



OPEN ACCESS

EDITED BY

Nidhi Singh,
Leibniz-Institut für Umweltmedizinische
Forschung (IUF), Germany

REVIEWED BY

Senbeta Guteta Abdissa,
Addis Ababa University, Ethiopia
Roberto Giovanni Carbone,
University of Genoa, Italy

*CORRESPONDENCE

Gang Luo
✉ luogang1982@163.com
Qiuyu Liu
✉ q.liu@swmu.edu.cn
Mengnan Liu
✉ liumengnan@swmu.edu.cn

[†]These authors have contributed equally to
this work

RECEIVED 11 May 2025

ACCEPTED 27 October 2025

PUBLISHED 27 November 2025

CITATION

Chen L, Jiang Y, Wang J, Wan Z, Peng T,
Luo G, Liu Q and Liu M (2025) Temporal
trends and global burden of ischemic heart
disease attributable to non-optimal
temperatures from 1990 to 2021: an analysis
of the Global Burden of Disease Study 2021.
Front. Public Health 13:1626504.
doi: 10.3389/fpubh.2025.1626504

COPYRIGHT

© 2025 Chen, Jiang, Wang, Wan, Peng, Luo,
Liu and Liu. This is an open-access article
distributed under the terms of the [Creative
Commons Attribution License \(CC BY\)](#). The
use, distribution or reproduction in other
forums is permitted, provided the original
author(s) and the copyright owner(s) are
credited and that the original publication in
this journal is cited, in accordance with
accepted academic practice. No use,
distribution or reproduction is permitted
which does not comply with these terms.

Temporal trends and global burden of ischemic heart disease attributable to non-optimal temperatures from 1990 to 2021: an analysis of the Global Burden of Disease Study 2021

Li Chen^{1†}, Yan Jiang^{1†}, Jingyuan Wang^{2†}, Zhenxun Wan¹,
Ting Peng¹, Gang Luo^{1*}, Qiuyu Liu^{3*} and Mengnan Liu^{1*}

¹Affiliated Traditional Chinese Medicine Hospital, Southwest Medical University, Luzhou, China,

²Department of Pediatrics, Southwest Medical University, Luzhou, China, ³School of Pharmacy, Southwest Medical University, Luzhou, China

Background: Global climate change has intensified non-optimal temperature impacts on cardiovascular health. Ischemic heart disease (IHD), a leading cause of mortality, is increasingly linked to temperature anomalies driven by climate change, yet their association remains underexplored. Using Global Burden of Disease (GBD) 2021 data, this study analyzes spatiotemporal trends in temperature-attributable IHD burden from 1990 to 2021.

Methods: GBD 2021 data on IHD mortality and disability-adjusted life years (DALYs) across 204 countries were analyzed via joinpoint regression. Stratified analyses by age, sex, region, and sociodemographic index (SDI) assessed subpopulation disparities.

Results: In 2021, non-optimal temperatures were responsible for an absolute burden of 610,000 IHD deaths (95% UI, 459, 000 to 862, 000) and 1.24 million DALYs (95% UI, 915,900 to 1.76 million) globally. While these absolute figures represented increases of 41.8 and 37.8% since 1990, the age-standardized mortality rate (ASMR) and DALY rate (ASDR) actually decreased by 3.18 and 55.91%, respectively, over the same period, indicating that population growth and aging are key drivers of the rising absolute count. When examining the attribution of temperatures, the impact of low temperatures (accounting for 81.8% of the burden) was significantly higher than that of high temperatures (accounting for 18.2% of the burden). Regional disparities persisted, with high-SDI regions experiencing the largest decline in ASMR (6.5%), while low/middle-SDI regions faced rising burdens. The impact of high temperatures grew faster in these vulnerable regions. Males had higher absolute deaths and ASMR than females, and population of older adults were most vulnerable.

Conclusion: Non-optimal temperatures, particularly rising high-temperature impacts, are critical environmental risks for IHD. The accelerating high-temperature-attributable ASMR over the past decade highlights underestimated risks. Region-specific strategies addressing climatic and demographic vulnerabilities are urgently needed to mitigate future IHD burdens.

KEYWORDS

Global Burden of Disease, non-optimal temperature, ischemic heart disease, climate change, time trend

Introduction

IHD, as one of the leading global causes of morbidity and mortality, exhibits a disease burden intricately linked to diverse environmental and socioeconomic factors (1). According to the 2021 GBD, IHD has remained the foremost cause of death worldwide over the past three decades, resulting in nearly 9 million deaths in 2021 and contributing to 16% of global total mortality (2). With the advancements of medical technology and public health interventions have driven a decline in IHD ASMR in high-income countries (3). However, the burden remains persistently elevated in low- and middle-income nations, particularly those impacted by rapid urbanization, air pollution, and lifestyle transitions (4). In recent years, the escalating frequency of extreme temperature events induced by climate change has heightened global attention toward the influence of environmental temperature on cardiovascular health (5). Non-optimal temperature, defined as exposures to temperatures deviating from the human thermoneutral zone (including both heat and cold), has been progressively quantified in GBD studies as a contributor to disease burden (6). Epidemiological evidence indicates that temperature anomalies constitute a major risk factor for cardiovascular diseases, with strong associations observed for cause-specific mortality and morbidity (7, 8). Both heat and cold may trigger acute IHD events through direct or indirect mechanisms such as increased blood viscosity, blood pressure fluctuations, and exacerbated inflammatory responses (9). However, existing research has predominantly focused on the short-term health impacts of singular extreme temperature events (e.g., heatwaves or cold spells) (10), leaving a critical gap in systematic analyses of long-term temporal trends and regional heterogeneity in IHD burden attributable to varied temperature exposures (heat, cold, and non-optimal temperatures) (11).

GBD database serves as an authoritative data foundation for evaluating spatiotemporal variations in health impacts attributable to diverse risk factors (12); however its analyses of temperature-IHD associations have been predominantly confined to specific years or geographical regions with insufficient interpretation of dynamic trends across temporal intervals (13, 14). Leveraging GBD 2021 data this study presents the first systematic assessment of global regional and national-level temporal trends in IHD mortality and DALYs attributable to non-optimal temperatures while examining how population aging climate adaptation capacity and socioeconomic disparities influence disease burden distribution. The cumulative long-term effects of temperature-related IHD burdens are further elucidated through longitudinal analysis. These findings not only address critical gaps in understanding protracted temporal patterns of temperature-associated IHD but also deliver essential evidence to inform climate-resilient public health policy formulation where epidemiological insights into thermal exposure impacts are required. The analytical framework developed demonstrates how

temperature-related health burdens may be modulated by demographic transitions and adaptive capacities which could guide targeted interventions for vulnerable populations. It should be emphasized that the quantified disease burden estimates reflect interactions between environmental exposures and population vulnerability factors that were rigorously analyzed through advanced statistical modeling techniques.

Materials and methods

Study data

GBD database represents the most comprehensive epidemiological surveillance system globally and has been extensively utilized in health policy formulation and disease burden reporting across numerous studies. It estimates health losses attributable to premature mortality and non-fatal disability by quantifying disease burdens from 87 risk factors, 369 diseases and injuries, and 286 causes of death across 204 countries and territories. The risk factors encompass metabolic, behavioral, and environmental determinants (2). This investigation extracted mortality data, DALYs, ASMR, and ASDR related to IHD attributable to high temperature (based on the minimum mortality temperature benchmark, the range of hot temperatures that lead to increased risk of death), low temperature (based on the minimum mortality temperature benchmark, the range of cold temperatures that lead to increased risk of death), and non-optimal temperature (the sum of health risks from high and low temperatures) exposure from the GBD database between 1990 and 2021¹ (6, 15). SDI was employed to evaluate regional development levels through a composite metric integrating lag-distributed per capita income, average educational attainment among individuals aged ≥ 15 years, and total fertility rates for those under 25. Countries and territories were categorized into quintiles based on SDI values (ranging geometrically from 0 to 1): low (<0.46), low-middle (0.46–0.60), middle (0.61–0.69), high-middle (0.70–0.81), and high (>0.81), with elevated values indicating superior socio-demographic development (16). The methodology adheres to the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) (17), ensuring compliance with international standards for epidemiological reporting.

