisation growth, and climate change impact the future temperature-related mortality.[16,17] For instance, not including demographic changes can lead to an underestimation of the health burden attributable to temperature[18] since older people are generally more vulnerable to extreme temperatures.[11,19] The last Lancet Report on the impact of climate change on health estimated that, between 1991–2000 and 2013–2022, yearly averaged heat-related mortality of people aged above 65 years increased by 85%, driven by both warming and changing demographics.[6] It is therefore important to include demographic projections to estimate future temperature-related mortality.

In the present study, we assess the future temperature-attributable mortality for Brussels, considering climate and demographic changes. First, the historical temperature–mortality relationship is estimated in the 19 municipalities forming Brussels and pooled using a meta-analysis to establish the relationship for all Brussels. Based on this pooled association, we evaluate the temperature-attributable mortality for two future periods (2020–2044 and 2045–2069) and disaggregate the contributions of demographic changes and climate change.

Methods

Data source

The daily numbers of deaths and the annual population of the 19 municipalities forming Brussels (officially named the Brussels-Capital Region) were provided by Statbel, the Belgian statistical office. Mortality information included the date of death, sex, and age (5-year age groups) from 1992 to 2021. The daily maximum temperature and average relative humidity were extracted from a reanalysis-driven dynamic-downscaling simulation over Brussels at 1-km spatial resolution and averaged per municipality of Brussels from 1990 to 2019. For that purpose, a modelling chain using the regional climate models ALARO, the off-line land-surface model SURFEX[20] and ALARO-SURFEX (coupled in-line) were used as follows: 1) ALARO was run at 20 km over a large domain over Western Europe using ERA-Interim[21] as lateral boundary conditions; 2) this run was used to force a 4-km ALARO-SURFEX run at the lateral boundary condition of a domain over Belgium; 3) this run, in turn, was used to force stand-alone SURFEX at a 1-km resolution over a domain over Brussels. 4) Finally, these data were averaged at the municipality level. The temperature data generated for Brussels were validated in Duchêne et al.[21] (Table 3) with a focus on summer heatwave and the urban heat island (UHI) using three stations: one in a dense urban location, one in the suburban areas of Uccle, and the reference one in a rural area called Brussegem. Those data were used to assess the historical temperature–mortality relationship over the period 1992–2019 and for bias correction of the climate projections.

Future projections of temperature and humidity were taken from a statistical–dynamical downscaled ensemble of 10 (EURO-CORDEX) regional climate models (RCMs) simulations over 130 years (1971–2100) under the RCP 8.5 emission scenario, as described in Duchêne et al.,[15] again at a 1-km resolution. As put forward by Vicedo-Cabrera et al.,[22] each model was bias-corrected using the approach of Hempel et al.[23] This method ensures that the trend and the variability of the temperature projections are preserved. Since the year 2006 was used as a transition year between the historical and the future projected temperature periods, data were not available for this year.[15] The Federal Planning Bureau provided yearly mortality rates and population projections for Brussels, by age and sex, from 1992 to 2070. Population projections are calculated using a deterministic cohort-component method. Assumptions made on the future fertility, mortality, and migration rates are updated annually.[24,25] Those data sets were used to assess the future temperature-attributable mortality.

Historical temperature–mortality relationship

In the first step, we estimated the historical temperature–mortality relationships in each municipality of Brussels using quasi-Poisson regressions and distributed-lag non-linear models (dlnm)[26] to take into account the non-linear and lagged relationship between temperature and mortality. We used a natural cubic spline (ns) with three internal knots placed at the 10th, 75th, and 90th percentiles of the temperature distribution to model the temperature–mortality relationship and considered other percentiles (the 5th, 50th, and 95th percentiles) in a sensitivity analysis. For the lag–mortality relationship, we used a natural cubic spline with three internal knots placed at equal distances on the log scale. The model was as follows:

$$Log(deaths) = cb + dow + holiday + ns(humidity) + ns(time, df) + offset = \log(pop)$$

where cb is the cross-basis combining the temperature–mortality and lag–temperature relationships, *dow* is the day of the week, *holiday* is a binary variable that allows controlling for public holidays, and *ns(humidity)* is a natural cubic spline of the daily mean humidity with 2 degrees of freedom (df); in two separate sensitivity analyses, we run a model with df = 4 and another model without humidity. *ns(time, df)* is a natural cubic spline of the date with df = 7 per week to control for the time trend. We finally included the yearly population as an offset to consider the population of the municipalities and their evolution.

