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The impact of population ageing on temperature-related mortality projections in the Czech Republic

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Abstract

Climate change and population ageing are jointly reshaping temperature-related mortality patterns in Europe; however, their combined effects remain insufficiently quantified on the national scale. In the Czech Republic, cold-related mortality has historically exceeded heat-related mortality, but this pattern is expected to shift under future climate and demographic transitions. Here, we projected future heat- and cold-attributable mortality under both climate-only and population ageing scenarios. We estimated age-specific (<75 and ≥75 years) temperature–mortality associations for all 14 NUTS-3 regions using a three-stage time-series modelling framework and combined them with high-resolution EURO-CORDEX climate projections and Shared Socioeconomic Pathway population scenarios under RCP4.5/SSP2 and RCP8.5/SSP5. Heat- and cold-attributable mortalities were projected across four future periods. Heat-attributable mortality increases substantially, rising from 2 deaths historically to 20 deaths by the 2090s under RCP8.5/SSP5. Cold-attributable mortality declines under climate-only scenarios but increases markedly when population ageing is included, reaching 105 deaths by the 2090s and reversing climate-driven reductions. The combined net temperature-related mortality burden increased from 82 deaths in the historical period to 124 under population ageing scenarios, with ageing contributing to 71 additional deaths by the 2070s. Our findings demonstrate that population ageing outweighs climate-driven changes in shaping future temperature-related mortality in the Czech Republic. Ignoring demographic changes leads to a substantial underestimation of future health burdens. Integrating age-specific population projections into climate-health assessments is essential for adaptation planning and public health preparedness in ageing societies.

Introduction

Climate change and population ageing are jointly reshaping temperature-related health risks across Europe (Wu et al., 2025). Globally, the population aged 65 years and older is projected to increase from about 9% at present to 16% by 2050 (United Nations, 2019), expanding the share of vulnerable groups to non-optimal temperatures (Gu et al., 2020; KC & Lutz, 2017). Historically, cold-related mortality has exceeded heat-related mortality in most European regions (García-León et al., 2024; Kephart et al., 2022; Zhao et al., 2021; Gasparrini et al., 2015). This historical pattern, however, is being reshaped under climatic warming and changing population structures (Huang et al., 2023). Recent analyses have indicated substantial increases in heat-related mortality in Europe, particularly among older adults (Ballester et al., 2023; Vicedo-Cabrera et al., 2021). Simultaneously, projected declines in cold-related mortality under climate-only scenarios remain uncertain once ageing and adaptation dynamics are considered (Masselot et al., 2025). These trends highlight the growing need to jointly assess heat- and cold-related health risks in ageing societies.

Despite growing concerns, most projections of temperature-related mortality have concentrated on climatic drivers, with limited integration of demographic change (Martínez-Solanas et al., 2021; Lee et al., 2018; Gasparrini et al., 2017). Although large-scale modelling studies have recently advanced our understanding of future mortality risks (Wu et al., 2025; Chen et al., 2024; García-León et al., 2024), each has limitations for national-scale public health planning; some analyses focus only on heat (Wu et al., 2025), others do not explicitly integrate demographic change (García-León et al., 2024), and some rely on city-level datasets rather than comprehensive national coverage (Masselot et al., 2025; Chen et al., 2024). Not accounting for demographic change may lead to substantial underestimation of future mortality.

Over the past decade, Europe has become a hotspot for climate-related health vulnerability, with heatwaves recognized as one of the deadliest weather-related hazards (Hundessa et al., 2025; Zhao et al., 2024), including the 2022 European heatwave that caused tens of thousands of excess deaths (Ballester et al., 2023). Europe's high vulnerability to temperature-related heat exposure is closely linked to its ageing population (Watts et al., 2019). Older individuals are particularly vulnerable because age-related physiological and functional changes reduce their ability to cope with temperature extremes (Diaz et al., 2020; EASAC, 2019). Reduced thermoregulation, including lower sweating capacity, reduced cardiovascular function, and medication use, further increases this vulnerability (Parsons et al., 2026; Layton et al., 2020; Meade et al., 2020). The Czech Republic mirrors these broader patterns, with national evidence showing an increase in heat-related mortality, especially among older age groups (Janoš et al., 2024; Urban et al., 2022). However, the combined influence of climate change and ageing on future heat- and cold-related mortality has not been systematically assessed.

This study addresses this gap by projecting future temperature-related mortality in the Czech Republic under integrated climate and population scenarios. Daily mortality and temperature records from all 14 Nomenclature of Territorial Units for Statistics (NUTS 3, level 3) regions were used to estimate historical age-specific exposure-response relationships. These estimates were integrated with the bias-corrected, high-resolution regional climate model (RCM) ensemble under Representative Concentration Pathways RCP4.5 (a stabilization pathway with moderate mitigation) and RCP8.5 (high emissions) (van Vuuren et al., 2011), together with population projections from the Wittgenstein Centre's Shared Socioeconomic Pathways (SSP2 and SSP5) (O'Neill et al., 2017). Both constant population scenarios (climate-only) and changing population scenarios (combined climate and population) were evaluated for four future time slices. The findings demonstrate how climate and population ageing together may shape future temperature-related mortality, supporting adaptation planning and health system preparedness in an ageing society.

Methodology

Data sources

Observed Data

Daily all-cause mortality records for 1994-2020 were obtained from the Institute of Health Information and Statistics of the Czech Republic and the Czech Statistical Office. The Czech

Republic, which has approximately 10.9 million inhabitants. These individual-level data included the date of death, age, sex, and place of residence of the deceased, enabling stratification by 14 NUTS 3 regions and two age groups (<75 and ≥75 years).

For the analysis of historical associations between temperature and mortality, the 1994-2005 period was used as the historical baseline, selected to align with the data constraints of the EURO-CORDEX framework and the design of the methodological setup. The daily mean temperature in the 14 NUTS 3 regions was derived from the hourly ERA5 reanalysis obtained from Copernicus Climate Data Store (Hersbach et al., 2023).