The temperature estimates are derived from the gridded reanalysis dataset generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) which features $0.25^\circ \times 0.25^\circ$ spatial resolution and sub-daily temporal resolution (18). This high-resolution dataset provides the foundational exposure data required for assessing temperature-related health risks. Building upon this data, the burden of IHD attributable to high, low, and non-optimal temperatures is estimated through comprehensive methodological approaches adopted in the GBD study. For the estimation of temperature-related IHD burden, the present analysis adhered to the established methodological framework of the GBD Study 2019 (15). This framework integrates high-resolution temperature exposure data with exposure-response relationships between temperature and IHD. The foundational exposure-response relationships were derived from

Abbreviations: IHD, Ischemic heart disease; GBD, Global Burden of Disease; DALYs, Disability-adjusted life years; SDI, Sociodemographic index; ASMR, Age-standardized mortality rate; ASDR, DALY rate; GATHER, the Guidelines for Accurate Transparent Health Estimates Reporting; ECMWF, European Centre for Medium-Range Weather Forecasts; MR-BRT, Meta-Regression Bayesian Regularized Trimmed Tool; AAPCs, Average annual percentage changes; CI, confidence intervals.

1 <http://ghdx.healthdata.org/gbd-results-tool>

specific regions with available epidemiological data, such as North America, Europe, and East Asia. To generalize these relationships across diverse geographical locations globally, the GBD framework employed a meta-regression framework—Meta-Regression Bayesian Regularized Trimmed Tool (MR-BRT)—and comparative risk assessment metrics (16). By incorporating country-level covariates, including the Socio-demographic Index, average temperature, and healthcare access, the core exposure-response curves were adapted and refined (16). This process is predicated on the key assumption that while the overall shape of the temperature-health relationship is similar across regions, its magnitude may be modified by the aforementioned macro-level covariates. In this study, the regionally adjusted exposure-response curves were combined with daily gridded temperature data for each unit, enabling the calculation of the IHD burden attributable to high temperature, low temperature, and non-optimal temperature.

Statistical analysis

This study employed Joinpoint regression models to estimate the uncertainty intervals (95% UI) for deaths, DALYs, ASMR, and ASDR attributable to non-optimal temperature-related IHD, which were demonstrated to depend on categorical or hierarchical variables, and the result of analysis were addressed from GBD's original models. The 95% UI represents the 2.5th and 97.5th percentiles of 1,000 draw-level estimates generated in this study for each parameter. Age-standardized rates were applied using the GBD global reference population to enable comparisons across regions and periods. Two hundred four countries and territories were categorized into 21 GBD regions based on geographical proximity and stratified into five SDI regions according to their sociodemographic index levels. The global, regional, and national burdens of temperature-variation-induced IHD from 1990 to 2021 were systematically estimated using publicly accessible GBD 2021 data (GBD Cause of Death Summaries; ICD-10 codes I20–I25). Percentage changes and average annual percentage changes (AAPCs) were utilized to assess temporal trends during this 32-year period. The AAPCs were derived in this study through Joinpoint regression modeling (Version 4.9.1.0; National Cancer Institute in Rockville, Maryland, USA) which incorporates segmented linear statistical models to objectively evaluate temporal patterns in disease burden (19, 20). This methodology was designed to overcome the inherent subjectivity of conventional linear trend analyses through implementation of least squares regression for identifying inflection points in incidence variations. The model computes the sum of squared residuals between estimated and observed values to determine optimal transition points in temporal trends.

In this study, the AAPCs and their 95% confidence intervals (CIs) for ASMR or ASDR were calculated through segmented linear regression analysis where y represents ASMR or ASDR, i denotes the slope coefficient for each segment within the projected timeframe, and w_i indicates the length of each segment. The number of joinpoints was determined through permutation tests with a default maximum of three (21). Trends were classified as increasing if both AAPCs and corresponding 95% CIs exceeded zero whereas decreasing trends were defined by AAPCs with 95% CIs below zero. Otherwise, ASMR and ASDR were considered stable. Subsequent analyses illustrated temporal patterns in IHD burden attributable to temperature

variations across different SDI regions and thermal conditions. The associations between 2021 AAPCs and country-level ASMR, ASDR, and SDI were further explored and analyzed using scatterplot smoothing techniques. Stratified analyses were conducted to identify vulnerable populations affected by high, low, and non-optimal temperatures in IHD outcomes, with subgroup evaluations based on age, sex, and SDI regional classifications. All statistical procedures were implemented in R programming language (version 4.3.2; R Core Team) using key packages including segmented (v1.6–4) for joinpoint regression and ggplot2 (v3.4.4) for visualization, with methodological rigor maintained through adherence to the Global Burden of Disease 2021 analytical framework. Notably, trends exhibiting AAPCs with 95% CIs spanning zero were interpreted as demonstrating stability rather than directional changes.

Results

The temporal trends in the global burden of IHD attributable to non-optimal temperatures from 1990 to 2021

As presented in Table 1, the global mortality attributable to non-optimal temperatures (encompassing both heat and cold exposure) for IHD exhibited an increase from 355,000 deaths (95% UI, 291,000 to 465,000) to 610,000 deaths (95% UI, 459,000 to 862,000) between 1990 and 2021, representing a 41.8% elevation. Simultaneously, DALYs associated with temperature-related IHD demonstrated growth from 772,100 (95% UI, 622,800 to 1,015,700) to 1,241,600 (95% UI, 915,900 to 1,764,000), corresponding to a 37.8% increment. The substantially larger decrease in ASDR likely reflects improvements in survival leading to longer lifespans with potential disability, alongside advancements in managing non-fatal IHD outcomes. The ASMR and age-standardized ASDR displayed declines of 3.18 and 55.91%, respectively, during this period. This epidemiological pattern indicates that demographic aging processes combined with population expansion have been recognized as predominant contributors to the observed escalation in absolute disease burden.

Regional and sociodemographic index-stratified analyse

IHD attributable to non-optimal temperatures exhibited substantial geographical heterogeneity between 1990 and 2021. Among the five SDI regions, mortality counts demonstrated divergent trends with high-SDI countries experiencing declines while the remaining four regions showed increases (Table 1; Figures 1A–C). Notably, low- and low-middle SDI nations displayed pronounced mortality growth under high-temperature conditions. ASMR revealed distinct temporal patterns across SDI quintiles (Table 1; Figures 1D–F). Low-SDI countries exhibited marginal ASMR increases from 6.35% (95% UI, 4.02–9.13) to 6.41% (95% UI, 4.17–9.00) with AAPC 0.04 (95% CI, −1.78–1.89), while low-middle SDI regions showed more marked elevation from 9.00% (5.48–12.90) to 9.53% (5.74–14.23) with AAPC 0.23 (−1.47–1.95). The absolute mortality surge of 64.1% in low-middle SDI countries

TABLE 1 The deaths and ASMR of IHD attributed to non-optimal temperatures in 1990 and 2021, and its temporal trends from 1990 to 2021.

