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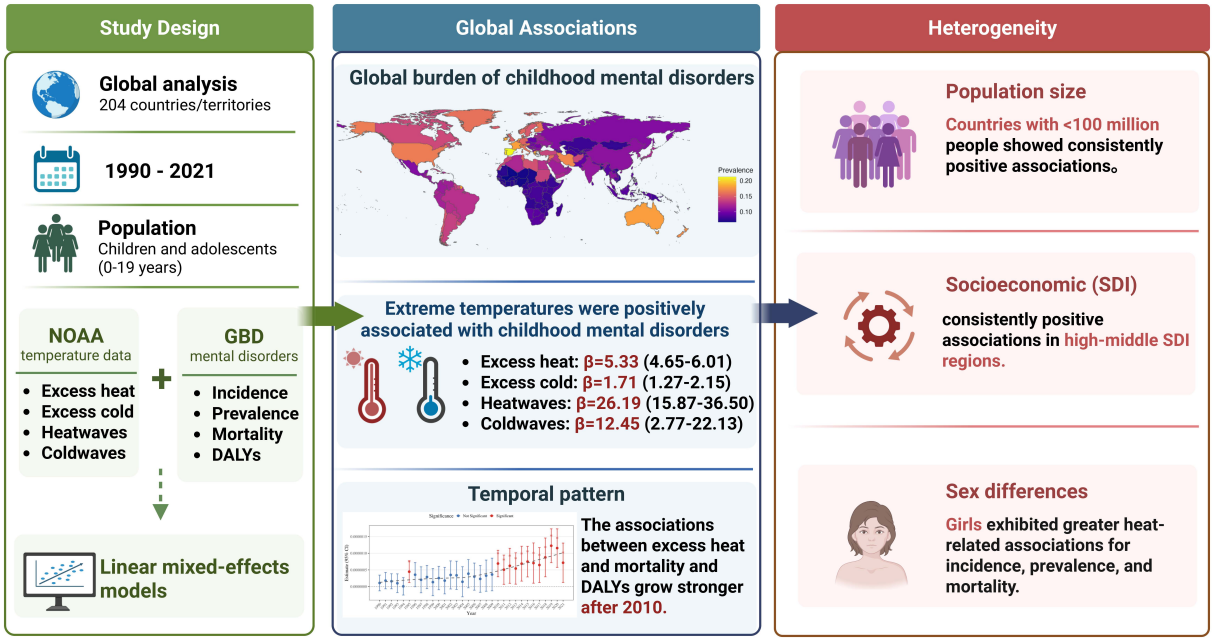
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Graphical Abstract



Highlights:

- A global analysis of 204 countries examined temperature-related childhood mental disorder burden.
- Excess heat and heatwaves were associated with higher incidence and prevalence.
- Excsee-heat associations strengthened over time and varied by SDI and sex.

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Spatiotemporal heterogeneity in the association between extreme temperatures and childhood mental disorders: a global analysis from 1990 to 2021

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Abstract: **Background:** Evidence linking extreme temperature exposure to mental disorders is increasing, yet global epidemiological evidence focusing specifically on children remains limited. This study quantified the association between extreme temperature exposure and the burden of childhood mental disorders worldwide from 1990 to 2021, and examined geographic, sociodemographic, and temporal patterns. **Methods:** Daily maximum and minimum temperature data were obtained from the National Oceanic and Atmospheric Administration database. Extreme temperature exposure was defined using two metrics: excess heat and cold relative to location-specific optimal temperatures, and extreme temperature events (heatwaves and cold waves). Data on childhood mental disorders were retrieved from the Global Burden of Disease 2021 study. Linear mixed-effects models were used to assess the relationship between extreme temperatures and mental health outcomes. **Findings:** Extreme temperature exposure was positively associated with an increased burden of childhood mental disorders. Excess heat and heatwaves were positively associated with childhood mental disorder incidence (β = 5.33, 95% CI: 4.65–6.01; and β = 26.19, 95% CI: 15.87–36.50, respectively). Positive associations were also observed for prevalence, with corresponding estimates of 8.95 (95% CI: 7.64–10.25) and 70.91 (95% CI: 51.33–90.49) cases per 100,000 population. The burden attributable to excess heat increased markedly over time, with rises in mortality and disability-adjusted life years (DALYs). Associations varied by socioeconomic development level and population size, and female children exhibited greater vulnerability to heat exposure. **Interpretation:** Exposure to extreme temperatures is associated with a growing burden of childhood mental disorders globally, with notable disparities across populations and heightened risks among girls.

Keywords: extreme temperature; childhood mental disorders; global burden of disease; linear mixed-effects model; spatiotemporal trend analysis

1. Introduction

Globally, climate change has exerted a complex and far-reaching impact on human living conditions and health. In recent decades, the frequency, intensity, and duration of extreme temperature events have risen markedly, posing growing threats to human health [1]. Although their impacts on cardiovascular and respiratory outcomes have been widely documented, mental health has emerged as an additional and potentially vulnerable domain.

Mental disorders constitute a major and rising cause of global disease burden, driven by demographic transitions, environmental changes, and sociopolitical challenges [2]. Accumulating epidemiological evidence suggests that extreme temperatures are associated with adverse mental health outcomes [3–5]. Short-term exposure to extreme heat or cold has been linked to increased depressive symptoms, anxiety disorders, schizophrenia incidence, and mental-related emergency department visits [6,7]. Time-series and case-crossover studies from high-income settings, including the United States, have reported elevated risks of mental disorder-related hospital visits during periods of extreme temperature exposure [8,9]. Experimental and clinical studies further suggest that

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heatwaves may impair cognitive and emotional functioning among individuals with severe mental illness [10]. Reviews synthesizing global evidence have consistently concluded that high temperature increase the incidence and mortality of mental disorders, with proposed mechanisms including neurotransmitter dysregulation, neuroinflammation, circadian rhythm disruption, and altered stress hormone responses [11,12].

Mental disorders frequently originate early in life, with incidence peaking during adolescence [12,13]. According to the Global Burden of Disease (GBD) study, over 235 million children and adolescents worldwide suffer from at least one diagnosable mental disorder, accounting for a substantial proportion of mental disorder-related mortality and disability [2,14]. Early-onset mental disorders are associated with long-term adverse consequences, including impaired physical health, social functioning, educational attainment, and increased suicide risk [1,15]. Given children's physiological immaturity and developmental vulnerability, they may be particularly susceptible to the mental health effects of extreme temperature exposure [11,16]. Emerging evidence from cohort and neuroimaging studies suggests that exposure to both heat and cold during childhood and adolescence may be associated with behavioral problems, altered brain connectivity, and poorer mental health outcomes [17,18]. These observations underscore the urgency of examining how extreme temperature exposure influences the burden of mental disorders in children at a global scale.

