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Impact of temperature variations on burden of lower respiratory infections under climate change (1990–2021)

Weiqi Huang[1], Long Yin[1], Hongyu Li[1], Wangxuan Yang[1], Shiying Huang[1], Liuying Wang[1], Kexin Wang[1], Yanhua Hao[1,2], Qunhong Wu[1] and Huan Liu[1,2*]

Abstract

Objectives We aimed to evaluate the global burden and trends of lower respiratory infections (LRIs) attributable to non-optimal temperatures between 1990 and 2021, focusing on age, period, and cohort effects as well as health inequalities to inform targeted public health policies.

Methods Using the Global Burden of Disease 2021 database, we obtained the age-standardized mortality rate (ASMR) and disability-adjusted life-years rate (ASDR) for LRIs related to non-optimal temperatures. We calculated estimated annual percentage changes (EAPC) to assess LRIs burden trends and applied age-period-cohort modeling to quantify age, period, and cohort effects. Health inequalities were evaluated using the slope index of inequality and the concentration index.

Results In 2021, the highest ASDR for LRIs due to high temperatures occurred in children under 5 (347.66/100,000), whereas the highest ASMR for LRIs due to low temperatures occurred in adults aged ≥ 65 (338.49/100,000). Globally, the LRIs burden from non-optimal temperatures declined (EAPC: ASMR −2.48; ASDR −3.33). However, among the five climate zones, the LRIs burden in the boreal zone due to high temperatures increased (EAPC: ASMR 24.14; ASDR 45.14), whereas all other climate zones showed decreasing trends. In lower Sociodemographic Index (SDI) regions, the high-temperature–related LRIs burden was more pronounced. Relative inequities driven by non-optimal temperatures worsened in low-SDI regions.

Conclusion From 1990 to 2021, the global burden of LRIs attributable to non-optimal temperatures declined overall; however, high-temperature–related LRIs increased in boreal zones. These health inequalities underscore the urgent need for targeted climate adaptation policies, such as providing international assistance, improving infrastructure, offering healthcare resources, and promoting vaccine coverage, particularly for vulnerable populations in low-SDI regions and boreal zones.

Keywords Infectious disease, Global disease burden, Temperature, Health equity, Health policy, Climate zones

*Correspondence:
Huan Liu
liuhuan00813@163.com
[1] Department of Social Medicine, School of Health Management, Harbin Medical University, Harbin, China
[2] Health Emergency Center, School of Health Management, Harbin Medical University, Harbin, China

Introduction

Lower respiratory infections (LRIs) remain one of the leading infectious causes of mortality worldwide [1]. In 2021, an estimated 344 million people were affected by LRIs globally, resulting in 21.8 million deaths [2]. Although there has been global progress in reducing the

LRIs mortality rate, the disease burden remains severe, particularly in low- and middle-income countries [2].

Climate change has become a major health risk of the twenty-first century [3]. Over the last two decades, non-optimal temperatures have consistently ranked among the top ten global causes of death [4], contributing to over 5 million deaths annually from extreme temperatures [5]. More importantly, non-optimal temperatures significantly contribute to LRIs [6, 7]. According to the 2021 Global Burden of Disease (GBD) data, global exposure to non-optimal temperatures led to nearly 200,000 deaths from LRIs [8]. Furthermore, several studies have found that the relationship between temperature and LRIs incidence follows a V-shaped curve, indicating that both excessively high and low temperatures can increase LRIs incidence [9–11]. Mechanistically, exposure to either high or low temperatures can exacerbate the incidence and severity of LRIs [7, 12]. Exposure to low temperatures causes vasoconstriction of the bronchial and respiratory mucosal blood vessels, triggering cold stress and suppressing immune responses. These pathological and physiological reactions reduce the body's resistance to LRIs [12]. Exposure to high temperatures may increase the risk of infection by affecting the stability and transmission rate of respiratory viruses [13, 14].

Previous studies have extensively examined the relationship between temperature and LRIs [10, 15]; however, few have quantified the LRIs disease burden attributable to temperature extremes [6, 16]. Most relevant research has focused on the impact of low or non-optimal temperatures on LRIs burden [6, 17], even though LRIs represent the largest share of disability-adjusted life years (DALYs) and mortality attributable to high temperatures [7]. Moreover, scholars analyzing non-optimal temperature–attributable LRIs burden have not sufficiently quantified the separate contributions of low versus high temperatures [6].

Moreover, previous investigations have largely described the global distribution of LRIs burden due to non-optimal temperatures across countries and regions [2, 17], but they often overlook how socioeconomic, geographic, and climatic factors influence these variations [6, 16]. Specifically, they fail to reveal the spatial heterogeneity of LRIs burden attributable to high, low, and non-optimal temperatures across socio-demographic index (SDI) regions and climate zones. Additionally, few studies have analyzed temporal trends in LRIs burden across different SDI regions and climate zones; although some have provided preliminary descriptions based on 2021 data [18], they have not fully addressed regional health inequalities.

Given the rising frequency of extreme weather events worldwide and varying adaptive capacities across birth cohorts [15, 19], the LRIs burden attributable to temperature may differ by cohort. Indeed, studies of non-optimal temperature–related LRIs burden from 1990 to 2019 revealed declining trends over time and across cohorts, identifying children and the elderly as the most vulnerable groups [6]. However, detailed cohort- and period-specific analyses of LRIs burden due to high versus low temperatures remain lacking [6, 15].

Overall, this study aims to evaluate the global LRIs burden attributable to high, low, and non-optimal temperatures from 1990 to 2021 and to analyze trends across SDI regions and climate zones, with a particular focus on health inequities and age-period-cohort effects. Furthermore, this study will explore the impact of temperature on LRIs burden in the context of global climate change, thereby providing empirical evidence to inform targeted health policies and interventions.