Characteristics	1990		2021		1990–2021 AAPCs No.(95% CI)
	Deaths No. × 10 ³ (95% UI)	ASMR No. (95% UI)	Deaths No. × 10 ³ (95% UI)	ASMR No. (95% UI)	
Global	355.69 (291.4, 465.06)	10.57 (8.63, 13.74)	610.52 (459.42, 862.75)	7.39 (5.57, 10.44)	−1.20 (−2.07, −0.33)
Sex					
Female	170.01 (137.75, 220.71)	8.95 (7.26, 11.57)	270.73 (203.91, 380.65)	5.79 (4.35, 8.14)	−1.46 (−2.30, −0.61)
Male	185.68 (150.37, 244.73)	12.50 (10.22, 16.41)	339.80 (255.30, 473.53)	9.33 (7.05, 12.98)	−0.99 (−1.88, −0.09)
Temperature					
High	32.57 (−0.68, 86.63)	0.90 (−0.03, 2.46)	112.40 (17.05, 256.43)	1.34 (0.20, 3.07)	1.29 (−1.61, 4.27)
Low	325.85 (285.69, 387.32)	9.74 (8.52, 11.60)	505.30 (432.02, 619.92)	6.14 (5.23, 7.53)	−1.48 (−2.42, −0.54)
SDI level					
Low SDI	12.35 (7.84, 17.92)	6.35 (4.02, 9.13)	27.32 (17.63, 38.69)	6.41 (4.17, 9.00)	0.04 (−1.78, 1.89)
Low-middle SDI	47.96 (28.87, 68.70)	9.00 (5.48, 12.90)	124.31 (74.28, 186.37)	9.53 (5.74, 14.23)	0.23 (−1.47, 1.95)
Middle SDI	65.83 (48.10, 88.91)	8.06 (5.83, 10.80)	184.32 (137.99, 251.71)	7.85 (5.93, 10.74)	−0.10(−1.00, 0.81)
High-middle SDI	111.04 (96.12, 141.41)	13.43 (11.58, 17.12)	241.84 (140.20, 241.84)	9.07 (7.30, 12.61)	−1.43 (−2.41, −0.43)
High SDI	118.03 (100.41, 154.88)	10.75 (9.12, 14.12)	99.83 (79.89, 136.20)	4.25 (3.43, 5.82)	−3.05 (−4.18, −1.91)
Super region					
Central Europe, eastern Europe, and central Asia	84.40 (75.18, 108.44)	20.20 (17.88, 25.98)	100.73 (83.99, 137.26)	15.27 (12.73, 20.81)	−0.98(−2.13, 0.18)
Latin American and Caribbean	9.29 (7.51, 11.45)	4.85 (3.90, 5.95)	19.15 (16.19, 22.87)	3.19 (2.69, 3.81)	−1.42 (−3.26, 0.46)
North Africa and Middle East	35.32 (24.16, 50.52)	5.26 (17.37, 35.90)	73.54 (49.93, 111.85)	19.25 (13.23, 28.87)	−0.83 (−2.15, 0.50)
Southeast Asia, east Asia, and Oceania	49.22 (37.26, 66.45)	5.8 (4.35, 7.90)	168.791 (127.25, 234.43)	7.17 (5.41, 10.03)	0.55 (−0.60, 1.72)
Sub-Saharan Africa	5.47 (3.09, 7.81)	3.18 (1.79, 4.58)	11.63 (8.55, 15.70)	3.07 (2.28, 4.19)	−0.11 (−1.57, 1.38)
South Asia	49.03 (26.28, 71.94)	9.56 (5.08, 14.12)	144.16 (78.93, 211.40)	10.70 (5.88, 15.64)	0.33 (−1.99, 2.71)
High income	111.04 (96.12, 141.41)	13.43 (11.58, 17.12)	92.53 (73.74, 119.99)	3.62 (2.95, 4.70)	−3.40 (−4.48, −2.31)

No., number; UI, uncertainty interval; CI, confidential interval; ASMR, Age-standardized mortality rate (per 100,000); AAPCs, average annual percentage change; SDI, Socio-demographic index.

substantially exceeded global averages. Contrastingly, middle-, high-middle-, and high-SDI regions demonstrated declining trends: middle SDI [8.06% (5.83–10.80) to 7.85% (5.93–10.74); AAPC −0.10 (−1.47–1.95)], high-middle SDI [13.43% (11.58–17.12) to 9.07% (7.30–12.61); AAPC −1.43 (−2.41–0.43)], and high SDI [10.75% (9.12–14.12) to 4.25% (3.43–5.82); AAPC −3.05 (−4.18–1.91)]. The health inequality analysis results demonstrated in Figure 2 reveal that the concentration index (CII) (quantify indicators of the concentration of health burdens associated with socioeconomic status) of (DALYs) per 100,000 population attributable to non-optimal temperatures was 0.14 (0.05, 0.21) in 1990 and 0.03 (−0.05, 0.11) in 2021, indicating that the disparity in IHD burden between high-income and low-income countries was substantially reduced throughout the 1990–2021 observation period. This progressive narrowing of health inequality gap was evidenced by the CII approaching statistical neutrality over the three decades, suggesting improved equity in temperature-related cardiovascular health outcomes across nations with varying socioeconomic statuses. At the super-regional level in 2021, Central-Eastern Europe and Central Asia recorded the highest ASMR whereas sub-Saharan Africa and Latin America showed the lowest (Figure 3A). South Asia, Southeast Asia, East Asia, and

Oceania were identified as regions with rising AAPC trends (Table 1). Frontier analyses delineated the evolving relationship between SDI and ASDR across development levels (Figures 3B, 4A,B). An inverse pattern emerged where high-SDI (>0.85) countries like Canada and Norway experienced ASDR increases while low-SDI (<0.50) nations such as Gambia and Togo demonstrated reductions. These findings suggest greater potential for burden mitigation in higher-SDI regions despite their current epidemiological advantages. The data collectively underscore critical interactions between socioeconomic development, environmental exposures, and cardiovascular health outcomes. The widening health disparities and divergent mortality trends emphasize the necessity for context-specific public health interventions that account for regional climate vulnerabilities and healthcare infrastructure capacities.

IHD burden attributable to non-optimal temperature by age and gender

Figure 5 demonstrates the age-period-cohort effects of global IHD deaths attributable to non-optimal temperatures, indicating

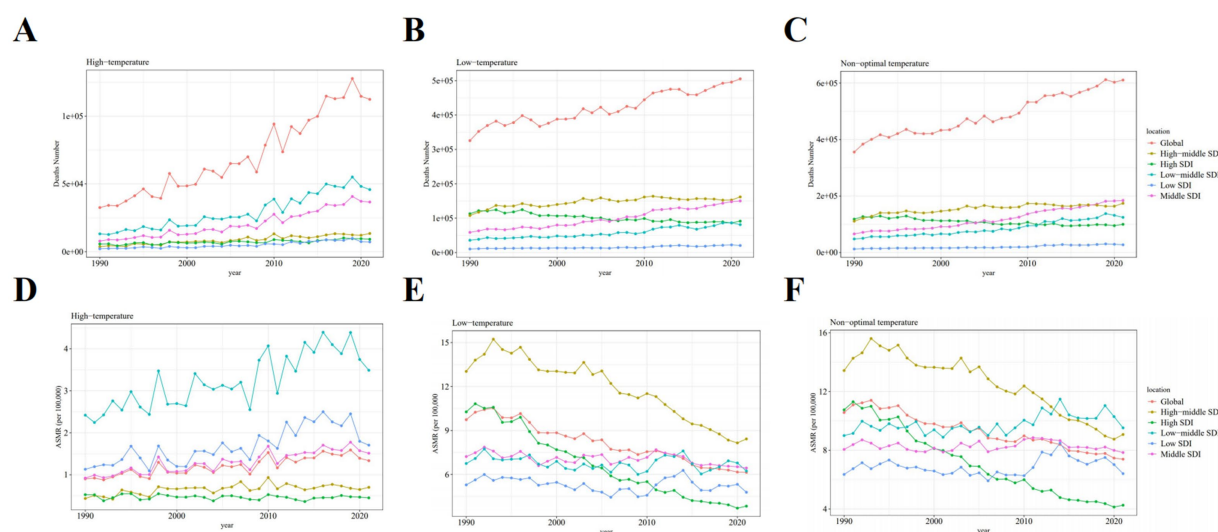


FIGURE 1

Trends in IHD deaths attributable to high, low, and non-optimal temperatures globally and across SDI-specific regions from 1990 to 2019. (A,D) High temperature. (B,E) Low temperature. (C,F) Non-optimal temperature. ASMR, age-standardized mortality rate. SDI, sociodemographic index.