Despite this growing body of research, existing studies have largely focused on specific cities or regions, emphasized short-term exposure, and seldom examined children as a distinct population group. Global-scale assessments that capture dynamic changes, geographic heterogeneity, and sociodemographic disparities in children remain scarce. To address these gaps, this study examines the associations between extreme temperature exposure and the incidence, prevalence, mortality, and disability burden of childhood mental disorders worldwide from 1990 to 2021. By providing comprehensive, child-focused global evidence, this study provides new insights and valuable guidance to inform policies and interventions in the context of extreme temperature and mental health.

2. Methods

2.1. Extreme temperature exposure

Daily temperature data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Global Meteorological database (https://www.ncei.noaa.gov/maps/hourly/), covering 237 countries and 20867 stations worldwide (Figure S1). After standardized data cleaning, daily maximum and minimum temperatures were derived for each station from 1990 to 2021. Extreme temperature exposure was defined in two ways: (1) Excess temperature: The temperature range between the 10th and 90th percentiles of daily temperatures was defined as the optimal temperature range. Excess cold was calculated as the cumulative difference between the daily minimum temperature and the 10th percentile when the former was lower. Conversely, excess heat was calculated as the cumulative difference between the daily maximum temperature and the 90th percentile when the former was higher [19]. (2) Extreme temperature events: A coldwave was defined as a period during which the daily minimum temperature remained below the local 10th percentile for at least three consecutive days. A heatwave was defined as a period during which the daily maximum temperature exceeded the local 90th percentile for at least three consecutive days [20–22].

To derive national-level exposure estimates, site-level measures were aggregated using a station-weighted averaging approach [23,24]. Annual frequencies of heatwaves and coldwaves were calculated for each station and subsequently averaged across all stations within each country.

2.2. Mental disorders in children and adolescents (0–19 years)

Data on childhood mental disorders were obtained from the GBD Results Tool (http://ghdx.healthdata.org/gbd-results-tool). GBD 2021 provides a comprehensive assessment of 371 diseases and injuries and 87 risk factors across 204 countries or territories worldwide from 1990 to 2021, and systematically organized the data by age, gender, geographical location and year. Mental disorders were defined according to the GBD classification, including depressive disorders, attention deficit hyperactivity disorder, eating disorders, developmental intellectual disabilities, and related categories. This study extracted data on incidence, prevalence, mortality and disability-adjusted life years (DALYs) among individuals under the age of 20 in 204 countries and territories from 1990 to 2021, and further obtained subcategory-specific data for each defined mental disorder. All data are publicly available through the Institute for Health Metrics and Evaluation (IHME).

2.3. Covariates

Social-demographic variables included the Socio-demographic Index (SDI) and population structure data. SDI is a composite indicator reflecting regional development, based on income per capita, educational attainment, and fertility rate, and ranges from 0 to 1. Countries and territories worldwide were classified into five groups (low, low-middle, middle, high-middle, and high) according to GBD 2021 definitions.

Demographic data were sourced from the GBD database, which compiles information from official statistics, censuses, surveys, academic research, and other authoritative sources. These data encompass population size and structure across regions, time periods, genders, and age groups, and serve as the foundational basis for calculating key indicators such as incidence, mortality and DALYs in the assessment of disease burden.

2.4. Data analysis

Spatial distributions of childhood mental disorder prevalence and extreme temperature exposure were visualized using global maps for 1990 and 2021. Comparisons of color gradients across countries between the two time points allowed visualization of geographic patterns as well as temporal changes.

To evaluate associations between extreme temperature exposure and mental health outcomes, we employed Linear Mixed-Effects Models using annual data from 204 countries and territories between 1990 and 2021. This approach is particularly suitable for analyzing hierarchical panel data with repeated annual measurements across multiple countries, as it effectively accounts for both within-country and between-year variations. Outcome measures included incidence, prevalence, mortality, and DALYs, assessed as counts and rates. Exposure variables included excess heat, excess cold, and the annual mean number of heatwave and coldwave events per station at the country level. Models included SDI value and population groups as fixed effects, with random intercepts for calendar year and GBD region to account for temporal variation and regional clustering. The model structure was specified as: $Outcome_{i,t} = \beta_0 + \beta_1 \cdot Exposure_{i,t} + \beta_2 \cdot SDI\ value_{i,t} + \beta_3 \cdot Population\ group_{i,t} + u_{year(t)} + u_{region(i)} + \varepsilon_{i,t}$.

To assess the robustness of the findings to the choice of temperature thresholds, sensitivity analyses were conducted using alternative exposure thresholds based on the 5th and 95th percentiles. Additionally, to assess whether the associations were driven by geographically large countries, we conducted a sensitivity analysis by excluding the seven countries with the largest areas (Russia, Canada, China, the United States, Brazil, Australia, and India) and refitting the primary models. Further stratified analyses were performed by sex, SDI level, and population group. To assess differences in GBD estimation uncertainty across SDI levels, we compared the relative widths of the 95% uncertainty intervals for childhood mental disorder incidence and prevalence. To evaluate temporal changes, we used year-specific models. Moreover, the health outcomes were also disaggregated by specific mental disorder categories to investigate exposure effects on each classification.

All models were fitted using the lmer function in the lme4 package in R (version 4.5.1). Regression results are presented as estimated coefficients (β) for exposure variables along with their 95% confidence intervals (CI), and statistical significance was defined as two-sided $p < 0.05$.

3. Results

3.1. Global prevalence of mental disorders in children

This study utilized data from 204 countries and territories between 1990 and 2021. Globally, all major indicators of childhood mental disorders increased over the study period. In 1990, there were 58,658,984 incident cases and 206,639,135 prevalent cases worldwide, with approximately 17 deaths attributed to mental disorders. By 2021, incident cases had risen to 85,593,014 (a 45.91% increase), and prevalent cases rose to 252,256,612 (a 22.08% increase). Although mortality attributable to childhood mental disorders remained low, the consistent increases in incidence and prevalence underscore the growing global burden of mental disorders among children.

Figure 1 displays the spatial distribution of childhood mental disorders worldwide in 1990 and 2021. In 1990, higher prevalence rates were observed mainly in Western European and Australia, while lower levels were observed in parts of sub-Saharan Africa, Central Asia and South Asia. By 2021, prevalence rates had further increased in Western Europe and Australia, with Europe and North America continuing to exhibit high burden levels. Notable increases were also observed in South America, Southeast Asia, and the Middle East. Although baseline prevalence remained relatively low in many African countries, most still experienced varying degrees of increase. Overall, increases were more pronounced in middle- and high- income countries.

3.2. Global extreme temperature exposure

Figure 2 illustrates the geographical distribution patterns of heatwaves and coldwaves in 1990 and 2021. The frequency of heatwaves has shown a notable increase especially in regions such as North America, East Asia, the Middle East and Australia. Countries located in mid-to-high latitudes have emerged as the areas most severely affected by heatwaves. Similarly, coldwaves have also shown an overall upward trend globally, with substantial increases observed in tropical and sub-tropical regions, including Central and Western Africa, Southeast Asia and Central America.

