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ORIGINAL PAPER

Evolving threats in an unforgiving climate: impact of non-optimal temperatures on life expectancy

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Abstract

This study examines how climate conditions influence life expectancy in Europe based on the impact of year-to-year temperature variability adjusted for economic changes. By focusing on a narrow range of ambient temperatures, we made the model sensitive to both extreme weather and moderately adverse conditions, such as low-temperature modulation of the winter infection season. Regional trend estimates from 1990 to 2019 were pooled to evaluate the overall relationship. We also assessed climate change impacts from 1979–1982 to 2019–2022 and 1981–2010 to 2041–2070 under the RCP 4.5 scenario. Colder-than-optimal temperatures had a greater effect on mortality than warmer ones. In Europe's coldest regions, harsh winters reduced life expectancy by up to 24 months, while warmer areas like the Azores saw reductions of just 2 months. Overall, climate change has had a small impact in Northern Europe: life expectancy increased by about 1 month due to milder winters but decreased by half a month due to hotter summers. In Southern Europe, the effects were mixed: Atlantic regions gained up to 3 months, while Mediterranean-bordering areas lost up to 3 months. Economic growth maintained a modest effect on life expectancy, even in highly developed regions. Assuming unchanged vulnerability, due to warmer winters life expectancy should be increased by a month, but regions south of the Alps this would be offset by higher heatwave-related deaths.

Keywords Winter mortality · Climate change · Winter infection · Heatwave · Life expectancy · Climate

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Introduction

While the toll of extreme weather events often captures media attention, it may divert focus from dominating causes of death. Actual deaths resulting from extreme weather events are on the decline and account for less than 0.1% of deaths in the developed world (Goklany, 2009; Kahn, 2005). Nevertheless, the majority of temperature-related deaths are attributed to moderately low temperatures (Gasparrini et al., 2015; Zhang et al., 2020). In colder regions like Europe, they cause ten times more deaths than heatwaves (Martínez-Solanas et al., 2021). Furthermore, low temperatures predominantly lead to indirect fatalities as they influence the timing and amplify the mortality associated with winter viral infections (Reichert et al., 2004).

Assessing the net impact of climate change presents a challenge. While various studies meticulously analyze the escalating occurrence of heatwaves and the expansion of vector-borne diseases (Daalen et al., 2022; Rocque et al., 2021; WHO, 2014), they generally barely acknowledge, without scrutinizing possible impact on endemic winter respiratory infections, which take a toll of a magnitude higher. A more comprehensive approach was developed by Gasparrini et al. (2015). They estimated the local relationship between temperature and mortality and then extrapolated it under changing climate conditions. Nevertheless, while it recognizes the resilience of warmer regions to high temperatures, it also simultaneously assumes that areas currently experiencing cold climates would indefinitely remain highly vulnerable to rising temperatures (Gasparrini et al., 2015, 2017; Madaniyazi et al., 2024; Martin et al., 2012; Martínez-Solanas et al., 2021). Further refining of this method led Kinney et al. to the conclusion that the actual reduction of winter mortality under global warming would be small, as those deaths are not being caused by cold per se (Kinney et al., 2015). On the other hand, Chau and Woo arrived at a different result: for Hong Kong, a subtropical climate, global warming has resulted in reduced winter mortality without a corresponding increase in heat-related deaths (Chau & Woo, 2015). However, other studies employing a variant of this methodology have pointed out that this approach is suitable only for addressing changes in the annual mortality pattern while being unsuitable for answering the fundamental question of whether the shifted deaths are occurring earlier or later than expected (Prevezanos et al., 2022).

Adding to the complexity, attributing deaths to specific causes is challenging. For instance, only a small percentage of influenza-associated deaths are officially linked to influenza (Schanzer et al., 2007; Walkowiak & Walkowiak, 2023). Even in situations where the issue is a priority, as in the COVID-19 pandemic, many countries faced a significant mismatch between reported deaths and excess mortality (Alicandro et al., 2022; Walkowiak & Walkowiak, 2022). This led the WHO to rely more on excess mortality than official attribution (WHO, 2023). As the seemingly straightforward detection of viral infections proved to be cumbersome, exercising even more caution is crucial when attributing the deaths of frail individuals to adverse weather conditions. Further complicating matters, deaths related to heat and cold are not equal even in terms of years of life lost. Heatwave-related deaths often exhibit mortality displacement, where subsequent-week mortality falls below the trendline (Davis et al., 2023; Qiao et al., 2015) because a significant share of those who died otherwise would have had only a few weeks left to live.