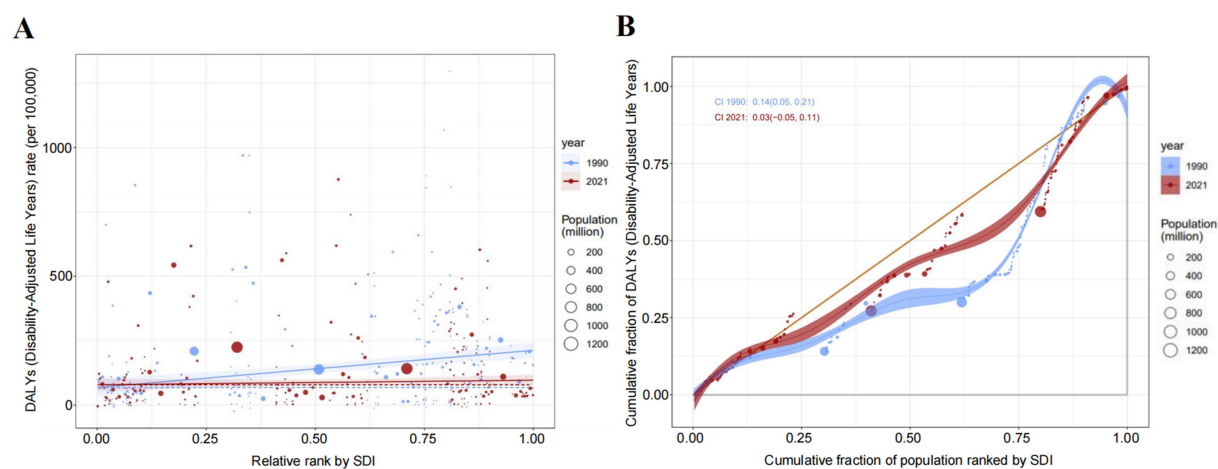
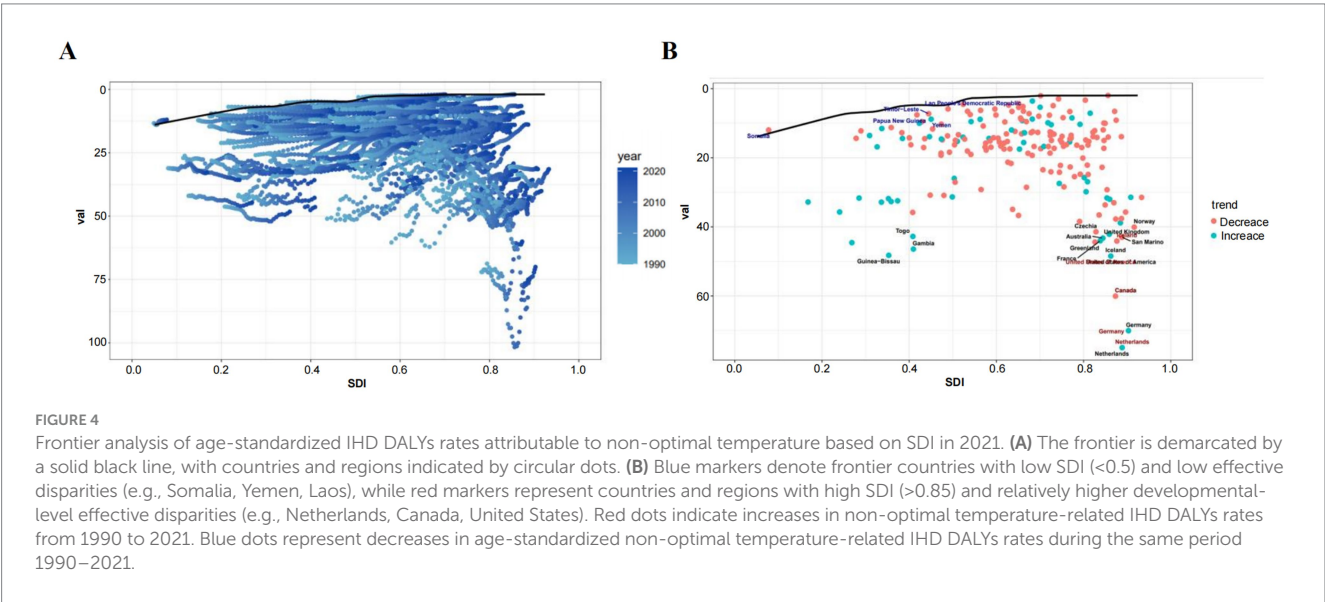
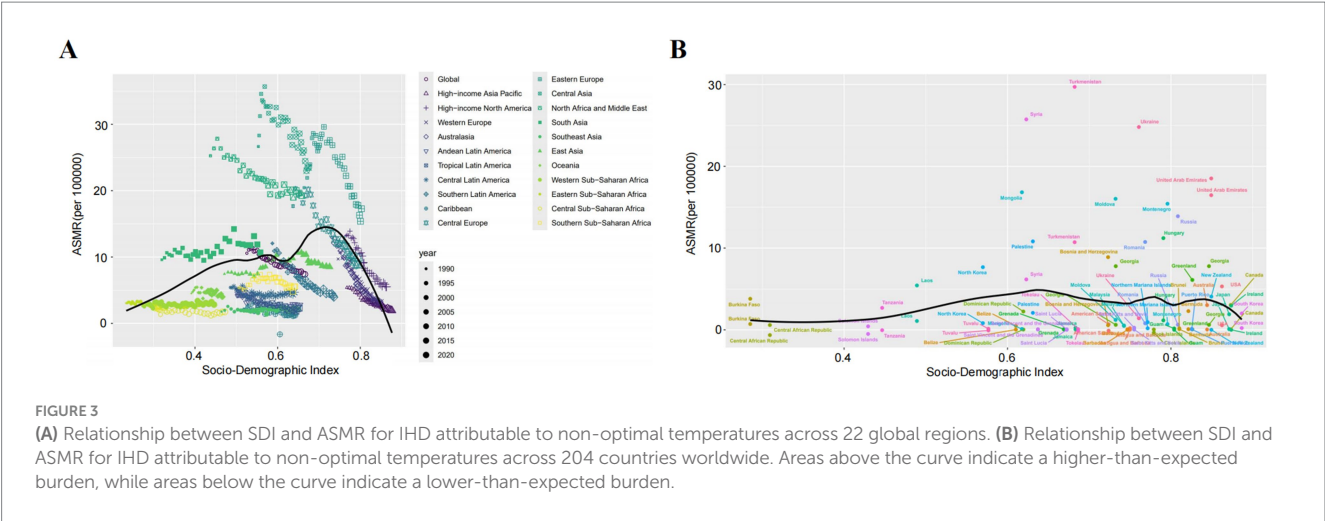


FIGURE 2

Health inequality analysis. Regression lines presenting income-related health inequalities in the burden of IHD attributable to non-optimal temperatures from 1990 to 2021. (A) Absolute inequality analysis; (B) Relative inequality analysis.

that IHD mortality rates initially increase with age before subsequently declining. As illustrated in Figure 6 the mortality counts for males and females exhibited progressive escalation across age strata reaching peak values in the 85–89 age group. A notable mortality reduction was observed specifically in males aged 75–79 years. The ASMR displayed exponential growth with advancing age while maintaining consistently higher values in males compared to females (Figures 6A,B). Regarding DALYs the maximum burden occurred earlier in the 65–69 age group for both genders with the age-standardized ASMR demonstrating an incremental pattern associated with aging (Figures 6C,D). A critical

observation reveals that beyond 79 years the ASMR for both sexes undergoes dramatic acceleration suggesting population of older adults bear the predominant burden of temperature-related IHD morbidity. Joinpoint regression analysis indicates an overall downward trend in ASMR for non-optimal temperature-attributable IHD from 1990 to 2021 with male AAPC estimated at -0.99 (95% CI, -1.88 to -0.09) and female AAPC at -1.46 (95% CI, -2.30 to -0.61). Despite these temporal reductions male subjects consistently exhibited higher absolute mortality counts and ASMR values throughout the observation period compared to their female counterparts (Figures 7A–C).