A comparison of Figures 1 and 2 suggests that regions experiencing more frequent heatwaves or coldwaves generally exhibited larger increases in childhood mental disorder prevalence, indicating that extreme temperature exposure may contribute to the rising burden of mental disorders in children.

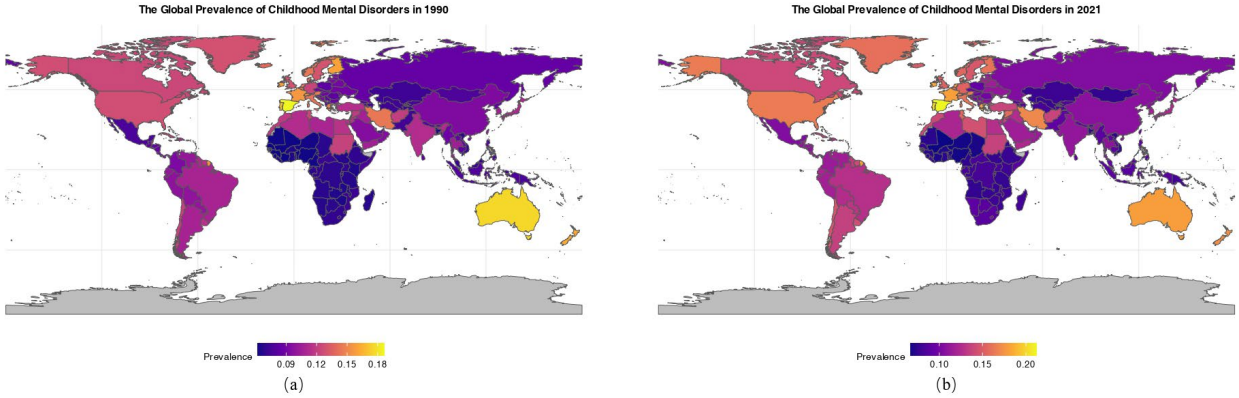


Figure 1. Gobal distribution of childhood mental disorder prevalence in 1990 and 2021. Maps show the prevalence of childhood mental disorders worldwide in **(a)** 1990 and **(b)** 2021.

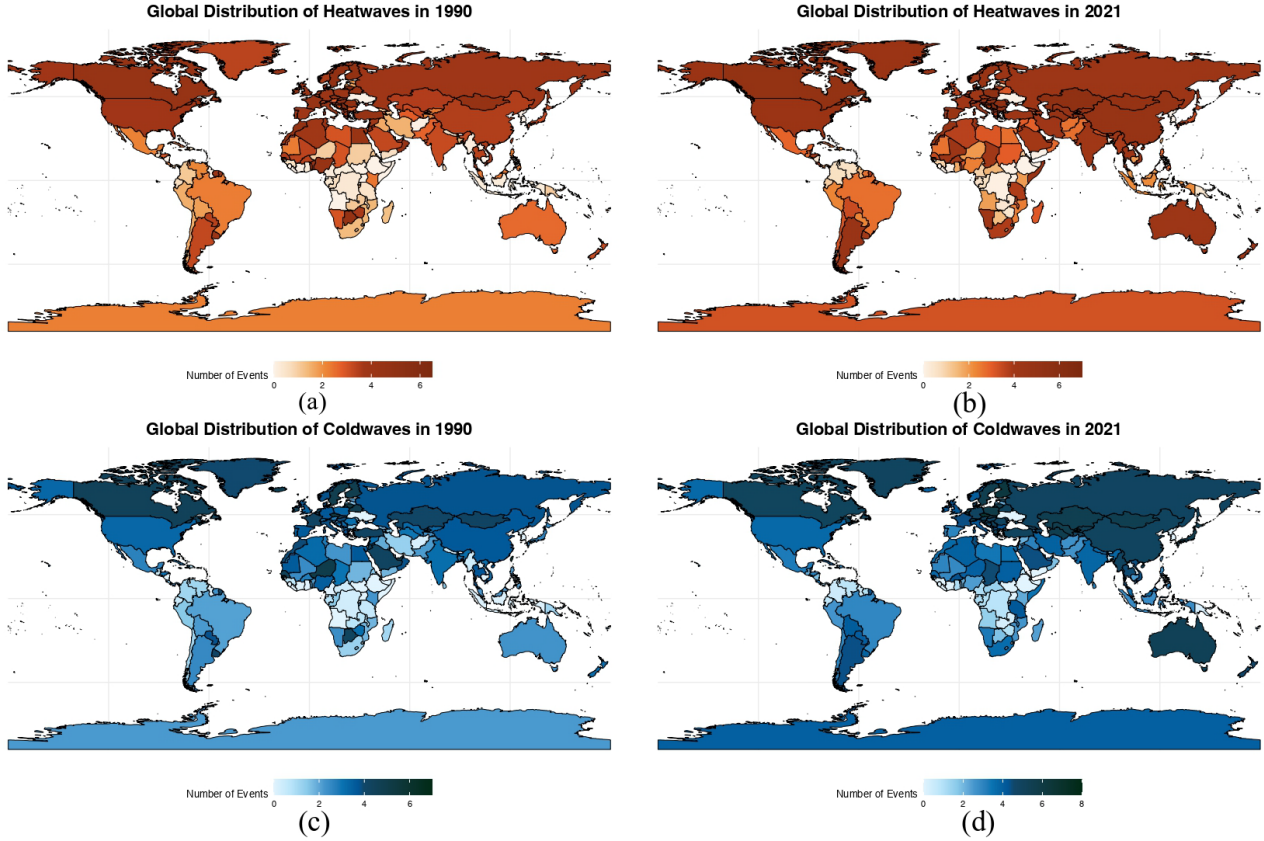


Figure 2. Gbal distribution of heatwaves and coldwaves in 1990 and 2021. Panels show the global distribution of heatwaves in **(a)** 1990 and **(b)** 2021, and coldwaves in **(c)** 1990 and **(d)** 2021.