Nonetheless, one particularly well-documented mechanism remains underappreciated in its significance. At this very moment, we are witnessing fluctuations in weather patterns, and their impacts can be quantified. It is not only the effects of heatwaves that are evident; studies have also shown that temperature drop leads to an increase in the number of respiratory infections the subsequent week (Imai et al., 2015; Meerhoff et al., 2009). Milder than usual winters are linked to a reduced number of hospitalizations (Royé et al., 2016) and lower mortality rates (Goggins et al., 2015; Hajat, 2017; Madaniyazi et al., 2021; Rehill et al., 2015). While a single data series estimation would inherently carry a significant margin of error, pooling multiple time series can yield a more precise and useful estimate. The objective of this study is to accurately assess the influence of temperatures both below and above the optimal range on life expectancy. By consistently estimating both impacts concurrently, we can effectively measure the effects of climate change without any preconceived bias towards specific climate conditions. Additionally, since there is a discernible relationship not only between the general level of economic development (Zare et al., 2015) and annual shifts in economic activity (Ballester et al., 2019), our study employs the same methodology to control for changes in economic output. This dual approach allows us to disentangle the concurrent processes of economic development and climate change. Furthermore, our study aims to provide valuable insights into climates that genuinely promote human well-being.

Methods

Data source

The data for this study were sourced from (Eurostat 2023). Regions were classified according to the Nomenclature of Territorial Units for Statistics (NUTS) and encompassed all available regions up to the NUTS 2 classification. The analysis period was determined by data availability. However, the evaluation of temperature fluctuation impacts on life expectancy was confined to data up to 2019, considering the repercussions of the COVID-19 pandemic, which led to an extraordinary reduction in life expectancy, especially in Eastern Europe (Bonnet et al., 2024). Information concerning life expectancy at birth for both genders was accessible from 1990. Given that prior studies consistently highlight the Preston curve's importance in linking life expectancy changes to economic output (Jetter et al., 2019; Mackenbach & Looman, 2013), this factor was also incorporated into the model to account for these variations. Gross domestic product (GDP) per capita in constant prices, available from 2000, was used as the economic development indicator.

Prior studies clearly demonstrate that there is no single fixed optimal temperature associated with the lowest human mortality, as this temperature is related to local climate conditions (Gasparrini et al., 2015, 2017; Walkowiak et al., 2024). Therefore, any selected threshold could be seen as somewhat arbitrary. Nevertheless, as this work aims to capture not only extreme weather events but also the often-overlooked impact of moderately suboptimal temperatures, the suitable metric should provide a relatively narrow range. Due to data availability and compatibility, this favors the use of annual heating degree days (HDD) and cooling degree days (CDD) collected by Eurostat. While those metrics were intended for building energy requirements, they are being used as climate proxy indicators (Spinoni et al., 2018). For HDD, where indoor heating is considered, a base temperature of 18 °C is adopted. The HDD value is determined by summing the differences between 18 °C and the daily mean air temperature (Tmean) for days when Tmean ≤ 15 °C. Conversely, for CDD, indicating cooling requirements, a base temperature of 21 °C is utilized. The CDD value is obtained by summing the differences between the daily mean air temperature (Tmean) and 21 °C for days when Tmean ≥ 24 °C. These temperature indices were available for the timeframe spanning 1979 to 2022. For projection purposes, we relied on Copernicus' "Heating and Cooling Degree Days from 1979 to 2100" (Copernicus, 2024). As RCP 8.5 is considered unlikely (Huard et al., 2022), we selected the only other available projection for RCP 4.5. Due to the dataset being divided into three-decade intervals and to minimize projection error, we opted for the shorter period from 1981–2010 to 2041–2070.

Calculation

Regions with a time series of 12 or fewer consecutive observations were excluded. Regions classified across multiple NUTS layers were removed to avoid duplication. However, when hierarchical regions differed in weighting by Eurostat for life expectancy and temperature, or when there were discrepancies in the length of time series—often with higher-level regions having longer records than their subdivisions—such datasets were retained.

To assess the yearly fluctuations in life expectancy influenced by economic and climatic factors for each gender, a model capable of accommodating non-independent observations was indispensable. Furthermore, the complexity was heightened by the presence of numerous additional local factors renowned for their predictive impact, which could not be directly incorporated—such as variations in alcohol and tobacco consumption, and the gender-specific effects of social inequalities (Rochelle et al., 2015; Zare et al., 2015). Panel regression models were considered and are presented in the supplementary materials for reference. While a fixed effects model could account for unobserved region-specific factors, it relies on the counterfactual assumption that these factors have uniform impacts across all regions. Similarly, a random effects model was deemed unsuitable, as the theoretical framework does not support the assumption that regional differences in sensitivity follow a normal distribution or are uncorrelated with explanatory variables (see Fig. 1, which illustrates systematic variation, contradicting the assumption of both models). Given these limitations, a two-step approach was adopted as the primary method: regional estimations were conducted using the Auto-Regressive Integrated Moving Average with