Materials and methods

Data sources

Estimated LRIs burden due to temperatures

The GBD 2021 database provides data on the burden of LRIs attributed to high, low, and non-optimal temperatures [20]. This dataset includes age-standardized mortality rates (ASMR) and age-standardized disability-adjusted life year rates (ASDR) for LRIs, collected between 1990 and 2021 for 204 countries and territories, stratified by sex and age, with rates expressed per 100,000 people.

In GBD 2021, LRIs are defined by specific disease codes from the 9th and 10th editions of the International Classification of Diseases [1]. Non-optimal temperatures include high and low temperatures, defined as those above and below the theoretical minimum risk exposure level, respectively [20]. Detailed methodologies for calculating the global burden of LRIs associated with temperature variations have been described previously [20, 21]. Data on national population and disease mortality for 2021 were obtained from the WorldPop and GBD risk factor databases [22].

SDI data

The SDI, obtained from the Global Health Data Exchange, is a composite index of development status strongly correlated with health outcomes. It is calculated as the geometric mean of three indicators: the total fertility rate under age 25, mean education level for individuals aged 15 and older, and lag-distributed income per capita. The SDI ranges from 0 to 1, with higher values indicating greater socioeconomic development [23]. The global countries and territories were classified into five SDI regions [24].

Temperature data

The Climatic Research Unit Time Series dataset, well known for climate analysis, provides temperature data for

204 countries. It features a 0.5° latitude by 0.5° longitude spatial resolution, covering all terrestrial regions globally except Antarctica. The dataset is based on interpolated monthly climate anomalies across an extensive network of meteorological stations. Angular-distance weighting ensures that each gridded value is traceable to its originating observations, enabling diagnostics that assess potential geographical variations in data quality [25]. Based on previous studies and using average annual temperature data from 1990 to 2021, regions were classified into five climate zones [26].

Statistical analysis

This study calculated ASMRs and ASDRs to evaluate the burden of LRIs associated with temperature from 1990 to 2021. Previous studies have described in detail the indicators used for disease burden estimation, including ASMR and ASDR [27]. In brief, ASMR and ASDR measure the severity of disease burden by capturing both fatal and nonfatal components [27, 28]. These indicators eliminate the influence of differences in age structure on LRIs burden estimates, facilitating comparisons across regions and time periods [29–31]. Furthermore, results were stratified by age, sex, region, country, global climate zone, and SDI level to assess temporal trends in LRIs burden ascribed to high, low, and non-optimal temperatures. Specifically, Pearson correlation coefficient analysis was used to examine the association between SDI and LRIs burden.

The estimated annual percent change (EAPC) is useful for analyzing long-term trends because it indicates whether rates are generally rising or falling over time, independent of short-term fluctuations. When the EAPC and the lower bound of its 95% confidence interval are both above zero, it signifies a statistically significant upward trend. Conversely, if the EAPC and the upper bound of its 95% confidence interval are both below zero, it indicates a significant downward trend [32]. Thus, the study employed EAPC to evaluate the trend in the burden of LRIs attributed to temperature. EAPC was derived by fitting a regression model to the natural logarithm of the age-standardized rate, represented by the equation $y = \alpha + \beta x + \varepsilon$. In this equation, x denotes the calendar year, α is the intercept, β is the slope, and ε denotes the random error term. The EAPC value was calculated using the formula $100 \times (exp[\beta] - 1)$, with 95% confidence intervals estimated within the model to provide precision for the trend estimates [33]. EAPC was employed to analyze trends in LRIs burden attributable to high, low, and non-optimum temperatures globally, across countries and regions, and within different SDI regions, climate zones, and age groups for the years 1990 to 2021.

Subsequently, locally estimated scatterplot smoothing (LOESS) was employed to fit smooth curves. To optimize the span parameter for our dataset, we performed a five-fold cross-validation sensitivity analysis. Candidate span values ranged from 0.1 to 1.0 in increments of 0.005, balancing computational efficiency with parameter sensitivity. For each region, the optimal span was selected by minimizing the root mean squared error, and these span values were then applied independently to ensure the best possible fit to the data distribution.

This study employs the slope index of inequality (SII) and the concentration index (CI), as recommended by WHO, to assess absolute and relative health inequalities [34]. These indices specialize in evaluating disparities across ordered socio-economic groups while accounting for population size and gradient structure [34]. Previous GBD studies have suggested that, compared with general inequality measures such as the Gini coefficient and the Theil index, the SII and CI more accurately reflect income-related health inequalities [35, 36]. The SII was estimated by fitting a linear regression model of health outcomes on cumulative population ranks by SDI, and the CI was calculated by numerically integrating the area under the Lorenz curve [37].

Age–period–cohort (APC) modeling, based on a Poisson distribution, was applied to assess the contributions of age, period, and birth-cohort effects to the observed trends. The age effect reflects the impact of aging on disease burden; the period effect captures changes over time across all age groups; and the cohort effect represents differences in health outcomes among birth cohorts after adjusting for age and period effects (for further details, see prior GBD studies [38, 39]). To address the "identifiability issue" (collinearity among age, period, and cohort effects), we used the APC Web Tool developed by the U.S. National Cancer Institute. This tool resolves collinearity by constructing orthogonal cohort biases, ensuring that age, period, and cohort effects do not interfere with each other [40]. Additionally, the tool performs a Wald test to assess the significance of local drift in the APC function ($P < 0.05$), which helps verify whether the APC results have effectively addressed this problem [40, 41]. If the local drift is significant, it indicates that there is no serious collinearity issue between age, period, and cohort effects. All data analyses were performed using R version 4.4.1, while ArcGIS version 10.8 was used for mapping. Statistical significance was set at $P < 0.05$.