3.3. Associations of extreme temperature exposure with mental disorders in overall and specific categories

Figures 3 and 4, Figures S2 and S3 present the association between extreme temperature exposure and the incidence, prevalence, mortality and DALYs of childhood mental disorders worldwide. All forms of extreme temperature exposure—namely, excess heat, excess cold, heatwaves, and coldwaves—were significantly and positively associated with the incidence of childhood mental disorders. Specifically, excess heat and excess cold were associated with higher incidence rates, with estimated coefficients of 5.33 (95% CI: 4.65–6.01) and 1.71 (95% CI: 1.27–2.15) cases per 100,000 population, respectively. Similarly, heatwaves and coldwaves were positively associated with incidence, with corresponding estimates of 26.19 (95% CI: 15.87–36.50) and 12.45 (95% CI: 2.77–22.13) cases per 100,000 population, respectively. Also, all forms of extreme temperature exposure showed significant positive associations with global childhood mental disorder prevalence. Excess heat and excess cold were associated with higher prevalence rates, with estimated coefficients of 8.95 (95% CI: 7.64–10.25) and 1.89 (95% CI: 1.05–2.73) cases per 100,000 population, respectively. Heatwaves and coldwaves were similarly

associated with higher prevalence rates, with corresponding estimates of 70.91 (95% CI: 51.33–90.49) and 59.72 (95% CI: 41.35–78.09) cases per 100,000 population, respectively. Similarly, significant positive association was observed between exposure to extreme temperature and elevated mortality. Excess heat was associated with a 1.37×10^{-5} increase in mortality (95% CI: 1.05×10^{-5}–1.69×10^{-5}), excess cold with a 4.70×10^{-6} increase (95% CI: 2.66×10^{-6}–6.73×10^{-6}), heatwaves with a 7.33×10^{-5} increase (95% CI: 2.56×10^{-5}–12.09×10^{-5}) and coldwaves with a 4.41×10^{-5} increase (95% CI: -5.20×10^{-5} -8.88×10^{-5}). Moreover, in terms of DALYs, significant positive association was observed in excess heat, heatwaves and coldwaves. Excess heat was associated with an increase of 550.71 person-years (95% CI: 320.19–781.24), heatwaves was associated with an increase of 5587.48 person-years (95% CI: 2158.82–9016.15), and coldwaves was associated with an increase of 5252.44 person-years (95% CI: 2037.72–8467.15) in DALYs. Tables S1 and S2 present the results of sensitivity analyses in which extreme temperature exposure was redefined using the 5th–95th percentile thresholds for optimal temperature, and the associations remained generally consistent with the main findings. Tables S3 and S4 show the results of sensitivity analyses excluding the seven geographically largest countries, with the overall results presenting a consistent association direction.

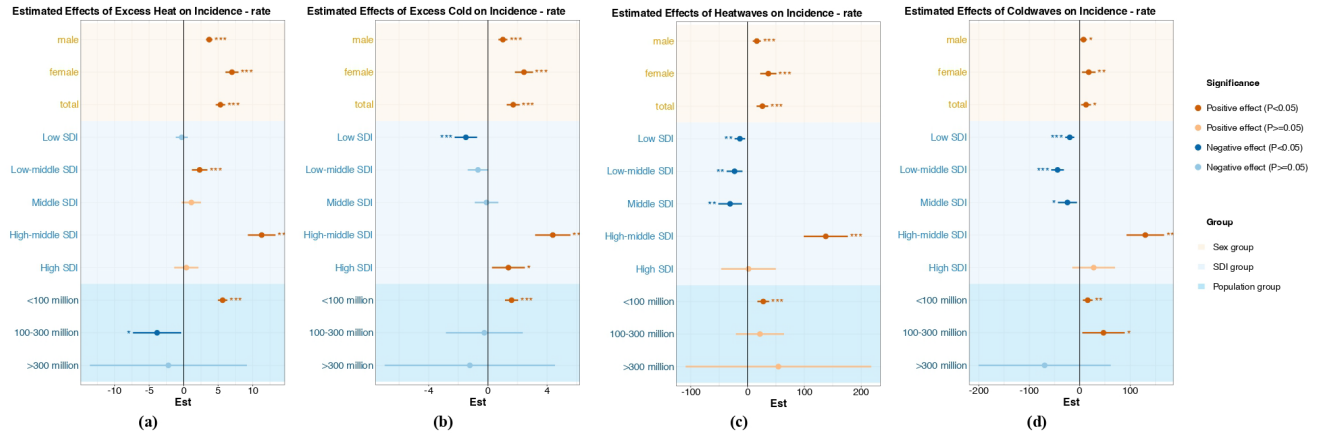


Figure 3. Association between extreme temperatures and the incidence of childhood mental disorders. Forest plots show estimated effects (rate change per 100,000 population) and 95% confidence intervals, stratified by sex, SDI level, and population group. Panels show results for **(a)** excess heat, **(b)** excess cold, **(c)** heatwaves, and **(d)** coldwaves. Asterisks indicate statistical significance (*p < 0.05, **p < 0.01, ***p < 0.001). SDI, Socio-demographic Index.

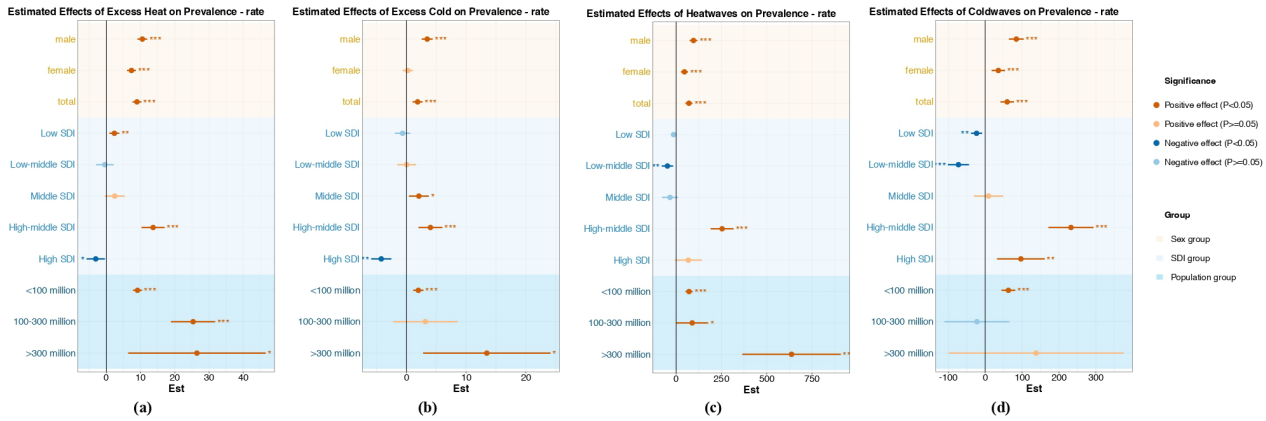


Figure 4. Associations between extreme temperatures and the DALYs of childhood mental disorders. Forest plots show estimated differences in DALYs (person-years) and 95% confidence intervals, stratified by sex, SDI level, and population group. Panels show results for **(a)** excess heat, **(b)** excess cold, **(c)** heatwaves, and **(d)** coldwaves. Asterisks indicate statistical significance (*p < 0.05, **p < 0.01, ***p < 0.001). SDI, Socio-demographic Index.