Projected Data

Daily mean temperature projections were obtained from the EURO-CORDEX (https://euro-cordex.net/) ensemble of ten RCMs at a horizontal resolution of ~ 0.11° (Table S1 in the Supplementary Materials). These RCM simulations (figure 1a) were integrated with population projection scenarios to account for population ageing in the projected impacts of heat and cold on mortality.

Population projections were obtained from the Wittgenstein Centre Human Capital Data Explorer (https://dataexplorer.wittgensteincentre.org/wcde-v2/) following Masselot et al. (2025). For each SSP representing global socio-economic narratives describing alternative demographic and technological futures (O'Neill et al., 2017), national-level projections of age-specific population counts, and survival ratios were extracted at 5-year intervals. We used SSP2 and SSP5, where SSP2 represents a "middle road" socioeconomic pathway with medium fertility and mortality rates, and SSP5 combines low fertility and low mortality assumptions with a high-migration variant (KC et al., 2024). Projected deaths for each period were estimated by applying age-specific survival ratios to the population, and annualized mortality rates were subsequently derived. Mortality rates for the 0-64, 65-74, 75-84, and ≥85 age groups were aggregated into <75 and ≥75 age groups. This age stratification aligns with prior research, showing that temperature-related mortality risks increase markedly with age (Rodrigues et al., 2021; Ragettli et al., 2017). While recognizing the commonly used ≥65-year threshold for elderly populations, the ≥75-year threshold was retained in the primary analysis to maintain sufficient observations within the age groups. A sensitivity analysis using <65, 65-74, and ≥75 years was conducted to assess the robustness of the results to the choice of age-group classification.

National projections were downscaled to the NUTS 3 level using region-specific correction factors derived from the ratio of national values from the Wittgenstein Centre to the corresponding regional values from EUROSTAT (https://ec.europa.eu/eurostat) for the period 1994-2005; national SSP-driven changes were then applied proportionally to each region. This period was chosen to maintain consistency with historical baseline used in the temperature-mortality modelling.

Temperature–Mortality Modelling and Projections

The analysis was conducted using a three-stage study design following a well-established methodological framework (Sera et al., 2019; Vicedo-Cabrera et al., 2019). Each stage is described separately below.

Stage 1 – Region-specific Modelling

In the first stage, the relative risk of temperature-related mortality for individual NUTS 3 regions and the two age groups during the historical baseline period was estimated using quasi-Poisson generalized linear models (GLMs) (Wood, 2006), adjusting for long-term trends. The short-term association between temperature and mortality was modelled using a distributed lag non-linear model (DLNM) framework (Gasparrini et al., 2010). Model specification and parameterization followed previous studies (e.g.,Vicedo-Cabrera et al., 2021; Sera et al., 2019). Specifically, the temperature-mortality relationship was modelled through a cross-basis function, combining a natural spline (ns) with three internal knots (10th, 75th, 90th percentiles of region-specific temperature distribution) for temperature and a natural spline with three internal knots equally spaced on the logarithmic scale for lags up to 21 days. The overall exposure-response association was then reduced to a one-dimensional cumulative exposure-response curve, representing the region- and age group-specific relative risk (RR) of mortality relative to the minimum mortality temperature (MMT) (Tobías et al., 2021).

Stage 2 – National Meta-regression

In the second stage, region-specific exposure–response associations were pooled separately for each age group using a multivariate meta-regression framework (Sera et al., 2019). This approach accounts for regional heterogeneity by including region-specific mean temperature and temperature range as meta-predictors. From the pooled model, we obtained the best linear unbiased predictions (BLUPs), which represent refined region- and age-specific exposure-response functions (ERFs) of temperature-related mortality (Gasparrini et al., 2012). For the sensitivity analysis, the first- and second-stage models were re-estimated separately for the <65, 65-74, and ≥75 age groups, and the corresponding pooled temperature-mortality associations are presented in figure S1.

Stage 3 – Mortality Projections

In the third stage, the BLUPs from Stage 2 were combined with climate and population scenarios to estimate spatiotemporal changes in heat- and cold-related mortality in the Czech Republic. Two scenario combinations were analyzed (RCP4.5/SSP2, and RCP8.5/SSP5). Each was evaluated under constant and changing population conditions to distinguish climate-driven effects from demographic ageing. Future daily mean temperature projections were obtained from the EURO-CORDEX ensemble under RCP4.5 and RCP8.5. These simulations were bias-corrected using the trend-preserving approach of Hempel et al. (2013), with ERA5 data serving as the reference.

For each NUTS 3 region and age group, the attributable fraction (AF%), the percentage of deaths on days above (heat) or below (cold) the region-specific MMT attributable to temperature was calculated. The corresponding attributable numbers (ANs) were obtained by multiplying AFs by projected deaths under RCP4.5 and RCP8.5 for the historical baseline and four future periods labeled as 2030 (2025-2036), 2050 (2045-2056), 2070 (2065-2076), and 2090 (2085-2096). These ANs were expressed as annual excess death rates per 100,000 population using population estimates from the Czech Statistical Office. Results for 'All ages' represent aggregated outcomes from the two age-group models (<75 and ≥75).

Uncertainty was assessed using Monte Carlo simulation with 1,000 iterations of the coefficients defining the exposure-response functions, following (Vicedo-Cabrera et al., 2021). For each iteration, the full projection process was repeated for each climate model in the EURO-CORDEX ensemble, producing distributions of AFs and ANs for each climate and population scenario, region, and age group. The final estimates were based on the ensemble mean across all climate models, from which empirical 95% confidence intervals were derived. This approach accounts for both the statistical uncertainty of the epidemiological model and variability across climate model projections.

All projections assume constant adaptive capacity over time, consistent with observational evidence of limited adaptation in the Czech Republic (Urban et al., 2022). Demographic ageing is conceptualized here as a structural driver of vulnerability that intensifies future mortality burdens even in the absence of behavioral or infrastructural change.

