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Associations between monthly temperature anomalies and mortality among children younger than five years in low- and middle-income countries

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Abstract

Background This study examined associations between anomalous temperatures and under-five mortality (U5M) in low- and middle-income countries (LMICs).

Methods Between 1998 and 2019, data were collected on 1,745,132 live births across 56 LMICs. The median age was 27.0 months (interquartile range: 12.0, 43.0), and 51.0% were male. Monthly temperature anomalies were calculated as deviations from the long-term average temperature for the same calendar months. We developed a two-dimensional exposure-response function (ERF) based on a varying-coefficient model to examine the relationship between U5M and both long-term average temperatures and anomalous temperatures.

Results Here we show, in the multicenter model, each 1 °C increase in positive temperature anomalies or decrease in negative temperature anomalies is associated with an 8% (95% confidence interval [CI]: 6%, 11%) or 2% (95% CI: -1%, 4%) excess risk of U5M, respectively. The two-dimensional ERF reveals considerable heterogeneity in the impact of anomalous temperatures on U5M across different temperature zones. Positive temperature anomalies pose a significant hazard to children in warm and hot zones, whereas negative anomalies are primarily hazardous in cold zones but appear protective in hot zones. The sibling-matched model demonstrates nonlinear and heterogeneous effect estimates consistent with the multicenter model findings.

Conclusions Anomalous temperatures of both heat and cold are associated with an increased risk of child mortality in LMICs, with the effect varying by temperature zone, reflecting the adaptive capacity of populations to local climates. There is an urgent need to develop regionally adaptive strategies to protect child health amid global climate change.

Plain language summary

Climate change is making weather more unstable, especially with unusual changes in temperature. These changes can be harmful to children's health. While we already know that short-term exposure to very hot or cold weather can increase the risk of death in children, we know less about the effects of longer-lasting unusual temperatures. In this study, we looked at how abnormal temperature changes affect child deaths in low- and middle-income countries. We found that both unusual heat and cold can raise the risk of children dying, and the impact is different in each region depending on the local climate. This means we need climate-based health plans that are tailored to different regions to better protect children's health.

Climate change is increasingly recognized as a major public health concern, significantly impacting survival rates worldwide¹. It is estimated that climate change has displaced approximately 600 million people beyond the human climate niche, with projections indicating that up to 3 billion people may live outside the ideal temperature range by the end of this century². From 2013 to

2022, the global 10-year mean temperature rose to 1.14 °C above pre-industrial levels¹. Recent estimates suggest that around 1.9 million (95% confidence interval [CI]: 1.7, 2.2 million) premature deaths could be attributed to exposure to non-optimal temperatures globally³. The accelerating pace of global warming has led to unprecedented changes in the

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intensity and variability of temperature exposure⁴, with increasingly frequent reports of extreme temperature events across many regions⁵.

Growing evidence has linked exposure to non-optimal temperatures with increased risks of morbidity and mortality^{4,6–8}. However, limited evidence exists on the health effects of temperature anomalies, particularly in the middle to long term, despite the widespread use of anomalies as an indicator of weather stability in climate science^{4,9–11}. Moreover, most existing studies focus on developed countries, such as the United States⁴ and Australia¹², and the region of New England¹⁰, whereas low- and middle-income countries (LMICs) are disproportionately impacted by climate change and experience the most pronounced temperature anomalies¹³. LMICs face considerable challenges in adapting to and mitigating climate-related threats due to limited resources. Previous studies have highlighted that children are among the most vulnerable to climate change effects due to their underdeveloped physical and immune systems^{9,14}. According to World Bank estimates, over 98% of under-five mortalities (U5M) occur in LMICs. Therefore, understanding the specific adverse health effects of anomalous temperatures on children in LMICs is crucial for improving child health outcomes and addressing climate-related health inequities. However, quantitative evidence on the association between U5M and anomalous temperature remains limited.

Mitigating climate change requires precise quantification of the attributable disease burden, which in turn relies on accurate estimates of the exposure-response function (ERF) between temperature and mortality^{6–8}. One of the key challenges in current ERF estimates is characterizing the geographical heterogeneity in temperature-related health effects. Existing efforts have attempted to address this by incorporating multicenter population data and modeling variations in center-specific effects as an empirical function of geographic features such as climate zone, socioeconomic status, and land use. However, explainable heterogeneities in temperature-related health effects remain underexplored. One important factor is adaptation to the local temperature zone, represented by long-term average temperatures. To clarify this, it is essential to focus on the health effects of temperature variations that are independent of long-term averages. Temperature anomaly, defined as the deviation from the long-term average, captures this partial variation, enabling its effect to be analyzed independently and parametrized by temperature zone. In other words, developing a generalizable and explainable ERF for temperature and mortality requires incorporating the health effects of both average and anomalous temperatures. The resulting ERF between temperature and U5M could support the creation of early warning systems tailored to local climate conditions, helping to mitigate health risks associated with climate change.

In this study, using multicenter data from 1,745,132 live births across 56 LMICs, we examined the heterogeneous association between temperature anomalies and U5M. Employing a varying-coefficient nonlinear model, we derived a two-dimensional ERF that parametrizes the nonlinear effects of temperature anomalies on U5M as a function of temperature zone. Findings from this study provide a foundation for accurately quantifying the burden of child mortality attributable to global temperature changes in the future.