Differences in IHD disease burden by temperature type

As shown in Table 1, substantial increases in IHD deaths and DALYs attributable to high temperature, low temperature, and non-optimal temperature were observed between 1990 and 2019. The mortality and DALYs induced by low-temperature exposure consistently exceeded those associated with high temperatures throughout this period. Notably however, the ASMR related to high temperature demonstrated an accelerated upward trend during the past decade. At the SDI regional level, middle-low income countries exhibited more pronounced increases in both absolute high temperature-related IHD deaths and ASMR compared to middle-high income nations (Table 1; Figures 1A, 7D) with the disparities being particularly marked in mortality statistics. Although high-income countries maintained the highest absolute low temperature-attributable IHD mortality, the ASMR across all five SDI regions displayed consistent downward trajectories (Table 1; Figures 7E,F) indicating a progressive decline

in the impact of low temperature on IHD disease burden. The epidemiological transition pattern reveals that middle-low income countries are experiencing disproportionately elevated climate-related cardiovascular risks particularly from heat exposure whereas cold-related burdens show gradual mitigation across socioeconomic strata. This divergence underscores the emerging public health challenge posed by global warming in vulnerable populations despite ongoing reductions in cold-associated mortality burden (see Figure 8).

Discussion

This study, based on GBD data, comprehensively assessed the long-term effects and dynamic trends of non-optimal temperatures (i.e., exposure to environments that deviate from the optimal temperature range) on the burden of IHD globally between 1990 and 2021. Previous studies, such as Wei et al. (22), showed an upward trend in IHD due to non-optimal temperatures, but this study revealed that,

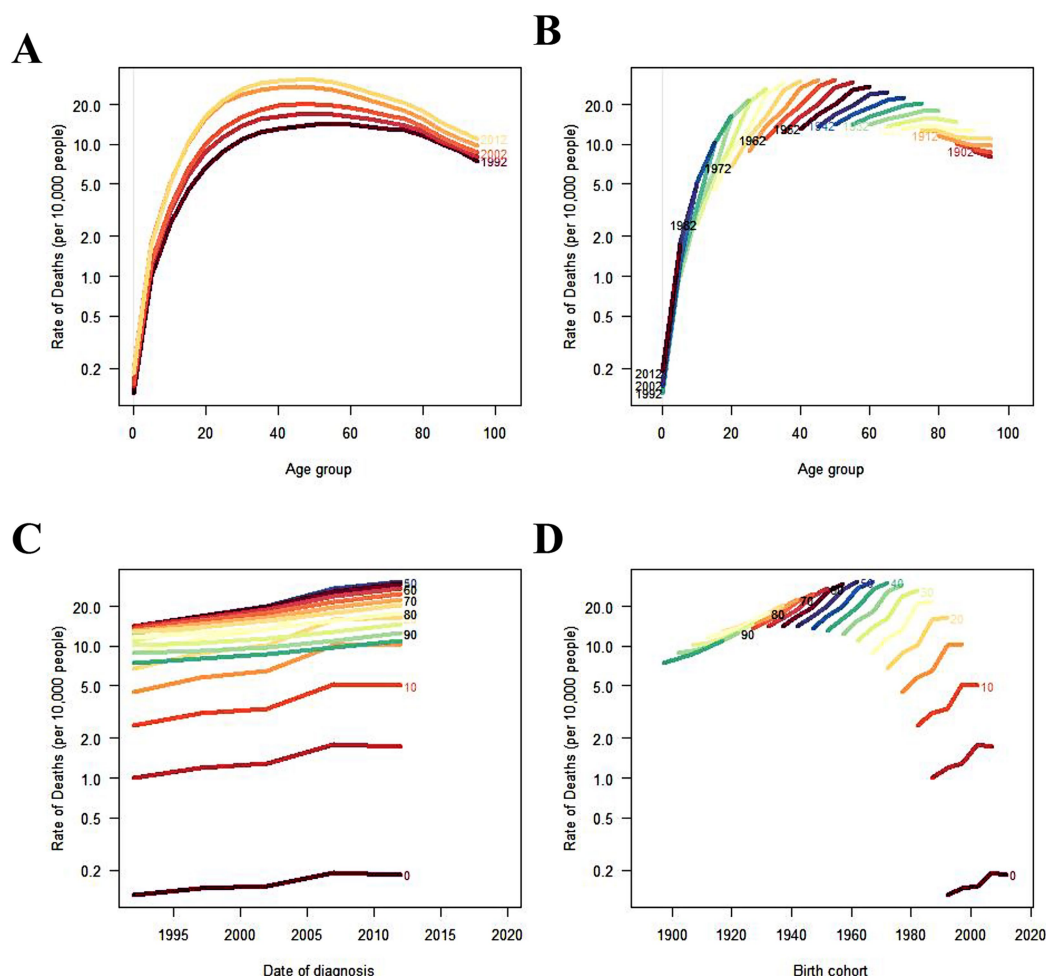


FIGURE 5

Trends of age-specific, period-based and cohort-based variation of IHD mortality attributable to non-optimal temperatures globally. (A,B) IHD mortality across different age groups. (C) Period-based IHD mortality rates. (D) Cohort-based IHD mortality rates.

over the past decade, age-standardized mortality rates associated with IHD caused by non-optimal temperatures have declined, although the burden remains significant. Non-optimal temperatures may exacerbate the global health inequality associated with cardiovascular diseases, thereby increasing the burden of IHD worldwide. The IHD-related deaths and DALYs caused by non-optimal temperatures account for 18.2% (95% UI, 14.6 to 21.8%) of the global burden, with considerable differences in trends and severity across regions and countries. Specifically, the death burden caused by low temperatures is significantly higher than that caused by high temperatures, which is consistent with previous research (23). However, this study found that the age-standardized mortality rate associated with high temperatures has accelerated over the past decade, which differs significantly from previous studies (24). Gasparrini et al.'s (7) team, based on multi-country data, found that the relative risk of cardiovascular disease due to low temperatures is higher than that due to high temperatures, but they did not specifically distinguish the specific impact of temperature types on IHD. This study, through integrating climate zoning models and GBD data, revealed the individual impacts of high, low, and non-optimal temperatures as independent risk factors on the burden

of IHD. Moreover, this study extended the time-trend analysis to the period following the COVID-19 pandemic (2020–2021), revealing that the increase in IHD mortality associated with high temperatures in middle and low-income countries was 1.3 times that of 2010–2019, suggesting that the interaction between climate change and the vulnerability of health systems may exacerbate the global inequality of disease burden.

