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The impact of extreme weather events on public health

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Published in
Frontiers in Public Health

ISSN 1664-8714
ISBN 978-2-8325-6690-9
DOI 10.3389/978-2-8325-6690-9

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The impact of extreme weather events on public health

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Citation
Niu, Y., Gao, J., Tong, M., Vardoulakis, S., eds. (2025). *The impact of extreme weather events on public health*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-6690-9

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frontiers | Frontiers in Public Health

TYPE Editorial
PUBLISHED 25 July 2025
DOI 10.3389/fpubh.2025.1645681

OPEN ACCESS

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RECEIVED 12 June 2025
ACCEPTED 11 July 2025
PUBLISHED 25 July 2025

CITATION
Tong M (2025) Editorial: The impact of extreme weather events on public health. *Front. Public Health* 13:1645681. doi: 10.3389/fpubh.2025.1645681

Editorial: The impact of extreme weather events on public health

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KEYWORDS

climate change, extreme weather events, environmental health, public health, health risk assessment, climate change adaptation, heatwave, flood

Editorial on the Research Topic
The impact of extreme weather events on public health

Anthropogenic climate change has intensified the frequency, severity, and complexity of extreme weather events worldwide, as underscored by the Intergovernmental Panel on Climate Change's Sixth Assessment Report (1). Heatwaves, droughts, wildfires, cyclones, and heavy precipitation pose escalating threats to public health, with consequences observed across multiple domains. From the record-breaking heatwaves in Europe to the devastating droughts in Africa and destructive wildfires in America (2–4), the public health implications are both immediate and profound. These events drive a wide range of adverse health outcomes, including heat-related illnesses, exacerbation of chronic diseases, physical injuries, significant mental health burdens, and excess mortality. However, these health impacts of extreme weather events are heterogeneous and shaped by factors such as population vulnerability, socio-economic conditions, and regional climatic variability.

This Research Topic brings together nine articles that collectively advance our understanding of these complex dynamics, integrating epidemiological, mechanistic, and intervention-focused research, and disaster communication case study to inform future research, health policies, and public health practices.

A prominent theme across the collection is the public health impact of climate change and extreme heat. Chen S. et al. employed a novel application of bivariate frequency analysis using copula functions, that offers a refined approach to quantify heatwave characteristics and associated mortality risks in urban China. This methodological innovation offers accurate forecasting and adaptive planning in cities increasingly vulnerable to extreme heat. Further, contributions extend beyond epidemiology to illuminate the biological mechanisms underpinning the health impacts. Wen et al.'s longitudinal multi-omics profiling study showed intricate molecular responses to acute heat exposure, identifying novel biomarkers predictive of cardiopulmonary function changes. Such mechanistic insights deepen our understanding of the physiological stress imposed by extreme heat and may guide the development of clinical interventions. Complementing these studies, Ning et al. investigated the synergistic effects of cold spells and particulate matter pollution on mortality in a high-altitude setting, highlighting the compounded health risks from multiple environmental stressors. The study underscored the necessity of integrating meteorological and pollution exposures to fully capture public health risks.

Mental health impacts of climate change related extreme weather events are also prominently featured. Akram and Mushtaq's mini-review shed light on the often-overlooked mental health consequences of displacement due to flooding, emphasizing the importance of incorporating psychological support into disaster response frameworks.

Moreover, Chen D-D et al.'s systematic review and meta-analysis of climate change and suicide revealed high temperatures and air pollution increased suicide attempts, suicide deaths, anxiety and self-harm, emphasizing the need for targeted public health strategies.

Another contribution comes from Zou and Lv, who analyzed social media data to track public discussion of disaster risk and emergency knowledge across the different phases of Typhoon Yagi in China during the typhoon warning, occurrence and recovery period. This highlights the co-evolutionary nature of disaster risk diffusion and emergency knowledge dissemination, providing a case study for future responses to extreme weather events on disaster risk management and emergency knowledge dissemination.

Studies in this collection underscore the disproportionate risks faced by vulnerable populations. Sankar et al. describe a protocol for evaluating the effectiveness of heat stress interventions among outdoor workers, a group at the frontline of climate exposure. Addressing occupational heat risk is a critical priority in low- and middle-income settings where adaptation capacity is limited.

In addition, Thongsak et al. link long-term exposure to air pollution from crop burning and forest fires to increased liver cancer mortality, adding to the growing evidence on chronic disease burdens exacerbated by environmental degradation in the context of climate change, particularly from the forest fires or wildfires due to climate change. Their findings reinforce the need for air quality control as part of comprehensive climate and health strategies.

Collectively, these studies underscore the multifaceted nature of extreme weather impacts on health, spanning acute and chronic outcomes, physical and mental health. They also highlight the urgent need for interdisciplinary approaches that combine advanced data analytics, molecular biology, social science, and occupational health to develop effective adaptation and mitigation strategies.

Importantly, this body of work points toward practical avenues for public health interventions. These include the development of heat stress management protocols tailored to vulnerable workers, incorporation of mental health services into disaster response, deployment of real-time risk communication strategies, and application of novel biomarkers for health monitoring during extreme heat exposure. As climate change continues to intensify the frequency and severity of extreme weather events, such evidence-based strategies will be essential to protect health and promote resilience.

This Research Topic serves as a timely resource, synthesizing cutting-edge research that bridges gaps in knowledge and offers practical insights for policymakers, public health professionals, clinical practitioners, and researchers. The integration of epidemiological data, mechanistic studies, intervention frameworks, disaster response and management offer a comprehensive lens to understand and address the public health challenges posed by extreme weather events. Continued investment in interdisciplinary research and cross-sector collaboration will be essential to enhance resilience and protect vulnerable populations due to extreme weather events in the face of climate change.

Author contributions

MT: Writing – original draft, Writing – review & editing.

Conflict of interest

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

Generative AI statement

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

Publisher's note

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frontiers | Frontiers in Public Health

TYPE Original Research
PUBLISHED 15 May 2024
DOI 10.3389/fpubh.2024.1414945

OPEN ACCESS

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RECEIVED 09 April 2024
ACCEPTED 02 May 2024
PUBLISHED 15 May 2024

CITATION
Ning Z, He S, Liu Q, Ma H, Ma C, Wu J, Ma Y and Zhang Y (2024) Effects of the interaction between cold spells and fine particulate matter on mortality risk in Xining: a case-crossover study at high altitude. *Front. Public Health* 12:1414945.
doi: 10.3389/fpubh.2024.1414945

Effects of the interaction between cold spells and fine particulate matter on mortality risk in Xining: a case-crossover study at high altitude

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Background: With global climate change, the health impacts of cold spells and air pollution caused by $PM_{2.5}$ are increasingly aggravated, especially in high-altitude areas, which are particularly sensitive. Exploring their interactions is crucial for public health.

Methods: We collected time-series data on meteorology, air pollution, and various causes of death in Xining. This study employed a time-stratified case-crossover design and conditional logistic regression models to explore the association between cold spells, $PM_{2.5}$ exposure, and various causes of death, and to assess their interaction. We quantitatively analyzed the interaction using the relative excess odds due to interaction (REOI), attributable proportion due to interaction (AP), and synergy index (S). Moreover, we conducted stratified analyses by average altitude, sex, age, and educational level to identify potential vulnerable groups.

Results: We found significant associations between cold spells, $PM_{2.5}$, and various causes of death, with noticeable effects on respiratory disease mortality and COPD mortality. We identified significant synergistic effects (REOI>0, AP > 0, S > 1) between cold spells and $PM_{2.5}$ on various causes of death, which generally weakened with a stricter definition of cold spells and longer duration. It was estimated that up to 9.56% of non-accidental deaths could be attributed to concurrent exposure to cold spells and high-level $PM_{2.5}$. High-altitude areas, males, the older adults, and individuals with lower educational levels were more sensitive. The interaction mainly varied among age groups, indicating significant impacts and a synergistic action that increased mortality risk.

Conclusion: Our study found that in high-altitude areas, exposure to cold spells and $PM_{2.5}$ significantly increased the mortality risk from specific diseases among the older adults, males, and those with lower educational levels, and there was an interaction between cold spells and $PM_{2.5}$. The results underscore the importance of reducing these exposures to protect public health.

KEYWORDS

cold spell, fine particulate matter, mortality, air pollution, climate change

1 Introduction

In the current context of global climate change, the frequency and intensity of extreme weather events are showing an upward trend, posing significant threats to human health and society (1). Cold spells, characterized by sudden and severe drops in temperature, together with the ongoing issue of air pollution, exacerbate the risks to public health (2, 3). Several studies have revealed the association between cold environments and $PM_{2.5}$ pollution with a range of health problems, including cardiovascular diseases, respiratory diseases, and diabetes (4, 5). In high-altitude areas, thin air, strong ultraviolet radiation, and increased human activities may have exacerbated the problem of air pollution in the environment (6–8). Studies have shown that air pollution in high-altitude regions has a significant impact on human health (9, 10). For example, a time-series analysis revealed a correlation between air pollution and respiratory health issues in children in the Xining area (11). Moreover, the impact of indoor air pollution in these areas on residents' health is even more severe (12, 13). Research on the health impacts of cold spells and air pollution in high-altitude areas is relatively scarce due to their unique geographical and climatic conditions and the specificity of population distribution, limiting our comprehensive understanding of the health impacts of extreme climate and air pollution in these regions. Additionally, the low oxygen and low pressure environment of high-altitude areas may negatively impact health through various physiological mechanisms, such as triggering the activation of hypoxia-inducible factors, enhancing inflammatory responses, and damaging mitochondrial function (14–17). Under extreme weather conditions, such as cold spells, these health effects may be further amplified. Therefore, in high-altitude areas, it is crucial to fully elucidate the correlation between cold spells, air pollution, and health outcomes for a thorough understanding and targeted prevention and adaptation.

Several studies have shown that the combination of extreme weather events and air pollution can have negative effects on human health (18, 19). However, most of these studies have focused on the impact of extreme high temperatures, with less attention given to the potential health impacts of different intensities, frequencies, and durations of extreme weather events such as cold spells. Furthermore, these studies assess the interaction between the two factors by calculating the relative excess risk due to interaction (RERI), but this single indicator does not take into account the possible complex synergistic effects between them. Xining City, being a high-altitude area, may exacerbate the negative health effects of air pollution due to its unique geographical and climatic conditions. The city experiences a six-month heating period during the winter and longer cold periods. This scenario highlights the need for a more comprehensive and detailed assessment method when considering the combined effects of extreme weather events and air pollution in high-altitude areas, in order to fully understand and evaluate the potential health impacts of these environmental factors' synergistic effects.

To complement existing research, this study aims to quantitatively assess the interactive effects of cold spells and $PM_{2.5}$ exposure on the risk of various causes of death in high-altitude areas and to calculate the corresponding excess mortality rates and numbers. In addition, this study will conduct stratified analyses to identify potentially vulnerable groups, in particular through stratification by average altitude, to further explore the effects of cold spells in high-altitude areas.

2 Materials and methods

2.1 Data collection and definition of cold spell

We collected mortality data from January 1, 2016, to December 31, 2021, from the Xining City Center for Disease Control and Prevention, including age, sex, level of education, disease diagnosis, and codes according to the International Classification of Diseases, Tenth Revision (ICD-10). The data were categorized by average altitude (2,500 m and 3,000 m), sex (male and female), age (0–64 years and ≥ 65 years), level of education (junior high school and below, high school and above), and specific causes of death: non-accidental (ICD-10:A00-R99), cardiovascular disease (ICD-10:I00-I99), ischemic heart disease (IHD, ICD-10:I20-I25), stroke (ICD-10:I60-I69), respiratory disease (ICD-10:J00-J99), chronic obstructive pulmonary disease (COPD, ICD-10:J40-J47), and diabetes (ICD-10:E10-E14). For altitude classification, we referred to the categories proposed by Bärtsch et al. in 2008 (near sea level 0–500 meters, low altitude 500–2,000 meters, mid altitude 2000–3,000 meters, high altitude 3,000–5,500 meters, extreme altitude above 5,500 meters) (20, 21). Meteorological data were obtained from the Qinghai Provincial Meteorological Bureau, including daily average temperature and humidity, with no missing data. Air pollutant data were sourced from the China Air Quality Online Monitoring and Analysis Platform,[1] supplemented by five national control monitoring stations in the urban area of Xining. The overall missing rate of air pollutant data was about 1.76%, including daily average concentrations of $PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2, and CO. For missing air pollution data, we used the median imputation method for data filling. We used Spearman's correlation analysis of meteorological factors and pollutants.

Based on previous studies, cold spells were defined as daily average temperatures falling below specific percentiles (2.5, 5, 7.5, or 10th) and persisting for a minimum of 2 to 4 consecutive days (22, 23).