Methods

Study population

Individual data on 1,745,132 live births across 56 LMICs (Fig. 1) were obtained from demographic and health surveys (DHSs) for this multicenter analysis. Briefly, each DHS survey used a stratified two-stage cluster design to conduct a nationally representative household survey, collecting data on fertility, mortality, reproductive health, and child health in a specific LMIC. Standardized questionnaires were administered by trained fieldworkers to women of reproductive age (15–49 years), gathering household information, fertility history, and the survival status of children born within the five years preceding the survey date. Survey cluster coordinates were routinely recorded in recently surveyed countries using global positioning system devices. To protect respondent confidentiality, the DHS program applied random displacement to the geographic

coordinates, introducing a positional error of 0–2 km for urban clusters and 0–5 km for rural clusters. Further methodological details on the child health and geographic information collected by DHS are available on the official website (<https://dhsprogram.com/>) and in our previously published works^{15–17}. The DHS data are publicly accessible, and data collection and use were reviewed and approved by the ICF Institutional Review Board (IRB). Additionally, country-specific DHS survey protocols are reviewed by the ICF IRB and typically by an IRB in the host country. ICF IRB ensures that the survey complies with the U.S. Department of Health and Human Services regulations for the protection of human subjects, while the host country IRB ensures that the survey complies with laws and norms of the nation. Informed consent has been obtained from each participant or from a parent or legal guardian in the case of children and adolescents. Protocol numbers and additional ethical details are available on the official DHS website. All DHS datasets are freely available for research purposes upon registration and approval through the DHS Program's official data request platform.

The study period was restricted to 1998–2019 due to the availability of particulate matter (PM_{2.5}) data, a key confounder in analyzing the association between temperature and mortality. Children were eligible for inclusion if they had valid survival information, accurate geographic data for exposure assessment, and recorded dates of birth. Ultimately, 1,745,132 live births from 142 surveys conducted across 56 LMICs were included in the analyses.

Exposure assessment

The household cluster coordinates of surveyed children were used to assess environmental exposure. These environmental exposure data were then matched to the corresponding health data of children for statistical analysis. The primary exposure period was defined as one month prior to the survey date for surviving children and one month prior to the date of death for deceased children. Monthly temperature data were sourced from the enhanced global dataset for the land component of the fifth generation of European Reanalysis (ERA5-Land)¹⁸. ERA5-Land generates state-of-the-art numerical weather estimates by integrating data from in-situ observations, satellite remote sensing, and numerical weather predictions. This dataset provides a highly accurate and consistent view of meteorological variable trends extending back decades to the near present, with a high spatial resolution of approximately 10 × 10 km. Its high temporal and spatial resolution make ERA5-Land a valuable resource for environmental studies.

Following previous studies^{4,19–23}, we calculated monthly temperature anomalies (a) as deviations in the current temperature at a specific location ($T_{s,y,m}$) from the historic long-term average for that month ($\mu_{s,m}$), based on time-series temperature data from 1998 to 2019 for each pixel. The calculation is represented by the following equations:

$$a_{s,y,m} = T_{s,y,m} - \mu_{s,m}, \quad \mu_{s,m} = \left(\sum_{y=1}^{22} T_{s,y,m} \right) / 22 \quad (1)$$

where s , y , and m denote indices for the spatial pixel, calendar year, and month, respectively. Unlike the temperature exposure variable, this measure captures variations in the distribution and intensity of extreme temperature shocks across locations and may assume positive or negative values. A positive anomaly indicates that the observed temperature for that month exceeded the location-specific norm, while a negative anomaly indicates a temperature below the location-specific norm. Using 10 × 10 km grid data on monthly average and anomalous temperatures, along with corresponding under-five child population data from WorldPop, we calculated the annually long-term average and anomalous temperatures across the studied LMICs, weighted by the under-five child population. These values were derived as the sum of the product of each grid's population fraction and the respective annual long-term average or anomalous temperature.

To adjust for environmental confounders, we also collected monthly average precipitation and PM_{2.5} data for each child. Precipitation data was