Most early studies primarily focused on the acute health effects of extreme temperature events while underestimating the cumulative impacts of persistent non-optimal temperature deviations below extreme threshold (25). This study revealed that non-extreme heat exposure (daily mean temperatures exceeding regional optimal thresholds without reaching extreme levels) accounted for 64.2% of heat-related IHD mortality burden with its annual growth rate surpassing that of extreme heat events. The long-term cumulative effects of non-optimal temperatures on IHD have been substantially underestimated which challenges conventional public health strategies centered on extreme events and highlights the necessity to shift prevention priorities toward continuous temperature deviation monitoring. A pronounced gender disparity in temperature-related IHD mortality burden was identified with males exhibiting higher vulnerability than females across all thermal

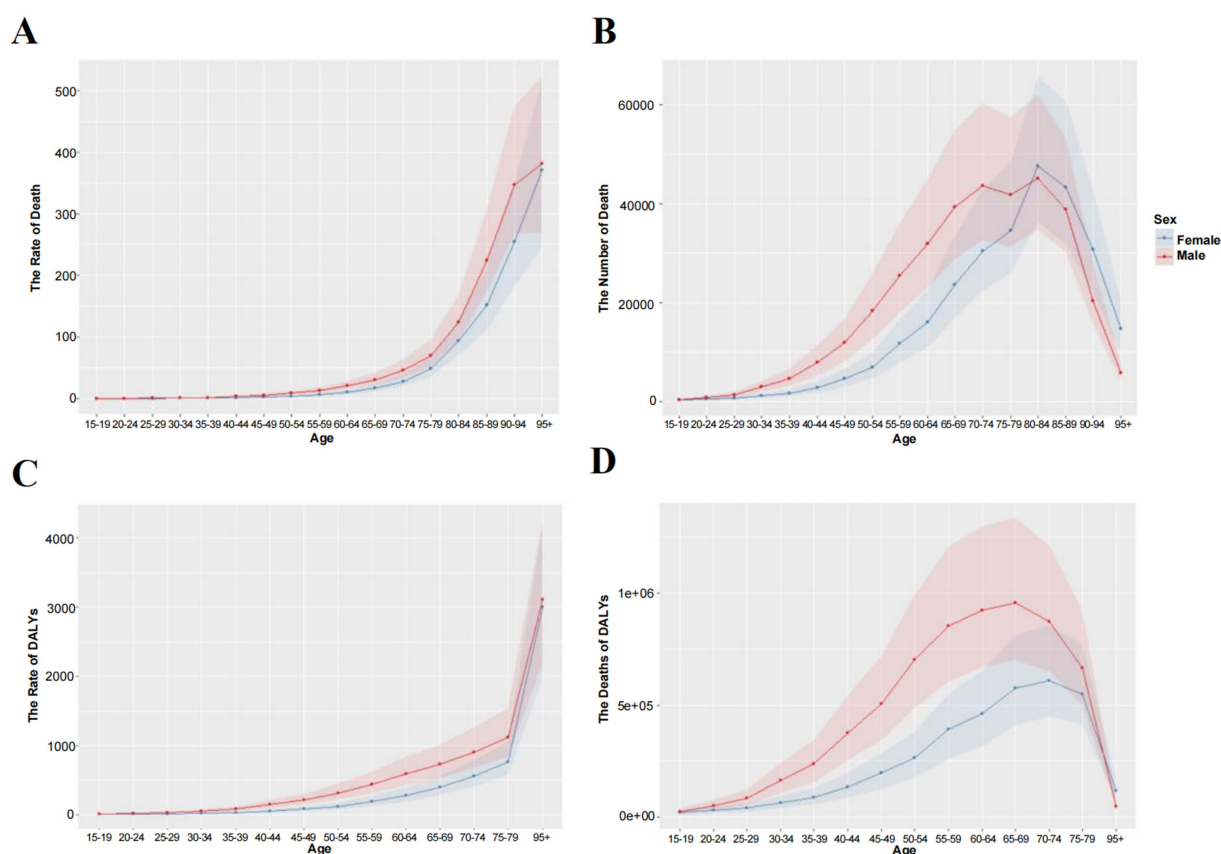


FIGURE 6

Line chart. Global age-specific mortality and deaths from IHD attributable to non-optimal temperatures in 2021. (A) Age-specific mortality rate. (B) Age-specific death count. (C) Number of DALYs. (D) DALY rate.

exposures (heat cold and non-optimal temperatures). From 1990 to 2021 the annual average percentage change in ASMR of cardiovascular diseases demonstrated greater decline among females across all age groups aligning with previous observations (26). These differential outcomes may stem from variations in thermoregulatory capacity physiological responses and socioeconomic or cultural determinants as hypothesized by researchers (24). Population of older adults showed heightened susceptibility to non-optimal temperature exposure compared to younger adults consistent with findings from Chen et al.'s (27) research. Notably the population of people over 80 years old exhibited significantly higher mortality among females than males warranting further investigation through prospective studies. The temperature-related IHD burden displayed substantial heterogeneity across SDI regions with high-SDI areas demonstrating greater absolute mortality despite middle-income countries showing escalating annual death counts particularly in heat-attributable IHD mortality within low-middle SDI nations. Investigations by Guo et al. (28). Romanello et al. (29) suggested that most low-to-middle SDI countries situated in tropical/subtropical zones experience intensified heat impacts compounded by occupational exposures in agriculture and construction sectors prevalent among their populations. Geographically Southeast Asia Eastern Europe and Sub-Saharan Africa bore heavier burdens from extreme temperature exposures whereas South Asia's substantial population base resulted in the highest absolute burden. Frontier analyses indicated marked disparities in 2021 DALYs burden across SDI regions with higher-SDI areas demonstrating greater potential

for burden reduction through improved healthcare accessibility. This threshold effect of medical resource availability on temperature-related health risks provides empirical justification for prioritizing primary healthcare system enhancements in low-middle income countries (6).

While this study addresses the critical gap in investigating long-term trends of temperature-related IHD burden, several limitations warrant acknowledgment. (1) the spatiotemporal resolution of exposure assessment remains constrained (30). Although GBD 2021 employed $0.5^\circ \times 0.5^\circ$ gridded climate data, microenvironmental temperature exposures at the individual level—including indoor occupational conditions and air conditioning prevalence—were not fully captured, which might lead to underestimation of risks among high-risk occupational populations such as outdoor workers. (2) residual confounding effects persist despite the GBD model's adjustment for covariates such as age, gender, and socioeconomic status. Other temperature-associated environmental covariates (e.g., air pollution and humidity) or behavioral factors (e.g., dietary patterns and physical activity levels) might not have been sufficiently controlled (31, 32), potentially compromising the reliability of causal inferences. (3) while the findings emphasize global and regional trends, they lack granular analysis of differential risk profiles among subnational vulnerable populations including aging communities and low-income groups (33, 34). Future research directions should prioritize the following aspects. (1) Climate-health integrated prediction models should be developed by synthesizing climate scenarios from the IPCC

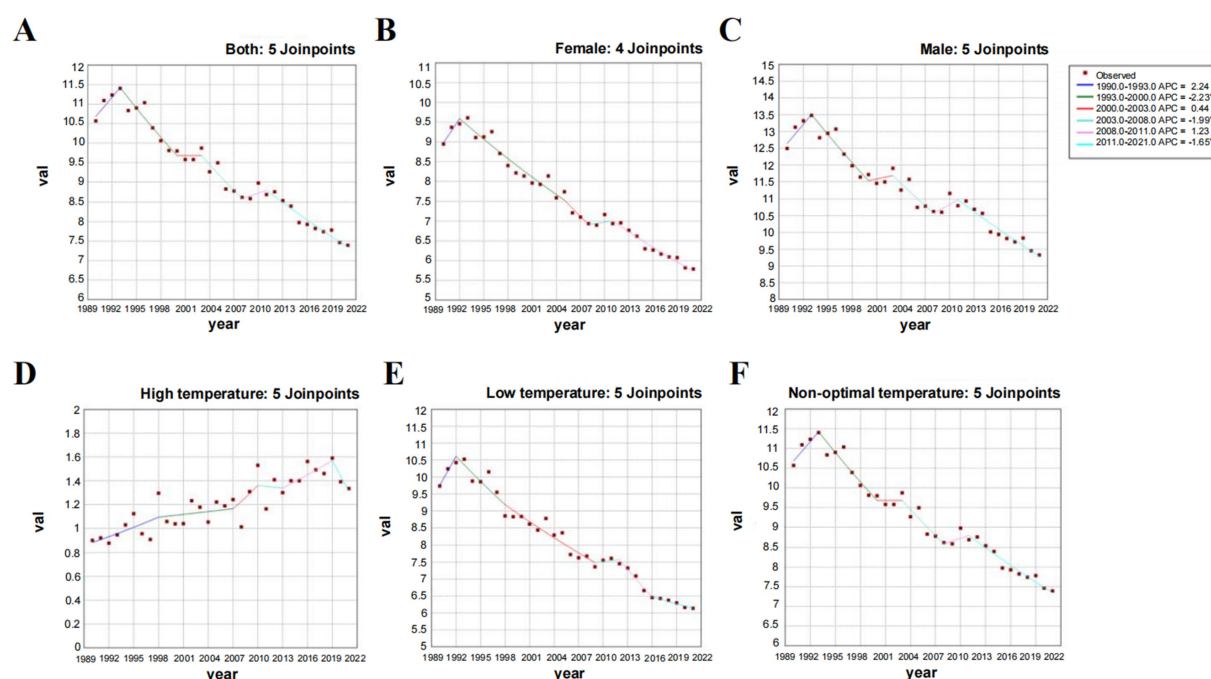


FIGURE 7

(A–C) Joinpoint regression analysis of global age-standardized mortality rates from IHD attributed to non-optimal temperatures by gender (1990–2021): (A) Overall. (B) Female. (C) Male. (D–F) Joinpoint regression analysis of global age-standardized mortality rates from IHD attributed to high temperature, low temperature, and non-optimal temperatures (1990–2021): (D) High temperature. (E) Low temperature. (F) Non-optimal temperatures.