Then, we defined the overall cumulative temperature–mortality association by accumulating the risks over the lags 0–21 days before death.[27] This period of 22 days allows to take into account the harvesting effect and long delayed effect of cold extremes.[12,22] Finally, the municipality-specific estimates were pooled with a random-effect meta-analysis and restricted maximum-likelihood estimation[28] to obtain the temperature–mortality relationship for all Brussels. From the latter, we extracted the minimum mortality temperature (MMT), the temperature for which the mortality risk is the lowest, and defined cold and heat as temperatures below/above the MMT. We tested residual heterogeneity using the Cochran Q test and I^2 statistic.

Future temperature-attributable mortality

The daily temperature-attributable number of deaths (AN) was calculated as follows[22,29]:

$$AN = \left(1 - e^{-(f(Tproj,\theta) - f(MMT,\theta))}\right) \times N$$

where Θ are the coefficients of the unidimensional overall cumulative temperature–mortality curve with the reduced lag dimension estimated previously and T_{proj}, the daily projected temperature. N corresponds to the total daily number of deaths and was calculated as the product of the Brussels yearly population and the daily projected mortality rate. Assuming the daily mortality proportion to be unchanged over the study period, the latter was calculated as the observed daily mortality proportion over the years of the historical period multiplied by the yearly projected mortality rate, thus keeping into account the seasonal structure of the observed mortality series.[30] Attributable fractions were calculated as the ratio between the attributable number of deaths and the total number of deaths. In order to estimate the uncertainty on the population projections, a sensitivity analysis was performed using another set of population projections considering a lower fertility rate.

The daily results were averaged over the ten RCMs and aggregated by 25-year periods for the baseline (1994–2019)[d] and for the near (2020–2044) and mid future (2045–2069) periods. Globally, the periods 2020–2044 and 2045–2069 correspond more or less to global warming levels of 1.5 °C and 2.5 °C, respectively (see Table 3 in Duchêne et al.[21]).

To quantify the uncertainty associated with the temperature–mortality relationship estimation and the temperature projections, we have performed 1000 samples of the estimated spline model coefficients using Monte Carlo simulations assuming that the coefficients followed a multivariate normal distribution.[22] We generated simulations for each of the ten RCMs and reported results as averages over them. The 2.5th and 97.5th percentiles of the empirical distribution across the samples defined 95% empirical confidence intervals (eCIs). Additionally, to evaluate the uncertainty due to the climate projections only, we repeated this step but held the model coefficients at their initial values.

We have considered three different scenarios. In a scenario with demographic and climate changes (DEM + CLIM), we used the projected temperature and projected number of deaths. In scenario CLIM, we assumed the total number of deaths to be constant over the three 25-year periods (corresponding to the number of deaths for the period 1994–2019). Hence, as compared to the baseline reference period 1994–2019, this scenario allows capturing the contribution of climate change. Similarly, in scenario DEM, we assumed the absence of climate change (by reconsidering the climate of 1994–2019) to capture the contribution of demographic changes (as compared to the baseline reference period). Demographic changes concern population size, age structure, and mortality-rate changes.

We did all statistical analyses using R with the packages dlnm and mixmeta.[31,32]

Results

Temperature and mortality data

Table 1 describes the population and mortality numbers by age group for the periods 1994–2019, 2020–2044, and 2045–2069. We observe a decrease in the number of deaths over the three periods of time in all age groups except for people aged ≥85 years. The total population is expected to increase in the future in all age groups except for people aged ≤64 years, for which we observe a decrease between 2020–2044 and 2045–2069 (Fig. S1). The number of people aged ≥85 years is expected to double between 1994–2019 and 2045–2069. On the contrary, the mortality rates decrease in all the age groups, the decrease being more important in people aged ≤64 years. Regarding future temperatures, the daily maximum temperature is expected to increase by approximately 2.5–3 °C during the period 1994–2069 (Table S1, Figs. S2 and S3) under the RCP 8.5 scenario. Municipality-specific historical temperature–mortality relationships show U-shaped curves (Figs. S4–S5) and little heterogeneity (Cochran Q test *P*-value = 0.16, I^2 = 14.2%). The MMT obtained from the pooled relationship is 24.0 °C.