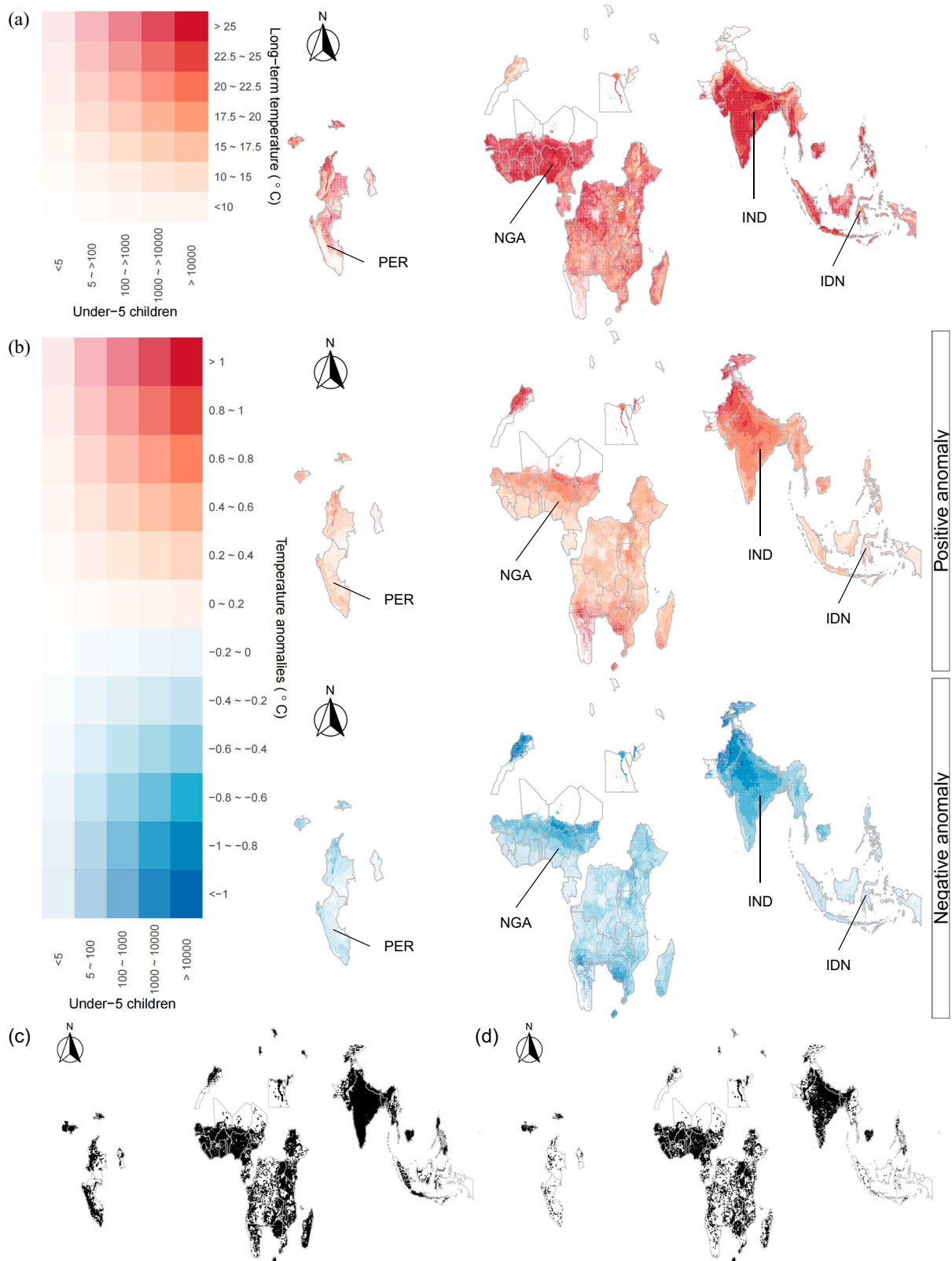


Fig. 1 | Spatial distributions of average and anomalous temperature level from 1998 to 2019, and the analyzed samples, across the 56 low- and middle-income countries (LMICs). In (a), the color of pixels shows the distribution of long-term average temperature respectively, and its transparency shows the corresponding size of population at exposure (i.e., under-5 children). In (b), the color of pixels shows the

distribution of average monthly temperature anomalies by positive and negative changes. c, d Display spatial distribution of the analyzed samples of under-5 children from 56 LMICs, for the multicenter design and the siblings-matched design. PER Peru, NGA Nigeria, IND India, and IDN Indonesia.

sourced from the ERA5-Land dataset, whereas PM_{2.5} data, with a resolution of 1 × 1 km, was obtained from a comprehensive global product. This PM_{2.5} dataset combines multiple data sources, including satellite retrievals of aerosol optical depth, chemical transport models, and ground-based measurements²⁴.

Statistics and reproducibility

In this study, we utilized two distinct study designs—the multicenter cohort design and the siblings-matched design—to estimate the association between U5M and temperature anomalies among children in LMICs. By comparing the estimates from both designs, we aimed to evaluate the robustness of the findings. The siblings-matched design, which we have applied in previous studies^{16,25}, is a well-established approach to investigate associations between environmental exposures and adverse health outcomes in children. In the siblings-matched design, each deceased child (case) is matched with their surviving siblings from the same mother, who serve as controls. This design allows for a comparison of temporal variations in environmental exposures between deceased cases and their surviving siblings. A primary advantage of this approach is that it inherently controls for observed and unobserved time-invariant household and maternal confounders, such as genetic factors and socioeconomic status. However, this approach only includes a selective subset of the sample, which may affect the representativeness of the data to some extent.

For both study designs, we estimated the linear associations between anomalous temperature and U5M using a Cox regression model with fixed effects, which is equivalent to the conditional Cox regression model. The model can be parameterized as follows:

$$h_{ij}(t) = h_0(t) \exp(a_{ij}\beta + z_{ij}\gamma + \theta_i), \quad (2)$$

where $h_{ij}(t)$ represents the hazard function for the j^{th} child, and t denotes survival time (age in months). Here, a is the level of temperature anomaly exposure, z represents adjusted covariates, θ is the fixed effect, and β and γ are the corresponding coefficients. In the multicenter analysis, i denotes the sampling center index, with θ_i serving as a fixed effect to control for the center-specific baseline of child mortality. In the siblings-matched analysis, i refers to the family ID (where all children born to the same mother are considered a family unit), and θ_i functions as a fixed effect to control for family-level invariant risk factors.

The covariates (z) considered in our study included several categories: environmental factors, including PM_{2.5} concentration and a precipitation variable modeled as a spline function with three degrees of freedom (DF); demographic factors, including child sex and breastfeeding status; pregnancy-related factors, such as delivery method (cesarean section or not), place of delivery, number of antenatal visits, singleton or multiple birth status, and parity (nulliparous or multiparous); maternal factors, including a 3-DF spline for maternal age, a 3-DF spline for birth interval (months), maternal body mass index, and maternal employment status; household factors, encompassing the sex of household head, a 3-DF spline for household head's age, source of drinking water, type of toilet, and type of cooking fuel; and spatiotemporal factors, which included a 10-DF spline function for survey year, season of survey, and Köppen Climate Zones²⁶. To balance model complexity and accuracy, the degrees of freedom for the spline functions were determined based on both the Akaike Information Criterion and previous studies^{16,25}. To handle missing values in several covariates, we used multivariate imputation by chained equations (MICE) approach and performed a single imputation (i.e., number of imputations set to one)^{16,27}. To ensure data representativeness, household sampling weights provided by the DHS program were incorporated into the Cox regression model using the *weights* argument in the *coxph* function. For sensitivity analysis, we adjusted the exposure timeframe to cover the period from 2 to 6 months prior to the outcome dates to explore the lagged effect of anomalous temperature.