Results

Projected Temperature and Population Trends

The temporal evolution of mean temperature anomalies and projected annual deaths in the Czech Republic under RCPs and population scenarios is shown in figure 1. Panel "a" presents the ensemble mean of annual mean temperature from EURO-CORDEX simulations under climate scenarios (RCP4.5 and RCP8.5), indicating a gradual warming throughout the 21st century, with more pronounced increases under RCP8.5. Panel "b" shows the projected annual deaths by age group based on SSP2 and SSP5 population projections. Mortality among older adults is projected to rise markedly due to population ageing, particularly under SSP5, while deaths at all ages are expected to peak around mid-century before stabilizing or slightly declining toward 2100. These projections provide the climate and population ageing basis for estimating heat- and cold-attributable mortality rates across future decades under each combined RCP-SSP scenario. Consistent with the projected warming, the annual number of days above the region-specific minimum mortality temperature (T > MMT) increased progressively throughout the century, whereas the annual number of days below the MMT (T < MMT) decreased, with substantially larger changes under RCP8.5 than under RCP4.5 (figure S2). These projected exposure changes provide additional context for interpreting the mortality projections presented below, illustrating the increasing heat exposure and decreasing cold exposure associated with future climate warming.

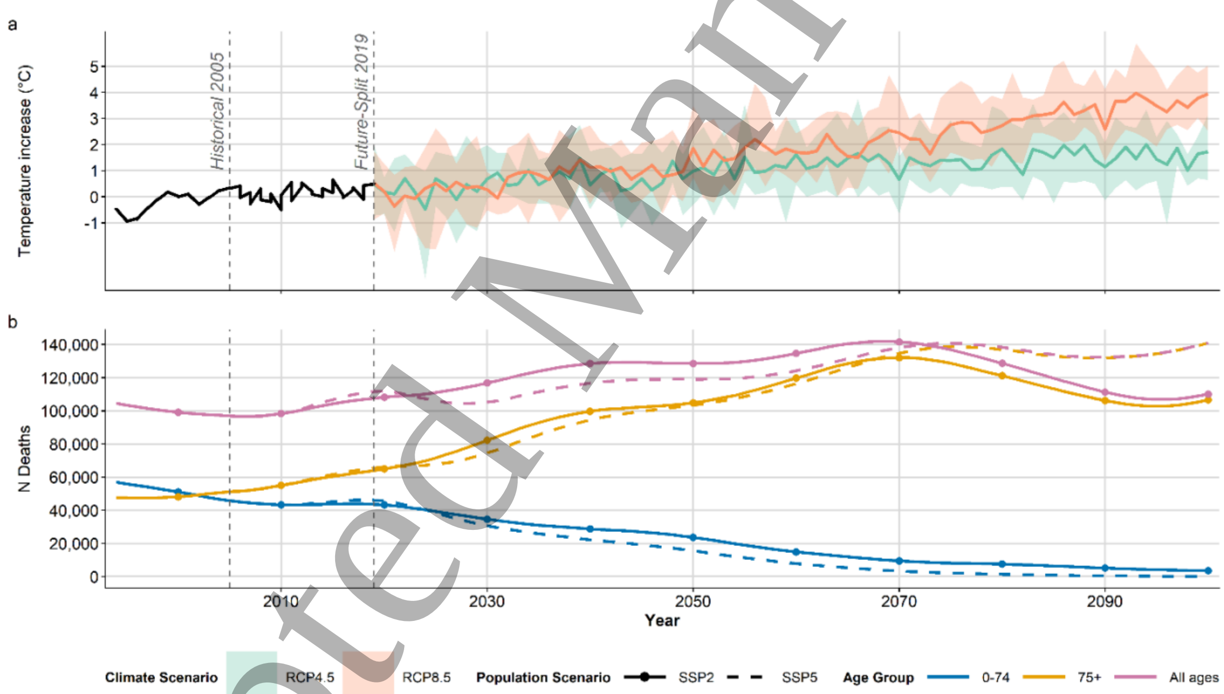

Figure 1: (a) Deviation of annual daily mean temperature development in the Czech Republic under RCP 4.5 and RCP 8.5 scenarios compared to the historical period (1994-2005); (b) Annual number of deaths in the Czech Republic according to SSPs population projections (2020-2100).

Historical and Future Heat- and Cold-Attributable Mortality

National projections revealed that both heat- and cold-attributable annual death rates (per 100,000 person-years) were strongly shaped by population ageing (tables 1-2; figure 2). For heat, the historical annual attributable death rate was estimated to be 2 (95% CI: 1 to 4) (table 1; figure 2a). By the 2090s, this is projected to rise to 9 (95% CI: 3 to 16) deaths under constant populations and 20 (95% CI: 9 to 30) under changing populations in RCP8.5. The largest divergence between scenarios occurred in the 2090s, meaning that ageing added +11 (95% CI: 6 to 14) deaths in that decade (table 1). The results for AF% are in table S2 and figure S3 (a-b).

For cold, the historical annual death rate was 80 (95% CI: 59 to 100) deaths (table 1; figure 2b). Under constant populations, cold ANs declined to 58 (95% CI: 43 to 74) deaths by the 2090s in RCP8.5. With population ageing, however, cold ANs remained considerably higher, reaching 105 (95% CI: 77 to 132) deaths in the same period (table 1; figure 2b). Thus, while climate alone reduces cold burdens by -22 (95% CI: -26 to -16) deaths compared to historical, ageing adds back +47 (95% CI: 34 to 58) deaths, cancelling the decline and leaving the cold-attributable mortality burden persistently elevated.

The combined net effect of heat and cold mortality underscores the dominance of ageing (table 2). Historically, the net effect was 82 (95% CI: 60 to 103) deaths per 100,000 person-years. Under a constant population, this declines modestly, reaching 75 (95% CI: 55 to 94) deaths by the 2090s in RCP4.5 and 68 (95% CI: 49 to 86) deaths in RCP8.5. In contrast, when population ageing was included, the net effect increased substantially, reaching 121 (95% CI: 91 to 151) and 124 (95% CI: 93 to 156) deaths, respectively. Thus, while climate alone produces small net declines (-3 to -14 deaths across the scenarios and periods compared to historical), ageing reverses this pattern.