[d] The year 2006 being excluded from the analyses (see Data source).

Table 1
Average yearly descriptive statistics of population and mortality in Brussels for the periods 1994–2019, 2020–2044, and 2045–2069.

Age groups	Periods	N[a]	Pop[b]	MR[c]
0–64	1994–2019	44,802	897,649	199.6
	2020–2044	32,488	1,078,164	120.5
	2045–2069	19,359	1,063,582	72.8
65–74	1994–2019	41,507	79,054	2,100.2
	2020–2044	35,453	96,121	1,475.3
	2045–2069	28,707	109,917	1,044.7
75–84	1994–2019	72,236	55,270	5,227.9
	2020–2044	56,550	61,151	3,699.0
	2045–2069	54,398	82,632	2,633.3
85 +	1994–2019	84,536	23,320	14,500.2
	2020–2044	91,516	28,147	13,005.4
	2045–2069	132,257	46,266	11,434.5
Total	1994–2019	243,081	1,055,293	921.4
	2020–2044	216,007	1,263,582	683.8
	2045–2069	234,721	1,302,396	720.9

[a] N: cumulated number of deaths.
[b] Pop: yearly averaged population.
[c] MR: yearly averaged mortality rate per 100,000 inhabitants.

Future temperature-attributable fraction

Under demographic and temperature changes (scenario DEM + CLIM), 6.22% (95% eCI: 1.76%; 10.52%) of deaths are attributable to cold in 1994–2019, and this fraction decreases to 5.17% (1.08%; 9.09%) in 2045–2069 (Fig. 1, Table S2). On the other hand, heat-related attributable fractions increase from 1.02% (0.59%; 1.47%) in 1994–2019 to 1.83% (0.82%; 2.96%) in 2045–2069. In total, the temperature-attributable mortality slightly decreases from 1994 to 2019 to reach 7.00% (2.68%; 11.16%) in 2045–2069.

Drivers of the future temperature-attributable mortality

For cold, considering climate and demographic changes (scenario DEM + CLIM), we find a decrease of 2641 (1180; 4078) and 2997 (1745; 4228) attributable deaths for 2020–2044 and 2045–2069 compared to the reference period (1994–2019), where 15,131 (4286; 25,570) deaths were observed (Fig. 2, Table S3). Both scenario CLIM and scenario DEM contribute in this decrease (Fig. 2), the latter being driven by a decrease in the mortality rates compared to 1994–2019 (Table 1). The contribution of climate change (scenario CLIM) is, however, lower than the contribution of demographic changes (scenario DEM) (Table S3, Fig. S6), with a decrease of, respectively, 1076 (788; 1383) and 1676 (487; 2846) attributable deaths in 2020–2044, compared to the baseline reference period (1994–2019). Fig. 3 details the temperature-attributable number of deaths by age group. In scenario DEM + CLIM, we observe a decrease in cold-related mortality in the near (2020–2044) and the mid (2045–2069) future for all age groups except for people aged ≥85 years in the mid future, where 6815 (1424; 12,003) deaths are expected compared to 5245 (1462; 8867) deaths in 1994–2019 (Table S4). In this age group, in contrast to other age groups, demographic changes (scenario DEM), and more specifically population growth (Table 1), conduct to an increased number of deaths. In all age groups, the contribution of demography (scenario DEM) is higher than the contribution of climate (scenario CLIM).

Regarding the heat impact, we find an overall increase in the attributable number of deaths (scenario DEM + CLIM) with 190 (−31; 814) and 1810 (492; 3373) additional deaths in 2020–2044 and 2045–2069, respectively, compared to 1994–2019, where 2481 (1441; 3567) deaths are observed (Fig. 2, Table S3). While

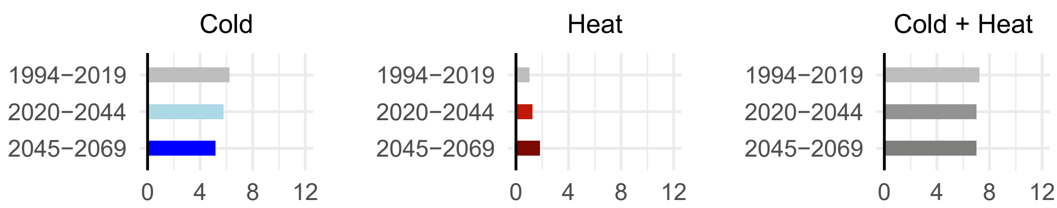

Fig. 1. Temperature-attributable fractions for the periods 1994–2019, 2020–2044, and 2045–2069.