Results

Global burden by age and sex (1990–2021)

In 2021, children under 5 years of age and individuals aged ≥65 years were identified as vulnerable to LRIs

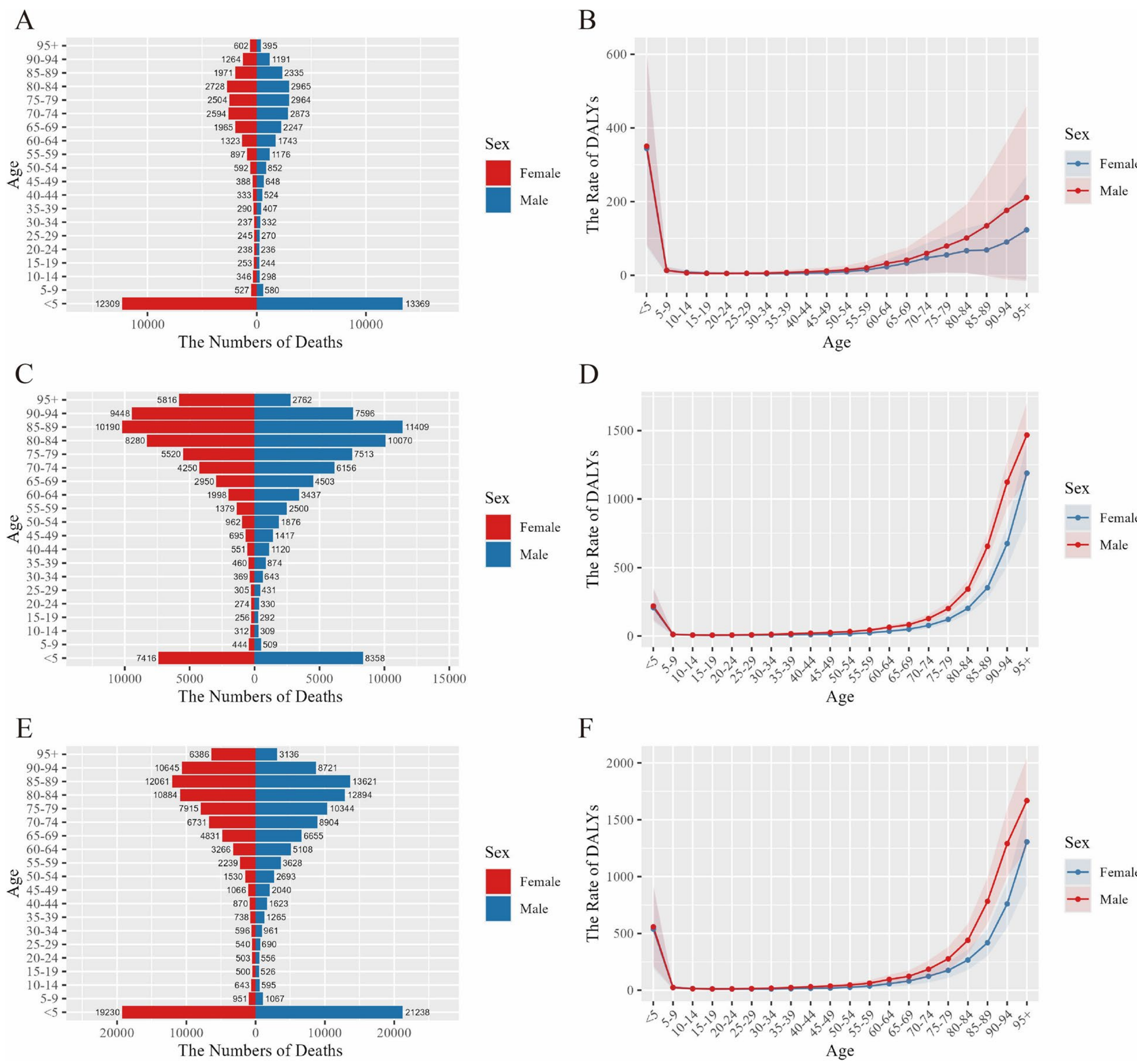

Fig. 1 The numbers of deaths and the rate of disability-adjusted life-years (DALYs) for LRIs attributable to high, low, and non-optimal temperature globally by ages and sexes in 2021. **A** The numbers of deaths of high temperature. **B** The rate of DALYs of high temperature. **C** The numbers of deaths of low temperature. **D** The rate of DALYs of low temperature. **E** The numbers of deaths of non-optimal temperature. **F** The rate of DALYs of non-optimal temperature

burden attributable to non-optimal temperatures. Specifically, the burden of LRIs due to high temperatures was highest among children under 5 years (ASMR: 3.90; ASDR: 347.66), while the burden associated with low temperatures was most pronounced among individuals aged ≥65 years (ASMR: 338.49; ASDR: 3,139.31) (Fig. 1, Fig. S1). Regarding sex, the LRIs burden attributable to high temperatures from 1990 to 2021 exhibited relatively minor differences. However, ASMRs and ASDRs for LRIs caused by low and non-optimal temperatures were higher in males than in females, with the largest sex differences observed among individuals aged ≥65 years (Fig. S1). These findings indicate that, in the context of global climate change, children under 5 years of age, individuals aged ≥65 years, and males are particularly vulnerable to LRIs burden under extreme temperature conditions.