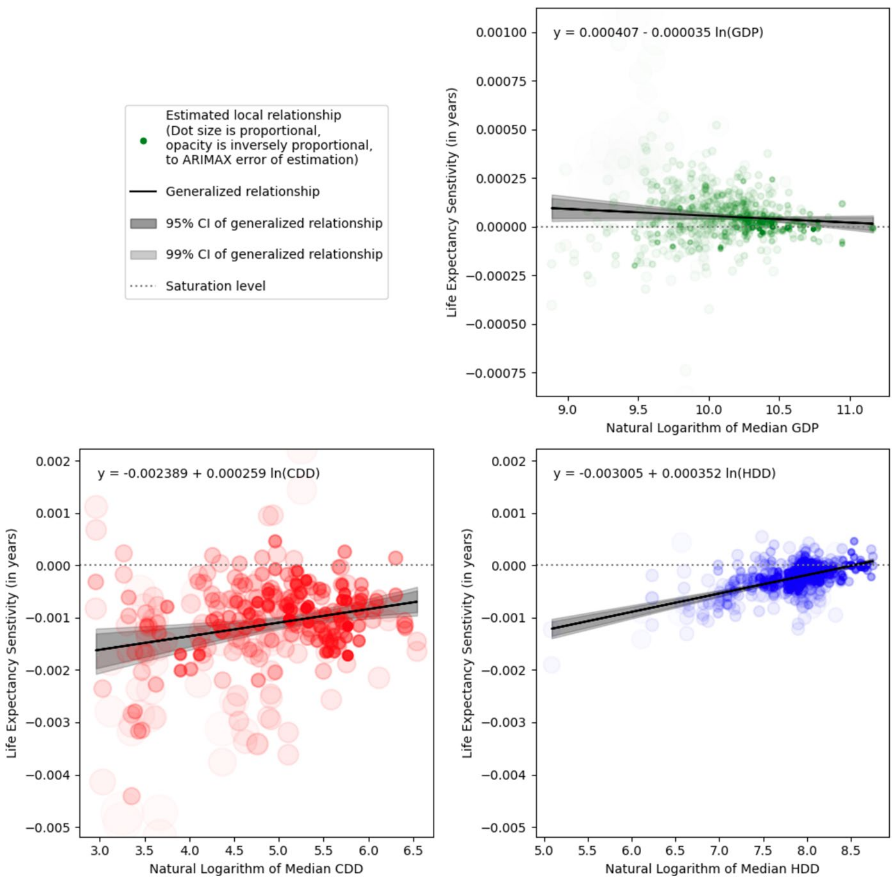

Fig. 1 Sensitivity of life expectancy to economic and weather variations

eXplanatory variables (ARIMAX) model, followed by pooling the coefficients under the assumption of diminishing marginal effects. Rather than pinpointing individual local factors affecting life expectancy, the model takes an initial level as input and gauges whether observed changes in explanatory variables correspond to changes in the output variable. By default, estimating the coefficient for the auto-regressive component allows the model to capture long-term shifts driven by technological or lifestyle changes that are unrelated to the variability of the explanatory variables. The model also adapts to external changes provided they exert a lasting influence, based on the underlying assumption that the estimated relationship remains consistent for a specific region during the observed period. Given the evident autocorrelation, the narrow range of change within each time series allowing the assumption of stationarity without the need for integration, and the inconsistent behavior of the moving average pattern, we opted for an ARIMAX (1,0,0) model. Explanatory variables capturing year-to-year changes in economic conditions (GDP), temperature deviations above the optimum (CDD), and deviations below the optimum (HDD) were utilized, with nominal calculations assumed as gradients to avoid presuming specific relationships among variables. Corrections for GDP impacts were applicable only from 2000 due to data availability. Regions with median CDD values below 25 were not assessed for the impact of this factor, as it was unfeasible to estimate the impact of heatwaves for regions effectively lacking even a single week with an average temperature of 25 °C.

Regional coefficients signifying the impact of estimated factors were subsequently consolidated. Notably, it was not assumed that the impact of these factors followed a linear pattern across regions; however, a discernible relationship between the magnitude of observed variables and their impact was considered. Given shorter time series or regions with restricted exposure to specific influential factors displaying notable variance, conventional linear regression was deemed unsuitable due to the breach of assumptions. In its place, robust regression was employed, employing the Huber Loss function to alleviate these issues and estimate the impact of temperature variables. A statistical significance level of $p < 0.01$ was adopted, along with 10,000 runs for bootstrapping and 95% confidence intervals. The estimation of the GDP's impact serves a dual purpose: it acts as a control for a highly pertinent variable that underwent changes during the analyzed period, and it validates the model's consistency with previous research. Exact regional estimations for the impact of temperature were presented in supplementary materials.

The calculations were conducted using Python 3.10, incorporating the built-in library math, as well as utilizing libraries such as pandas 1.4.3 and numpy 1.21.1. The models were computed using statsmodels 1.13.5, and for data visualization, geopandas 0.13.2 and matplotlib 3.7.1 were utilized.

Results

There were 618 suitable time series for which the impact of explanatory variables was estimated using ARIMAX model and fitted coefficients are plotted in Fig. 1. Subsequently, for each factor, the marginal impact of the relevant variable was estimated in the form of $y = a - b * \ln(x)$. In all instances, the *p*-value for all variables was lower than 0.001, while variables a and b exhibited opposing signs, reflecting the diminishing effect of the variable. An increase in GDP per capita, as anticipated, had a positive impact of 0.407 [C.I. 0.153 to 0.661] years per 1000 euro increase, mitigated by a reduction of 0.035 [0.010 to 0.060] in the logarithm of GDP per capita. The impact of below optimal temperature was pronounced, with every annual 1000 HDD reducing life expectancy by 3.005 [C.I. 2.743 to 3.268] years, countered by a decrease of 0.352 [C.I. 0.319 to 0.386] in the logarithm of HDD. Above optimal temperature demonstrated slightly less lethality, with every 1000 CDD resulting in a decrease of life expectancy by 2.389 [C.I. 1.872 to 2.906], accompanied by a reduction of 0.258 [C.I. 0.152 to 0.365] in the logarithm of CDD.