2.2 Study sites

Xining City is located in the northwest of China and the northeast of the Tibetan Plateau, with an altitude range of 2091–4,857 meters, making it one of the world's high-altitude cities. The terrain is higher in the southwest and lower in the northeast, with a total population of about 2.4756 million people (in 2021), accounting for approximately 42% of Qinghai Province (Figure 1). The climate is characterized by a high mountain plateau climate, with cold and prolonged winters and pleasant summers.

2.3 Statistical analysis

We used a time-stratified case-crossover design and conditional logistic regression to quantitatively analyze the association between cold spells, $PM_{2.5}$, and mortality (24). The case-crossover design considers each study subject as its own control, with the visit date

1 https://www.aqistudy.cn/

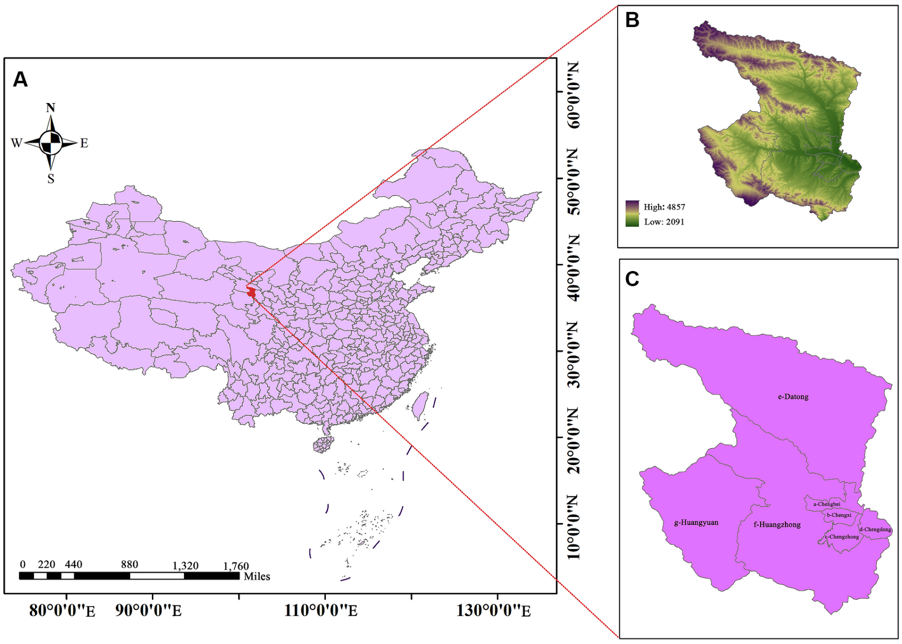

FIGURE 1
Location, altitude range and topography of Xining, China (**C**: a is Chengbei District, b is Chengxi District, c is Chengzhong District, d is Chengdong District, e is Datong County, f is Huangzhong District, and g is Huangyuan County). The average altitude of a-d is about 2500 m, and the average altitude of e-g is about 3000 m.

defined as the case day, and other dates in the same year, month, and week as the case day defined as control days. Each case period is matched with three or four control periods before or after the case period to control for long-term trends, seasonal trends, and the effects of the day of the week.

A distributed lag non-linear model (DLNM) was applied to fit separate exposure-response and lag-response relationships for cold spells, $PM_{2.5}$, and mortality (25). Based on previous studies, the exposure-response relationship was modeled using a linear function (26), while the lag-response relationship was fitted using a natural spline function with 3 degrees of freedom (df) (23). Previous studies have shown that the lag effect for cold spells was typically 21 days (4), while for $PM_{2.5}$ it was 7 days (27). A natural spline with 3 df was used to control for the confounding effects of relative humidity (28). The formula was as follows:

$$\log\left(E(Y)\right) = \alpha + cb\left(CS_i \,/\, pm_i, lag\right) + ns\left(rh, 3\right) + stratum + holiday$$

where *E(Y)* is the expected daily number of deaths; α is the intercept; *cb(CS), cb(pm)* are the cross-basis functions for cold spells and $PM_{2.5}$, respectively, used to examine lag effects; *stratum* is the time stratification variable, used to control for the impact of time factors such as long-term trends and seasonal changes; *ns(rh, 3)* is the natural cubic spline for relative humidity with 3 df; *holiday* is a binary variable used to control for Chinese holidays.

To further evaluate the interactive effects of exposure to cold spells and $PM_{2.5}$ on mortality, we classified $PM_{2.5}$ exposure into a binary variable (low concentration: $\leq 37.5\,\mu g/m^3$, high concentration: $>37.5\,\mu g/m^3$) according to the interim target 3 for $PM_{2.5}$ in the World Health Organization's 2021 air quality guidelines (29, 30). We created a new variable with four levels representing the combinations of exposure to cold spells and $PM_{2.5}$, including: (1) non-cold spell and low-level $PM_{2.5}$ (Level 1); (2) cold spell and low-level $PM_{2.5}$ (Level 2); (3) non-cold spell and high-level $PM_{2.5}$ (Level 3); (4) cold spell and high-level $PM_{2.5}$ (Level 4), with Level 1 serving as the reference group. By incorporating this variable into the conditional logistic regression model, we used three measures to assess this impact, including the relative excess odds due to interaction (REOI), the proportion attributable to interaction (AP), and the synergy index (S), which represents the part of the effect due to interaction (31, 32). The proportion of the joint effect due to interaction, as well as the ratio of the joint effect to the independent effects, were calculated using the following formulas:

$$REOI = \left(OR_{11} - 1\right) - \left(OR_{10} - 1\right) - \left(OR_{01} - 1\right) = OR_{11} - OR_{10} - OR_{01} + 1$$

$$AP = \frac{REOI}{OR_{11}}$$

$$S = \frac{OR_{11} - 1}{\left(OR_{10} - 1\right) + \left(OR_{01} - -1\right)}$$

where OR_{10}, OR_{01}, OR_{11} are the OR values of Levels 2, 3, and 4 relative to Level 1 ($OR_{00} = 1$), respectively. REOI = 0, AP = 0, S = 1 indicates that there is no interaction between cold spells and $PM_{2.5}$ on mortality; REOI>0, AP > 0, S > 1 indicates that the combined effect of cold spells and $PM_{2.5}$ on mortality is greater than the sum of the effects of exposure alone (synergistic effect); whereas REOI<0, AP < 0, S < 1 indicates that the combined effect is less than the sum of the effects of each exposure alone. The 95% confidence intervals (CI) for the three indicators are calculated using the delta method (33).

To estimate the excess mortality attributable to simultaneous exposure to cold spells and high levels of $PM_{2.5}$, this study used the calculation method [exp(β)-1], where β represents the coefficient of the fourth level of exposure in the conditional logistic regression model (34).

To identify potential vulnerable groups, we classified them by altitude, sex, age, and level of education to assess the independent impacts of cold spells and $PM_{2.5}$ on non-accidental deaths and their interaction. We used a two-sample z-test to examine the differences in the effects estimated for each stratified variable (35–37).

$$Z = \frac{\beta_{2500m} - \beta_{3000m}}{\sqrt{SE_{2500m}^2 - SE_{3000m}^2}}$$

where β represents the specific point estimate in the conditional logistic regression model; *SE* represents the standard error corresponding to each β.

2.4 Sensitivity analysis

Several sensitivity analyses were performed to test the robustness of our results. The lag days for cold spells were adjusted from 0–21 days to 0–27 days, and for $PM_{2.5}$ from 0–7 days to 0–10 days, while the degrees of freedom for relative humidity in the model were adjusted from 3 to 6. Simultaneously, we incorporated individual air pollutants (NO_2, CO, SO_2, and O_3) and a combination of air pollutants (NO_2 & SO_2 & CO) into the model. A new variable of different levels was created using the value of 39.5 μg/m^3 for $PM_{2.5}$ categorization to observe changes in the synergistic effect. Moreover, to observe potential disturbances brought by the COVID-19 pandemic, we divided the study data into two periods: 2016–2019 as the pre-pandemic control period and 2020–2021 as the pandemic period. This study primarily utilized R software for statistical analysis (version 4.3.1). $p < 0.05$ (two-sided) were considered statistically significant.

3 Results

Supplementary Table S1 presents a descriptive analysis of meteorological elements, atmospheric pollutants, and the number of specific causes of death. During the study period, the average daily temperature and relative humidity in Xining City were 6.46 ± 9.15 (°C) and 56.69 ± 16.20 (%), respectively. The daily average concentrations of $PM_{2.5}$, SO_2, NO_2, CO, and O_3 were 40.20 ± 27.90 μg/m^3, 20.03 ± 13.12 μg/m^3, 39.31 ± 16.11 μg/m^3, 1.36 ± 0.78 mg/m^3, and 93.31 ± 33.47 μg/m^3, respectively. From 2016 to 2021, there were a total of 64,128 non-accidental deaths, 29,906 deaths from circulatory disease, 8,553 from respiratory disease, 11,617 from IHD, 12,237 from stroke, 7,074 from COPD, and 2,560 from diabetes. Figure 2 reveals the trend of $PM_{2.5}$ versus temperature over time, showing the temporal synchronization of high $PM_{2.5}$ levels with the occurrence of low temperatures. A low to moderate correlation existed between the average daily temperature and other variables ($p < 0.05$; Supplementary Figure S1). Among these variables, the correlation between $PM_{2.5}$ and PM_{10} was relatively strong ($p < 0.05$), with a correlation coefficient greater than 0.8. However, the correlation between O_3 and relative humidity was minimal ($p > 0.05$).

Table 1 shows the number of non-accidental deaths at different exposure levels in Xining City from 2016 to 2021. According to the definition of a cold spell by 7th4D, there were 142 cold spell days, with 4,102 cases (6.4%) of deaths occurring on cold spell days, and the majority of deaths (60,026 cases) occurred on non-cold spell days. Among these, 87.9% (3,605) of the deaths occurred under the condition of simultaneous exposure to cold spells and high levels of $PM_{2.5}$, while 12.1% (497) occurred under simultaneous exposure to cold spells and low levels of $PM_{2.5}$. Overall, the number of non-accidental deaths during cold spell days decreased with lower temperature thresholds and longer durations.

Figures 3A–C and Supplementary Figures S2A–D show the relationship between exposure to cold spells and various causes of death. We observed a significant increase in the risk of death from all causes associated with exposure to cold spells. According to the 5th2D definition of cold spells, the odds ratios (OR) for total non-accidental deaths, deaths from circulatory disease, and respiratory disease were 1.168 (95%CI: 1.085, 1.258), 1.182 (1.061, 1.317), and 1.556 (1.294, 1.871), respectively, indicating an increase in death risk of 16.8% (8.5, 25.8%), 18.2% (6.1, 31.7%), and 55.6% (29.4, 87.1%). Overall, the risk of death decreased with stricter definitions of cold spells, and the confidence intervals of effect estimates became wider, with a higher risk of death from respiratory disease.

Figures 3D–F and Supplementary Figures S2E–H show the association between exposure to $PM_{2.5}$ and various causes of death. After adjusting for different definitions of cold spells in the model, the OR for total non-accidental deaths, deaths from circulatory disease, and respiratory disease monotonically increased with higher exposure to $PM_{2.5}$, with the highest risk for respiratory disease.

Figure 4 and Supplementary Figure S3 show the additive interactive effects on specific causes of death due to exposure to cold spells and $PM_{2.5}$. According to the 7th4D definition of cold spells, the REOI for total non-accidental deaths, deaths from circulatory disease, respiratory disease, IHD, stroke, COPD, and diabetes were 0.159 (95%CI: 0.045, 0.272), 0.173 (0.012, 0.334), 0.501 (0.199, 0.802), 0.353 (0.077, 0.628), 0.431 (0.189, 0.673), 0.354 (0.009, 0.699), and 1.109 (0.621, 1.598), respectively. Except for IHD, COPD, and diabetes, other causes indicated a significant synergistic effect of exposure to cold spells and $PM_{2.5}$ on mortality (indicated by REOI >0, AP >0, and S > 1; all $p < 0.05$). Overall, the REOI, AP, and S decreased with lower temperature thresholds and longer durations of cold spells, and the confidence intervals also became wider.

Figure 5 and Supplementary Figures S4, S5 show the excess fraction and number of excess deaths due to exposure to cold spells and high-levels of $PM_{2.5}$. According to the 7th3D definition of cold spells, the excess mortality rates for total non-accidental deaths, deaths from circulatory disease, respiratory disease, IHD, stroke, COPD, and diabetes were 0.083 (95%CI: 0.007, 0.166), 0.070 (−0.038, 0.191), 0.428 (0.188, 0.716), 0.330 (0.129, 0.567), 0.216 (0.033, 0.430), 0.421 (0.183, 0.708), and 0.607 (0.179, 1.191), respectively. Overall, significant findings were mainly concentrated between 7th2D to 7th4D, with lower excess mortality rates associated with lower temperature thresholds and longer durations of cold spells.

Table 2 and Supplementary Figures S6, S7 show the OR and additive interactive effects for non-accidental deaths under different definitions of cold spells, stratified by average altitude, sex, age, and education level.