Spatial distribution of the burden across 204 countries, 2021

As shown in Fig. 2, the countries with the highest ASMR and ASDR for LRIs due to high temperatures were Mauritania (ASMR: 12.34, 95% UI: 2.89, 20.94) and Chad (ASDR: 451.78,

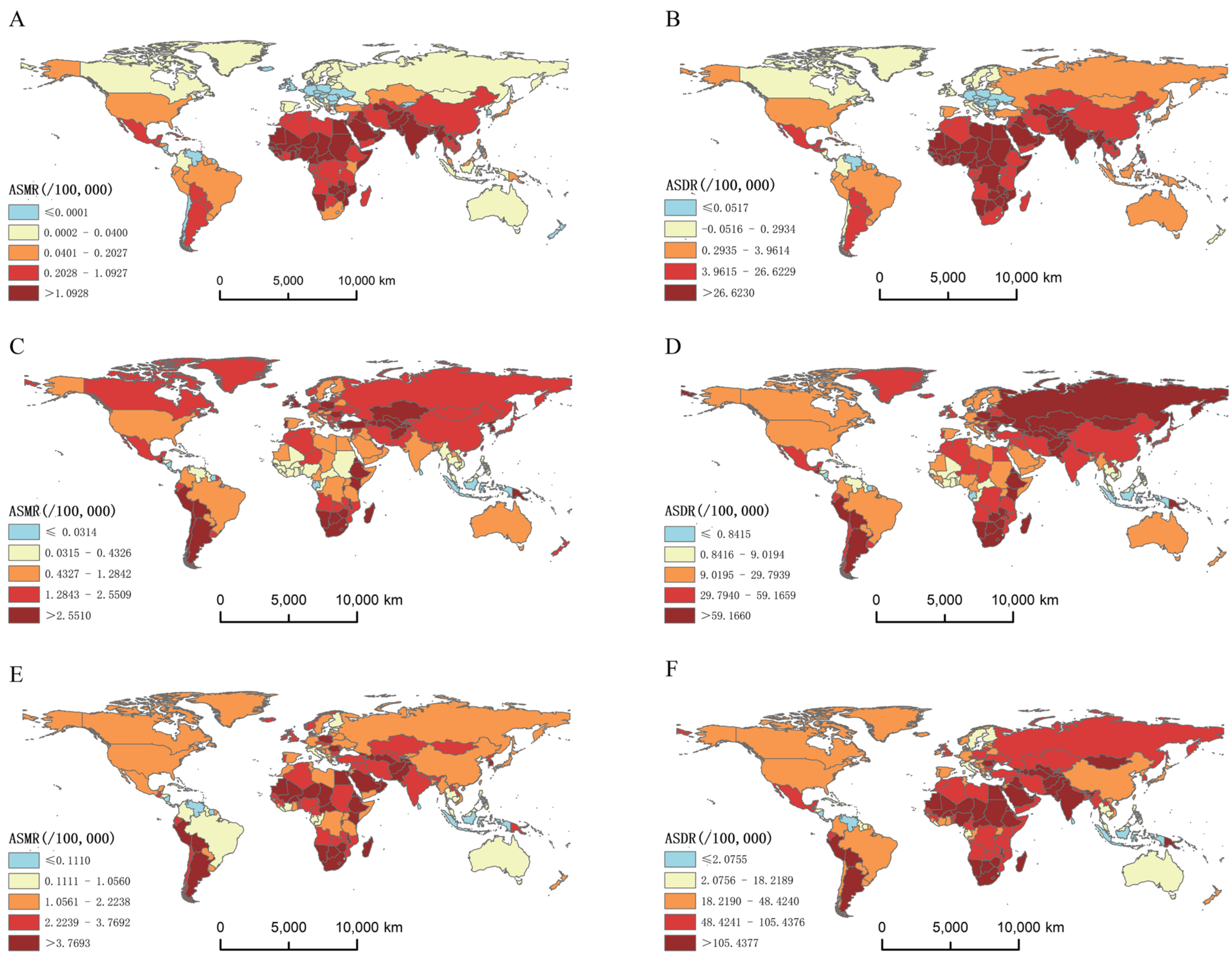

Fig. 2 Spatial distributions of age-standardized mortality and DALYs rates (per 100 000 population) for LRIs attributable to high, low, and non-optimal temperatures in 2021. **A** The ASMR of high temperature. **B** The ASDR of high temperature. **C** The ASMR of low temperature. **D** The ASDR of low temperature. **E** The ASMR of non-optimal temperature. **F** The ASDR of non-optimal temperature

95% UI: 192.57, 744.95). The countries with the lowest rates were Nauru (ASMR: −0.45, 95% UI: −0.97, 0.09) and Tokelau (ASDR: −21.43, 95% UI: −47.11, 1.53) (Fig. 2A, B). Lesotho had the highest LRIs burden attributed to low temperatures (ASMR: 22.29, 95% UI: 17.54, 29.08; ASDR: 853.10, 95% UI: 666.03, 1094.93), while the lowest values were observed in Mauritius (ASMR: −0.10, 95% UI: −0.66, 0.15; ASDR: −2.61, 95% UI: −17.33, 3.89) (Fig. 2.C, D). Overall, Lesotho exhibited the highest LRIs burden due to non-optimal temperatures. This burden was primarily distributed across Central Asia, Africa, and Oceania (Fig. 2E, F). Specifically, high-temperature–related burden was concentrated in Africa and South Asia, whereas low-temperature burden was concentrated in Latin America, Sub-Saharan Africa, and Oceania.

Correlation analysis of burden across 21 regions (1990–2021)

We examined correlations between ASMRs, ASDRs, and the SDI across 21 regions worldwide. The LRIs burden ascribed to high temperatures was significantly negatively correlated with SDI (ASMR: $r = -0.64$, $P < 0.001$; ASDR: $r = -0.68$, $P < 0.001$) (Fig. S2. A, B). ASDRs due to low temperatures also showed a negative correlation with SDI ($r = -0.34$, $P < 0.001$) (Fig. S2. C, D). For non-optimal temperatures, both ASMRs and ASDRs were negatively correlated with SDI (ASMR: $r = -0.37$, $P < 0.001$; ASDR: $r = -0.56$, $P < 0.001$) (Fig. S2. E, F). These findings highlight that low SDI regions tend to experience a high temperature–related LRIs burden.