To investigate the nonlinear associations between U5M and anomalous temperature, we first stratified the study population based on exposure

to either positive or negative temperature anomalies. Then, we developed a V-shaped model to assess the distinct effects of each anomaly type on U5M by incorporating an interaction term between subpopulation type (positive vs. negative anomaly exposure) and anomalous temperature in the Cox regression model. Subsequently, we examined the nonlinear exposure-response relationship between U5M and anomalous temperature by incorporating a natural spline function of temperature anomalies within the Cox regression model. The nonlinear model can be parameterized as follows:

$$h_{ij}(t) = h_0(t) \exp\left(\text{ns}(a_{ij}, \text{DF} = 3) + z_{ij}\gamma + \theta_i\right), \quad (3)$$

where $\text{ns}(a_{ij}, \text{DF} = 3)$ represents the nonlinear natural spline function of temperature anomalies with three degrees of freedom.

Additionally, we explored geographical heterogeneity in the impacts of anomalous temperature on U5M across LMICs. A series of subpopulation analyses were conducted to estimate the heterogeneous associations between U5M and anomalous temperature by different temperature zones and subpopulations with varying socioeconomic status. Using a varying-coefficient regression model, we examined how linear associations between U5M and temperature anomalies varied with long-term average temperature. The varying-coefficient model was parameterized as follows:

$$h_{ij}(t) = h_0(t) \exp[f(a_{ij}|\mu_{ij}) + z_{ij}\gamma + \theta_i], \quad (4)$$

where $f(a_{ij}|\mu_{ij})$ represents the linear association between U5M and anomalous temperature, which varies according to the long-term average temperature (μ_{ij}).

Finally, we assessed geographical heterogeneity in the nonlinear associations between U5M and anomalous temperature. Through subpopulation analysis, we initially examined individual effects of exposure to either positive or negative temperature anomalies on U5M across various temperature zones, and subsequently developed nonlinear ERFs that link U5M to temperature anomalies specific to each temperature zone. Employing a varying-coefficient nonlinear regression model, we incorporated the interaction between average and anomalous temperatures to construct a two-dimensional ERF, capturing the nonlinear impact of temperature anomalies on U5M as a function of temperature zone. This approach enables effect estimates across diverse combinations of average and anomalous temperature exposures. The varying-coefficient nonlinear regression model was achieved by parameterizing $f(a_{ij}|\mu_{ij})$ in Equation 4 as a cross-product of two spline terms: one for anomalous temperature and another for long-term average temperature.

All statistical analyses were performed using R software (version 4.1.3; The R Foundation for Statistical Computing, Vienna, Austria). The fixed-effects Cox regression model was implemented using the R package *survival*, and data imputation was conducted with the *mice* package.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Results

Population characteristics

In the multicenter analysis, a total of 1,745,132 children were included, with a median survival duration of 27.0 months (interquartile range [IQR]: 12.0, 43.0); 890,210 (51.0%) were male. The monthly long-term average temperature for these children was 24.1 °C (standard deviation [SD]: 5.12), and the median temperature anomaly was 0.01 °C (IQR: −0.39, 0.43). Surviving children had a median temperature anomaly of 0.01 °C (IQR: −0.39, 0.43), compared to −0.03 °C (IQR: −0.43, 0.39) for deceased children. Basic population characteristics are provided in Supplementary Data 1. For the siblings-matched design, 120,868 children were analyzed, with an average survival length of 17.0 months (SD: 17.5). The monthly long-term average

temperature for this group was 24.6 °C (SD: 4.84), with a median temperature anomaly of −0.02 °C (IQR: −0.40, 0.40). Figure 1 illustrates the spatial distribution of average and anomalous temperature levels across the 56 LMICs included in the study. For these LMICs, the annually long-term average temperature, weighted by the under-five child population, was 22.26 ± 3.23 °C, with weighted average monthly temperature anomalies ranging from −2.14 °C to 1.89 °C.

Associations between U5M and anomalous temperature

Using both the multicenter and siblings-matched designs, we evaluated the nonlinear exposure-response relationship between U5M and temperature anomalies (Fig. 2). Our analysis uncovered a U-shaped relationship,

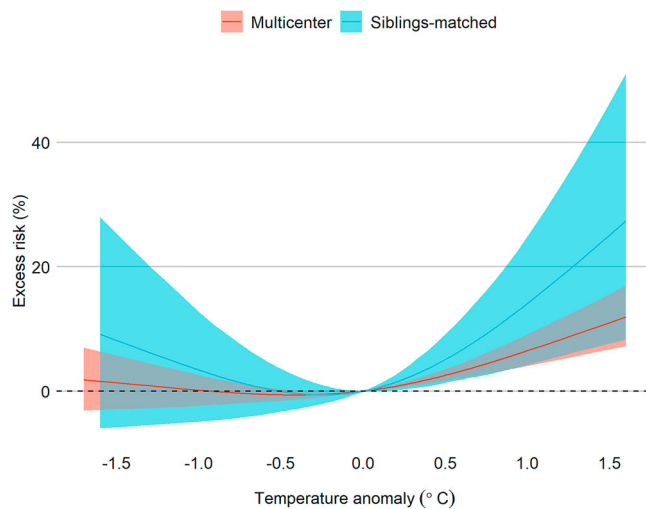


Fig. 2 | The estimated nonlinear associations between under-5 mortality and anomalous temperature, based on both multicenter and siblings-matched designs. The nonlinear exposure-response relationships are shown as lines with 95%-CI error ribbons ($n = 1,745,132$ biologically independent samples for the multicenter design and $n = 120,868$ for the siblings-matched design).