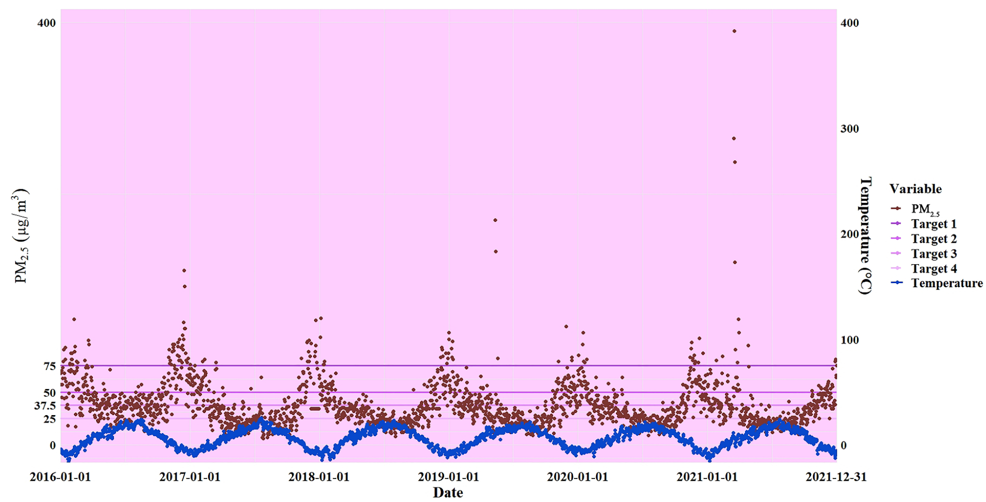

FIGURE 2
Trends in temperature and $PM_{2.5}$ over time and interim targets for daily average $PM_{2.5}$ concentrations according to the World Health Organization's 2021 Air Quality Guidelines (interim target 4 is 25 μg/m³, 3 is 37.5 μg/m³, 2 is 50 μg/m³, 4 is 75 μg/m³, and HIGH is greater than 75 μg/m³).

TABLE 1 Number of non-accidental deaths during cold spell events in Xining, China, 2016–2021.

Definition	Days	Deaths (%)		
		Overall	With low-level $PM_{2.5}$	With high-level $PM_{2.5}$
10th2D	201	6,976	10,11(14.5)	5,965(85.5)
10th3D	182	6,288	923(14.7)	5,365(85.3)
10th4D	164	5,647	685(12.1)	4,962(87.9)
7.5th2D	163	5,703	869(15.2)	4,834(84.8)
7.5th3D	142	4,994	664(13.3)	4,330(86.7)
7.5th4D	119	4,102	497(12.1)	3,605(87.9)
5th2D	98	3,398	428(12.6)	2,970(87.4)
5th3D	81	2,809	396(14.1)	2,413(85.9)
5th4D	63	2,209	311(14.1)	1,898(85.9)
2.5th2D	46	1,530	287(18.8)	1,243(81.2)
2.5th3D	40	1,342	287(21.4)	1,055(78.6)
2.5th4D	31	1,142	233(20.4)	909(79.6)

We observed that, in the independent effects of exposure to cold spells on non-accidental deaths, the effect was slightly higher in populations living at an average altitude of 3,000 m compared to those at 2,500 m, slightly higher in males compared to females, lower in the 0–64 age group compared to those aged ≥65, and higher in individuals with lower educational levels compared to those with higher educational levels; however, no statistically significant differences were observed between them ($p > 0.05$; Supplementary Figure S6). In the independent effects of exposure to $PM_{2.5}$ on non-accidental deaths, the effect was slightly lower in populations living at an average altitude of 3,000 m compared to those at 2,500 m, similar between males and females, lower in the 0–64 age group compared to those aged ≥65, and higher in individuals with lower educational levels compared to those with higher educational levels, but no significant differences were observed across the groups ($p > 0.05$; Supplementary Figure S7). We observed a significant synergistic effect ($p < 0.05$; Table 2) in the interaction between exposure to cold spells and $PM_{2.5}$ on non-accidental deaths for the age group ≥65 compared with the age group 0–64 in the 7th3D and 7th4D definitions, indicating a significant synergistic effect. No significant differences in the synergistic effect (meeting the conditions of REOI >0, AP >0, and S > 1) were observed between average altitude, sex, or education level ($p > 0.05$; Supplementary Tables S2, S4).

By adjusting the lag days for cold spells from 0–21 days to 0–27 days, the lag days for $PM_{2.5}$ from 0–7 days to 0–10 days, modifying the degrees of freedom for relative humidity in the model, and including both individual air pollutants (SO_2, NO_2, CO,and O_3) and combined air pollutants (NO_2&SO_2&CO) in a sensitivity analysis, the estimated values for both independent and interactive effects were similar, showing minor variations (Supplementary Figures S8–S10). When using a $PM_{2.5}$ categorization value of 39.5 μg/m³, the association between cold spells and $PM_{2.5}$ with non-accidental deaths was stable (Supplementary Figures S11, S12), but the estimated value for the interaction effect between exposure to cold spells and $PM_{2.5}$ on non-accidental deaths slightly decreased. Furthermore, the study results from different periods suggested that, during 2020–2021, the individual effects of cold spells and $PM_{2.5}$ slightly decreased compared to previous years (Supplementary Figure S13), with the COVID-19 pandemic potentially acting as a confounding factor but also possibly related to the reduced time span and global warming. This indicated that the impact of large-scale public health events on assessing the health effects of environmental factors needs to be considered.

4 Discussion

We studied the association between cold spells and $PM_{2.5}$ with mortality in high-altitude areas (Xining) and quantified their interaction. In this case-crossover study, we found a significant

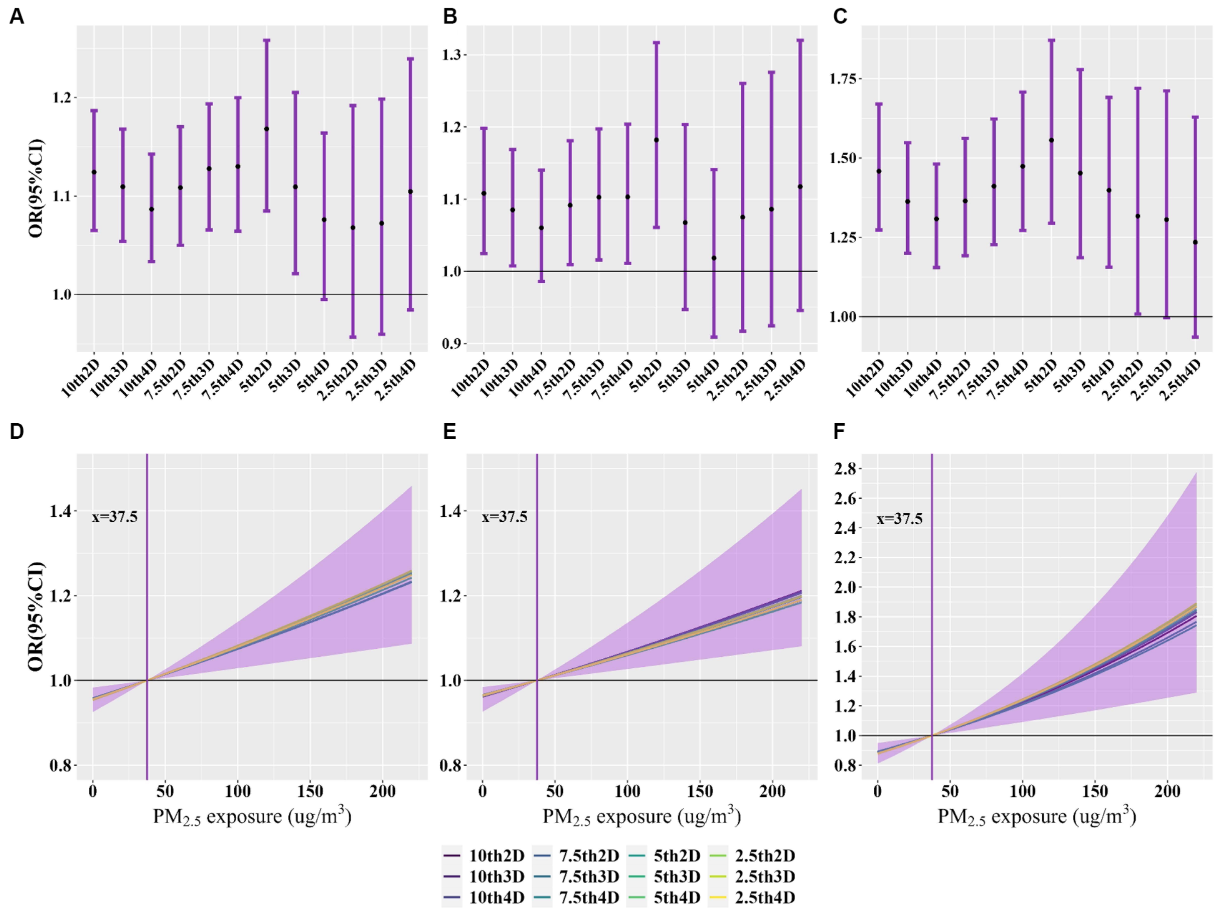

FIGURE 3
Association of exposure to cold spells and $PM_{2.5}$ with non-accidental, cardiovascular and respiratory disease deaths. **(A–C)** OR (95%CI) for nonaccidental, cardiovascular, and respiratory disease deaths with exposure to cold spells, respectively. **(D–F)** Exposure-response curves for the association between exposure to ambient $PM_{2.5}$ and non-accidental, cardiovascular and respiratory disease deaths, respectively.

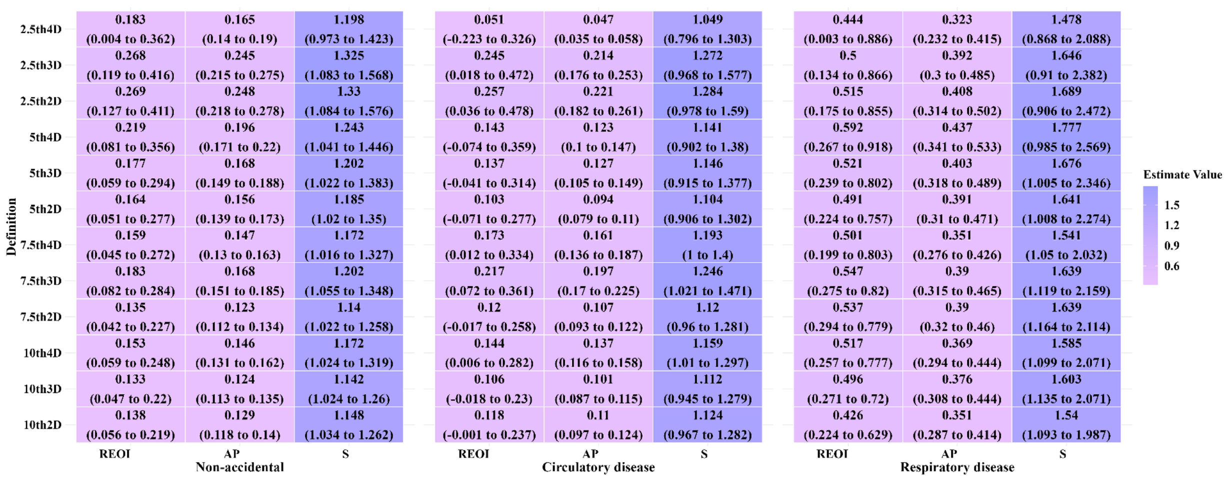

FIGURE 4
Additive interaction effects of exposure to cold periods and $PM_{2.5}$ on non-accidental, cardiovascular and respiratory disease mortality.

correlation between exposure to cold spells and $PM_{2.5}$ and an increase in various causes of death. Cold spells could synergistically interact with $PM_{2.5}$ to increase the risk of death, especially the risk of respiratory disease and COPD deaths. The individual effects of cold spells and $PM_{2.5}$, as well as their interaction on various causes of death, decreased with lower temperature thresholds and longer durations.