Overall burden across the global, SDI regions, and climate zones (1990–2021)

The global burden of LRIs attributable to non-optimal temperatures declined from 1990 to 2021 (Fig. 3). Specifically, declines in ASMRs and ASDRs for LRIs attributable to high temperatures were more gradual than those for low temperatures. For low temperatures,

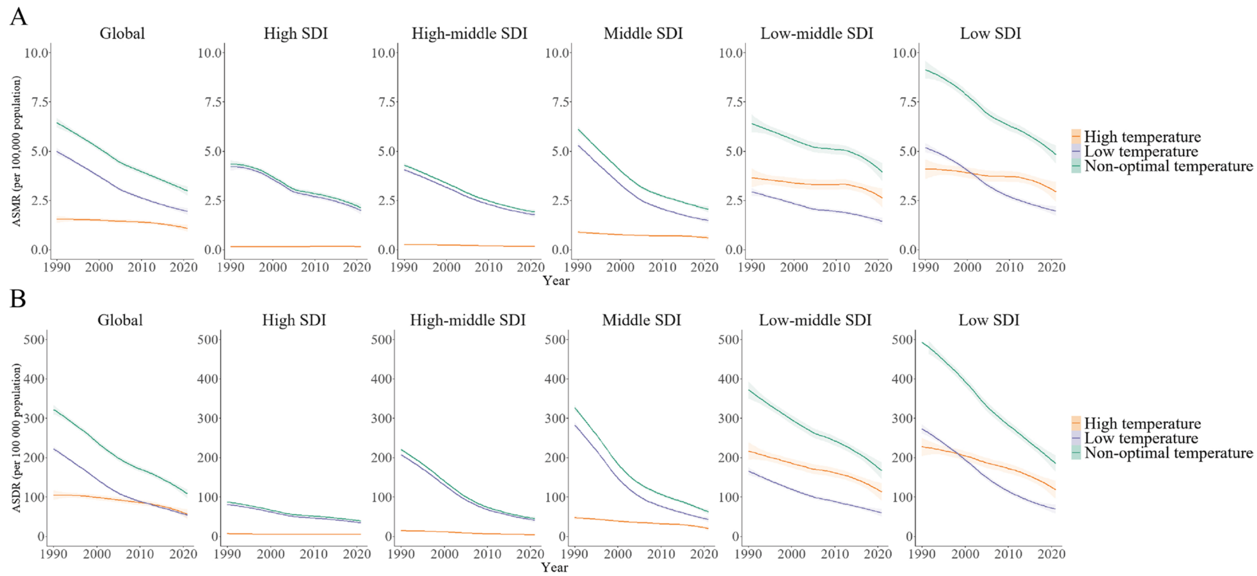

Fig. 3 Temporal trends in the age-standardized mortality rate (per 100 000 population) (**A**) and the age-standardized DALYs rate (per 100 000 population) (**B**) for lower respiratory infections (LRIs) associated with high, low, and non-optimal temperatures globally and across socio-demographic index regions, 1990–2021

the EAPCs were −3.12 (−3.29, −2.95) for ASMRs and −4.50 (−4.69, −4.30) for ASDRs; for high temperatures, they were −1.71 (−2.16, −1.26) for ASMRs and −0.95 (−1.37, −0.52) for ASDRs (Table S1).

By sex, the LRIs burden attributable to high, low, and non-optimal temperatures declined in both males and females, although males consistently exhibited higher rates than those exhibited by females (Table S1). However, in the 20–44 age group and among individuals aged ≥ 65 years, LRIs burden attributable to high temperatures increased, with an average EAPC of 0.74% for both ASMRs and ASDRs in the 20–44 age group and 1.30% for ASMRs and 1.28% for ASDRs in those aged ≥ 65 years. The burden attributable to low and non-optimal temperatures decreased consistently across all age groups (Table S2).

In 2021, ASMRs and ASDRs for LRIs attributable to low temperatures exceeded those for high temperatures in high, high-middle, and middle SDI regions. Conversely, in low-middle and low SDI regions, ASMRs and ASDRs were higher for high temperatures than for low temperatures (Fig. 3). Across all SDI categories, ASMRs and ASDRs attributable to high, low, and non-optimal temperatures declined, except in high SDI regions. Notably, in high SDI regions, the ASMR for LRIs due to high temperatures increased (EAPC = 0.66; 95% CI: 0.21, 1.11) (Table S1). Moreover, the LRIs burden showed a similarly decreasing trend among both males and females across all SDI regions (Fig. S3).

As shown in Fig. 4, the LRIs burden due to non-optimal temperatures declined across all climate zones. Specifically, in 2021, ASMRs and ASDRs for high-temperature–related LRIs exceeded those for low-temperature-related LRIs in tropical zones. Conversely, in subtropical, warm-temperate, cold-temperate, and boreal zones, low-temperature LRIs burden predominated among non-optimal temperatures. Notably, while the LOESS regression did not reveal a clear upward trend in the LRIs burden attributable to high temperatures, the EAPC estimates demonstrated a significant increase (EAPC: ASMR 24.14 [7.73, 43.04]; ASDR 45.14 [18.57, 77.66]) (Fig. 4; Table S1). This discrepancy may stem from the relatively small contribution of high-temperature-related burden to overall non-optimal temperature-related LRIs in the LOESS model, making trends less detectable. In contrast, the EAPC method, which captures long-term relative changes from baseline, highlighted a marked increase over time. Furthermore, this burden also exhibited an increasing trend in both males and females, with the trend being more pronounced in males (EAPC: ASMR 30.62 [12.06, 52.24]; ASDR 57.92 [27.36, 95.81]) than in females (EAPC: ASMR 19.88 [6.34, 35.13]; ASDR 38.22 [15.02, 66.11]) (Fig. S4; Table S3). These findings suggest that boreal zones may face an increasing LRIs burden due to high temperatures in the context of global climate change.