Table 1 presents the impact of excess temperature and extreme temperature events on the number of cases across specific diagnostic categories of childhood mental disorders. Subtype-specific analyses showed that excess heat and heatwaves were generally associated with higher incident case counts across the examined mental disorder categories. Coldwaves were also positively associated with several disorder subtypes, whereas no statistically significant associations were observed for excess cold. Among the examined subtypes, depression showed

relatively large absolute regression estimates for heat-related exposure metrics. Excess heat was associated with 726.45 (95% CI: 511.65–941.26) cases of increase in depression, heatwaves and coldwaves with 10273.25 (95% CI: 6279.34–14267.16) and 7276.12 (95% CI: 3420.81–11131.43), respectively. To contextualize the magnitude of these estimates, the coefficients for excess heat (β = 726.45) and heatwaves (β = 10,273.25) were numerically equivalent to 2.21% and 31.20%, respectively, of the median annual number of incident depression cases across country-year observations (32,923.12 cases; IQR: 5897.63–115,830.00). These coefficients represent associations with absolute incident case counts rather than incidence rates.

Table 1. Associations between extreme temperature exposure and childhood mental disorder subtypes.

Outcome	Exposure	Estimate (95% CI)	p value
Anxiety Disorders	Excess Heat	354.79 (253.68–455.89)	< 0.001***
Anxiety Disorders	Excess Cold	7.04 (−58.55–72.63)	0.833
Anxiety Disorders	Heatwaves	4792.77 (2911.73–6673.81)	< 0.001***
Anxiety Disorders	Coldwaves	3914.08 (2099.04–5729.12)	< 0.001***
Conduct Disorders	Excess Heat	327.77 (221.93–433.62)	< 0.001***
Conduct Disorders	Excess Cold	−30.75 (−99.36–37.85)	0.380
Conduct Disorders	Heatwaves	5057.14 (3089.62–7024.66)	< 0.001***
Conduct Disorders	Coldwaves	4822.05 (2924.61–6719.49)	< 0.001***
Eating Disorders	Excess Heat	102.57 (73.16–131.98)	< 0.001***
Eating Disorders	Excess Cold	3.90 (−15.18–22.98)	0.689
Eating Disorders	Heatwaves	1476.89 (929.87–2023.91)	< 0.001***
Eating Disorders	Coldwaves	1371.41 (843.81–1899.02)	< 0.001***
Depression	Excess Heat	726.45 (511.65–941.26)	< 0.001***
Depression	Excess Cold	110.24 (−29.01–249.48)	0.121
Depression	Heatwaves	10273.25 (6279.34–14267.16)	< 0.001***
Depression	Coldwaves	7276.12 (3420.81–11131.43)	< 0.001***
ADHD	Excess Heat	82.07 (28.35–135.79)	0.003**
ADHD	Excess Cold	17.69 (−17.04–52.43)	0.318
ADHD	Heatwaves	1104.84 (106.90–2102.79)	0.030*
ADHD	Coldwaves	957.41 (−5.02–1919.83)	0.051

Estimates represent the change in the number of incident cases of each mental disorder associated with exposure to excess heat, excess cold, heatwaves, and coldwaves. *p < 0.05, **p < 0.01, ***p < 0.001.

3.4. Differential associations across sociodemographic subgroups

Figures 3 and 4, Figures S2 and S3 present the impact of excess temperature as well as extreme temperature events on childhood mental disorder indicators across different SDI levels, population size, and gender. In SDI-stratified analyses, the associations between temperature-related exposures and childhood mental disorders varied markedly by development level. In high-middle SDI countries, all four temperature metrics (excess heat, excess cold, heatwaves and coldwaves) were consistently associated with higher incidence and prevalence, with all estimates being positive and statistically significant. For DALYs in this group, excess heat, excess cold and heatwaves were also positively associated with disease burden, whereas the association for coldwaves was positive but not statistically significant, and excess heat and excess cold were additionally linked to higher mortality. By contrast, low and low-middle SDI settings showed predominantly inverse or null associations, especially for incidence and prevalence. In low SDI countries, excess cold, heatwaves and coldwaves were significantly associated with lower incidence, while excess heat showed no clear effect; for prevalence, excess heat was positively associated, coldwaves were inversely associated, and other contrasts were small and non-significant. In low-middle SDI countries, heatwaves and coldwaves were significantly associated with lower incidence and prevalence, excess heat was positively associated with incidence but not prevalence, and all three temperature indices (excess heat, excess cold and heatwaves) were associated with lower mortality. Middle-SDI countries showed a mixed pattern, with heatwaves and coldwaves inversely associated with incidence, excess cold positively associated with prevalence, excess heat inversely associated with mortality, and excess heat, excess cold, and coldwaves positively associated with DALYs. In high-SDI countries, associations were heterogeneous. Excess cold was associated with higher incidence but lower prevalence, while excess heat was positively associated with mortality and DALYs but inversely associated with prevalence. Coldwaves were positively associated with prevalence but inversely associated with DALYs, and heatwaves showed no statistically significant associations with any outcome. Overall, these results suggest a clear gradient whereby high-middle SDI countries experience the most consistently positive associations between temperature stressors and mental health burden, whereas low and low-middle SDI countries often exhibit inverse or null relationships, and high-SDI settings show mixed patterns across different outcomes. An additional assessment showed greater relative uncertainty in GBD incidence estimates in low-SDI settings (median: 38.66%) than in other SDI groups (34.90%–36.53%), whereas prevalence estimates showed comparable uncertainty across SDI levels (Table S5).

Population-stratified analyses revealed substantial heterogeneity in temperature–health associations across countries of different population sizes. In countries with populations less than 100 million, all four temperature metrics were consistently positively associated with incidence, prevalence, and DALYs. Positive associations with mortality were also observed for excess heat and excess cold, indicating broadly heightened sensitivity to temperature stress in smaller-population settings. In countries with 100–300 million people, the associations were markedly weaker, with only limited significant effects observed: excess heat was inversely associated with incidence, whereas coldwaves showed a positive association with incidence. Both excess heat and heatwaves were positively associated with prevalence, while excess cold, heatwaves, and coldwaves were inversely associated with DALYs. No statistically significant associations were observed for mortality. In countries with populations over 300 million, significant associations were sparse, with no detectable effects on incidence or DALYs; prevalence increased with several exposures; and all four temperature metrics were associated with modest increases in mortality.

Gender-stratified analysis revealed that excess heat and heatwaves had a more significant impact on the incidence, prevalence, and mortality of mental disorders among females compared to males. However, for DALYs, the burden was slightly higher in males. No substantial gender differences were observed for excess cold. These results imply that female children might be more sensitive to heat exposure, and its impact on their mental health may be more pronounced.

3.5. Temporal trends in the impact of extreme temperature on the burden of mental disorders

Figures S4 and S5 display the annual trend in the impact of excess heat on the percentage of global childhood mental disorders. Temporally, the effect of excess heat on both mortality and DALYs indicators exhibited a clear upward trend, exhibiting a steeper upward trend after 2010. While associations were largely statistically insignificant in the early 1990s, significant effects were consistently observed in most years between 2017 and 2021. These findings suggest that the estimated associations between excess heat and childhood mental disorder burden were generally stronger in more recent years, particularly after 2010.