The acquired gradient was integrated to determine the overall impact of suboptimal temperature. The resulting function took the form of $ax + bx\ln(x) - bx$, where the inclusion of the constant of integration could be omitted. While some level of quasi-constant excess mortality within this favorable range might exist, this method

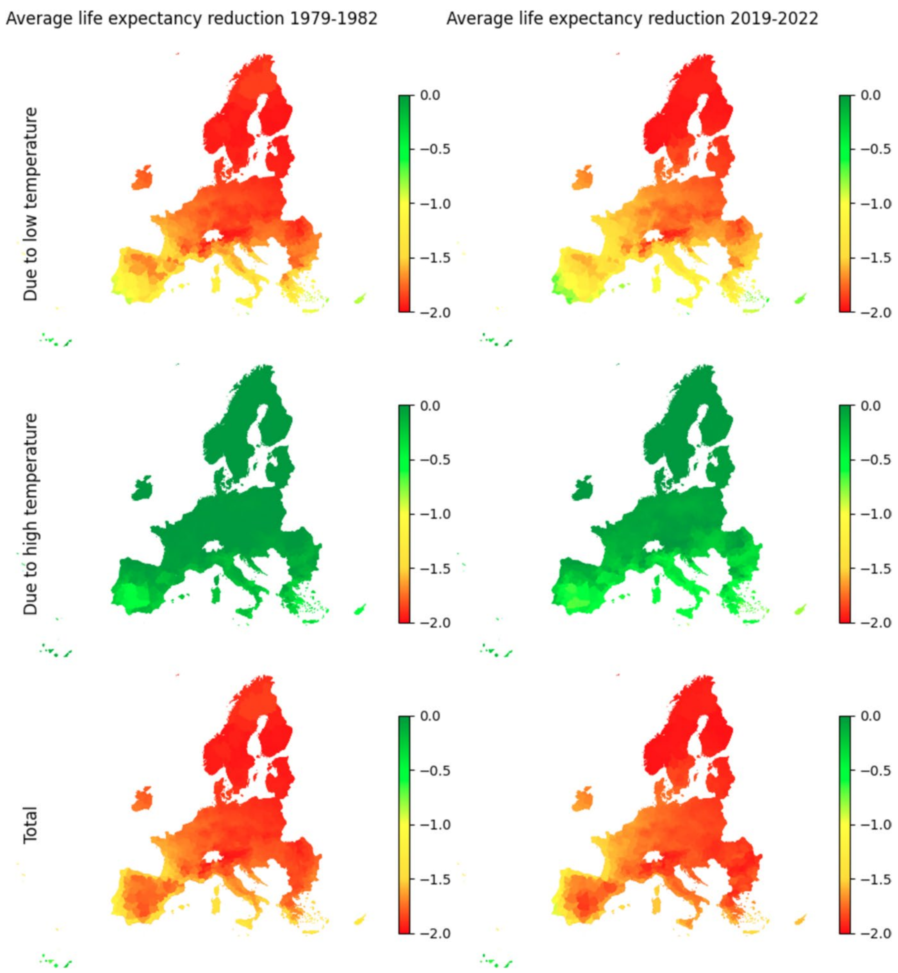

Fig. 2 Life expectancy reduction in years due to non-optimal temperature in years 1979–1982 and 2019–2022

was not suited to detect it. The outcomes were depicted in Fig. 2, illustrating the reduction in life expectancy attributed to temperatures below the optimum, temperatures above the optimum, and their cumulative effects, both during the periods of 1979–1982 and 2019–2022. It is important to note that this estimation reflects a generalized impact of such weather conditions fluctuations on mortality which at that period were overshadowed by COVID-19 pandemics.

As shown in Fig. 2, life expectancy was predominantly reduced by temperatures below the optimum. In the harshest regions, such as northern Scandinavia or the Alps, this reduction reached 24 months, after which this factor exhausted its impact. Conversely, the loss of life expectancy due to temperatures above the optimum was only discernible south of the Alps, and even there, it was at most 8 months. The cumulative impact was most pronounced in colder regions. Meanwhile, the most favorable regions for life were those with warm winters, yet moderated summer temperatures due to proximity to the sea—such as the Azores. Coastal areas near the Mediterranean or the Bay of Biscay also exhibited highly favorable conditions. The difference in life expectancy due to climate reasons between the harshest and most benign regions was 19 months.