APC model of global burden (1990–2021)

The age effect highlights within-cohort risk: ASMRs for LRIs attributable to temperature peaked among individuals aged ≥ 65 years, whereas ASDRs peaked among children under 5 years (Fig. S5). The period effect showed

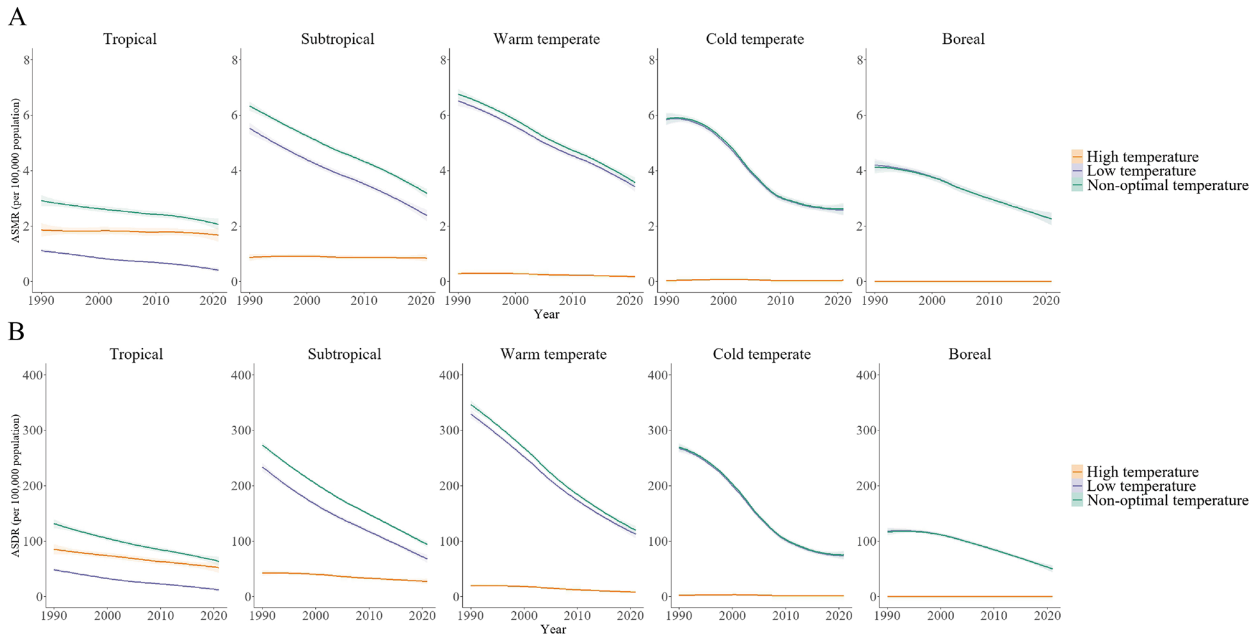

Fig. 4 Temporal trends in the age-standardized mortality rate (per 100 000 population) (**A**) and the age-standardized DALYs rate (per 100 000 population) (**B**) for LRIs associated with high, low, and non-optimal temperatures in different climate zones, 1990–2021

that LRIs burden attributable to high temperatures increased over time, while burden due to low temperatures declined (Fig. S6). The cohort effect revealed that high-temperature–related burden rose among cohorts born 1890–1990 and declined thereafter, whereas low-temperature–related burden declined steadily across cohorts born from 1890 to 2021 (Fig. S7). Wald test results confirmed significant local drift in the APC model ($P < 0.001$), indicating that collinearity among age, period, and cohort effects was effectively addressed.

Health inequality of global burden (1990–2021)

The SII indicates that the gap in ASDR between the highest and lowest SDI country LRIs due to high temperatures decreased from −89.38 (95% CI: −98.88, −79.88; $P < 0.001$) in 1990 to −24.99 (95% CI: −29.22, −20.76; $P < 0.001$) in 2021 (Fig. 5A). The CI decreased from 0.545 ($P < 0.001$) in 1990 to 0.490 ($P < 0.001$) in 2021 (Fig. 5B). In other words, in countries with low SDI, the absolute inequality in the burden of LRIs attributable to high temperatures has significantly decreased, yet they still bear a relatively high burden of inequality. The absolute inequality of the ASDR for LRIs caused by low and non-optimal temperatures decreased; however, the change was not statistically significant. The relative inequality of ASDR for LRIs decreased in the context of low temperatures; however, it increased for non-optimal temperatures (Fig. 5C, D, E, F).

Discussion

Our findings reveal an increasing trend in LRIs burden due to high temperatures in boreal regions. Significant differences in LRIs burden across countries persist, with lower-SDI regions continuing to experience high burdens. Moreover, relative health inequality attributable to non-optimal temperatures is growing across SDI regions. Children under 5 years and individuals aged ≥65 years remain key vulnerable populations. These results underscore the complex link between extreme temperatures and the global health burden of LRIs, highlighting the urgent need for targeted interventions to protect vulnerable groups and high-risk regions.