In other words, the larger reduction in cold-related mortality under RCP8.5 resulted in a lower net burden than under RCP4.5 by the 2090s, when the constant population scenario was considered. On the contrary, the ageing contribution alone pushed the combined net burden above historical levels. Age-stratified results confirmed that these shifts were driven almost entirely by the population aged ≥ 75 years (figure S4 (a-b)).

Moreover, the sensitivity analysis using <65, 65-74, and ≥75 years showed that projected cold-related mortality in the 65-74 age group generally declined over the century, while projected heat-related mortality remained relatively low. In contrast, the ≥75 age group showed substantially higher projected heat- and cold-related mortality throughout the projection period (figure S5), consistent with the age-related patterns observed in the primary analysis.

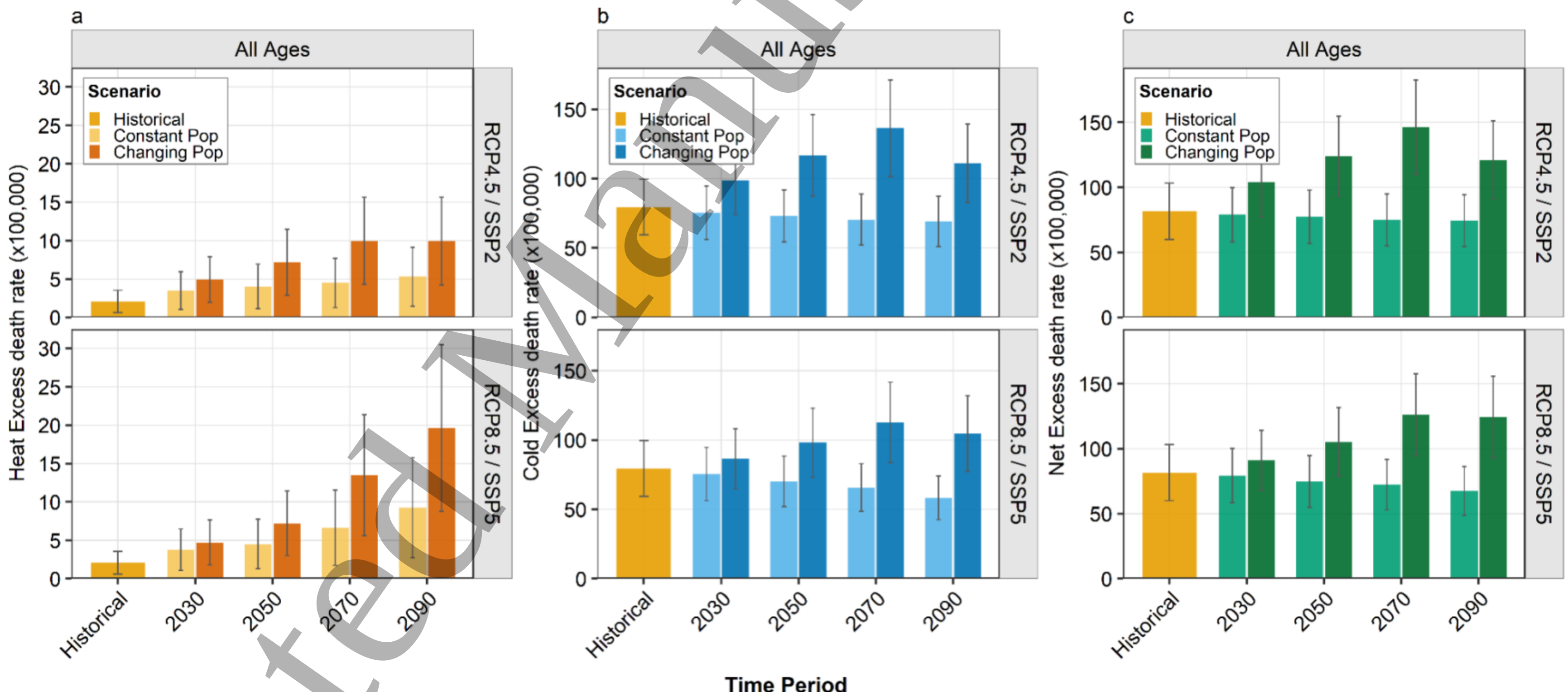

Figure 2. Annual heat- (a), cold- (b), and net effect (c) excess death rates (x100,000 person-years) in the Czech Republic across age groups "All ages" under RCP4.5/SSP2 (top rows) and RCP8.5/SSP5 (bottom rows). Bars represent historical and future periods under constant- and changing-population scenarios. Error bars indicate 95% confidence intervals. Note that the range of y-axis in "a" differs from b and c.

Table 1. *Annual Historical and future distribution of heat- and cold-attributable excess death rates (x100,000 person-years) (ANs), differences (AN change), and scenarios difference with constant and changing populations under the RCP4.5/SSP2, RCP8.5/SSP5 scenario for four future periods*