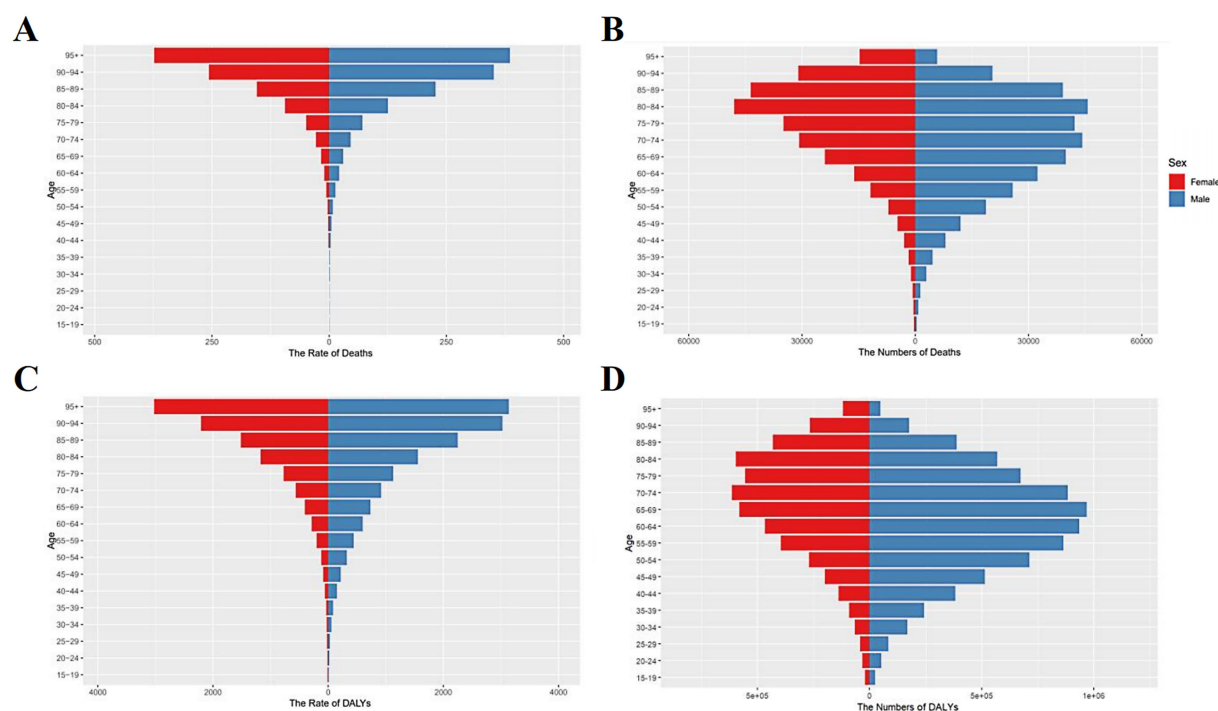


FIGURE 8

Dual-axis chart. Global burden count and proportion of IHD attributable to non-optimal temperatures by sex and age in 2021. (A) Death count. (B) Death rate. (C) DALYs number; (D) DALY rate.

Sixth Assessment Report (AR6) with demographic projections to simulate spatiotemporal evolution patterns of IHD burden under diverse warming pathways (35). (2) The robustness of findings could be enhanced through systematic implementation of stratified analyses and multivariate regression models to mitigate confounding biases (36). (3) Regionally tailored interventions targeting special populations must be advanced, exemplified by pilot programs integrating heat-health early warning systems with primary care infrastructure. Such initiatives involving regional surveillance mechanisms and prospective health adaptation frameworks may facilitate targeted risk mitigation among vulnerable subgroups (29, 37). Targeted interventions—such as through targeted social care policies to protect the population of older adults, in order to enhance healthcare resilience and reduce temperature-related IHD mortality and disability rates, especially in severely affected regions and population groups.

Conclusion

In summary, a significant association has been identified between non-optimal temperatures and IHD burden from 1990 to 2021. Globally, the burden of IHD attributable to non-optimal temperatures has exhibited complex temporal trends which pose a non-negligible threat to public health systems. Vulnerable populations particularly in low- and middle-income countries as well as older adults are disproportionately affected, with this environmental health challenge exacerbating existing strains on already overstretched healthcare resources and socioeconomic development in these regions. Future efforts must prioritize the translation of epidemiological evidence into actionable public health practices within an interdisciplinary framework to address the persistent threat posed by climate change to cardiovascular health. Multisectoral interventions should be urgently implemented to strengthen healthcare resilience and protect susceptible populations from temperature-related IHD mortality and disability.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repository and accession number(s) can be found in the article/supplementary material.

Author contributions

LC: Data curation, Investigation, Methodology, Writing – original draft. YJ: Conceptualization, Formal analysis, Investigation, Writing – review & editing. JW: Software, Validation, Visualization, Writing – original draft. ZW: Writing – review & editing. TP: Methodology,

Software, Supervision, Writing – review & editing. GL: Funding acquisition, Project administration, Writing-review & editing. QL: Writing – review & editing. ML: Funding acquisition, Project administration, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the National Natural Science Foundation of China (No. 82074378), the Project of Science & Technology Department of Sichuan Province (No. 2022YFS0618), Project of Office of Science & Technology and talent work of Luzhou (Nos. 2023JYJ029 and 2022JYJ104) and the Project of Southwest Medical University (Nos. 2023XGZX009, 2023ZYYQ04 and 2024ZKZ007).

Acknowledgments

Thanks to the Global Burden of Disease (GBD) database for providing the data that made this research possible.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

1. Roth GA, Mensah GA, Johnson CO, Addolorato G, Ammirati E, Baddour LM, et al. Global burden of cardiovascular diseases and risk factors, 1990–2019. *J Am Coll Cardiol.* (2020) 76:2982–3021. doi: 10.1016/j.jacc.2020.11.010
2. Naghavi M, Ong KL, Aali A, Ababneh HS, Abate YH, Abbafati C, et al. Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990–2021: a systematic analysis for the global burden of disease study 2021. *Lancet.* (2024) 403:2100–32. doi: 10.1016/S0140-6736(24)00367-2
3. Leong DP, Joseph PG, McKee M, Anand SS, Teo KK, Schwalm J-D, et al. Reducing the global burden of cardiovascular disease, part 2: prevention and treatment of cardiovascular disease. *Circ Res.* (2017) 121:695–710. doi: 10.1161/CIRCRESAHA.117.311849