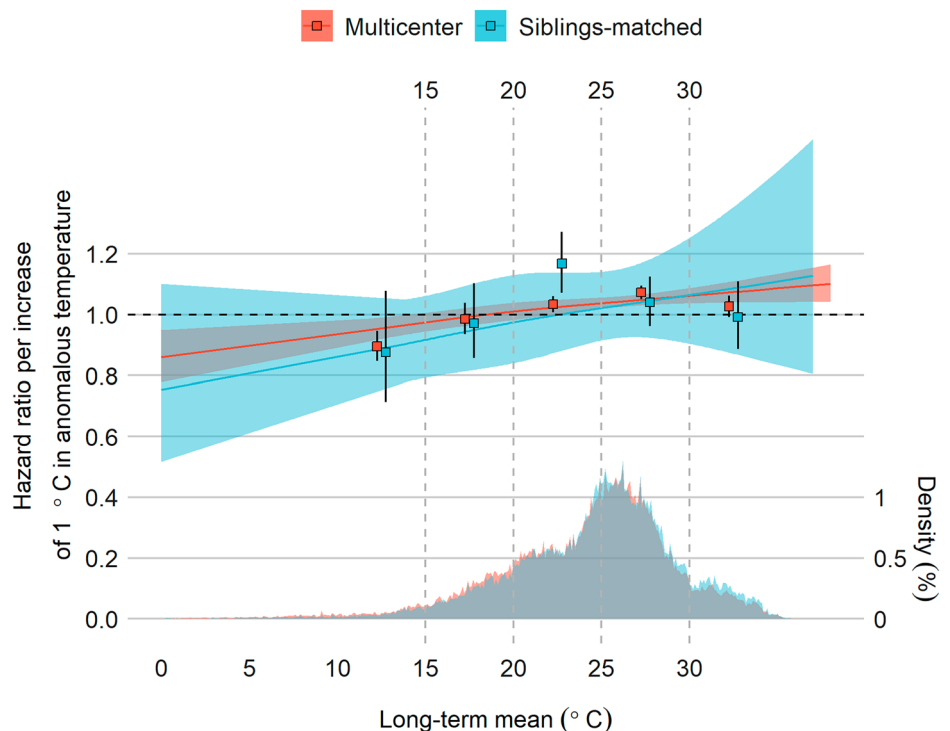
indicating that both positive and negative temperature anomalies contributed to increased U5M risk. Notably, positive temperature anomalies had a pronounced impact on child health, with risk escalating sub-linearly as temperature anomalies intensified. In contrast, the hazardous effects of negative temperature anomalies in our study population did not reach statistical significance. Both the multicenter and siblings-matched designs produced ERFs with comparable trends, underscoring the robustness of our findings.

Additionally, we examined the linear associations between U5M and anomalous temperature across various average temperature levels (Supplementary Figs. S1 and S2). In the fully-adjusted, weighted multicenter model, each 1 °C increase in temperature anomalies corresponded to a 1% excess risk of U5M (95% CI: −1%, 3%) (Supplementary Fig. S1). The siblings-matched model indicated a higher excess risk, estimating a 5% increase in U5M risk (95% CI: 1%, 10%) per 1 °C anomaly increase. The siblings-matched design provided stricter control over family-invariant confounders, thus producing estimates with lower bias but higher variance compared to the multicenter model. In both models, the estimated U5M association with temperature anomalies remained largely consistent across varying levels of confounder adjustments and regression weights, although spatiotemporal heterogeneity impacted these associations. Stratifying the study population based on exposure to positive and negative temperature anomalies (Supplementary Fig. S2) revealed that, in the multicenter model, each 1 °C increase in positive temperature anomalies or decrease in negative temperature anomalies corresponded to an 8% (95% CI: 6%, 11%) and 2% (95% CI: −1%, 4%) excess risk of U5M, respectively, suggesting a U-shaped nonlinear association. Further, lagged effect analysis indicated that the impact of exposure to either positive or negative temperature anomalies on U5M persisted for several months post-exposure (Supplementary Figs. S2 and S3). When using different epidemiological designs, we found various structures of lagged effects (i.e., a 2-months lag reported by the multicenter analysis, and a 4-months lag by the sibling-matched analysis).

Heterogeneous linear effects of anomalous temperature

Our findings indicate substantial heterogeneity in the association between U5M and temperature anomalies, influenced by both temperature zones

Fig. 3 | Heterogeneous associations between under-5 mortality and anomalous temperature, by different temperature zones. The heterogeneous linear associations between U5M and temperature anomalies by different temperature zones are shown as points with 95%-CI error bars ($n = 1,745,132$ biologically independent samples for the multicenter design and $n = 120,868$ for the siblings-matched design). The nonlinear associations between U5M and temperature anomalies across long-term average temperature levels are shown as lines with 95%-CI error ribbons.



and certain socioeconomic factors (Fig. 3, Supplementary Figs. S4 and S5). Utilizing a varying-coefficient regression model, we quantified the diverse associations between U5M and temperature anomalies across long-term average temperature levels (Fig. 3). For children residing in warmer regions (long-term average temperatures exceeding 22.5 °C), we observed a positive correlation between U5M and temperature anomalies, indicating elevated mortality risk with increasing anomalies. Conversely, in cooler regions (average temperatures below 22.5 °C), the association was negative. Further stratification by socioeconomic status (Supplementary Fig. S5) revealed that the adverse impact of anomalous temperatures was particularly pronounced among children from lower socioeconomic backgrounds, especially those living in rural areas and in households lacking access to improved sanitation, drinking water, and clean cooking energy sources.