All ages		**AN**		**AN change vs Hist.**		**Scenarios diff.**
		Constant Pop	Changing Pop	Constant Pop	Changing Pop	Changing Pop vs Constant Pop
Heat						
Historical = 2 *(95% CI 1 to 4)*						
RCP4.5/SSP2	**2030**	4 *(1 to 6)*	5 *(2 to 8)*	2 *(0 to 2)*	3 *(1 to 4)*	1 *(1 to 2)*
	2050	4 *(1 to 7)*	7 *(3 to 11)*	2 *(0 to 3)*	5 *(2 to 7)*	3 *(2 to 4)*
	2070	4 *(1 to 8)*	10 *(4 to 16)*	2 *(0 to 4)*	8 *(3 to 12)*	6 *(3 to 8)*
	2090	5 *(1 to 9)*	10 *(4 to 16)*	3 *(0 to 5)*	8 *(3 to 12)*	5 *(3 to 7)*
RCP8.5/SSP5	**2030**	4 *(1 to 6)*	5 *(2 to 8)*	2 *(0 to 2)*	3 *(1 to 4)*	1 *(1 to 2)*
	2050	5 *(1 to 8)*	7 *(3 to 11)*	3 *(0 to 4)*	5 *(2 to 7)*	2 *(2 to 3)*
	2070	7 *(2 to 12)*	13 *(6 to 21)*	5 *(1 to 8)*	11 *(5 to 17)*	6 *(4 to 9)*
	2090	9 *(3 to 16)*	20 *(9 to 30)*	7 *(2 to 12)*	18 *(8 to 26)*	11 *(6 to 14)*
Cold						
Historical = 80 *(95% CI 59 to 100)*						
RCP4.5/SSP2	**2030**	76 *(56 to 95)*	99 *(74 to 124)*	-4 *(-5 to -3)*	19 *(15 to 24)*	23 *(18 to 29)*
	2050	73 *(54 to 92)*	117 *(87 to 146)*	-7 *(-8 to -5)*	37 *(28 to 46)*	44 *(33 to 54)*
	2070	71 *(52 to 89)*	136 *(102 to 171)*	-9 *(-11 to -7)*	56 *(43 to 71)*	65 *(50 to 82)*
	2090	69 *(51 to 87)*	111 *(83 to 139)*	-11 *(-13 to -8)*	31 *(24 to 39)*	42 *(32 to 52)*
RCP8.5/SSP5	**2030**	76 *(56 to 95)*	87 *(65 to 108)*	-4 *(-5 to -3)*	7 *(6 to 8)*	11 *(9 to 13)*
	2050	70 *(52 to 88)*	98 *(73 to 123)*	-10 *(-12 to -7)*	18 *(14 to 23)*	28 *(21 to 35)*
	2070	66 *(49 to 83)*	113 *(84 to 142)*	-14 *(-17 to -10)*	33 *(25 to 42)*	47 *(35 to 59)*
	2090	58 *(43 to 74)*	105 *(77 to 132)*	-22 *(-26 to -16)*	25 *(18 to 32)*	47 *(34 to 58)*

***Table 2**. Annual Net effect of historical and future distribution of heat- and cold-attributable number excess death rates (x100,000 person-years) (AN), difference (AN change), and scenario difference with constant and changing populations under the RCP4.5/SSP2, RCP8.5/SSP5 scenarios for four future periods.*

Net effect						
All ages		**AN**		**AN change vs Hist.**		**Scenarios diff.**
		Constant Pop	Changing Pop	Constant Pop	Changing Pop	Changing Pop vs Constant Pop
Historical = 82 *(95% CI 60 to 103)*						
RCP4.5/SSP2)	**2030**	79 *(58 to 100)*	104 *(78 to 130)*	-3 *(-3 to -2)*	22 *(18 to 27)*	25 *(20 to 30)*
	2050	77 *(57 to 98)*	124 *(93 to 155)*	-5 *(-5 to -3)*	42 *(33 to 52)*	47 *(36 to 57)*
	2070	75 *(55 to 95)*	146 *(110 to 183)*	-7 *(-8 to -5)*	64 *(50 to 80)*	71 *(55 to 88)*
	2090	75 *(55 to 94)*	121 *(91 to 151)*	-7 *(-9 to -5)*	39 *(31 to 48)*	46 *(36 to 57)*
RCP8.5/SSP5)	**2030**	79 *(58 to 100)*	91 *(68 to 114)*	-3 *(-3 to -2)*	9 *(8 to 11)*	12 *(10 to 14)*
	2050	75 *(55 to 95)*	105 *(79 to 132)*	-7 *(-8 to -5)*	23 *(19 to 29)*	30 *(24 to 37)*
	2070	72 *(53 to 92)*	126 *(95 to 158)*	-10 *(-11 to -7)*	44 *(35 to 55)*	54 *(42 to 66)*
	2090	68 *(49 to 86)*	124 *(93 to 156)*	-14 *(-17 to -11)*	42 *(33 to 53)*	56 *(44 to 70)*

Spatial Distribution of Heat- and Cold-Attributable Mortality

Regional projections showed clear spatial variability in future temperature-related mortality burdens (figure 3–4). For heat, historical values were uniformly low (approximately 0 to 6 deaths per 100,000 person-years across the country; figure 3a). Under constant populations in the 2070s (RCP8.5/SSP5), heat ANs increased in most regions by approximately 0 to 18 deaths (figure 3b). Under changing populations, heat-attributable ANs were higher, ranging from approximately 0 to 27 deaths (figure 3c), with the largest burdens concentrated in northern, eastern, and parts of central Czechia.

The constant vs. historical difference (figure 3d) ranged from approximately -2 to +13 deaths per 100,000 person-years countrywide, indicating mostly increases with small regional reductions in parts of the west. The changing vs. historical difference (figure 3e) spanned approximately -2 to +22 deaths, with the largest increases in the north/east and central zones. Comparing scenarios directly (figure 3f), heat-attributable mortality was generally higher under changing populations, reflecting the effect of ageing. These spatial patterns are consistent with the national averages (table 1) and net effects (table 2).

For cold, historical burdens were much higher (approximately 58 to 123 deaths per 100,000 person-years; figure 4a). Under constant populations in the 2070s, they decline to 47 to 105 deaths (figure 4b), whereas with ageing they remain elevated at 70 to 174 deaths (figure 4c), with substantial spatial heterogeneity across regions. The constant vs. historical difference (figure 4d) was uniformly negative (-12 to -18 deaths), indicating climate-driven declines everywhere. In contrast, the changing vs. historical difference (figure 4e) was positive (+9 to +62 deaths) across most areas, with regionally heterogeneous increases. The changing vs. constant (figure 4f) shows that ageing increases cold-attributable mortality by +21 to +80 deaths relative to constant populations, with considerable spatial variability across regions. These patterns match the national contrasts in table 1 for the 2070s (cold ANs 66 deaths rates under constant vs. 113 deaths rates with changing, RCP8.5).