4. Yusuf S, Reddy S, Ôunpuu S, Anand S. Global burden of cardiovascular diseases: part I: general considerations, the epidemiologic transition, risk factors, and impact of urbanization. *Circulation*. (2001) 104:2746–53. doi: 10.1161/hc4601.099487
5. Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, Errett NA, et al. Extreme weather and climate change: population health and health system implications. *Annu Rev Public Health*. (2021) 42:293–315. doi: 10.1146/annurev-publhealth-012420-105026
6. Zhao Q, Guo Y, Ye T, Gasparrini A, Tong S, Overcenco A, et al. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *Lancet Planet Health*. (2021) 5:e415–25. doi: 10.1016/S2542-5196(21)00081-4
7. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*. (2015) 386:369–75. doi: 10.1016/S0140-6736(14)62114-0
8. Vicedo-Cabrera AM, Scovronick N, Sera F, Royé D, Schneider R, Tobias A, et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat Clim Chang*. (2021) 11:492–500. doi: 10.1038/s41558-021-01058-x
9. Bhaskaran K, Hajat S, Haines A, Herrett E, Wilkinson P, Smeeth L. Effects of ambient temperature on the incidence of myocardial infarction. *Heart*. (2009) 95:1760–9. doi: 10.1136/hrt.2009.175000
10. Benmarhnia T, Sottille M-F, Plante C, Brand A, Casati B, Fournier M, et al. Variability in temperature-related mortality projections under climate change. *Environ Health Perspect*. (2014) 122:1293–8. doi: 10.1289/ehp.1306954
11. Madrigano J, Mittleman MA, Baccarelli A, Goldberg R, Melly S, Von Klot S, et al. Temperature, myocardial infarction, and mortality: effect modification by individual- and area-level characteristics. *Epidemiology*. (2013) 24:439–46. doi: 10.1097/EDE.0b013e3182878397
12. Feigin VL, Stark BA, Johnson CO, Roth GA, Bisignano C, Abady GG, et al. Global, regional, and national burden of stroke and its risk factors, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet Neurol*. (2021) 20:795–820. doi: 10.1016/S1474-4422(21)00252-0
13. Gasparrini A, Guo Y, Hashizume M, Kinney PL, Petkova EP, Lavigne E, et al. Temporal variation in heat-mortality associations: a multicountry study. *Environ Health Perspect*. (2015) 123:1200–7. doi: 10.1289/ehp.1409070
14. Vicedo-Cabrera AM, Guo Y, Sera F, Huber V, Schleussner C-F, Mitchell D, et al. Temperature-related mortality impacts under and beyond Paris agreement climate change scenarios. *Clim Chang*. (2018) 150:391–402. doi: 10.1007/s10584-018-2274-3
15. GBD 2019 Meningitis Antimicrobial Resistance Collaborators. Global, regional, and national burden of meningitis and its aetiologies, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet Neurol*. (2023) 22:685–711. doi: 10.1016/S1474-4422(23)00195-3
16. Vos T, Lim SS, Abbafati C, Abbas KM, Abbasi M, Abbasifard M, et al. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet*. (2020) 396:1204–22. doi: 10.1016/S0140-6736(20)30925-9
17. Stevens GA, Alkema L, Black RE, Boerma JT, Collins GS, Ezzati M, et al. Guidelines for accurate and transparent health estimates reporting: the GATHER statement. *PLoS Med*. (2016) 13:e1002056. doi: 10.1371/journal.pmed.1002056
18. Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, et al. The ERA5 global reanalysis. *Q J R Meteorol Soc*. (2020) 146:1999–2049. doi: 10.1002/qj.3803
19. Kim H-J, Fay MP, Feuer EJ, Midthune DN. Permutation tests for joinpoint regression with applications to cancer rates. *Stat Med*. (2000) 19:335–51. doi: 10.1002/(sici)1097-0258(20000215)19:3<335::aid-sim336>3.0.co;2-z
20. Clegg LX, Hankey BF, Tiwari R, Feuer EJ, Edwards BK. Estimating average annual per cent change in trend analysis. *Stat Med*. (2009) 28:3670–82. doi: 10.1002/sim.3733
21. Tang LL, Chen WQ, Xue WQ, He YQ, Zheng RS, Zeng YX, et al. Global trends in incidence and mortality of nasopharyngeal carcinoma. *Cancer Lett*. (2016) 374:22–30. doi: 10.1016/j.canlet.2016.01.040
22. Wei J, Wang P, Xia F, Miao J, Zhou X, Yang Z, et al. Time trends in cardiovascular disease mortality attributable to non-optimal temperatures in China: an age-period-cohort analysis using the global burden of disease study 2019. *Front Public Health*. (2023) 10:1075551. doi: 10.3389/fpubh.2022.1075551
23. Xu C, Nie X, Xu R, Han G, Wang D. Burden trends and future predictions for hypertensive heart disease attributable to non-optimal temperatures in the older adults amidst climate change, 1990–2021. *Front Public Health*. (2025) 12:1525357. doi: 10.3389/fpubh.2024.1525357
24. Li X, Liu Z, Xie J, Shao H, Xia R, Li Y, et al. Global, regional, and national temporal trends in mortality and disability-adjusted life years for cardiovascular disease attributable to low temperature during 1990–2019: an age-period-cohort analysis of the global burden of disease 2019 study. *Front Public Health*. (2024) 12:1414979. doi: 10.3389/fpubh.2024.1414979
25. Guo Y, Gasparrini A, Armstrong B, Li S, Tawatsupa B, Tobias A, et al. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. *Epidemiology*. (2014) 25:781–789. doi: 10.1097/EDE.0000000000000165
26. EUGenMed, Cardiovascular Clinical Study Group. Gender in cardiovascular diseases: impact on clinical manifestations, management, and outcomes. *Eur Heart J*. (2016) 37:24–34. doi: 10.1093/eurheartj/ehv598
27. Chen R, Yin P, Wang L, Liu C, Niu Y, Wang W, et al. Association between ambient temperature and mortality risk and burden: time series study in 272 main Chinese cities. *BMJ*. (2018) 363:k4306. doi: 10.1136/bmj.k4306
28. Guo Y, Gasparrini A, Armstrong BG, Tawatsupa B, Tobias A, Lavigne E, et al. Temperature variability and mortality: a multi-country study. *Environ Health Perspect*. (2016) 124:1554–9. doi: 10.1289/EHP149
29. Romanello M, McGushin A, Di Napoli C, Drummond P, Hughes N, Jamart L, et al. The 2021 report of the lancet countdown on health and climate change: code red for a healthy future. *Lancet*. (2021) 398:1619–62. doi: 10.1016/S0140-6736(21)01787-6
30. Burkart KG, Brauer M, Aravkin AY, Godwin WW, Hay SI, He J, et al. Estimating the cause-specific relative risks of non-optimal temperature on daily mortality: a two-part modelling approach applied to the global burden of disease study. *Lancet*. (2021) 398:685–97. doi: 10.1016/S0140-6736(21)01700-1
31. Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015. *Lancet*. (2017) 389:1907–18. doi: 10.1016/S0140-6736(17)30505-6
32. Wu Y, Feng X, Li J, Li M, Wang Y, Lu W, et al. Exposure to high-temperature and high-humidity environments associated with cardiovascular mortality. *Ecotoxicol Environ Saf*. (2025) 290:117746. doi: 10.1016/j.ecoenv.2025.117746
33. Gronlund CJ. Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Curr Epidemiol Rep*. (2014) 1:165–73. doi: 10.1007/s40471-014-0014-4
34. Haines A, Ebi K. The imperative for climate action to protect health. *N Engl J Med*. (2019) 380:263–73. doi: 10.1056/NEJMra1807873
35. Gasparrini A, Guo Y, Sera F, Vicedo-Cabrera AM, Huber V, Tong S, et al. Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet Health*. (2017) 1:e360–7. doi: 10.1016/S2542-5196(17)30156-0
36. Haire-Joshu D, Hill-Briggs F. The next generation of diabetes translation: A path to health equity. *Annu Rev Public Health*. (2019) 40:391–410. doi: 10.1146/annurev-publhealth-040218-044158
37. Hess JJ, Lm S, Knowlton K, Saha S, Dutta P, Ganguly P, et al. Building resilience to climate change: pilot evaluation of the impact of India's first heat action plan on all-cause mortality. *J Environ Public Health*. (2018) 2018:1–8. doi: 10.1155/2018/7973519