4. Discussion

In this global analysis covering 204 countries and territories from 1990 to 2021, we found that extreme temperature exposure has become an important contributor to the burden of childhood mental disorders worldwide. The associations varied substantially across countries with different socioeconomic development levels and population size, increased over time for excess heat, and were consistently robust in sensitivity analyses. Gender-stratified analyses further suggested that females exhibited greater vulnerability to heat-related impacts compared to males.

Our findings that extreme temperatures are associated with an increased burden of mental disorders are broadly consistent with previous epidemiological evidence, although most existing studies have focused on adult populations. Studies from China, the United States, and Brazil have reported associations between non-optimal temperatures and increased risks of depression, mental health-related emergency visits, or hospital admissions [3,9]. Evidence from city-based studies has further shown increased mental health service utilization during heatwave periods [25]. Extending this literature, our child-focused global analysis demonstrated consistent associations across multiple outcomes, including incidence, prevalence, mortality, and DALYs, and across different extreme temperature metrics. To contextualize these associations, the estimated incidence differences associated with excess heat and heatwaves represented 0.19% and 0.95% of the median background incidence rate, respectively. Notably, the heatwave-associated incidence estimate was 1.87 times the median absolute annual change in incidence rates (13.97 cases per 100,000 population), suggesting potential public health relevance at the population level. This broader pattern suggests that children may be similarly or even more vulnerable to thermal stress, plausibly due to immature thermoregulation, heightened metabolic demands, and greater dependence on external caregiving and environmental conditions. Together, these findings highlight the importance to explicitly incorporating children into climate-mental health research.

Despite the overall consistency with prior evidence, some studies have reported partially divergent findings, including stronger associations with heat than cold in certain settings and sex-specific differences in vulnerability [7,26]. These discrepancies may reflect differences in exposure definitions, population characteristics, and study settings. Compared with single-site or single-country analyses, our study employed globally standardized exposure metrics and assessed multiple health burden indicators, providing a more comprehensive evaluation of temperature-mental health associations.

At the disorder-subtype level, both excess heat and heatwaves showed consistent positive associations with incidence, whereas excess cold showed no statistically significant associations. This pattern is broadly consistent with previous evidence reporting stronger associations between extreme heat and mental health outcomes than between extreme cold and these outcomes [27]. Notably, coldwaves were positively associated with several disorder subtypes, suggesting that cumulative cold exposure and

sustained extreme cold events may capture distinct exposure characteristics. These findings highlight the importance of considering different dimensions of extreme temperature exposure when evaluating subtype-specific mental health associations.

Stratified analyses revealed substantial heterogeneity by socioeconomic development level. Vulnerability did not follow a simple linear gradient, with high-middle SDI settings often exhibiting the strongest associations. The inverse or null associations in low-SDI settings may partly reflect differences in diagnostic coverage and primary data availability, consistent with documented gaps in GBD 2021 mental health data, particularly among children and in low-income countries [28]. Our exploratory analysis further showed slightly greater uncertainty in incidence estimates in low-SDI settings, whereas prevalence estimates exhibited comparable uncertainty across SDI groups. Population-stratified analyses further showed stronger associations in countries with population below 100 million. Many of these countries, particularly those with higher SDI levels, tend to have more homogeneous climatic conditions, more consistent health surveillance systems, and higher diagnostic coverage, which may facilitate clearer detection of temperature-related changes in mental health burden at the national level [13,29]. These findings highlight the importance of strengthening climate-sensitive mental health surveillance and investing in those services as part of broader adaptation and health-system strengthening agenda.

Sex-stratified analyses suggested stronger associations of excess heat and heatwaves with incidence, prevalence, and mortality among females, whereas the corresponding DALY estimates were slightly higher among males. These differences may reflect a combination of physiological and behavioral factors. Sex-related variations in thermosregulation, including sweating responses, thermal perception, and hormonal influences, may contribute to differential susceptibility to heat stress [30,31]. Furthermore, heat-related sleep disruption may affect emotional regulation and psychological well-being, with previous research suggesting greater temperature-related sleep loss among females [32]. In contrast, the slightly higher DALY estimates among males may reflect sex-related differences in neurodevelopmental vulnerability and functional impairment. Neurodevelopmental and externalizing disorders, including ADHD, autism spectrum disorder, and conduct disorder, are more prevalent among boys and exhibit distinct patterns of cognitive and behavioral regulation [33]. Recent evidence suggests that heat exposure is associated with impaired executive functioning, particularly among boys, and increased externalizing symptoms in children and adolescents [17,34]. These neurobehavioral pathways, together with sex-related differences in disorder profiles and disability burden, may partly explain why DALY associations differ from those observed for incidence and prevalence. These findings highlight the importance of incorporating sex-specific considerations into climate adaptation and childhood mental health interventions.

Temporal trend analyses suggested that the associations between excess heat and childhood mental disorder burden became stronger over time, aligning with the trend of global warming. This pattern emphasizes the growing public health relevance of extreme heat exposure for child mental health. Understanding temporal dynamics not only helps to identify particularly sensitive exposure indicators but also informs the development of early warning systems and targeted public health planning. As climate extremes intensify, proactive investment in preventive strategies for childhood mental health will be increasingly critical.

From a public health perspective, our findings highlight the importance of incorporating child mental health considerations into climate adaptation and extreme temperature preparedness strategies. First, public health authorities could consider integrating child-focused mental health information into existing heatwave and coldwave early-warning systems to improve awareness among parents, caregivers, and educators. Second, schools and communities could strengthen protective measures during extreme temperature events, such as improving access to thermally safe indoor environments and adjusting outdoor activities to reduce exposure to potentially hazardous temperatures. Third, pediatric healthcare providers and school-based health services could consider enhancing the monitoring of emotional and behavioral symptoms during prolonged extreme temperature events and facilitating timely mental health assessment and referral when necessary. Given the heterogeneity observed across socioeconomic and demographic groups, these strategies should be adapted to local climatic conditions and healthcare resources, with particular attention to children with limited access to protective environments and mental health services.