Together, figure 3–4 (a–f) and tables 1-2 demonstrate that climate alone increases heat mortality and reduces cold mortality, whereas ageing amplifies heat burdens and offsets climate-driven cold declines, yielding a larger net temperature-related mortality burden, particularly in the north/east and central parts of the country.

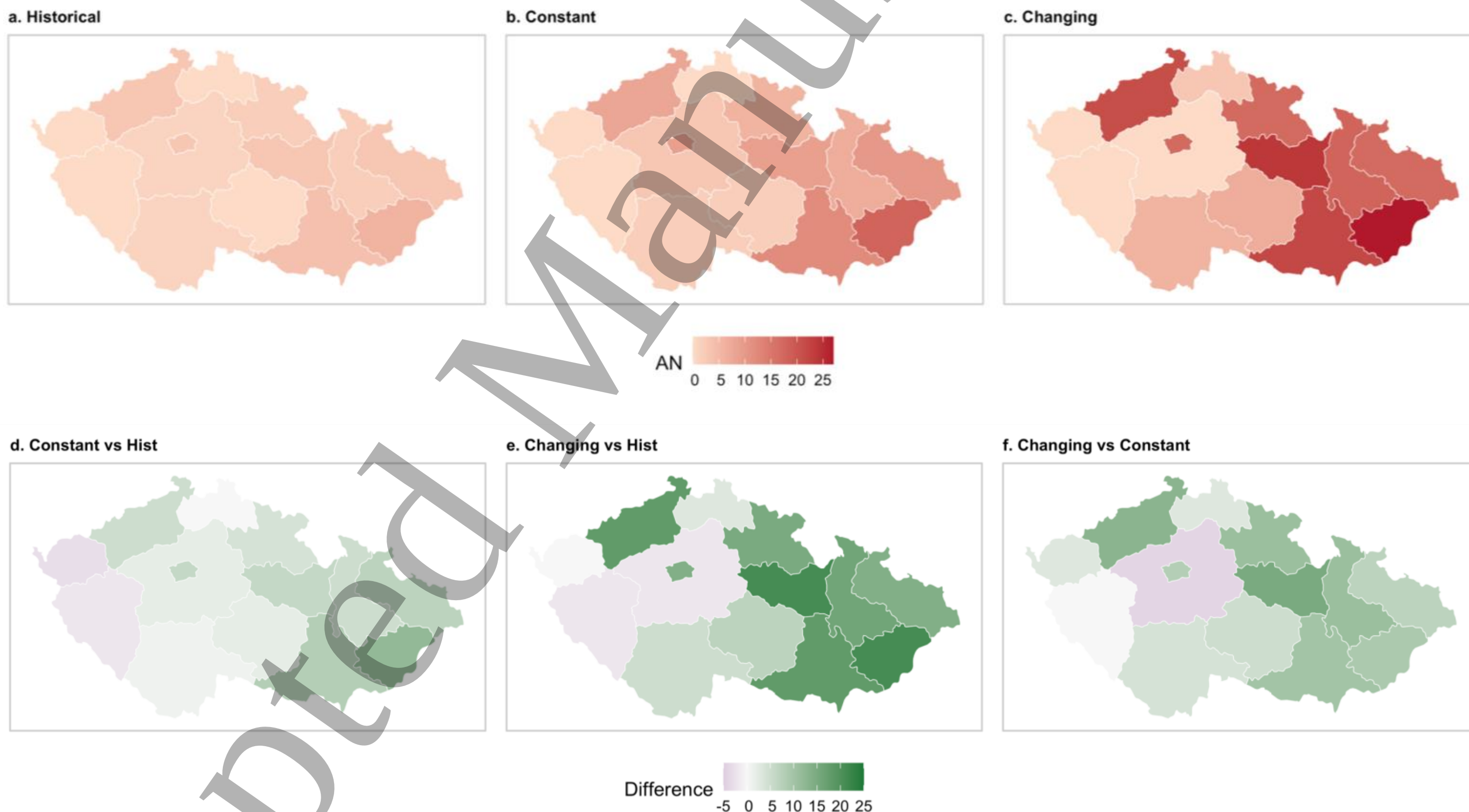

Figure 3. *Annual Heat (a-f) excess death rates (×100,000 person-years) in the Czech Republic for all ages in the historical period and future projections under RCP8.5/SSP5 for the 2070s. Panels a-c show the historical, constant-population, and changing-population scenarios, respectively. Panel d shows the difference between the constant-population and historical scenario (Constant-Historical), panel e shows the difference between the changing-population and historical scenario (Changing-Historical), and panel f shows the difference between the changing- and constant-population scenarios (Changing-Constant)*