We further analyzed the heterogeneous impacts of exposure to either positive or negative temperature anomalies on U5M by temperature zones (Supplementary Fig. S4). Results indicate that positive temperature anomalies exposure was significantly hazardous across both hot and cold regions. Based on the multicenter study, the most pronounced effect of positive temperature anomalies was observed in areas with a long-term average temperature of 25–30 °C. Here, a 1 °C increase in positive temperature anomaly corresponded to a hazard ratio (HR) of 1.16 (95% CI: 1.12, 1.19). The effect was weakest in regions where the average temperature was below 15 °C, showing an HR of 1.09 (95% CI: 1.01, 1.18). Exposure to negative temperature anomalies, on the other hand, primarily posed significant risks in colder regions (average temperatures below 15 °C), with each 1 °C decrease in negative temperature anomaly associated with an HR of 1.32 (95% CI: 1.22, 1.42).

Two-dimensional ERF

We initially examined heterogeneity in the nonlinear ERFs between U5M and temperature anomalies across various temperature zones, employing a multicenter analysis (Fig. 4a). For children in colder regions, with an average temperature below 12.5 °C, there was a positive association between U5M and negative temperature anomalies, while no significant effect was observed for positive temperature anomalies. In warmer regions, with average temperatures between 12.5 and 27.5 °C, the ERFs displayed a U-shaped pattern: as the average temperature increased, risks associated with positive temperature anomalies intensified, whereas risks related to negative anomalies exposure decreased. In hotter regions, where the average temperature exceeded 27.5 °C, we observed a positive association between U5M and anomalous temperature, with significant risk estimates for negative anomalies but nonsignificant estimates for positive anomalies.

Using a varying-coefficient nonlinear model, we constructed a two-dimensional ERF that correlates U5M with both average and anomalous temperatures and estimated ERF slices stratified by temperature zones, with a high excess risk of U5M indicating a low capacity of adaptability to anomalous temperature (Fig. 4). The ERF slices derived from the two-dimensional ERF (Fig. 4b) align with the temperature-zone-stratified ERF analysis (Fig. 4a), thereby affirming the robustness of the ERFs in capturing heterogeneity due to long-term adaptation to temperature. The two-dimensional ERF (Fig. 4c) elucidates the differential excess risks of U5M across various combinations of average and anomalous temperature exposures, thus capturing the nonlinear effects of temperature anomalies on U5M across different temperature zones. Here, we emphasize findings from the multicenter analysis, with the sibling-matched analysis results available in the supplement (Supplementary Fig. S6), which showed comparable trends. As shown in Fig. 4c, positive temperature anomalies significantly impacted children in warm and hot regions (average temperature >15 °C, as shown on the x axis of Fig. 4c), whereas negative anomalies were mainly detrimental for children in colder and moderate regions (average temperature <25 °C) but seemed to provide a protective effect for those in hotter regions (average temperature >25 °C).

Discussion

Using nationally representative U5M data from 56 LMICs, this study constructs a two-dimensional ERF linking U5M with both average and anomalous temperatures. Our findings reveal that associations between U5M and anomalous temperature differ across temperature zones, highlighting varying human adaptation capacities to local climates. Positive temperature anomaly is a significant hazard for children in warm and hot regions, whereas negative anomaly predominantly poses risks in colder zones, though it appears to have a protective effect for children in hotter zones. Sensitivity analyses using the siblings-matched model confirm nonlinear and heterogeneous effect estimates consistent with the multicenter model, reinforcing the robustness of our findings.

Temperature anomalies are projected to become more frequent as global climate change progresses. However, there are limited data on how these anomalies affect human health. Using time-series data on mortality and temperature over 38 years (1980–2017) in the USA, Parks et al.²³ found that a 1.5 °C anomalously warm year, where each month was 1.5 °C warmer than its long-term average, was associated with an estimated 1601 (95% CI: 1430, 1776) additional injury deaths. They also observed seasonal variations in the relationship between injury deaths and monthly temperature anomalies, with stronger effects of anomalously warm temperatures during hotter months. A cohort study among the Medicare population (aged > 65 years) in New England revealed that a 1 °C increase in the annual anomaly in summer and winter mean temperatures was associated with a 5% (95% CI: 4%, 6%) and a 1.5% (95% CI: 1%, 2%) increased risk of mortality, respectively²⁸. Several epidemiological studies have explored the effects of temperature variations on mortality. A cohort study in older hypertensive patients in China found a significant association between monthly temperature variation (the standard deviation of daily average temperatures) and an elevated risk of mortality (relative risk: 1.097, 95% CI: 1.051, 1.146)²⁹. Based on daily temperature and mortality data from 372 locations across 12 countries/regions, Guo et al.³⁰ assessed weekly temperature variability using the standard deviation of minimum and maximum temperatures during exposure days and found significant associations between mortality and temperature variability in cold, hot, and moderate seasons. They also observed that mortality risks associated with weekly temperature variability were higher in moderate areas than in cold and hot areas. Overall, our results were generally consistent with previous findings, confirming that anomalous temperatures deviating from the long-term local norm were significantly associated with mortality.