In Fig. 3, net changes in life expectancy in days due to climate change over the aforementioned last four decades are presented. A distinct decrease in sub-optimal temperatures during the winter is evident, with a median gain of 1 month, somewhat counteracted by a median loss of half a month due to summer temperatures above the optimum. Because the model was fitted with stressors that exhibit diminishing impacts with no mechanism against reversal, the best-fit line actually implied that due to warming some regions of Scandinavia actually would experience near exactly function minimum. If it is not an artifact, it would suggest a loss of 1 month in those sparsely populated regions. Certainly, no appreciable gain was discernible there,

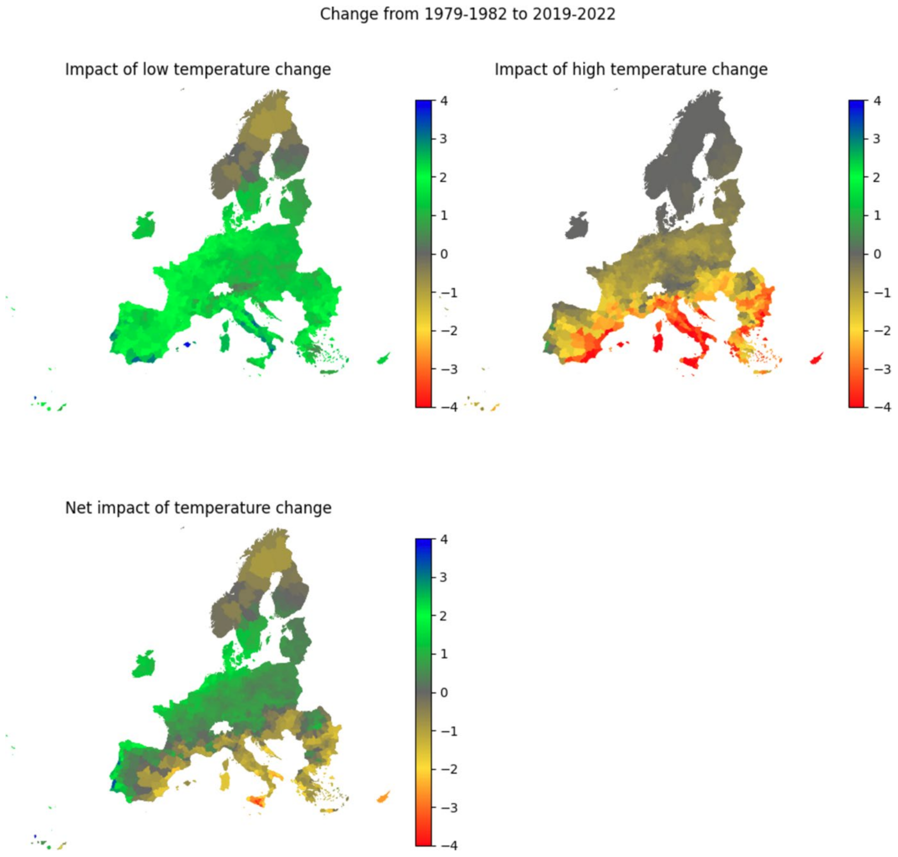

Fig. 3 Life expectancy change due to changes of non-optimal temperatures in months between years 1979–1982 and 2019–2022

while paradoxically, the highest gains were observed in regions that were already warm, amounting to up to 3 months in coastal areas around the Bay of Biscay. However, due to an increased occurrence of above-optimal temperatures, there was also a subtle (half-month) reduction in life expectancy in central Europe and a more significant reduction in Southern Europe. The net impact was the most detrimental in regions around the Mediterranean that experienced a net loss, with the southern edges of Italy losing 3 months. The primary beneficiaries were the warmer regions near the Atlantic, which had a net gain of 2 months. Continental regions tended to gain half a month, with gains exceeding a month in more temperate areas.

Predictions for the change in temperature impact between 1981–2010 and 2041–2070 under the RCP 4.5 scenario, assuming a constant temperature-mortality