Consistent with previous studies, we found that extreme temperatures are associated with increased DALYs in children and high mortality rates in the elderly [17, 42]. Physiological vulnerability from impaired immune function makes both groups primary victims of extreme-weather events [43, 44]. Our analysis further indicates that high-temperature LRIs disproportionately reduce quality of life in children under 5 years, whereas low-temperature LRIs more often result in mortality among adults aged ≥65 years. Children's developing physiology heightens their susceptibility to extreme heat, and climate-change–induced heat waves can exacerbate air pollution, further increasing LRIs risk [45, 46]. However, low temperatures have a more severe impact on lung function in the elderly [47]. The greatest risk of

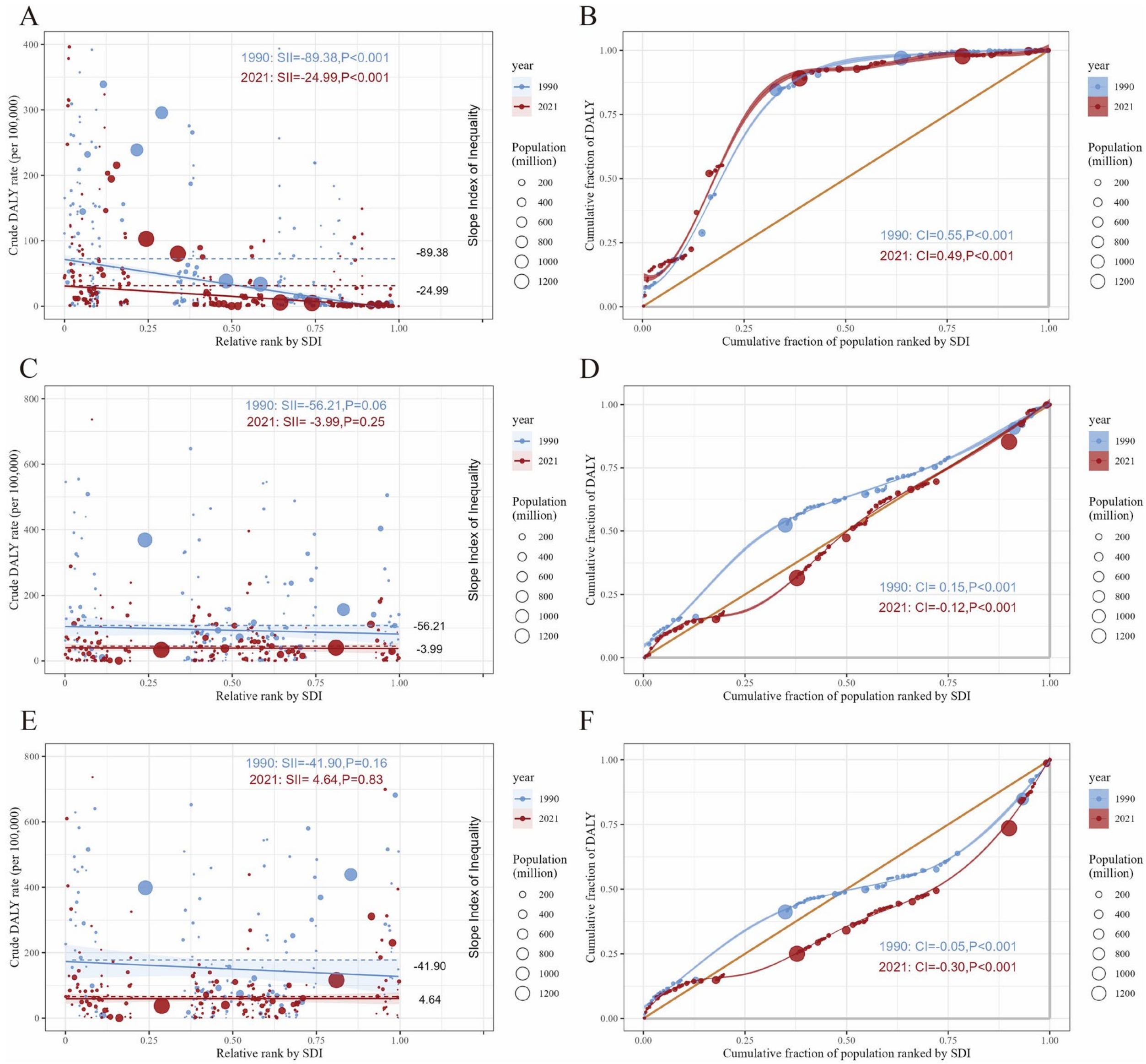

Fig. 5 Slope Index of Inequality analysis and Concentration index analysis for the DALYs of LRIs attributable to high, low, and non-optimal temperatures, 1990 vs. 2021. (**A** The ASMR of high temperature. **B** The ASDR of high temperature. **C** The ASMR of low temperature. **D** The ASDR of low temperature. **E** The ASMR of non-optimal temperature. **F** The ASDR of non-optimal temperature)

temperature-induced mortality in the elderly is pneumonia and respiratory diseases caused by low temperatures exposure [48]. With global population aging, the burden of temperature-related LRIs will likely grow. We therefore recommend prioritizing vaccination for children and the elderly [17], training healthcare workers to recognize and manage temperature-related stress, and implementing comprehensive medical and educational strategies to mitigate extreme-temperature impacts on vulnerable populations [49].

Regarding sex differences, males may be more frequently exposed to adverse climate conditions than females due to occupational and lifestyle factors, increasing their risk of contracting LRIs [50]. Physiological and biological differences also contribute to this disparity [51, 52]. For instance, males may exhibit greater peripheral vasoconstriction in cold environments, potentially reducing local immune responses [52]. Therefore, governments should establish early warning systems for extreme weather and issue temperature-exposure alerts to high-risk occupational groups to minimize non-optimal temperature exposure. They should also strengthen science communication to raise public awareness of climate change's health impacts and coping strategies—particularly among males—thereby effectively reducing LRIs risk.