Few existing studies have investigated associations between child mortality and temperature, with most focusing on short-term average temperature and extreme temperature exposures¹⁴. For example, Dimitrova et al.³¹ conducted a time-stratified case-crossover analysis to quantify the nonlinear association between daily ambient temperature and neonatal mortality, observing a U-shaped ERF. They estimated that 4.3% of neonatal deaths were associated with non-optimal temperatures across 29 LMICs. Son et al.³² examined mortality from heatwaves in seven major Korean cities and did not observe a significant association between heatwave exposure and mortality in children under 14 years. Although low-income countries are expected to be more vulnerable to environmental threats, evidence is still limited due to challenges in data access. In low-resource settings, where daily exposure data may be inaccessible, monthly exposure data play a crucial role in providing unbiased estimates of the effects of environmental exposures³³. Our study adds evidence to the U5M risk associated with anomalous temperature in LMICs.

Previous studies have suggested several biological mechanisms underlying the health impacts of long-term temperature exposure and temperature anomalies^{34,35}. First, both long-term temperature and its variabilities can have direct effects on the respiratory and urinary systems. For instance, positive associations have been observed between non-optimal temperature exposure and respiratory diseases^{36,37}, such as asthma³⁸, and kidney-associated diseases³⁹. Second, the distribution of disease-carrying vectors and the transmission of infectious pathogens are

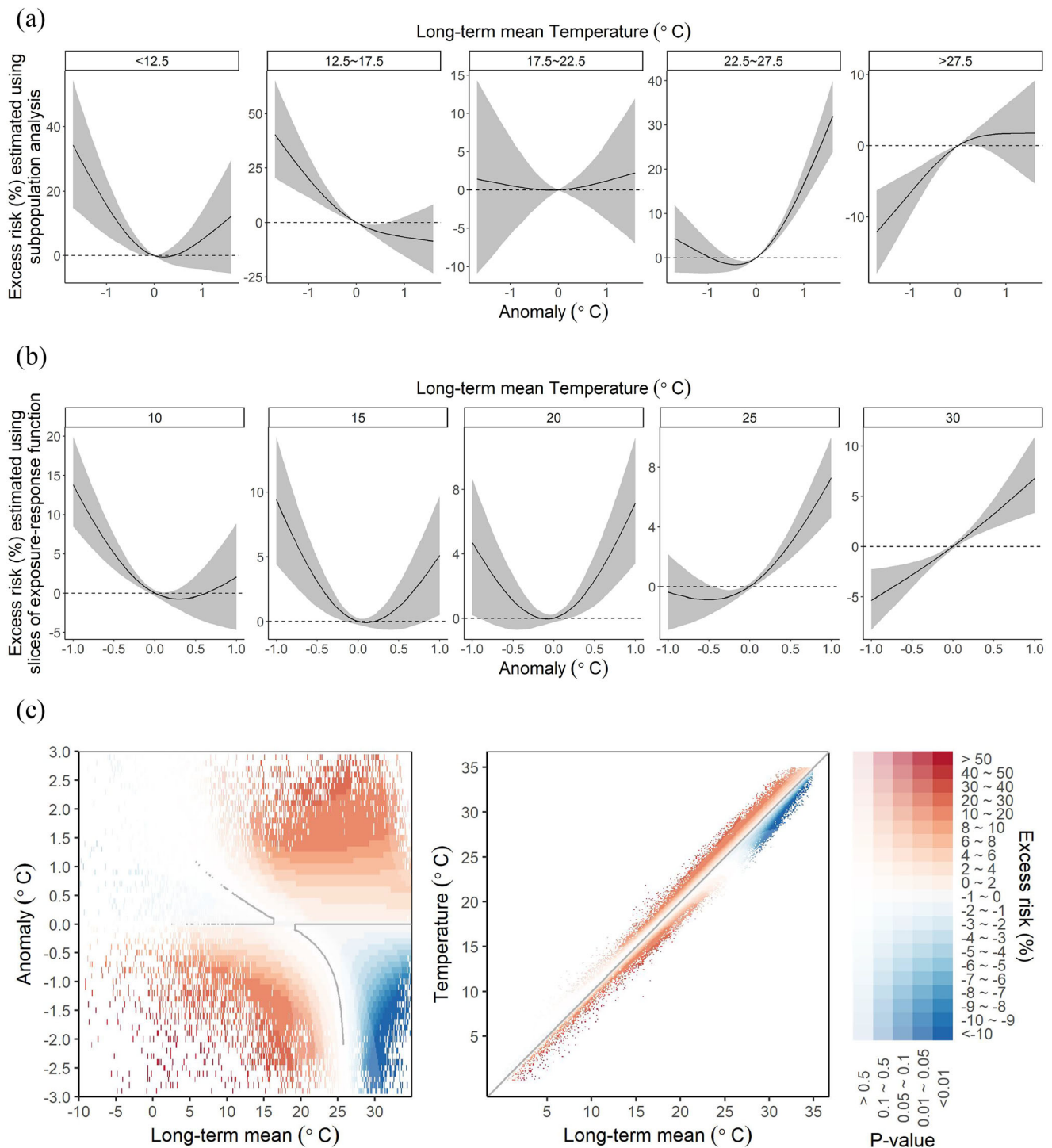


Fig. 4 | Heterogeneity in nonlinear exposure-response relationships between U5M and anomalous temperature by different temperature zones. a Shows the estimated nonlinear associations between under-5 mortality (U5M) and anomalous temperature by different temperature zones, based on subpopulation analysis using a multicenter design ($n = 1,745,132$ biologically independent samples). The exposure-response relationships are shown as solid lines with 95%-CI ribbons. **b** Shows different slices of the two-dimensional exposure-response function

estimated in (c) as solid lines with 95%-CI ribbons. **c** Shows the varied nonlinear associations estimated by a varying-coefficient nonlinear model. The directly estimated effect are presented both as a two-dimensional function of long-term temperature and its anomaly and as a function of temperature and its long-term average. **c** Illustrates how to infer the effect of temperature by correlating its fluctuations to variation in U5M.