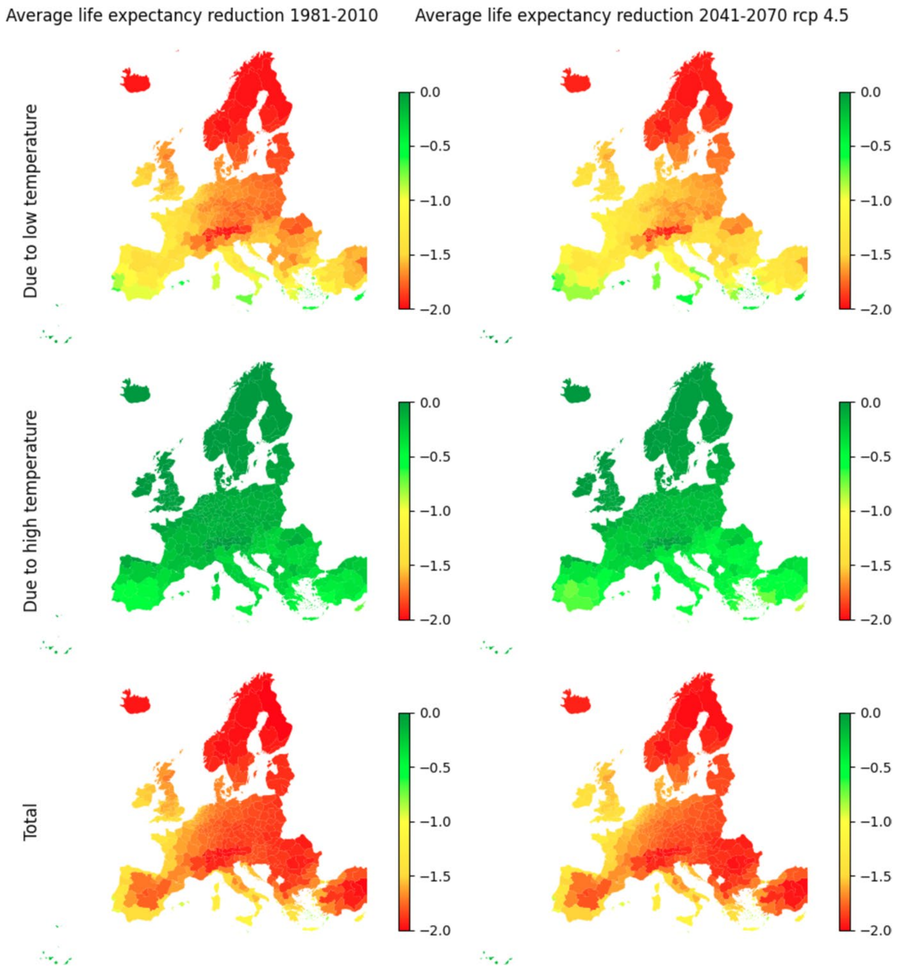

Fig. 4 Life expectancy reduction in years due to non-optimal temperature in years 1981–2010 and 2041–2070 under RCP 4.5 scenario

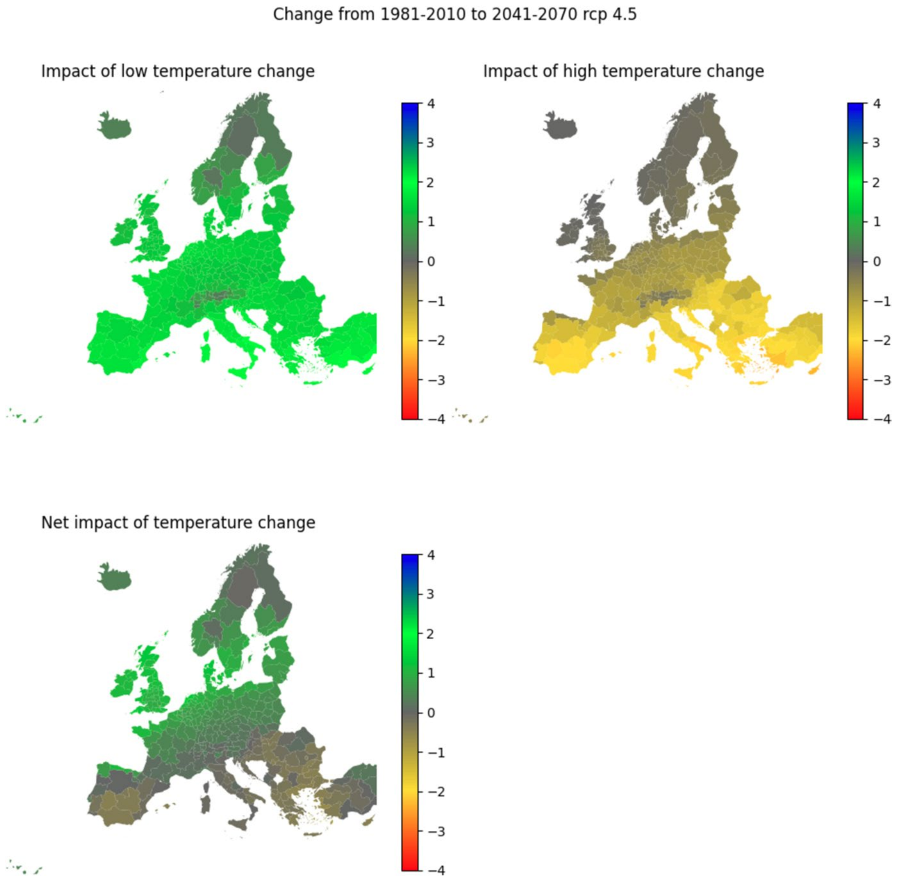

Fig. 5 Life expectancy change due to changes of non-optimal temperatures in months between years 1981–2010 and 2041–2070 under RCP 4.5 scenario

relationship, are presented in Figs. 4 and 5. Even in warmer climates, the warmest edges of Europe would maintain a relatively less deadly climate. The gains in life expectancy due to warmer winters would average around a single month, which would be effectively counterbalanced in the southern part of Europe by a comparable decrease due to hotter summers. Nevertheless, in some regions like southern Spain and the Balkans, life expectancy would be reduced by half a month. The main gains of around a net 1 month would be observed in the coastal belt stretching from the northern Spanish coast through the British Isles to southern Sweden, where milder winters would not be accompanied by a significant increase in heatwaves.