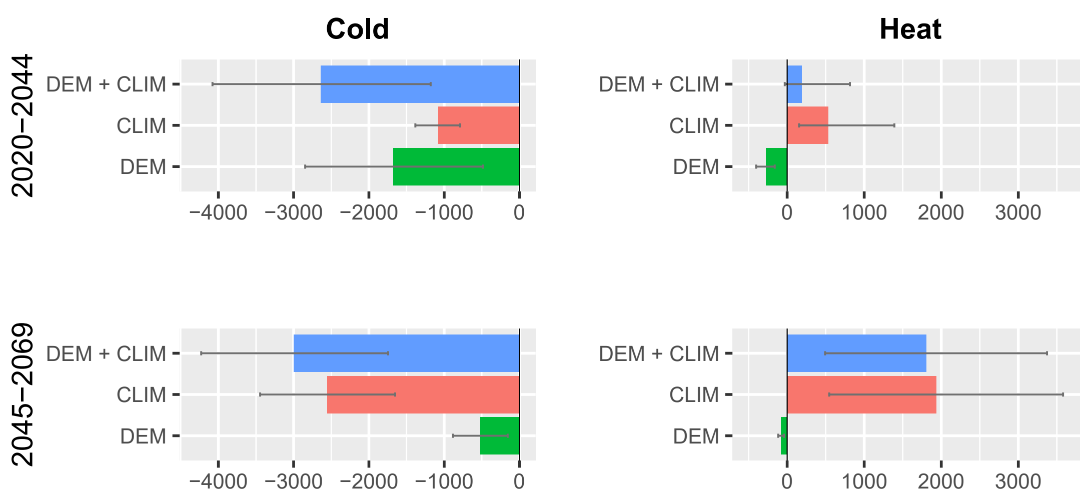

Fig. 2. Future temperature-attributable number of deaths under three climate and demographic scenarios: differences with the period 1994–2019. The cold- and heat-attributable numbers of deaths in 1994–2019 were 15,131 and 2481 deaths, respectively; scenario CLIM includes climate changes but constant demography; scenario DEM includes demographic changes but constant climate. DEM, demographic changes; CLIM, climate changes.

climate induces an increase in the number of deaths (scenario CLIM), the impact of demography is lower and in the opposite direction but very small, especially in the mid-future (scenario DEM) (Fig. 2, Fig. S6). In age groups' analyses, we observe an increased number of heat-attributable deaths over time for all age groups except for people aged ≤64 years (scenario DEM + CLIM), with 456 (265; 658) deaths in 1994–2019, 400 (212; 657) deaths in 2020–2044, and 344 (154; 561) deaths in 2045–2069 (Fig. 3, Table S5), the decrease being also driven by demographic changes (scenario DEM) (Fig. S6), and more particularly, by a decrease in the mortality rate (Table 1). We observe a considerable increase in the number of attributable deaths for people aged >85 years, the estimated rise being 261 (92; 608) additional deaths in 2020–2044 and 1577 (597; 2703) in 2045–2069. This rise is driven by both climate (scenario CLIM) and demographic changes (scenario DEM) and more particularly by a population growth in this age group (Table 1).

In sensitivity analyses, changes in the temperature–mortality relationship (place of the knots) (Fig. S7) in the humidity specification (Figs. S9–S10) or in population projections (Fig. S8) have very little effect on the results.

Overall, estimates show large eCIs. Fig. S11 shows the number of attributable deaths with eCIs reflecting uncertainties due to the climate projections only (not the model coefficients). Compared to the eCIs including both model coefficient and climate projections uncertainties (Fig. 2), there was a clear decrease in the uncertainty, and this decrease was more pronounced for cold than for heat (Table S6).

Discussion

Under the RCP 8.5 scenario, we predict an overall decrease in cold-related mortality in Brussels, induced by both climate and demographic changes. On the other hand, a rise in heat-related mortality, largely driven by climate change, is expected. Analyses stratified by age groups revealed that, due to demographic changes, in contrast to other age groups, the number of cold-attributable deaths will increase for people aged more than 85 years old and that people aged less than 64 years old will see a decrease in heat-related mortality.