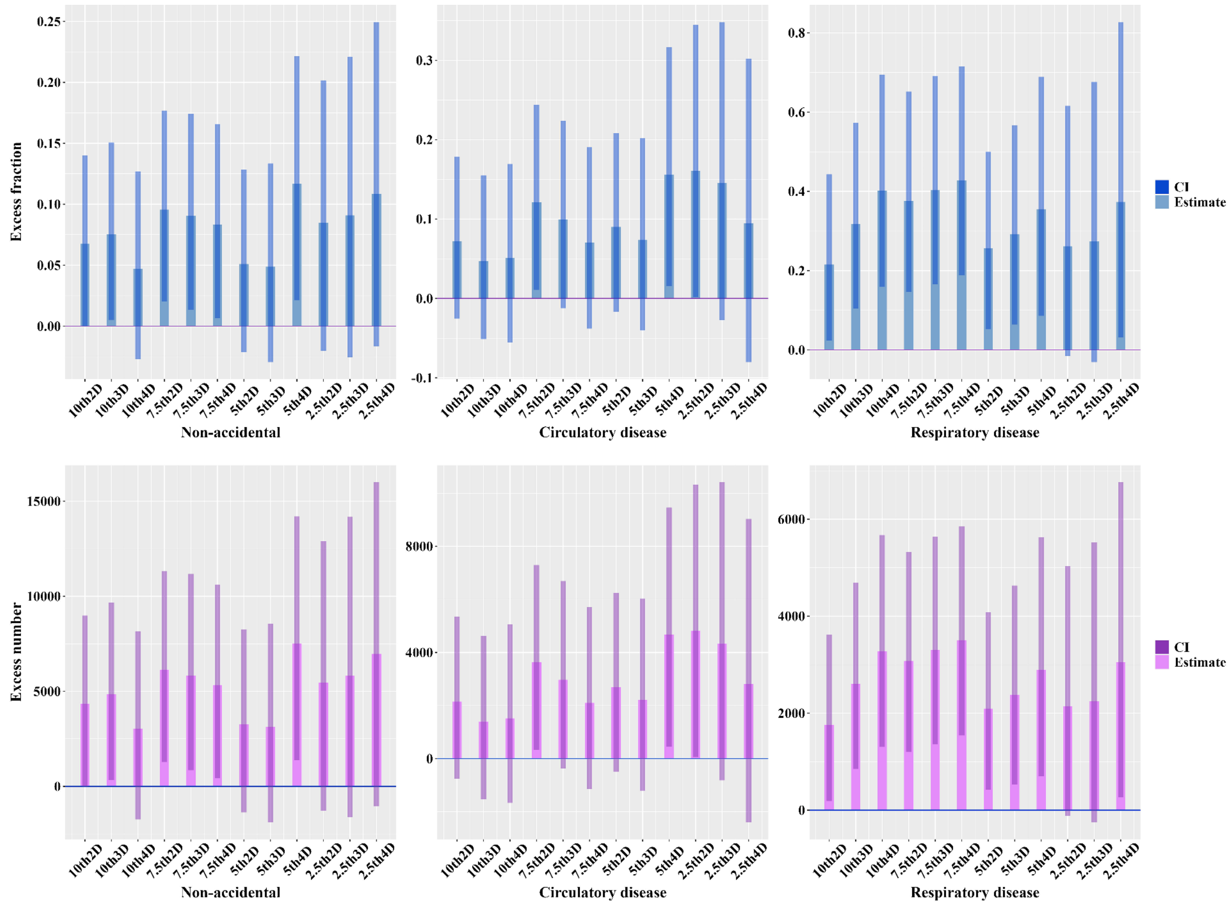

FIGURE 5
Excess fraction and number of excess deaths due to exposure to cold spells and high-level $PM_{2.5}$.

Populations that lived at an altitude of 3,000 m, males, the older adults, and those with lower educational levels seemed to be more susceptible to cold spells. The interaction between cold spells and $PM_{2.5}$ mainly varied across age groups ($p < 0.05$).

This study has identified a significant correlation between cold spells and various causes of death, providing an important supplement to the field of research on the impact of extreme climate conditions on human health. This study found results similar to those in Ningbo (OR 95%CI: 1.156, 1.095–1.221), Tianjin (1.26:1.15–1.39), and Jinan (1.08:1.06–1.11) regarding non-accidental deaths (22, 38, 39). This finding not only confirms the consistency of the increased risk of non-accidental deaths due to cold spells but also highlights the importance of conducting research in different geographical locations. Cold spells significantly impact public health in high-altitude areas. Research data indicate that during the cold period, there is a noticeable increase in the mortality risk in highland areas such as Tibet, Xining, and Yuxi (40–42). For instance, a study focusing on provincial capitals in China shows that during cold waves, the mortality risk in Xining is higher than in other western cities and similar latitude plain areas (22). In Tibet, studies also demonstrate that as temperatures continue to drop, the risk of death increases (42). These findings emphasize that in high-altitude regions, geographic and climatic characteristics play a crucial role in assessing health risks, which is particularly important for developing effective response strategies. In terms of specific disease categories, the risk of death from circulatory disease in this study was close to that in Jinan (1.06:1.03–1.10) (38). For the risk of respiratory disease, this study was close to those in Ningbo (1.444: 1.173–1.777) and Nanjing (1.54:1.16–2.04) (39, 43). These findings further emphasize the importance of protecting the cardiovascular and respiratory systems during cold spell events. Studies in southern China (such as Shenzhen, Guangzhou, and Wuhan) show that the risk of non-accidental deaths, cardiovascular disease, and respiratory disease due to cold spells was higher than the findings of this study (22, 44, 45), which could be related to different climate adaptabilities and cold adaptabilities of populations across regions, highlighting the role of environmental conditions in affecting the health effects of cold spells (46–48). Xining, being exposed to lower temperatures for longer periods, has a stronger cold adaptation. At the same time, significant differences between indoor and outdoor temperatures may exacerbate the risk of death from circulatory and respiratory disease (49, 50). Notably, the heating period in Xining lasts up to half a year, which may further amplify the impact of temperature differences on diseases. Additionally, the heterogeneity of this study's results may stem from inconsistencies in the definition of cold spells, the diversity of research methods, and population size differences. In terms of the risk of diabetes mortality, this study's results were higher than those in Harbin (1.223:1.054–1.418), Chongqing (1.201:1.006–1.434), and Korea (2.02: 1.37–2.99) (51, 52), which may be related to a higher

TABLE 2 The REOI, AP and S of exposure to cold spells and $PM_{2.5}$ on non-accidental mortality, by average altitude, sex, age and education level.

Definition	Altitude		Sex		Age (years)		Educational level	
	2,500 m	3,000 m	Male	Female	0–64	≥65	Low	High
REOI								
7.5th2D	0.226 (0.095 to 0.357)[a]	0.045 (−0.086 to 0.177)	0.126 (0.005 to 0.247)	0.145 (0.002 to 0.289)	0.013 (−0.158 to 0.184)	0.181(0.071 to 0.291)[a]	0.160 (0.060 to 0.259)[a]	−0.023 (−0.274 to 0.227)
7.5th3D	0.296 (0.155 to 0.437)[a]	0.071 (−0.076 to 0.217)	0.188 (0.054 to 0.322)[a]	0.176 (0.022 to 0.33)	−0.024 (−0.221 to 0.172)*	0.259 (0.140 to 0.378)[a]*	0.218 (0.111 to 0.325)[a]	−0.054 (−0.357 to 0.249)
7.5th4D	0.268 (0.114 to 0.422)[a]	0.044 (−0.125 to 0.214)	0.185 (0.036 to 0.335)	0.123 (−0.052 to 0.298)	−0.159 (−0.405 to 0.086)*	0.267 (0.139 to 0.396)[a]*	0.198 (0.077 to 0.319)[a]	−0.099 (−0.437 to 0.238)
AP								
7.5th2D	0.196 (0.172 to 0.22)[a]	0.043 (0.037 to 0.049)	0.121 (0.105 to 0.136)	0.125 (0.108 to 0.142)	0.014 (0.011 to 0.016)	0.158 (0.141 to 0.174)[a]	0.144 (0.13 to 0.158)[a]	−0.024 (−0.030 to −0.017)
7.5th3D	0.258 (0.225 to 0.291)[a]	0.068 (0.058 to 0.078)	0.176 (0.153 to 0.199)[a]	0.157 (0.134 to 0.180)	−0.026 (−0.032 to −0.020)*	0.227 (0.202 to 0.251)[a]*	0.199 (0.178 to 0.22)[a]	−0.051 (−0.068 to −0.035)
7.5th4D	0.241 (0.206 to 0.275)[a]	0.042 (0.035 to 0.049)	0.174 (0.148 to 0.199)	0.112 (0.093 to 0.130)	−0.164 (−0.209 to −0.120)*	0.238 (0.210 to 0.266)[a]*	0.181 (0.160 to 0.202)[a]	−0.100 (−0.136 to −0.063)
S								
7.5th2D	1.244 (1.059 to 1.429)[a]	1.045 (0.895 to 1.196)	1.137 (0.973 to 1.302)	1.143 (0.976 to 1.31)	1.014 (0.798 to 1.230)	1.187 (1.047 to 1.328)[a]	1.168 (1.037 to 1.299)[a]	0.977 (0.712 to 1.242)
7.5th3D	1.348 (1.104 to 1.592)[a]	1.073 (0.896 to 1.250)	1.214 (1.010 to 1.417)[a]	1.186 (0.976 to 1.396)	0.975 (0.752 to 1.198)*	1.293 (1.105 to 1.480)[a]*	1.248 (1.079 to 1.418)[a]	0.951 (0.684 to 1.218)
7.5th4D	1.317 (1.049 to 1.585)[a]	1.044 (0.861 to 1.226)	1.210 (0.984 to 1.436)	1.126 (0.914 to 1.337)	0.859 (0.668 to 1.050)*	1.313 (1.094 to 1.531)[a]*	1.221 (1.041 to 1.401)[a]	0.909 (0.625 to 1.194)

*$p < 0.05$, estimated using the 2-sample z test.

[a]Indicates that cold spells and $PM_{2.5}$ have additive interaction.

comorbidity rate of diabetes patients in this region and other chronic diseases such as hypertension, cerebrovascular disease, kidney disease, etc.

This study reveals that cold spells significantly increase the risk of circulatory and respiratory disease, associated with a series of physiological changes triggered by cold environments. Conditions of cold increase platelet and red blood cell counts, blood viscosity, and arterial pressure, collectively promoting thrombosis (53), and increasing the risk of heart attacks or strokes. Additionally, peripheral vasoconstriction leads to elevated blood pressure (54), further increasing the probability of cardiovascular diseases (55), such as hypertension (56). Regarding the respiratory system, cold environments may increase the number of granulocytes and macrophages in the respiratory tract (57), causing the respiratory mucosa to produce more mucus (58), leading to airway obstruction and inflammation (59). Additionally, it can cause reflexive constriction of the airways (60), increasing the risk of asthma and chronic cough. Furthermore, the cold affects the local immune defense of the respiratory tract (61), increasing the possibility of respiratory infections (62), such as pneumonia. This study further confirms the widespread consensus on the significant association between $PM_{2.5}$ and various causes of death (63, 64). Numerous experimental studies show that $PM_{2.5}$ can increase the risk of cardiovascular diseases by triggering inflammatory responses and oxidative stress (65), affecting vascular function, and promoting arteriosclerosis (66), thereby causing blood pressure to rise and cardiovascular events (67). Inhaling $PM_{2.5}$ also acts directly on the respiratory tract, inducing inflammation and airway allergic reactions, exacerbating diseases like asthma and COPD (65, 68). These findings highlight the importance of reducing $PM_{2.5}$ exposure to lower the risk of related diseases.

Despite increasing studies focusing on the synergistic effects of extreme weather events and $PM_{2.5}$ on human health, a comprehensive assessment of the synergistic effects of cold spells and $PM_{2.5}$ on specific causes of death is still lacking. This study, for the first time, uses the REOI, AP, and S to comprehensively assess the health impacts of cold spells and $PM_{2.5}$ interactions of varying intensities and durations, providing a new perspective for research in this field. This study confirms the synergistic effect of combined exposure to cold spells and $PM_{2.5}$ on specific causes of death, especially in increasing the risk of respiratory deaths, aligning with previous research results from the Shanghai region (69). As the intensity and duration of cold spells increased, the independent impact of the cold spells and their interaction with $PM_{2.5}$ on health appeared to diminish. This phenomenon is partly due to the strict definition of cold waves, which not only reduces the frequency of such events but also integrates with a more efficient early warning system. Therefore, the public is able to receive alerts in a timely manner and take corresponding preventive measures, such as enhancing warmth and limiting outdoor activities, effectively reducing health risks. However, some studies have not observed significant interactions between cold spells and $PM_{2.5}$ (19), even suggesting a possible antagonistic effect between the two (18, 70). These differences may be due to geographical variations, including climate characteristics, residents' adaptability, and differences in assessment methods. Other factors such as socioeconomic status, individual health conditions, and regional public health policies may also influence the results. Additionally, this study reveals that combined exposure to cold spells and high levels of $PM_{2.5}$ can lead to an excess mortality rate of up to 9.56% (95%CI: 2.02, 17.66%; non-accidental deaths). Therefore, optimizing early warning services for extreme weather events by reducing $PM_{2.5}$ exposure can significantly enhance public health protection. This conclusion highlights the importance of integrating air quality management when developing strategies to respond to extreme weather events and taking corresponding measures to reduce $PM_{2.5}$ exposure to mitigate its health impacts.