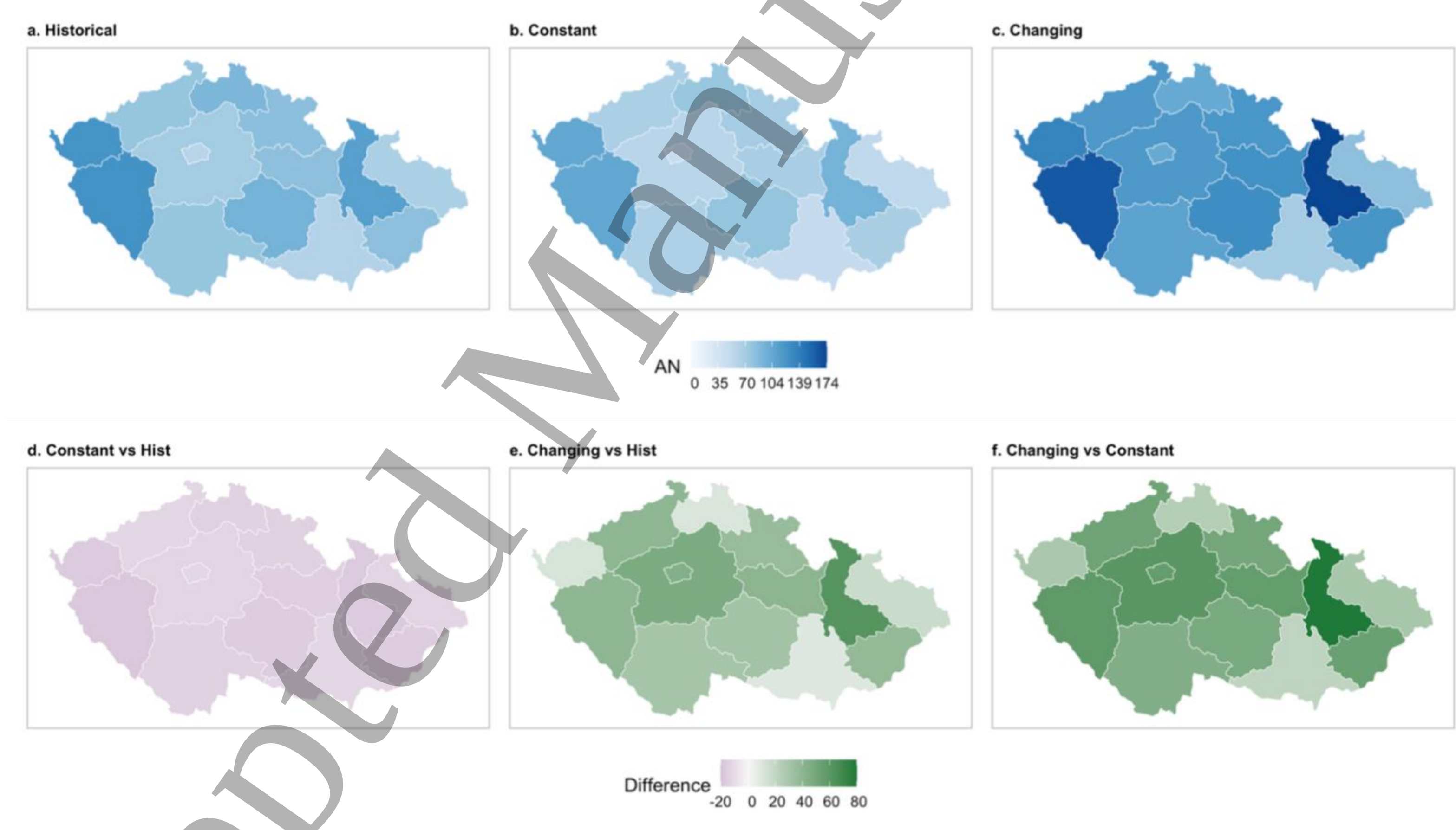

Figure 4. *Annual Cold (a-f) excess death rates (×100,000 person-years) in the Czech Republic for All ages in the historical period and future projections under RCP8.5/SSP5 for the 2070s. Panels a-c show the historical, constant-population, and changing-population scenarios, respectively. Panel d shows the difference between the constant-population and historical scenario (Constant-Historical), panel e shows the difference between the changing-population and historical scenario (Changing-Historical), and panel f shows the difference between the changing- and constant-population scenarios (Changing-Constant)*

Discussion

In this comprehensive projection study, we found that both heat- and cold-related mortality will substantially increase under climate and population ageing scenarios in the Czech Republic, with ageing playing a major role in shaping these future trends. Under the more pessimistic scenario (RCP8.5/SSP5), the overall heat-related mortality burden is projected to rise approximately 9.5-fold (+848%, Table S3) by the 2090s relative to the historical baseline, while cold-related mortality increases by +32%, effectively reversing the decline expected from the climate scenario alone. Although climate alone would have reduced cold-related deaths by 27% relative to the historical baseline, the rapid demographic shift toward older age groups more than offset this benefit, resulting in persistently high temperature-related burdens throughout the century. This contrasting response highlights the different roles of climate change and demographic ageing and may also be related to the different mechanisms through which heat and cold affect excess mortality. While heat increases the risk of mortality immediately (Gasparrini et al., 2015), reflecting direct physiological responses to elevated temperatures (Layton et al., 2020), the effects of cold are generally more indirect, occurring through respiratory infections and cold-induced cardiovascular stress (WHO, 2018), with mortality typically occurring over longer lag periods (Gasparrini et al., 2015). These differences may explain why cold-related mortality projections are more strongly influenced by general mortality patterns than heat-related mortality projections. However, they also introduce greater uncertainty into future cold-related mortality projections, as there is currently limited evidence on how climate change will affect the dynamics of acute respiratory infections. Overall, these findings indicate that population ageing substantially amplifies climate-driven increases in heat-related mortality and can counteract the expected benefits of warmer winters, with older adults (≥75) accounting for most of the projected impacts.

Our results broadly align with recent large-scale European and global assessments in both magnitude and direction. Comparable projection studies consistently show that population ageing substantially modifies future temperature-related mortality. In Switzerland, de Schrijver et al. (2023), using EURO-CORDEX RCP4.5/8.5 with SSP2/5 projections, attributed approximately 53% of the projected increase in heat-related mortality to population ageing and showed that demographic change largely offset the reduction in cold-related mortality expected under climate change alone, consistent with our findings. Similar patterns have also been reported using EURO-CORDEX projections with EUROPOP2019 (García-León et al., 2024), SSP3-7.0 scenarios without adaptation (Masselot et al., 2025), and global CMIP5 projections under SSP5-8.5 (Chen et al., 2024). Although the projected magnitudes differ from our national estimates, the overall direction of change is consistent, likely reflecting differences in climate and population scenarios, spatial scale, adaptation assumptions, and the use of globally pooled rather than country-specific age-structured risk functions.