Discussion

The observed relationship underscores that the natural climate affects life expectancy, and intriguingly, even after controlling for economic growth, a modest warming trend appears to offer a moderate benefit from the perspective of life expectancy. In Europe's most challenging regions, the climate reduces life expectancy by 24 months, whereas in the most favorable regions, the reduction is merely 2 months. Notably, the impacts of climate change are most prominently favorable along the Atlantic coast, while the Mediterranean region experiences the most significant losses, a pattern likely to persist under future climate changes.

Several factors contribute to the pronounced variability in impact, extending beyond regions that were already uncomfortably warm. Firstly, both stressors demonstrated a clear trend of diminishing impact. Consequently, the most substantial gains were realized in regions with relatively mild winters. Counterintuitively, there exists a straightforward mechanism that can elucidate this relationship—a shortening of the winter infection season. Therefore, the most pronounced gains would occur if the shortened season allowed frail individuals to avoid exposure to winter infections. This interpretation is in line with previous studies on the annual mortality cycle, revealing a marked difference between the gradual, sine-shaped infection cycle typical of continental climates and the sharply compressed cycle found in temperate or arid climates (Madaniyazi et al., 2022; Walkowiak & Walkowiak, 2024).

The relationship between a milder climate and higher life expectancy has been noted in prior works, although not always explicitly named as such. In studies covering Europe and adjacent countries, a negative relationship between CO_2 emissions and life expectancy was clearly observed. Poças et al. considered it a proxy for air pollution (Poças et al., 2020), while Radmehr and Tomiwa speculated on a mechanism related to carbon monoxide poisoning that could be prevented by CO_2 emission reduction (Radmehr & Adebayo, 2022). Moreover, a very similar pattern was observed in China, where Wang et al. noticed that life expectancy across the country is elegantly correlated with local GDP, except in the two warmest provinces, Guangxi and Hainan. This was deemed puzzling, and potential genetic factors were proposed (Wang et al., 2015). Other Chinese works have detected similar patterns, but favored explanations related to sea fish consumption and milder climates (Huang et al., 2017). It is telling that the longer life expectancy in warm seaside regions, attributed to various regional factors, can be explained by our model. Additionally, those studies appear to detect the benefits of warmer climates also in regions hotter than those in our sample.

The projection for changes during 2040–2070 should be understood in the context of how closely model assumptions align with reality. Prior studies covering over a century's worth of data on the relationship between life expectancy and GDP suggest that it has become effectively fixed in recent decades (Jetter et al., 2019; Mackenbach & Looman, 2013), justifying the assumption of stationarity for this relationship. However, regional studies indicate that the overall relationship between temperature and mortality has varied over centuries but appears to have stabilized in recent decades (Alcoforado et al., 2015; Landers & Mouzas, 1988; Telfar-Barnard et al., 2023), allowing for medium-term projections but cautioning against extrapolation towards the end of the century. While we assume these relationships to be constant for calculation purposes, recent studies consistently demonstrate a subtle decline in vulnerability to both low (Carson et al., 2006; Suulamo et al., 2024; Telfar-Barnard et al., 2023) and high temperatures (Achebak et al., 2018; Folkerts et al., 2020; Huber et al., 2022). Therefore, the projection should be interpreted as a high-end estimation of the role of climate in the mid-twenty-first century, with the actual impact likely to be somewhat weaker. Based on Ballester et al.'s study demonstrating how the global financial crisis increased winter mortality (Ballester et al., 2019) and research showing the relationship between the prevalence of air conditioning and vulnerability to heatwaves (Chua et al., 2023; Sera et al., 2020), we suspect that economic growth contributes to gains in life expectancy partially by enabling adaptations to adverse climate conditions.

While the estimation for Scandinavia may seem paradoxical, it is in fact in line with Gasparrini et al. who observed that the conventional U-shaped relationship between temperature and mortality appeared to be disrupted for Stockholm or Toronto (Gasparrini et al., 2015). Temperatures falling below zero were associated with a slight reduction in mortality in that context. Consequently, it becomes conceivable that the observed impact is genuine and potentially linked to alternative reactions, such as conditions becoming unfavorable for certain viruses. Notably, variations in optimal temperatures have been documented for different strains of influenza viruses (Chong et al., 2020; Peci et al., 2019), supporting this line of reasoning.

From our perspective, the contradictory conclusions drawn by Kinney et al. (2015) and Chau and Woo (2015) stem from the fact that their methods only detect changes in the annual pattern, which could at best serve as a proxy indicator for the overall impact on mortality. Reconciling our findings with Kinney et al. (2015) is not difficult. They openly state that even after controlling for the month, they detect some, albeit weaker, relationship between temperature and mortality. This raises the following question: What happens to frail people who nevertheless survived due to a warmer winter? If they die next infection season, according to their methodology, winter deaths would barely be affected, while our methodology would detect an increase in life expectancy by 1 year.

The observation of a subtle but noticeable impact of economic development on life expectancy, even in already-developed countries, is highly consistent with prior studies (Rochelle et al., 2015; Zare et al., 2015). The model successfully predicted diminishing returns and indicated the eventual plateauing of this factor after exceeding 100,000 euros per capita in 2020 prices. For example, Germany, with a GDP per capita of 43,300 euros in 2021, could derive marginal benefits from additional economic growth with the possibility of increasing life expectancy by approximately 3 months in case of increasing per capita GDP by 10,000 euros. Furthermore, since the relationship between life expectancy and GDP was calibrated based on the first two decades of the twenty-first century, it should be understood as reflecting the optimal health outcomes achievable during that specific period. However, the emergence of new costly treatment options is likely to alter this relationship in the future.