Our stratified analysis shows that the impact of cold spells varies among different populations, with those living at an average altitude of 3,000 m, males, the older adults, and individuals with lower educational levels being more sensitive. Populations residing at altitudes above 3,000 meters appear to be more sensitive to cold spells, possibly due to the combined effects of low temperatures and low oxygen environments at high altitudes on human physiological mechanisms (71, 72). These conditions may lead to increased blood pressure, and chronic residence can also cause chronic mountain sickness and endothelial dysfunction of the cardiovascular system (73). With increased altitude, the health risks individuals face also increase, including the risks of cardiovascular and respiratory disease (17, 74). From a social perspective, due to economic constraints, regions above 3,000 meters have insufficient heating and insulation facilities compared to lower altitudes. Conversely, the city center, at an altitude of 2,500 meters and with more frequent economic activities, faces the main challenge of higher $PM_{2.5}$ pollution. This also demonstrates the environmental challenges faced by different areas. In cold environments, males show more sensitive physiological responses than females, especially in terms of elevated blood pressure, cardiac responses, and metabolic reactions (75, 76). Meanwhile, short-term cold exposure increases central aortic pressure and cardiac load, further increasing cardiovascular health risks (77). Additionally, males are more likely to engage in outdoor work, experience greater indoor and outdoor temperature differences, and have smoking habits, all of which may diminish their adaptability to extreme environments. With the degradation of physiological processes and the immune system (78, 79), the older adults are more susceptible to extreme weather events and atmospheric pollutants, potentially leading to a higher incidence of pre-existing conditions. Individuals with lower educational levels are more susceptible to cold spells and $PM_{2.5}$, possibly related to factors such as low income, household sanitation conditions, insufficient heating facilities, shallow protective awareness, and demographic structure.

Limitations existed in this study. Meteorological and pollution data came from monitoring stations, not individual exposure data, which might have contributed to exposure inaccuracies. Our meteorological and $PM_{2.5}$ data were outdoor data, and most individuals spent more time indoors in cold weather, ignoring indoor-outdoor temperature differences. Third, the study area was high-altitude, had a peculiar environment, low average temperatures, and a tiny population, limiting generalization.

5 Conclusion

We discovered that cold spells and $PM_{2.5}$ increased particular disease deaths, especially in people who resided at an average altitude above 3,000 meters, males, the older adults, and those with lesser education. Cold spells could synergistically interact with $PM_{2.5}$ to increase the risk of death. Increased cold spell intensity and duration reduced the independent and interaction effects of cold spells and $PM_{2.5}$ on several causes of death. Our study shows that reducing cold spells and $PM_{2.5}$ in high-altitude areas can safeguard public health, with major public health consequences.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the mortality data in this paper cannot be published as they contain a great deal of personal information about the deceased and their families. However, they can be obtained from the corresponding author on reasonable request. Requests to access these datasets should be directed to SH, hehe3991391@126.com.

Ethics statement

The research protocol for this study has been approved by the Ethics Review Committee of the Xining Center for Disease Control and Prevention in Qinghai Province, China (Approval No.: qhxncdcllsc-2024004). All procedures were conducted in accordance with relevant guidelines and regulations. Daily death data were summarized at the city level, were retrospective, and were low-risk studies. All personal information involved in this article was conducted under the supervision of the relevant researchers at the Xining Municipal Center for Disease Control and Prevention, and only secondary aggregated data were used in the analysis, which did not involve participants' names, identifying information, telephone numbers, or residential addresses; therefore, the Ethics Review Committee of the Xining Center for Disease Control and Prevention waived written informed consent.

Author contributions

ZN: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. SH:

Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. QL: Writing – original draft. HM: Data curation, Investigation, Writing – original draft. CM: Resources, Supervision, Writing – review & editing. JW: Resources, Supervision, Writing – review & editing. YM: Data curation, Investigation, Writing – review & editing. YZ: Data curation, Investigation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This study was supported by a grant from the Science and Technology Project of Xining (2022-M-29), but there was no financial support.

Acknowledgments

We appreciate the support and guidance from Yu Wang at the Chinese Center for Disease Control and Prevention (China CDC).

Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1414945/full#supplementary-material

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frontiers | Frontiers in Public Health
TYPE Original Research
PUBLISHED 15 May 2024
DOI 10.3389/fpubh.2024.1384544

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OPEN ACCESS

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RECEIVED 09 February 2024
ACCEPTED 02 May 2024
PUBLISHED 15 May 2024

CITATION
Wen J, Cheng J, Wang L, Li C, Zou Y, Wu J and Liu J (2024) Dynamic molecular choreography induced by acute heat exposure in human males: a longitudinal multi-omics profiling study. *Front. Public Health* 12:1384544. doi: 10.3389/fpubh.2024.1384544

Dynamic molecular choreography induced by acute heat exposure in human males: a longitudinal multi-omics profiling study

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Introduction: Extreme heat events caused by occupational exposure and heat waves are becoming more common. However, the molecular changes underlying the response to heat exposure in humans remain to be elucidated.

Methods: This study used longitudinal multi-omics profiling to assess the impact of acute heat exposure (50°C for 30 min) in 24 subjects from a mine rescue team. Intravenous blood samples were collected before acute heat exposure (baseline) and at 5 min, 30 min, 1 h, and 24 h after acute heat exposure (recovery). In-depth multi-omics profiling was performed on each sample, including plasma proteomics (untargeted) and metabolomics (untargeted).

Results: After data curation and annotation, the final dataset contained 2,473 analytes, including 478 proteins and 1995 metabolites. Time-series analysis unveiled an orchestrated molecular choreography of changes involving the immune response, coagulation, acid–base balance, oxidative stress, cytoskeleton, and energy metabolism. Further analysis through protein–protein interactions and network analysis revealed potential regulators of acute heat exposure. Moreover, novel blood-based analytes that predicted change in cardiopulmonary function after acute heat exposure were identified.

Conclusion: This study provided a comprehensive investigation of the dynamic molecular changes that underlie the complex physiological processes that occur in human males who undergo heat exposure. Our findings will help health impact assessment of extreme high temperature and inspire future mechanistic and clinical studies.

KEYWORDS
acute heat exposure, proteomics, metabolomics, molecular choreography, health

1 Introduction

Prolonged exposure to extreme high temperatures in various industries, including steelmaking, tile production, mining, and rescue operations, can result in harmful health impact (1). Heat exposure can lead to heat-related illnesses encompassing a spectrum of syndromes like heat edema, muscle cramps, heat exhaustion and heatstroke (2, 3). Notably, numerous studies have highlighted moisture and heat as the most perceived adverse factors in deep underground work environments (4–6). For instance, Hunt et al. found that 79% of underground mine workers across three mine sites in northern Australia experienced symptoms of heat illness (7). Additionally, an analysis of hazards faced by mine rescuers revealed that the challenging mine environment led to body overheating and heatstroke, which accounted for 26% of total fatalities (8). Furthermore, several studies have demonstrated that the extreme heat environment places significant physiological and thermoregulatory stresses on firefighters, leading to stress, overexertion, and even death (9–11). In addition to occupational exposure, the general population is also vulnerable to extreme high temperature exposure due to the effects of climate change, including global warming (12). In 2019, heat waves in China resulted in approximately 26,800 deaths (13). Consequently, these studies have sparked significant concerns regarding the potential health impacts of extreme high temperatures on populations that are regularly exposed to heat.

The previous studies primarily concentrated on detailing the phenotypic and physiological reactions linked to heat exposure. Within the deep mine, miners sustained a core body temperature of 38°C throughout most of the day, leading to a notable rise in heart rate and severe dehydration (14, 15). Similarly, firefighters working in hot environments experienced elevated core body temperature, skin temperature, fluid intake, and heart rate (16–18). Another study showed that prolonged heat overload in firefighters working in hot environments increased arterial stiffness and vasodilation (19). These findings highlight the importance of assessing tissue and organ damage and anticipating potential long-term complications after heat exposure. It is crucial to note that delayed monitoring of core temperature or other physiological symptoms may lead to unexpected instances of severe heat-related conditions, such as heatstroke.

Molecular responses induced by extreme high temperatures can provide valuable indications of the physiological and metabolic changes that occur under such conditions. By monitoring these molecular responses, we can gain a better understanding of the body's adaptive capacity to extreme high temperature and assess the potential degree of damage before clear clinical signs of thermal injury emerge. For example, analysis of blood mononuclear gene expression patterns in individuals exposed to extreme heat in a sauna (temperature of 75.7 ± 0.86°C) showed rapid changes in gene expression without a significant increase in core temperature. The reprogrammed transcriptome was mainly inhibitory, as genes involved in protein synthesis, mitochondrial bioenergetics, and immune function showing reduced expression (20). In another study by Bouchama et al. (21) the whole genome transcriptome in peripheral blood mononuclear cells of an adult cohort with heatstroke was examined. It was found that in heatstroke, the heat shock response was robust but failed to restore homeostasis due to proteotoxicity and a reduction in energy production (21). A meta-analysis of public gene expression database from human and mouse samples identified previously overlooked genes responding to heat, such as ABHD3, ZFAND2A, and USPL1 (22). However, knowledge of the response to heat exposure is limited to a small range of molecules and biological processes. This highlights the critical need of a systematic exploration of molecular dynamics in individuals exposed to extreme high temperature environments. In this study, we hypothesize that after heat exposure, the molecules undergo dynamic changes with distinct trends. While some molecules show reversible alterations, others do not. These diverse trends partly reflect the body's adaptive capacity and the extent of damage sustained.

The objective of this study was to perform longitudinal multi-omics profiling of blood components from 24 mine rescuers, before and after a 30 min stay in a simulated extreme high temperature environment (50°C). The goal was to understand the short-term tolerance of humans to extreme high temperature and characterize the detailed series of events that occur in response to acute heat exposure. Our findings revealed an orchestrated molecular choreography of changes involving numerous molecules and pathways, and demonstrate the potential of multi-omics analytes application in monitoring recovery and predict complications following heat exposure. This study provides a comprehensive overview of the physiological processes that occur in humans who undergo extreme high temperature exposure and will inspire novel prevention strategies to reduce organ damage and long-term sequelae.

2 Methods

2.1 Study subjects

In May 2022, 24 participants were enlisted from the National Mine Emergency Rescue Furong Team (China) for this study. The study protocol received approval from the Ethics Review Committee (IRB number, 1351) of West China Hospital of Sichuan University. Prior to engaging in any study procedures, all participants provided written informed consent. A health questionnaire was used to screen for contraindications and/or comorbidities that might have prevented their exposure to extreme high temperatures. None of the participants had a history of underlying cardiovascular disease, cancer, or other chronic illnesses, and none had undergone heat or other stress training within 3 months prior to the study commencement.

2.2 Study design

In a systematic review assessing the impact of occupational heat strain, the studies included in the analysis reported a wide range of wet-bulb globe temperature (WBGT, 19.3 to 52.0°C) and air temperature (21.2–150.0°C, this extreme value was observed in a steel plant worksite) (23). Additionally, the rising global temperatures are pushing the human to endure extreme heat, with temperatures even reaching up to 54°C. As a balance between the intention of extreme high temperature exposure investigation and security considerations, we specifically chose 50°C as the environmental exposure temperature. Regarding the exposure time, a duration of 30 min was used based on the previous study that employed passive whole-body heat exposure (24–26). The research comprised three phases: baseline, exposure, and recovery. The baseline phase spanned from 09:00 am on the day prior to exposure until the day of exposure. The exposure phase occurred between 09:00 and 09:30 am. The recovery phase extended from 09:30 am until 09:30 am the following morning.

2.2.1 Baseline period

Subjects' physical condition was assessed on the day preceding exposure. Oral temperature was measured using a liquid crystal thermometer (Watermark^{TM}). Grip strength of both hands was assessed using a grip dynamometer (EH 101, CAMRY). Objective fatigue was measured using performance tasks (BD-V-302A, BD-V-509A, Beda Qingniao). Pulmonary function was measured using spirometry. Heart function was examined with Doppler echocardiography. Urine specific gravity and pH were evaluated with urinalysis. Blood samples were collected at 07:30 am on the day of exposure.

2.2.2 Exposure period

At 09:00 am on the day of exposure, participants were subjected to a high-temperature environment of 50°C and 37–40% relative humidity for 30 min. This was achieved using a mine roadway simulating test device designed to replicate fire conditions and aid in the training of the National Mine Emergency Rescue Team. Industrial heaters (JH-H150F, Cameron, China) were positioned at both ends of the roadway to generate the heat. Throughout the acute heat exposure, changes in heart rate were monitored using an electrocardiogram patch.

2.2.3 Recovery period

Immediately after the heat exposure, oral temperature, grip strength, objective fatigue, subjective fatigue score, lung function, color Doppler echocardiography, urine samples were detected.