This study has several strengths. First, it uses globally representative data spanning over three decades and encompassing diverse climatic, geographic, and socioeconomic contexts, enhancing the generalizability of the findings. Second, it captures dynamic changes and inter-annual variations in both climate extremes and mental health outcomes. Third, by focusing specifically on children, it addresses a major gap in the climate-mental health literature and highlights a particularly vulnerable population. Nevertheless, this study has several limitations. Despite the use of station-weighted averaging, national-level temperature estimates may obscure within-country climatic heterogeneity and introduce exposure misclassification, particularly in geographically large countries. Furthermore, the ecological design precludes individual-level inference, and extrapolating country-level associations to individuals may lead to an ecological

fallacy. Also, the GBD framework does not allow detailed differentiation of mental disorder subtypes, limiting disorder-specific interpretation. In addition, only two approaches to defining extreme temperature exposure were examined. Although the models adjusted for SDI and population size, residual confounding by unmeasured factors, including BMI, healthcare accessibility, urbanization, cultural differences, and environmental co-exposures such as humidity, solar radiation, and air pollution, cannot be excluded [35,36]. These environmental exposures may co-vary with extreme temperatures and independently influence mental health outcomes, potentially leading to overestimation or underestimation of the observed associations. Future studies could employ multi-pollutant models to account for environmental co-exposures, distributed lag non-linear models with higher temporal resolution data to assess non-linear and delayed associations, and individual-level cohort studies incorporating residential histories to improve exposure assessment and confounder control. Further mechanistic investigations are also warranted to clarify the underlying biological and behavioral pathways.

Overall, this study found that exposure to extreme temperatures was associated with a significant increase in the burden of childhood mental disorders, with considerable heterogeneity across socioeconomic contexts, population sizes, and sex. These findings underscore the vulnerability of children to climate-related mental health risks and highlight the urgent need to prioritize childhood mental health within climate adaptation and public health policies. Implementing targeted prevention and intervention strategies for children is crucial to mitigate climate-related mental health risks and reduce the global burden of childhood mental disorders.

Data availability statement

A supplementary file is provided with this article, containing five supplementary tables (Tables S1–S5) presenting sensitivity analyses using alternative temperature thresholds and excluding geographically large countries, as well as assessments of uncertainty in GBD estimates across SDI groups. Five supplementary figures (Figures S1–S5) illustrate meteorological station persistence, stratified associations with mortality and DALYs, and temporal trends in temperature-related associations with childhood mental disorders. Data on childhood mental disorders are publicly available from the Global Burden of Disease (GBD) Results Tool (https://ghdx.healthdata.org/gbd-results-tool). Meteorological data are publicly available from the National Oceanic and Atmospheric Administration (NOAA; https://www.ncei.noaa.gov/maps/hourly/).

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. Specifically, the authors used ChatGPT (OpenAI) to assist with language polishing. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Conceptualization, Q.W. and Y.Z.; methodology, Q.W. and Y.Z.; software, R.G. and M.W.; visualization, R.G. and M.W.; formal analysis, R.G. and M.W.; data curation, Y.Z., L.Z. and W.M.; writing—original draft perparation, R.G. and M.W.; writing—review and editing, R.G. and M.W.; supervision, Q.W. and Y.Z. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no competing interests.

Ethical statement

This study was based exclusively on publicly available, aggregated data from the Global Burden of Disease (GBD) 2021 study and the National Oceanic and Atmospheric Administration (NOAA). No human participants were directly involved, and no identifiable individual-level data were accessed. Therefore, ethical approval and informed consent were not required.

References

[1] Scott KM, Von Korff M, Angermeyer MC, Benjet C, Bruffaerts R, *et al*. Association of childhood adversities and early-onset mental disorders with adult-onset chronic physical conditions. *Arch. Gen. Psychiatry* 2011, 68(8):838–844. DOI: https://doi.org/10.1001/archgenpsychiatry.2011.77

[2] Kieling C, Buchweitz C, Caye A, Silvani J, Ameis SH, *et al*. Worldwide prevalence and disability from mental disorders across childhood and adolescence: evidence from the Global Burden of Disease Study. *JAMA Psychiatry* 2024, 81(4):347–356. DOI: https://doi.org/10.1001/jamapsychiatry.2023.5051

[3] Jin J, Xu Z, Cao R, Wang Y, Zeng Q, *et al*. Long-term apparent temperature, extreme temperature exposure, and depressive symptoms: a longitudinal study in China. *Int. J. Environ. Res. Public Health* 2023, 20(4):3229. DOI: https://doi.org/10.3390/ijerph20043229

[4] PoshtMashhadi A, Ijadi Maghsoodi A, Wood LC. The impact of extreme temperatures on emergency department visits: a systematic review of heatwaves, cold waves, and daily temperature variations. *Sci. Total Environ.* 2025, 970:178869. DOI: https://doi.org/10.1016/j.scitotenv.2025.178869

[5] Liu T, Shi C, Wei J, Xu R, Li Y, *et al*. Extreme temperature events and dementia mortality in Chinese adults: a population-based, case-crossover study. *Int. J. Epidemiol.* 2024, 53(1):dyad119. DOI: https://doi.org/10.1093/ije/dyad119

[6] Shomuyiwa DO, Lucero-Prisno III DE. Climate change trauma and collective dissociation: unraveling the impact on mental health and advocating for collective action. *Glob. Ment. Health* 2025, 12:e5. DOI: https://doi.org/10.1017/gmh.2024.119

[7] Crank PJ, Hondula DM, Sailor DJ. Mental health and air temperature: attributable risk analysis for schizophrenia hospital admissions in arid urban climates. *Sci. Total Environ.* 2023, 862:160599. DOI: https://doi.org/10.1016/j.scitotenv.2022.160599

[8] Niu L, Girma B, Liu B, Schinasi LH, Clougherty JE, *et al*. Temperature and mental health-related emergency department and hospital encounters among children, adolescents and young adults. *Epidemiol. Psychiatr. Sci.* 2023, 32:e22. DOI: https://doi.org/10.1017/s2045796023000161

[9] Yoo EH, Eum Y, Roberts JE, Gao Q, Chen K. Association between extreme temperatures and emergency room visits related to mental disorders: a multi-region time-series study in New York, USA. *Sci. Total Environ.* 2021, 792:148246. DOI: https://doi.org/10.1016/j.scitotenv.2021.148246

[10] Dang TN, Vy NTT, Thuong DTH, Phung D, Van Dung D, *et al*. Main and added effects of heatwaves on hospitalizations for mental and behavioral disorders in a tropical megacity of Vietnam. *Environ. Sci. Pollut. Res. Int.* 2022, 29(39):59094–59103. DOI: https://doi.org/10.1007/s11356-022-19898-1

[11] Faravelli C, Lo Sauro C, Godini L, Lelli L, Benni L, *et al*. Childhood stressful events, HPA axis and anxiety disorders. *World J. Psychiatry* 2012, 2(1):13–25. DOI: https://doi.org/10.5498/wjp.v2.i1.13

[12] Solmi M, Radua J, Olivola M, Croce E, Soardo L, *et al*. Age at onset of mental disorders worldwide: large-scale meta-analysis of 192

epidemiological studies. *Mol. Psychiatry* 2022, 27(1):281–295. DOI: https://doi.org/10.1038/s41380-021-01161-7

[13] Patel V, Saxena S, Lund C, Thornicroft G, Baingana F, *et al*. The Lancet Commission on global mental health and sustainable development. *Lancet* 2018, 392(10157):1553–1598. DOI: https://doi.org/10.1016/s0140-6736(18)31612-x