Similar to previous findings, the burden of LRIs attributable to non-optimal temperatures is highest in economically underdeveloped regions—Southern and Central Africa, the Middle East, and southern South America [6]. This distribution reflects disparities in regions' capacity to adapt to temperature changes and allocate resources effectively [53]. Low-temperature–related LRIs burden predominates in high-SDI countries, but their more developed infrastructure and healthcare systems keep overall burden relatively low [6]. However, population aging has intensified mortality from low-temperature LRIs among the elderly in high-SDI regions [54]. Some scholars suggest this pattern may stem from differences in methods for calculating disease burden in the elderly [17]. Although the degree of health inequality has decreased, the burden of LRIs due to high temperatures remains disproportionately concentrated in lower SDI countries due to relatively insufficient economic and healthcare resources, consistent with previous studies [54]. Moreover, factors such as air pollution caused by biomass fuel heating and industrial emissions, along with fluctuations in extreme temperatures, further exacerbate the disease burden in these areas [6, 42]. International and non-governmental organizations (NGOs) should strengthen collaboration to support low-SDI regions with healthcare resources. Governments must integrate climate change's health impacts into public health policies and enhance behavioral and environmental adaptation strategies for aging populations in higher SDI regions (e.g., improved home heating, air conditioning, and urban infrastructure modifications). Advancing clean energy and improving air quality monitoring will also help mitigate pollution and temperature-related health risks.

A recent study has demonstrated a downward trend in the burden of LRIs caused by low temperatures across all climate zones [17], which is consistent with our findings. However, we also observed a significant increasing trend in the high-temperature-related LRIs burden in boreal zones, although the magnitude of this increase was relatively modest. With the temperatures expected to rise by 1.5 °C between 2021 and 2040 [55], global climate warming has significantly reduced the risk of LRIs associated with low temperatures while simultaneously exacerbating the frequency and duration of extreme high-temperature events in boreal zones, particularly in the Arctic and other high-latitude areas [2, 56]. Residents of boreal zones are less exposed to high temperatures, resulting in lower adaptive capacity and increased vulnerability to its adverse effects. Notably, some boreal countries (e.g., Russia, Canada) have begun addressing infectious disease impacts of high-temperature climate change by implementing heat warning systems and strengthening public health surveillance [57–59]. The WHO's Heat–Health Action Plan emphasizes enhancing capacity to prevent and control infectious diseases during extreme heat events, especially in high-latitude regions [60]. Boreal nations should adopt this recommendation and develop targeted policies to mitigate high-temperature–related infectious disease risks. Furthermore, urgent research into climate change adaptation—particularly the physiological adaptation of high-latitude populations to extreme heat—is needed to inform policy and long-term planning.

This study has several limitations. First, the GBD database provides estimated values of LRIs burden attributable to temperature; however, these data are current only through 2021 and may not fully reflect real-world conditions [1, 2]. Second, we classified annual average temperatures in 204 countries into five climate zones, but large temperature variations within individual countries may introduce potential errors. Third, although we incorporated SDI data—which partially reflect the effects of socioeconomic factors and health infrastructure on LRIs burden—we did not account for other confounders (e.g., healthcare resource allocation, environmental exposures, health behaviors). These omissions may introduce attribution bias and limit the interpretability of our findings. Fourth, we did not consider the impact of the Corona Virus Disease 2019 (COVID-19) pandemic on LRIs: because the GBD treats COVID-19 as a separate disease category, its effects on LRIs trends are not fully integrated. Moreover, pandemic interventions likely reduced the transmission of other infectious diseases, potentially leading to underestimation of non–COVID-19 LRIs burden. Future work will integrate more recent remote-sensing climate data, metrics on regional healthcare interventions, and alternative databases to validate our results—providing more accurate data and methodological support for public health policy development.

Conclusions

Overall, from 1990 to 2021, non-optimal temperatures were associated with a declining global burden of LRIs, driven mainly by reductions in low-temperature impacts. However, vulnerable groups, such as children, the elderly, and males, require particular attention. In boreal zones, the non-optimal temperature–related burden of LRIs has been increasing, primarily due to the contribution of high temperatures. Socioeconomic development has played a critical role in reducing the LRIs burden; however, the relative health inequities caused by non-optimal temperatures are widening across SDI regions. We recommend that governments, international organizations, and NGOs strengthen adaptation efforts by providing socioeconomic support, improving health infrastructure, and promoting targeted vaccination strategies. Future research should utilize diverse methods and data sources (e.g., remote sensing climate data and regional healthcare interventions) to continuously monitor LRIs burden trends related to non-optimal temperatures.

Abbreviations

LRIs	Lower respiratory infections
GBD	Global Burden of Disease
DALYs	Disability-adjusted life years
SDI	Socio-demographic index
ASMR	Age-standardized mortality rates
ASDR	Age-standardized DALYs rates
EAPC	Estimated annual percentage change
LOESS	Locally estimated scatterplot smoothing
SII	Slope Index of Inequality
CI	Concentration Index
APC	Age-period-cohort
NGOs	Non-governmental organizations
COVID-19	The Corona Virus Disease 2019

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-23203-3.

Supplementary Material 1.

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Authors' contributions
WQH contributed data analysis and manuscript drafting. HL and QHW designed, organized, and conducted this study, and served as guarantors for several revisions to the manuscript. LY contributed to the analysis of the results. HYL and LYW helps collect data. WXY helps manuscript drafting. SYH and KXW contributed to the revision of the paper. YHH supervised the paper. All authors contributed to the article and approved the submitted version.

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Data availability
The data of LRIs disease burden are available from open-access website at https://vizhub.healthdata.org/gbd-results/. The SDI data are available from the website at https://ghdx.healthdata.org/record/global-burden-disease-study-2021-gbd-2021-socio-demographic-index-sdi-1950%E2%80%932,021. The climate data are available from the website at https://www.uea.ac.uk/web/groups-and-centres/climatic-research-unit.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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