2.3 Objective fatigue

To measure the effects of heat exposure on fatigue, subjects were asked to perform two tasks. First, subjects participated in a bimanual interaction technique, where they controlled a cursor on a computer screen with a joystick using both hands, and the number of cursor-trajectory errors were recorded. Next, subjects participated in a visual reaction time test where they had to press color buttons as soon as corresponding-colored icons appeared on a screen using both hands. Reaction times were recorded.

2.4 Cardiopulmonary function tests

To assess the pulmonary function of subjects, we conducted a specific assay which measured Forced Expiratory Volume in One Second (FEV 1), Forced Vital Capacity (FVC), Vital Capacity (VC), Maximum Voluntary Ventilation (MVV), Maximum Mid-Respiratory Flow (MMF), and Maximum Expiratory Flow at 50% of Vital Capacity (V50). To assess the cardiac function of subjects, Echocardiograms were performed by experienced cardiologists using GE Vivid E9 and E9-S5 probes (1.6–3.2 MHz). According to international consensus guidelines, post-exposure images were obtained immediately after heat exposure, and imaging was satisfactory for all subjects. Echocardiography was analyzed according to the American Society of Echocardiography (ASE) guidelines (2015). Left ventricular function was quantified with the Simpson method using measurements of left ventricular ejection fraction (LVEF), stroke output (SV) and fractional shortening (FS). For statistical analysis of these parameters, Wilcoxon Signed Rank Test was performed as these quantitative data did not adhere to a normal distribution.

2.5 Blood collection and sample preparation

Following a 12-h overnight fast, blood samples were obtained from a vein in the upper forearm at baseline, 5 min, 30 min, and 1 h post-heat exposure, as well as the morning after heat exposure. The blood samples were collected in purple top vacutainers (BD), chilled on ice, and promptly processed. Subsequently, the blood samples were centrifuged at 3000 rpm for 10 min at 4°C. The top layer of EDTA plasma was removed, divided into 8 equal portions, and immediately frozen at −80°C. All blood samples were subjected to multi-level molecular profiling. An untargeted proteomics (proteins) and metabolomics (metabolites) approach was used to analyze the EDTA plasma samples.

2.6 Untargeted proteomics and data processing

Untargeted proteomics used Data independent acquisition (DIA). After the protein extraction from the plasma samples, protein concentration was determined using a BCA protein assay kit. Subsequently, 200 micrograms of each sample was subjected to 120 μL reducing buffer (10 mM DTT, 8 M Urea, 100 mM TEAB, pH 8.0). The solution was incubated at 60°C for 1 h, and IAA was added to the solution for 40 min at room temperature. Then the solutions were centrifuged on the filters at 12,000 rpm for 20 min at 4°C, followed by extensive washing. The purified samples were then subjected to overnight trypsin digestion at 37°C, resulting in the collection of peptides as filtrate. To facilitate further analysis, the peptide mixture was labeled using the TMT Tag Labeling kit. Then, all analyses were performed by a Q-Exactive HF mass spectrometer (Thermo, United States) equipped with a Nanospray Flex source (Thermo, United States). For the subsequent database search, Proteome Discoverer (v.2.4) was utilized to thoroughly search all raw data against the sample protein database. The database search was performed with Trypsin digestion specificity, considering alkylation on cysteine as fixed modifications. To ensure reliable results, a global false discovery rate (FDR) of 0.01 was set, and protein groups were considered for quantification only if they contained at least 2 peptides.

2.7 Untargeted metabolomics from plasma by liquid chromatography (LC)-MS

Plasma samples were prepared and analyzed in a random sequence. Progenesis QI software (v2.3, Non-linear Dynamics) was used to independently analyze data from each mode. Main parameters of 5 ppm precursor tolerance, 10 ppm product tolerance, and 5% product ion threshold were applied for qualitative analysis. Compound identification was conducted using databases such as The Human

Metabolome Database (HMDB), Lipidmaps (V2.3), Metlin, EMDB, and PMDB, as well as self-built databases. A data matrix was created from positive and negative ion data and imported into R for Principle Component Analysis (PCA) to observe overall sample distribution and analysis stability. Orthogonal Partial Least-Squares-Discriminant Analysis (OPLS-DA) and Partial Least-Squares-Discriminant Analysis (PLS-DA) were used to distinguish metabolites that differed between groups, with 7-fold cross-validation and 200 Response Permutation Testing (RPT) used to prevent overfitting. Variable Importance of Projection (VIP) values from the OPLS-DA model ranked the contribution of each variable to group discrimination, and a two-tailed Student's *T*-test verified significant differences in metabolites between groups with VIP values greater than 1.0 and *p*-values less than 0.05.

2.8 Quantification and statistical analysis

2.8.1 Differential expression analysis

Differential expression analysis was performed using the DESeq2 package, with a *q*-value <0.05 and a fold change >2 or fold change <0.5 set as the threshold for significant differential expression analytes. R (v 3.2.0) was employed to conduct hierarchical cluster analysis of the differential expression analytes, illustrating the expression pattern of analytes across different groups and samples.

2.8.2 Pathway enrichment analysis

To identify enriched pathways, Ingenuity pathway analysis (IPA, QIAGEN) was used to assess differentially expressed plasma analytes. The significance of each pathway was determined using hypergeometric probability (one-sided), while Fisher exact test was used to determine enrichment for proteins and metabolites. The *p*-values were corrected for multiple comparisons using the Benjamini-Hochberg method, with FDRs of <0.05 considered significant for proteins or metabolites, respectively. Fold change was estimated for significant molecules using the median of fold change relative to baseline, median of beta coefficients, and median of max (if up) or min (if down) fold change relative to baseline.

2.8.3 Pathway dynamic analysis

Differential expressed analytes (FDR <0.05) were identified, and STRING analysis was used to explore the protein–protein interaction network before and after acute heat exposure. In PPI, proteins are represented as nodes, and edges between nodes represent interactions.

2.8.4 WGCNA analysis

WGCNA was applied to analyze the co-expression modules and key analytes related to hub molecules. An adjacency matrix was transformed into a topological overlap matrix (TOM). Modules were identified with hierarchical clustering (minModuleSize =30). Module eigengenes were calculated. Module eigengenes (ME) and module memberships (MM) were used to determine key modules associated with hub molecules. The ME is defined as the first principal component of a given module and provides a representative expression profile. MM measured the relationship of a gene with the module eigengenes and reflects eigengene connectivity. The functions of metabolites in the key modules were investigated via Kyoto Encyclopedia of Genes and Genomes (KEGG) pathway enrichment analysis.

2.8.5 Fuzzy *c*-mean clustering

The data underwent log2-transformation and *Z*-score scaling before conducting fuzzy *c*-mean clustering with the 'Mfuzz' R package (v2.20.0). The 'elbow' method was utilized to determine the minimum centroid distance or a range of cluster numbers and to select the optimal number. Additionally, *t*-distributed stochastic neighbor embedding (tSNE) scatterplots were generated using the 'Rtsne' R package, with the parameters set as perplexity = 5 and theta = 0.05.

2.9 Enzyme-linked immunosorbent assay

Plasma samples collected at baseline and 5 min, 30 min, 1 h, and 24 h after heat exposure were immediately centrifuged at 3,000 g for 10 min. To validate the key regulators identified by multi-omics analysis, serum levels of VWF, PF4, THBS1, HSP90AB1, and MPO were measured using enzyme-linked immunosorbent assay (ELISA) kits (Mlbio, Shanghai, China), following the manufacturer's instructions. One-Way Repeated Measures ANOVA was employed to investigate the variability of parameters across different time points.

3 Results

3.1 Cohort characteristics and research design

This study included 24 subjects. All were male, with a mean age of 32.9 years, mean height of 170.9 cm, and mean weight of 67.7 kg (Supplementary Table S1). The schematic diagram of experimental process is shown in Figure 1A. In-depth multi-omics profiling was performed, including plasma proteomics (untargeted) and metabolomics (untargeted). After data curation and annotation, the final dataset contained 2,473 analytes, including 478 proteins and 1995 metabolites.

During acute heat exposure, there was an observed increase in heart rate (Figure 1B). Immediately after acute heat exposure, oral temperature rose to 37.2°C compared to 36.6°C at baseline. Cardiopulmonary function parameters with significant changes were also shown. The forced vital capacity (FVC), vital capacity (VC), left ventricular ejection fraction (EF), and fractional shortening (FS) decreased after acute heat exposure (Figure 1C and Supplementary Table S2). For the urinalysis, the urine specific gravity of the participants had no change after acute heat exposure, while the urine PH value decreased (Supplementary Figure S1). As Supplementary Figure S2 shown, the fatigue increased after acute heat exposure.

3.2 Proteins and metabolites expression signature

The boxplot reflected the expression patterns of proteins in each sample, indicating normal proteins expression patterns (Figure 2A). The omics datasets were assessed with principal component analysis, which suggested limited batch effects (Figures 2B,C). Additionally, the heatmap highlighted the expression of differentially expressed metabolites (Figure 2D). Exposure to an extreme high temperature environment of 50°C induced extensive changes in 2473 analytes

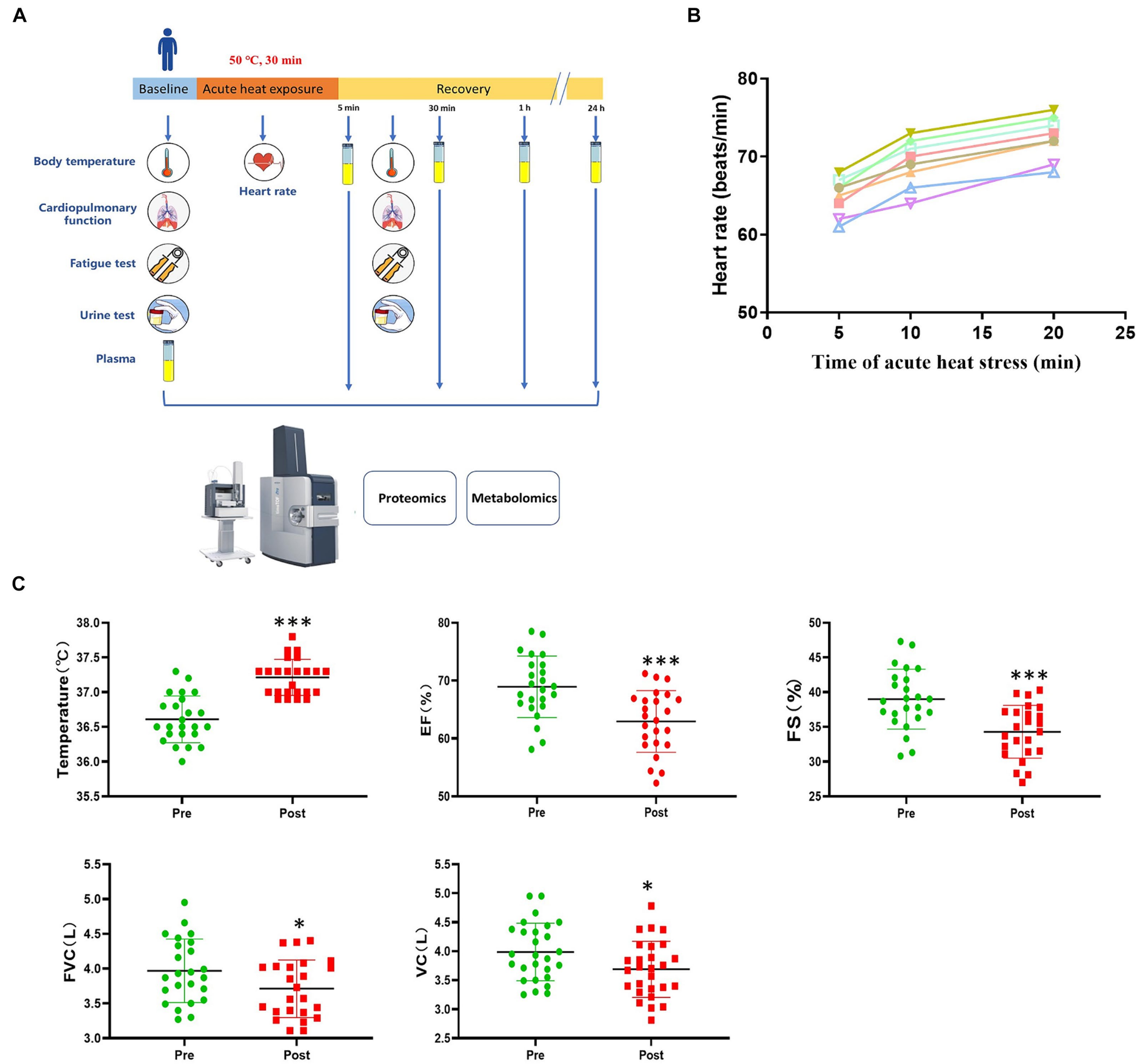

FIGURE 1
Study design and physiological response to acute heat exposure. **(A)** Overview of the study design. Subjects were exposed to an extreme high temperature environment of 50°C and 37–40% relative humidity for 30 min. Subjects underwent a physical examination before and after acute heat exposure. Intravenous blood samples were collected before acute heat exposure (baseline) and at 5 min, 30 min, 1 h, and 24 h after acute heat exposure (recovery) for the multi-omics analysis. **(B)** Heart rate changes were detected during 30 min high temperature environment simulation training. **(C)** Cardiopulmonary function changes in response to acute heat exposure. Core Temperature, the forced vital capacity (FVC), vital capacity (VC), left ventricular ejection fraction (EF), and fractional shortening (FS) were detected at pre- and post- acute heat exposure. * represents $p < 0.05$ and *** represents $p < 0.001$.

spanning multiple omics layers, indicating system-wide changes (Figure 2E). Levels of circulating plasma proteins and metabolites were altered compared to baseline across all time points, and a large proportion of plasma proteins and metabolites remained significantly different from baseline after 24 h of recovery.