The results have significant policy implications. Prior studies on the impact of heatwaves were open to interpretation, either emphasizing the high number of deaths or noting that those who died were already likely to die in the coming weeks. This study allows for calculations of the number of years of life lost that could be weighed against the cost of interventions. This, in turn, enables the design of public health interventions aimed at infrastructural adaptations, such as air conditioning or passive cooling systems for the most vulnerable populations (Chua et al., 2023; Sera et al., 2020). Nevertheless, this work shows that the dominant threat remains low-temperature mortality, which should no longer be neglected in the analysis of climate risk. The challenge is much greater here, as the temperature only serves as a modulating factor in spreading numerous winter infections. As presented by van Asten et al. the main threats were influenza A and RSV, though with increasing age, influenza B and parainfluenza also became deadly. For the oldest populations, norovirus is demonstrably lethal as well (van Asten et al., 2012). Combating these viruses will require further research and public health interventions. While the predicted impact on life expectancy due to increased high temperatures would be limited, new public health challenges may arise, such as the re-emergence of malaria in Europe (Piperaki, 2018) or a higher prevalence of postoperative infections (Anthony et al., 2017). Moreover, while otherwise beneficial shorter infection season, is shown to be much more intense (Madaniyazi et al., 2022; Walkowiak & Walkowiak, 2024), potentially causing warmer winters to be accompanied by a surge in medical service utilization. The model also allows for a better assessment of the socially optimal decarbonization path, balancing both the impacts of climate change and the economic costs.

In broad terms, the climate in Europe is likely to become marginally less hazardous for humans, as it has already been highly deadly. Understanding this notion also helps guide human migration to take advantage of climate differences. Opting for retirement migration to warmer locations should be encouraged as a health-conscious decision—a finding that mirrors the behavioral choices observed in previous studies. German retirees in the Canary Islands explicitly justified their decision on climate and health grounds (Breuer, 2005), while foreigners in Sweden were more likely to return to their home country for retirement if it was warmer (Klinthäll, 2006). Moreover, in the USA, retirement migration emerged as an independent predictor of life satisfaction, holding true even after accounting for factors such as income and health (Pearson & Kalenkoski, 2021). While our model analyzes life expectancy in a general context, studies on annual mortality patterns indicate that certain causes of death, like cancers, are largely unaffected by seasonal changes. Conversely, other causes, particularly respiratory and cardiovascular diseases, exhibit strong seasonality and temperature dependence (Bunker et al., 2016; Butala et al., 2018; Laaidi et al., 2006). This suggests that individuals who would otherwise be deemed at high risk of succumbing to such causes are likely to be sensitive to weather-related factors.

Conclusion

The primary climate threat that reduces life expectancy in Europe continues to be low temperatures. The least favorable climate is the continental type, whereas the most favorable is the Mediterranean climate. The last four decades of global warming have led to a net gain in life expectancy. The region as a whole seems to possess some degree of resistance to further climate change. The model also reveals a consistent increase in life expectancy for developed countries solely due to economic output growth. This suggests that prioritizing slowing down global warming over economic growth is unlikely to lead to maximization of life expectancy in the region. Moreover, considering the diverse impact of local climates on life expectancy, there is a potential benefit in encouraging retirees to migrate to warmer islands or coastal areas as a thoughtful policy.

Limitations

The model treats cold and heat-related deaths as two independent phenomena, whereas some studies have captured a subtle relationship between these stressors, with one stressor likely reducing the number of remaining potential victims for the other (Ha et al., 2011; Rocklöv et al., 2009; Walkowiak et al., 2024). While some work detects subtle gender differences in sensitivity to temperature (Achebak et al., 2018; Sheridan et al., 2021), in the analyzed sample, as presented in the supplementary materials, the differences were within the confidence intervals and thus could not be analyzed. The models do not include the impact of migration. There are ongoing controversies in the literature regarding the proper calculation of the GDP price deflator—especially due to the introduction of new products and the difficulty in directly measuring changes in service quality—highlighting that long-term changes in GDP are highly dependent on calculation assumptions (Feldstein, 2017; Kaufmann, 2020). Panel regression models, presented in the supplementary materials, suggest that it is mathematically possible to introduce an additional time variable that would reduce the impact of GDP changes. However, the model cannot determine whether this variable genuinely captures independent technological progress or simply reflects that, unlike heatwaves or winter infections, the effect of economic growth on life expectancy is non-immediate.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11111-025-00480-z.

Author contributions Marcin Piotr Walkowiak: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Roles/Writing – original draft; review & editing; Dariusz Walkowiak: review & editing; Project administration; Supervision; Validation; Jarosław Walkowiak: review & editing; Funding acquisition.

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Data availability All data are publicly available.

Declarations

Ethics approval Not applicable as this study utilized publicly available data.

Competing interests The authors declare that they have no competing interests.

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