Earlier European studies that assumed a fixed population structure, such as Lüthi et al. (2023) and Martínez-Solanas et al. (2021), projected declining cold-related mortality and moderate increases in heat-related deaths, likely underestimating future health burdens by neglecting the growing proportion of older adults. In contrast, by explicitly incorporating age-specific population ageing under SSPs, our analysis provides a more comprehensive and generally higher estimate of future temperature-related mortality, capturing the combined influence of climate and ageing.

Spatial patterns in relative change were heterogeneous. For heat, increases range from modest to very large, while some regions show slight decreases. At the national level, heat-related mortality increases by +550% relative to the historical baseline by the 2070s under RCP8.5/SSP5. For cold, regional changes under the changing population scenario range from +9% to +78% relative to the historical baseline, indicating that population ageing strongly amplifies future cold-related deaths. These spatial contrasts are broadly consistent with the findings of Janoš et al. (2024), who also reported substantial regional variability in temperature-related mortality and highlighted the importance of regional demographic and socioeconomic characteristics in explaining spatial heterogeneity. These spatial projections can help identify regions where targeted heat-health interventions may be most needed.

Our findings have important implications for climate adaptation planning in the Czech Republic. These findings highlight the importance of prioritizing adaptation measures for older adults, who consistently account for the largest future mortality burden. Strengthening heat-health action plans, early warning systems, and targeted public health interventions for vulnerable populations may help reduce future mortality risks. At the same time, our findings suggest that warmer winters alone should not be expected to substantially reduce cold-related mortality without considering the continuing demographic ageing of the Czech population.

Several limitations should be noted. First, the assumption of constant adaptive capacity may be overly conservative; however, evidence from the Czech Republic indicates that adaptation has been limited in past decades (Urban et al., 2022). Although future adaptation measures are expected to reduce temperature-related health risks, their magnitude and effectiveness remain uncertain. Moreover, because heat-related mortality is concentrated among the oldest adults (Janoš et al., 2025; Gallo et al., 2024), even substantial adaptation measures may have limited impact given the population ageing. Second, while the use of all-cause mortality avoids misclassification bias, it masks cause-specific pathways and non-fatal outcomes such as hospital admissions. Third, our approach applied countrywide SSP demographic projections uniformly across individual regions, which may not capture local variations in ageing patterns, migration flows, or socioeconomic factors that could influence regional demographic transitions and their health impacts. Regional demographic heterogeneity could lead to spatial variations in mortality burdens beyond those captured by our climate-driven spatial patterns. Therefore, the regional projections should be interpreted as illustrating broad demographic and climatic trends rather than precise forecasts of future regional population structures. Within the current modelling framework, it is not possible to disentangle the relative contributions of future regional demographic divergence and regional climate differences to the projected spatial variation in mortality. Fourth, although we used EURO-CORDEX RCP4.5 and RCP8.5 instead of CMIP6 SSP-based scenarios, these correspond closely to SSP2/4.5 and SSP5/8.5 forcing levels (Varney et al., 2023; Tebaldi et al., 2021). Their high spatial resolution (0.11°) and widespread use in recent European health-impact studies (e.g., García-León et al., 2024) ensure methodological consistency and comparability. Fifth, uncertainties persist in both climate and demographic projections, particularly under extreme scenarios. Nevertheless, the demographic trend in the Czech Republic suggests that substantial ageing is very likely even with potential shifts in fertility or migration, meaning that the role of ageing probably remains central in all future climate-health assessments. The relatively wide confidence intervals around the projected mortality estimates primarily reflect uncertainty in the estimated temperature-mortality exposure-response relationships and variability among future climate model projections. Future research should incorporate explicit adaptation scenarios, stratify vulnerabilities by socioeconomic status within age and sex groups, develop region-specific demographic projections that account for local migration and ageing patterns, and extend analyses to morbidity outcomes and cause-specific mortality pathways.

Conclusion

Our findings reinforce the emerging European consensus that demographic ageing substantially influences future temperature-related mortality patterns. In the Czech Republic, ageing transforms what would otherwise be a decline in cold-related deaths into a persistent or rising burden and roughly doubles heat-related mortality by the end of the century. By integrating high-resolution climate data with age-specific demographic projections, this study offers one of the most detailed national assessments in the Czech Republic. As future adaptation is not considered, these projections may represent an upper-bound estimate of temperature-related mortality. Nevertheless, the results underscore the need for public-health preparedness and adaptation planning to explicitly incorporate ageing into climate-related health risk.

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Data availability statement

The mortality data used in this study are anonymised and were obtained from the Institute of Health Information and Statistics of the Czech Republic and the Czech Statistical Office under a data-sharing agreement; therefore, they cannot be made publicly available. Access to these data may be granted upon request to the the original data provider or via the authors (Aleš Urban, urban@ufa.cas.cz).

Climate projections used in this study are publicly available through the EURO-CORDEX (https://euro-cordex.net/), while population data were sourced from the Wittgenstein Centre Data Explorer (https://dataexplorer.wittgensteincentre.org/wcde-v2/).

To support reproducibility, the exposure-response function coefficients from the first-stage analysis, along with the complete R code used in subsequent analyses, will be made openly available via GitHub (https://github.com/Falak260/Population-ageing.git) and archived in Zenodo (10.5281/zenodo.19224535) within one month of manuscript acceptance. All datasets used are routinely collected and contain no personal identifiable information.

Contributors

FN, AMCV, KJ and AU contributed to the design of the study. FN, KJ, TD, AU contributed to data collection, cleaning and evaluation. FN performed the analyses, drafted an internal summary report to circulate preliminary results and figures, and wrote the first version of the manuscript. AMVC and AU supervised the methodological framework. AU managed the project and provided supervision. All authors had full access to all the data in the study, contributed to the interpretation of the results, reviewed and edited the manuscript, and had final responsibility for the decision to submit for publication.

Conflict of interest

The authors declare no competing interests.

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