3.3 Functional analysis of differentially expressed proteins and metabolites at each time point

As depicted in Figure 3, the biological processes that were altered after heat exposure primarily encompassed immune response, complement activation, extracellular region, ECM-receptor interaction, and glycolysis. Similarly, as illustrated in Figure 4, the metabolic pathways that were affected by heat exposure predominantly involved biosynthesis of unsaturated fatty acids, protein digestion and absorption, amino acid metabolism, cholesterol metabolism, and sphingolipid metabolism. These findings indicated substantial molecular reactions following acute heat exposure, emphasizing the need for further investigation into the temporal dynamics of these molecular responses.

3.4 Time series system-wide proteomics data

Cluster analysis identified four clusters of circulating plasma proteins with different longitudinal trajectories. The levels of some

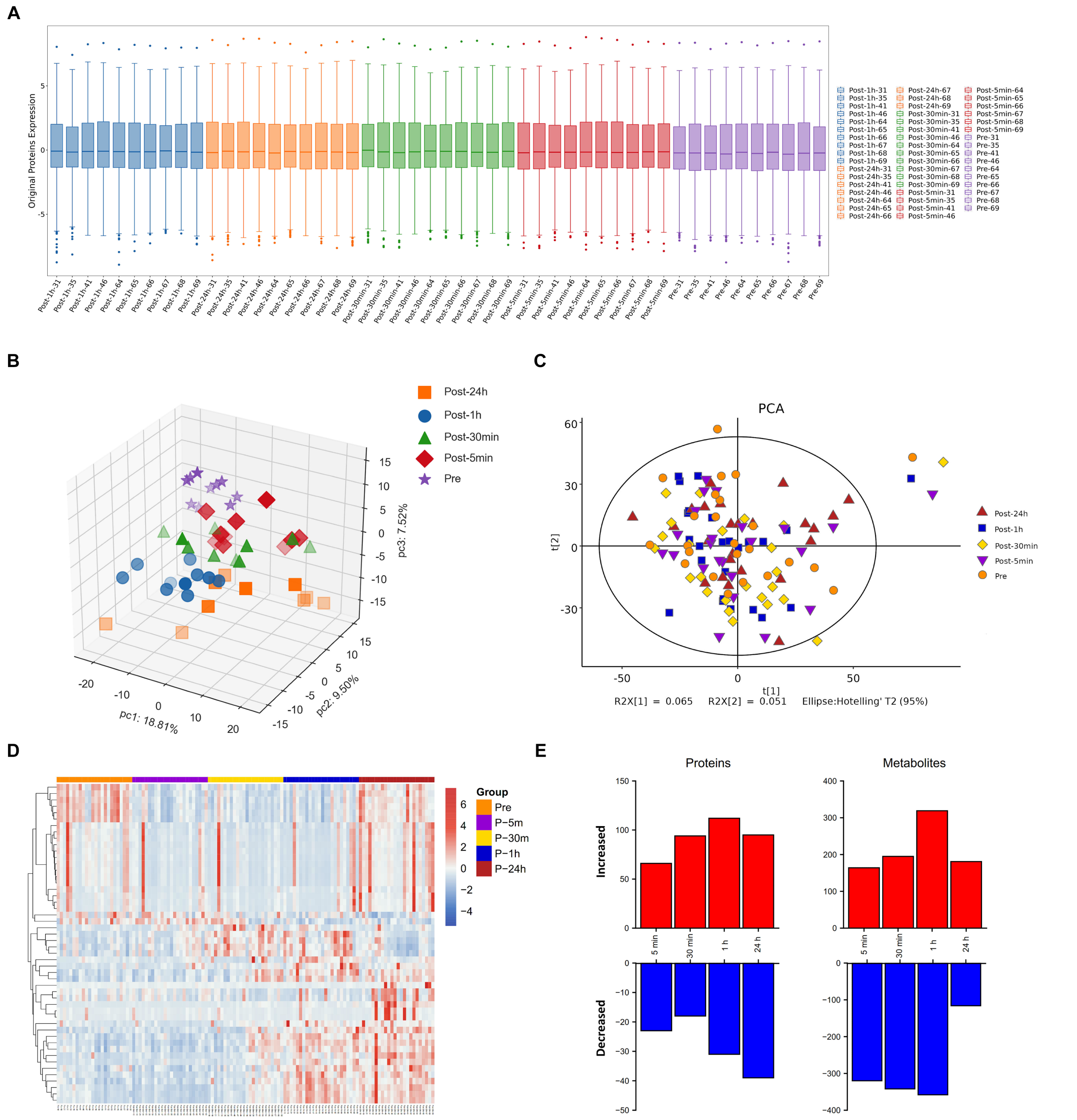

FIGURE 2
Molecular response to acute heat exposure. **(A)** Visualization display of credible protein expression distribution by boxplot. **(B,C)** Principal components analysis using proteomics **(B)** and metabolomics **(C)** data. **(D)** The heatmap showed the expression of differentially expressed metabolites. **(E)** Multi-omics analysis to explore changes in response to acute heat exposure across molecular layers at all the time points.

plasma proteins decreased after acute heat exposure and did not return to baseline within 24 h (cluster 1). The levels of some plasma proteins increased after acute heat exposure and continued to increase during recovery (cluster 2). There was a delayed increase in the levels of some plasma proteins after acute heat exposure (cluster 3). The levels of some plasma proteins increased after acute heat exposure, and quickly returned to baseline (cluster 4) (Figure 5A). Pathway enrichment analysis was performed on each cluster (Supplementary Figures S3, S4). As depicted in Figure 5B, cluster 1 encompassed proteins associated with the immune-related pathways (immune response, antigen binding etc.), cluster 2 included proteins associated with the coagulation-related pathways (blood coagulation, fibrin clot formation, plasminogen activation), cluster 3 consisted of proteins associated with the cytoskeleton and extracellular matrix (structural constituent of cytoskeleton, extracellular region, extracellular space), and cluster 4 comprised proteins associated with oxygen transport (organic acid binding, hemoglobin complex etc.).

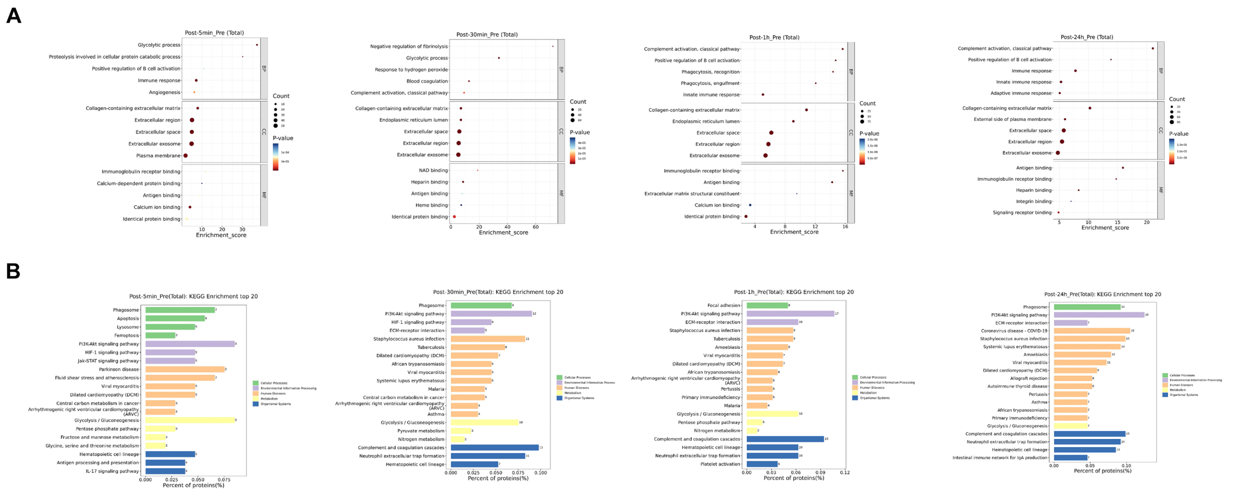

FIGURE 3
The enrichment analysis of protein changes in response to acute heat exposure. **(A)** Go enrichment analysis. The dot color represented pathway significance. The dot size represented number of proteins enriched in pathway. **(B)** KEGG enrichment analysis. Length represented the percent of proteins enriched in pathway.

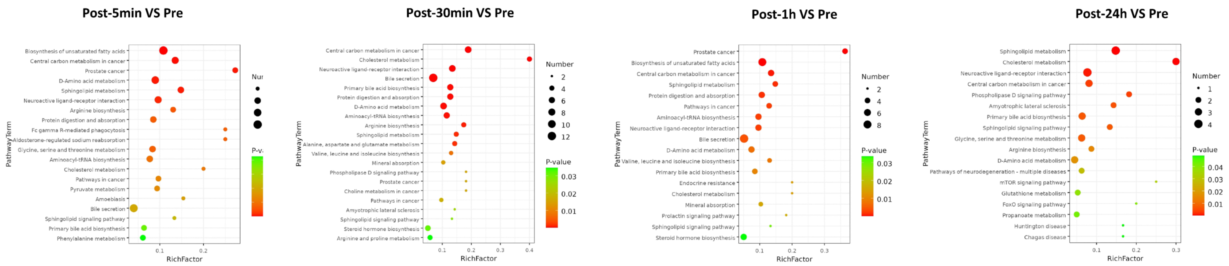

FIGURE 4
The enrichment analysis of metabolism changes in response to acute heat exposure. The dot color represented pathway significance in KEGG enrichment analysis. The dot size represented number of metabolites enriched in pathway.

3.4.1 Cluster 1

Cluster 1 was enriched in molecules associated with the innate and humoral immune response (Figure 5C). There was a sharp decrease in the plasma levels of immunoglobulin related fragments (i.e., IGHV3-73, IGLV6-57, IGHV3-38, IGHV3-15, IGHV3-9, IGHV3-43D, IGHV3-43, IGLL1, IGLV3-25, IGHV1-58, IGKV1-27, IGLV7-46, IGKV1D-33, IGKV1-33, IGHV1-45, IGLV2-11, IGKV1-8, FCGR3B, and IGLV3-1) and pattern recognition receptor (i.e., C-type mannose receptor 2). These data indicated that immune function was suppressed immediately by acute heat exposure and did not recovery in short term.

3.4.2 Cluster 2

Cluster 2 was enriched in molecules associated with the coagulation cascade (platelet glycoprotein V, platelet factor 4, coagulation factor VIII, thrombospondin 1, coagulation factor XIII A chain, coagulation factor IX, coagulation factor X, coagulation factor XII, coagulation factor XIII B chain, coagulation factor V, von Willebrand factor), stress related proteins (serine/threonine-protein kinase/endoribonuclease, heat stress protein 90-beta), and glyceraldehyde-3-phosphate dehydrogenase, which is a key glycolysis rate limiting enzyme (Figure 5D). These data implied elevated blood viscosity, risk of disseminated intravascular coagulation (DIC), anaerobic metabolism and the stress response induced by acute heat exposure.

3.4.3 Cluster 3

Cluster 3 was enriched in proteins of the cytoskeleton and components of intercellular junctions (keratin, type II cytoskeletal 2 epidermal, vimentin, coronin-1A, alpha-actinin-1, keratin, type II, cytoskeletal 1, keratin, type I cytoskeletal 10, keratin, type II cytoskeletal 6B, desmoglein-1, keratin, type II cytoskeletal 6C, matrix Gla protein) (Figure 5E). This could be a result from the degradation of cytoskeleton, a visible component diffusely distributed throughout the cell, caused by acute heat exposure. The damaged cytoskeleton elements were latterly released to the plasma and therefore detected in a delayed manner.