[14] Chen X, Li F, Zuo H, Zhu F. Trends in prevalent cases and disability-adjusted life-years of depressive disorders worldwide: findings from the Global Burden of Disease Study from 1990 to 2021. *Depress. Anxiety* 2025, 2025:5553491. DOI: https://doi.org/10.1155/da/5553491

[15] Chartier MJ, Bolton JM, Ekuma O, Mota N, Hensel JM, *et al*. Suicidal risk and adverse social outcomes in adulthood associated with child and adolescent mental disorders. *Can. J. Psychiatry* 2022, 67(7):512–523. DOI: https://doi.org/10.1177/07067437211055417

[16] Walinski A, Sander J, Gerlinger G, Clemens V, Meyer-Lindenberg A, *et al*. The effects of climate change on mental health. *Dtsch. Arztebl. Int.* 2023, 120(8):117–124. DOI: https://doi.org/10.3238/arztebl.m2022.0403

[17] Briker S, Tran KT, Visoki E, Gordon JH, Hoffman KW, *et al*. Association between extreme heat and externalizing symptoms in pre- and early adolescence: findings from the ABCD study. *JAACAP Open* 2025, 3(3):713–724. DOI: https://doi.org/10.1016/j.jaacop.2024.09.009

[18] Essers E, Kusters M, Granés L, Ballester J, Petricola S, *et al*. Temperature exposure and psychiatric symptoms in adolescents from 2 European birth cohorts. *JAMA Netw. Open* 2025, 8(1):e2456898. DOI: https://doi.org/10.1001/jamanetworkopen.2024.56898

[19] Weinberger KR, Spangler KR, Zanobetti A, Schwartz JD, Wellenius GA. Comparison of temperature-mortality associations estimated with different exposure metrics. *Environ. Epidemiol.* 2019, 3(5):e072. DOI: https://doi.org/10.1097/ee9.0000000000000072

[20] Faye M, Dème A, Diongue AK, Diouf I. Impact of different heat wave definitions on daily mortality in Bandafassi, Senegal. *PLoS One* 2021, 16(4):e0249199. DOI: https://doi.org/10.1371/journal.pone.0249199

[21] Awasthi A, Vishwakarma K, Pattnayak KC. Retrospection of heatwave and heat index. *Theor. Appl. Climatol.* 2022, 147(1–2):589–604. DOI: https://doi.org/10.1007/s00704-021-03854-z

[22] Ning Z, He S, Liao X, Ma C, Wu J. Health impacts of a cold wave and its economic loss assessment in China's high-altitude city, Xining. *Arch. Public Health* 2024, 82(1):52. DOI: https://doi.org/10.1186/s13690-024-01284-7

[23] Mistry MN, Schneider R, Masselot P, Royé D, Armstrong B, *et al*. Comparison of weather station and climate reanalysis data for modelling temperature-related mortality. *Sci. Rep.* 2022, 12(1):5178. DOI: https://doi.org/10.1038/s41598-022-09049-4

[24] de Schrijver E, Folly CL, Schneider R, Royé D, Tobias A, *et al*. A comparative analysis of the temperature-mortality risks using different weather datasets across heterogeneous regions. *GeoHealth* 2021, 5(5):e2020GH000363. DOI: https://doi.org/10.1029/2020gh000363

[25] Zhang H, Li X, Wang S, Wu T, Yang X, *et al*. Association between extreme heat and outpatient visits for mental disorders: a time-series analysis in Guangzhou, China. *GeoHealth* 2024, 8(10):e2024GH001165. DOI: https://doi.org/10.1029/2024gh001165

[26] Wang X, Lavigne E, Ouellette-kuntz H, Chen BE. Acute impacts of extreme temperature exposure on emergency room admissions related to mental and behavior disorders in Toronto, Canada. *J. Affect. Disord.* 2014, 155:154–161. DOI: https://doi.org/10.1016/j.jad.2013.10.042

[27] Li D, Zhang Y, Li X, Zhang K, Lu Y, *et al*. Climatic and meteorological exposure and mental and behavioral health: a systematic review and meta-analysis. *Sci. Total Environ.* 2023, 892:164435. DOI: https://doi.org/10.1016/j.scitotenv.2023.164435

[28] Casella CB, Kousoulis AA, Kohrt BA, Bantjes J, Kieling C, *et al*. Data gaps in prevalence rates of mental health conditions around the world: a retrospective analysis of nationally representative data. *Lancet Glob. Health* 2025, 13(5):e879–e887. DOI: https://doi.org/10.1016/s2214-109x(24)00563-1

[29] Romanello M, Napoli CD, Green C, Kennard H, Lampard P, *et al*. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *Lancet* 2023, 402(10419):2346–2394. DOI: https://doi.org/10.1016/s0140-6736(23)01859-7

[30] Greenfield AM, Alba BK, Giersch GEW, Seeley AD. Sex differences in thermal sensitivity and perception: implications for behavioral and autonomic thermoregulation. *Physiol. Behav.* 2023, 263:114126. DOI: https://doi.org/10.1016/j.physbeh.2023.114126

[31] Gagnon D, Kenny GP. Does sex have an independent effect on thermoeffector responses during exercise in the heat? *J. Physiol.* 2012, 590(23):5963–5973. DOI: https://doi.org/10.1113/jphysiol.2012.240739

[32] Minor K, Bjerre-Nielsen A, Jonasdottir SS, Lehmann S, Obradovich N. Rising temperatures erode human sleep globally. *One Earth* 2022, 5(5):534–549. DOI: https://doi.org/10.1016/j.oneear.2022.04.008

[33] Ojuri B, DeRonda A, Plotkin M, Mostofsky SH, Rosch KS. The impact of sex on cognitive control in ADHD: girls slow to inhibit, boys inhibit less, and both show higher response variability. *J. Atten. Disord.* 2024, 28(9):1275–1288. DOI: https://doi.org/10.1177/10870547241237242

[34] Hu L, Bao W, Jin Z, Hong J, Ge W, *et al*. Urban heat exposure patterns and domain-specific executive function in adolescents. *Environ. Res.* 2026, 301:124513. DOI: https://doi.org/10.1016/j.envres.2026.124513

[35] Bai Y, Liang X, Xia L, Yu S, Wu F, *et al*. Association between air pollutants and four major mental disorders: evidence from a Mendelian randomization study. *Ecotoxicol. Environ. Saf.* 2024, 283:116887. DOI: https://doi.org/10.1016/j.ecoenv.2024.116887

[36] Deng X, Brotzge J, Tracy M, Chang HH, Romeiko X, *et al*. Identifying joint impacts of sun radiation, temperature, humidity, and rain duration on triggering mental disorders using a high-resolution weather monitoring system. *Environ. Int.* 2022, 167:107411. DOI: https://doi.org/10.1016/j.envint.2022.107411