expected to be altered at different temperature zones and variabilities. Infectious diseases associated with these changes tend to disproportionately affect children in general, particularly those from socio-economically vulnerable backgrounds. Third, non-optimal temperatures and high temperature variability can complicate access to clean food and

water, exacerbating child malnutrition and heightening the risk of infections. Additionally, there is substantial evidence that the human thermoregulation system fails to respond effectively when anomalous temperatures of cold or heat exceed their thresholds, which can directly contribute to child mortality⁴.

Population adaptation plays a crucial role in determining climate-related health risks, yet it has not been explicitly modeled in previous studies. Adaptation to temperature may occur through various mechanisms, such as physiological acclimatization, behavioral adjustments (e.g., clothing choices and spending more time indoors), and planned adaptation measures (e.g., air-conditioning installation and public health interventions such as early warning systems)^{40,41}. In this study, we characterized population adaptation to temperature by examining vulnerability to temperature anomalies. Through the derived nonlinear exposure-response relationship between mortality and temperature anomalies, we observed varying human capacity to adapt to positive and negative temperature anomalies. Geographical differences in the adverse impacts of temperature anomalies across different temperature zones provide valuable insights into how populations in LMICs adapt to local temperature conditions. These findings help clarify previously inconsistent results regarding the link between child mortality and ambient temperature. Additionally, the remarkable variation in geographical and social vulnerability to positive and negative temperature anomalies underscores the potential for targeted interventions to enhance the resilience of communities most at risk. Our study reveals the complexity of temperature-associated health impacts. The two-dimensional ERF between anomalous temperature and mortality offers a framework to understand and characterize the geographical heterogeneity and nonlinearity of health effects of temperature. By incorporating local temperature conditions and population adaptation, the two-dimensional ERF provides broader generalizability across diverse climate regions and can pave the way for more precise quantification of the future burden of child mortality attributable to global temperature changes.

Despite the valuable insights provided by this study, several limitations should be acknowledged. First, the exposure assessment may be biased due to constraints in the DHS data. This potential bias arises from the displacement of global positioning system coordinates for survey clusters and the possibility that participants may have relocated during the study period. Second, we selected a one-month exposure window prior to the outcome to provide a conservative estimate of the effect of anomalous temperature. However, given the lagged effects of temperature anomalies identified in Fig. S2, this approach may underestimate the cumulative impact of both positive and negative anomalies over a longer period. Third, the information on U5M in DHS surveys was self-reported by mothers, which introduces potential recall bias in our outcome assessment. Additionally, some under-five deaths may have been underreported due to social stigma associated with reporting such incidents. Fourth, due to the computational burden of handling a large dataset, we performed a single imputation using the MICE approach. While this method is commonly used in large-scale studies^{16,27}, it may not fully account for the uncertainty associated with imputation, as multiple imputation methods do. This could lead to an underestimation of the variability in the estimated association coefficients. Fifth, the regression models did not account for certain crucial confounders, such as family socioeconomic characteristics, genetic factors, and individual adaptation to climate change, due to data limitations. However, we conducted a sensitivity analysis using a sibling-matched design, which allowed us to adjust for time-invariant household and maternal confounders. Our estimates remained generally robust across different study designs. Sixth, stillbirths were not included in our analyses, which might lead to an underestimation of the U5M burden attributable to anomalous temperature. Finally, we assumed the ERF between U5M and anomalous temperature was homogeneous across different LMICs. However, the generalizability of the estimated ERF may be limited by the disproportionate representation of Asian countries in our sample and the varying adaptation capacities to climate change across different countries. Therefore, cautious interpretation of our findings is necessary when assessing location-specific attributable burdens based on the estimated ERF.

Based on a large-scale dataset from 56 LMICs, this study adds to evidence that temperature anomalies, whether in the form of heat or cold, are associated with an increased risk of child mortality in LMICs. The

effect of anomalous temperature varied across different temperature zones, reflecting the capacity of human populations to adapt to local climates. These findings highlight the urgent need for region-specific adaptive strategies to safeguard child health in the face of global climate change.

Data availability

The demographic and health surveys (DHS) datasets used in this study are publicly available on the official DHS website (<https://dhsprogram.com/>). All DHS datasets are freely available for research purposes upon registration and approval through the DHS Program's official data request platform. The source data for Fig. 3 is in Supplementary Data 2. Any additional information required for reanalyzing the data reported in this paper is available from the corresponding author on reasonable request.

Code availability

All analyses were conducted using R (version 4.1.3; The R Foundation for Statistical Computing, Vienna, Austria). The R codes for the data collection and epidemiological analyses are available from the corresponding author on reasonable request.

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Pengfei Li: Conceptualization, Formal analysis, Writing original draft, Writing – review & editing, Supervision, Funding acquisition. Jingyi Wu: Formal analysis, Writing original draft, Writing – review & editing. Tao Xue: Conceptualization, Writing – review & editing, Supervision. Tong Zhu: Writing – review & editing. All authors have directly accessed and verified the underlying data reported in the manuscript. All authors confirm that they have full access to all the data in the study and accept responsibility to submit for publication.

Competing interests

The authors declare no competing interests.

Additional information

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