Decreases in future cold-attributable deaths and increases in heat-attributable deaths are observed worldwide[33,34] but depending on the location and the climate scenario considered, the moment at which the increase in heat-attributable deaths is expected to exceed the reduction of cold-attributable deaths varies.[17] In Brussels, under the RCP 8.5 scenario, we did not observe this shift during the study period. The increase in heat-related mortality was driven by climate change. Regarding the decrease in cold-related deaths, the contribution of demographic changes was the most important in all age groups but going in an opposite direction in

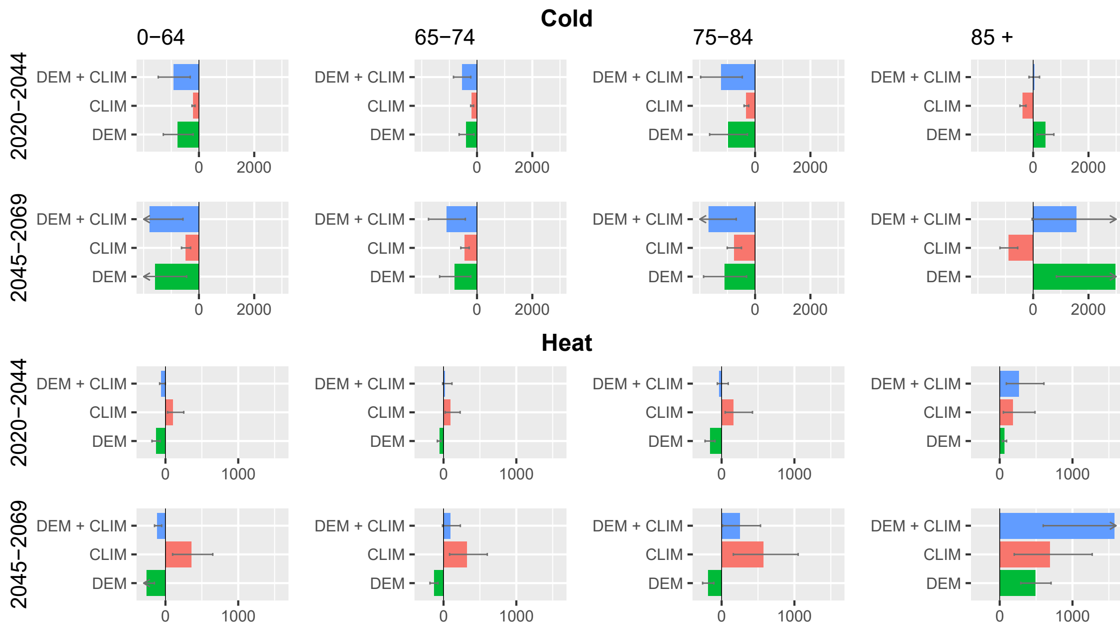

Fig. 3. Future temperature-attributable number of deaths under three climate and demographic scenarios by age group: differences with the period 1994–2019. The cold- and heat-attributable numbers of deaths in 1994–2019 were 15,131 and 2481 deaths, respectively; scenario DEM + CLIM includes climate and demographic changes; scenario CLIM includes climate changes but constant demography; scenario DEM includes demographic changes but constant climate. DEM, demographic changes; CLIM, climate changes.

people older than 85 years compared to the other age groups. In line with other studies,[18,35] we show that demographic changes are essential when investing the future temperature-related mortality studies since they greatly impact the future number of deaths. Studies have, for instance, highlighted the negative impact of ageing on future temperature-related mortality as its burden results in a rise in mortality.[6,18,35–37] In Brussels, we expect a substantial increase in the number of people older than 85 years.[24] This results in an increased number of cold-attributable deaths, although cold extremes will be less frequent in the future. Similarly, despite global warming, we found a decrease in heat-attributable deaths in people aged <65 years, which is due to an expected lower mortality rate in this age group.

However, our results indicate that, climate change will have a larger impact than demographic changes on future heat-attributable mortality. To limit this impact, studies have underscored the link between air pollution levels and climate change, indicating that air-pollution reductions would mitigate the health effects of temperature extremes.[38] Therefore, mitigation measures should include air-pollution emission reduction. Adaptation measures are also key to reduce temperature-related mortality.[6,7,39] This includes a better adaptative health system and health monitoring.[6,7,37,39] Specific policies can also be put in place to make cities more livable and reduce the impact of climate warming. One example is the expansion of urban green spaces and urban blue infrastructure. This includes roadside trees and street greenery, greening of facades and green roofs, and larger green spaces (parks, playgrounds) that promote recreation, air pollution control, and a diversity of microclimates.[37] Cugnon et al. showed that, in Brussels, this would have the largest impact on the urban heat island as compared to other adaptation measures.[40] Verdonck et al. also showed the importance of urban planning strategies in Brussels.[41]

Our results are in line with previous studies performed over Brussels. Regarding the historical temperature–mortality relationship, we observed an MMT of 24.0 °C, whereas De Troeyer et al.[13] and Demoury et al.[12] found optimum temperatures of 22.8 °C and 23.6 °C, respectively. Martinez-Solanas et al. estimated future attributable fractions of deaths in 147 European regions including Brussels. Under RCP 8.5, they found attributable fractions compatible with our results, although the cold-attributable fractions were slightly lower and the heat-attributable fractions were slightly higher. A lower MMT might explain the differences (see Figs. S1 and S10 in Martinez-Solanas et al.[14]).

In line with other studies,[42,43] our projections of temperature-attributable deaths showed large uncertainties. In particular, we found the uncertainty being largely due to the temperature–mortality relationship parameters as did Chen et al. (2022), who obtained similar findings for projections of heatwave-attributable deaths in mainland China.[30] A better understanding of the predictors of the temperature–mortality curve in particular living and working conditions could improve future estimates.[44] The remaining uncertainty due to climate projections were higher for heat than for cold, which might be explained by higher difficulties to predict (extremely high) temperatures not frequently observed during the historical period. Finally, another source of uncertainty is the extrapolation of the temperature–mortality curve beyond the historical data range.

Our study has strengths and weaknesses. The first weakness is the use of climate projections for the RCP 8.5 only. At the end of the 21st century, the RCP 8.5 scenario features a high radiative forcing (8.5 W/m^2) due to a lack of underlying mitigation measures, ensuing the global mean temperature rise to exceed 4 °C, and is therefore no longer considered plausible.[45] However, for the period under investigation (2040–2070), global warming ranges between 1.4 °C and 2.6 °C, which is well within the plausible future range (Table SPM-2 in Field et al.[46]). We have used high-resolution temperature data at a 1-km^2 spatial resolution coming from an ensemble of 10 different RCMs that allows taking account for the uncertainties of the climate projections.[15,17,21] We also considered uncertainty from other sources (temperature–mortality relationship and population projections) and made a thorough analysis of these sources of uncertainty. On the other hand, we worked with aggregated data and were thus not able to capture the real exposure to temperatures of the people, which can vary from one place to another. However, the historical temperature–mortality relationships were estimated by municipalities, whose surface areas are relatively small in Brussels. Real individual exposure also depends on air conditioning, life habits, and working conditions,[47–49] which were not considered in the study. We considered a constant temperature–mortality relationship throughout the study period, assuming that the physical climate-adaptive capacity would remain constant. Modelling adaptation remains challenging and often implies multiple assumptions because this requires, for instance, data on air-conditioning prevalence or people's behaviours during hot periods, which are rarely available.[50] Another strength of our study is the use of population- and mortality-rate projections, which were considered by only a few studies.[16,17] We have, however, to acknowledge that mortality rate projections used in the present study do not account for changes in vulnerability due to future changes in temperatures.

In conclusion, this study underscores the impact of both demographic and temperature changes on the future health burden. This study also highlights the vulnerability of the elderly since the number of deaths attributable to both cold and heat will increase in this age group. Taking into account these findings in public-health policies will allow better adaptation and mitigation strategies to limit climate-change impacts.

Author statements

Acknowledgements

The authors thank the Belgian statistical office and the Federal Planning Bureau for providing mortality and population data.

Ethical approval

Not applicable.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interests

None.

Author contributions

Clémentine Crouzier: Conceptualization, Methodology, Software, Writing - Original Draft. Bert Van Schaeybroeck: Conceptualization, Writing - Review & Editing. François Duchêne: Methodology, Writing - Review & Editing. Matthieu Duchêne: Software, Writing - Review & Editing. Rafiq Hamdi: Conceptualization, Writing - Review & Editing. Fati Kirakoya: Methodology, Writing - Review & Editing. Claire Demoury: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2024.07.028.

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