3.4.4 Cluster 4

Cluster 4 was enriched in hemoglobin (hemoglobin subunit alpha, hemoglobin subunit beta, hemoglobin subunit delta), carbonic

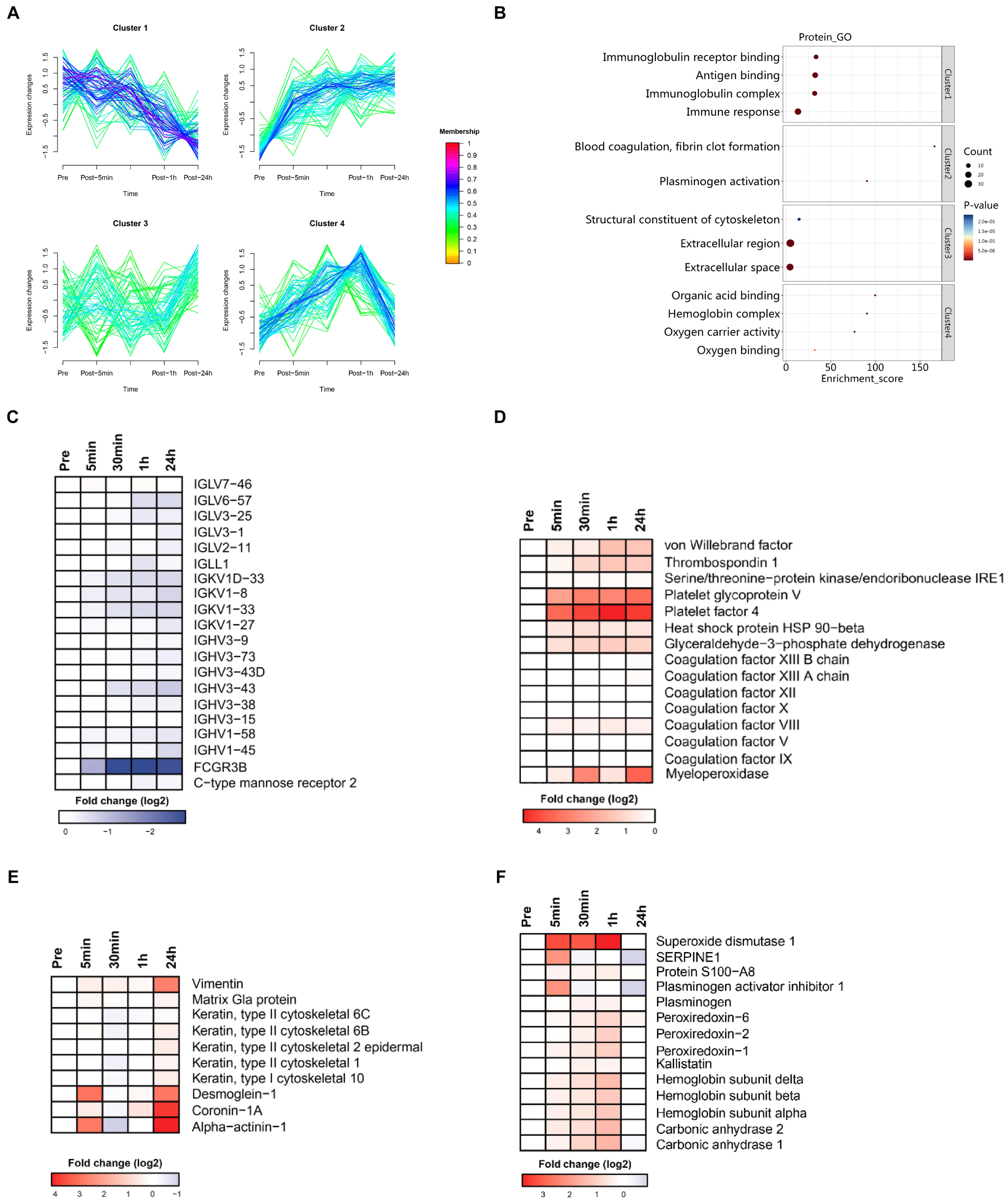

FIGURE 5
Time series system-wide proteomics data. **(A)** Clustering of longitudinal trajectories using significant plasma proteins (FDR <0.05). **(B)** Pathway enrichment analysis. Pathway direction is the median log2 fold change relative to baseline of significant molecules in each pathway (blue, downregulated; red, upregulated). Dot size represents pathway significance. **(C–F)** Heatmaps representing longitudinal trajectories of plasma proteins in cluster 1 **(C)**, cluster 2 **(D)**, cluster 3 **(E)**, and cluster 4 **(F)**. Protein names are listed on the right (blue, downregulated; red, upregulated).

anhydrase (carbonic anhydrase 2, carbonic anhydrase 1), plasminogen, S100A8, the anti-fibrinolytic system (plasminogen activator inhibitor 1) and antioxidants (peroxiredoxin-2, peroxiredoxin-6, kallistatin, superoxide dismutase 1) (Figure 5F). These data implied that hemoglobin and the maintenance of acid–base balance were mobilized under acute heat exposure and the fibrinolytic system and antifibrinolytic system were activated, possibly due to increased coagulation.

3.5 Time series system-wide metabolomics data

Cluster analysis identified six clusters of circulating plasma metabolites with different longitudinal trajectories. The levels of some plasma metabolites increased after acute heat exposure and did not return to baseline within 24 h (cluster 1). The levels of some plasma metabolites underwent a transient increase after acute heat exposure but followed by a decrease during recovery (cluster 2). The levels of some plasma metabolites decreased after acute heat exposure and returned to baseline within 24 h (cluster 3, cluster 4). The levels of some plasma metabolites increased after acute heat exposure and returned to baseline within 24 h (cluster 5, cluster 6) (Figure 6A).

Pathway enrichment analysis was performed on each cluster (Supplementary Figure S5). Cluster 1 was associated with alanine, aspartic acid, and glutamic acid metabolism. Cluster 2 was associated

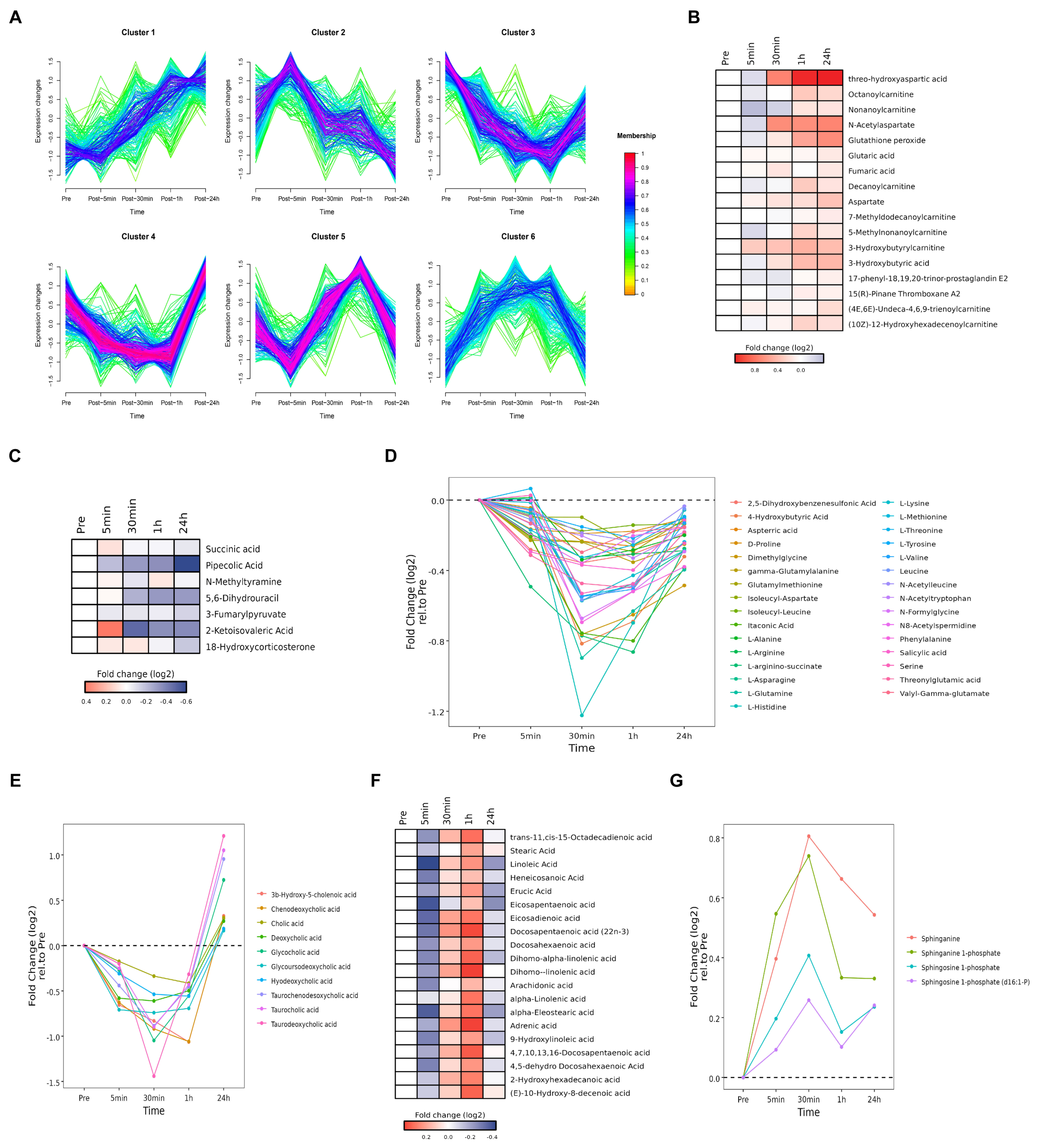

FIGURE 6
Time series system-wide metabolomics data. **(A)** Clustering of longitudinal trajectories using significant plasma metabolites (FDR <0.05). **(B,C,F)** Heatmaps representing longitudinal trajectories of plasma metabolites in cluster 1 **(B)**, cluster 2 **(C)** and cluster 5 **(F)**. Metabolite names are listed on the right (blue, downregulated; red, upregulated). **(D,E,G)** Time chart representing longitudinal trajectories of plasma metabolites in cluster 3 **(D)**, cluster 4 **(E)**, and cluster 6 **(G)**. Metabolite names are listed on the right.

with steroid hormone biosynthesis. Cluster 3 was associated with amino acid metabolism. Cluster 4 was associated with cholesterol metabolism. Cluster 5 was associated with the biosynthesis of unsaturated fatty acids. Cluster 6 was associated with sphingolipid metabolism.

3.5.1 Cluster 1

Cluster 1 was enriched in alanine, aspartic acid, and glutamic acid metabolites (i.e., threo-hydroxyaspartic acid, aspartate, *N*-acetylaspartate, fumaric acid, and glutaric acid) and carnitine and acyl carnitine metabolites [i.e., 3-hydroxybutyric acid, (10Z)-12-hydroxyhexadecenoylcarnitine, (4E,6E)-undeca-4,6,9-trienoylcarnitine, 3-hydroxybutyrylcarnitine, 5-methylnonanoylcarnitine, 7-methyldodecanoylcarnitine, decanoylcarnitine, nonanoylcarnitine, octanoylcarnitine] (Figure 6B). Accumulation of carnitine and acyl carnitine metabolites likely reflected disordered fatty acid metabolism. Accumulation of glutathione peroxide reflected oxidative stress. Accumulation of 17-phenyl-18,19,20-trinor-prostaglandin E2 and 15(R)-pinane thromboxane A2 suggested endothelial damage and increased coagulation.

3.5.2 Cluster 2

Cluster 2 was enriched in metabolites associated with tyrosine metabolism (i.e., *N*-methylamine, 3-fumarylpyruvate), pantothenate and CoA biosynthesis (i.e., 5,6-dihydrouracil, 2-ketoisovalic acid), and lysine decomposition (i.e., succinic acid, pipecolic acid) (Figure 6C). These data implied acute heat exposure was associated with the use of amino acids as an energy source. Accumulation of mineralocorticoid (i.e., 18-hydroxycorticosterone carbohydrate) suggested alterations in the regulation of water and salt balance.

3.5.3 Cluster 3

Cluster 3 was enriched in amino acids (i.e., L-tyrosine, L-argininosuccinate, threonylglutamic acid, itaconic acid, *N*-acetyltryptophan, gamma-glutamylalanine, 2,5-dihydroxybenzenesulfonic acid, dimethylglycine, L-arginine, D-proline, isoleucyl-leucine, glutamylmethionine, aspterric acid, L-methionine, *N*-formylglycine, valyl-gamma-glutamate, *N*-acetylleucine, L-valine, 4-hydroxybutyric acid, salicylic acid, L-asparagine, L-glutamine, N8-acetylspermidine, isoleucyl-aspartate, L-histidine, L-lysine, L-threonine, leucine, serine, L-alanine, phenylalanine) (Figure 6D). These data implied acute heat exposure was associated with the use of amino acids as an energy source, suggesting protein supplementation may be helpful after exposure to extreme heat.

3.5.4 Cluster 4

Cluster 4 was enriched in bile acid metabolites, including chenodeoxycholic acid, 3β-hydroxy-5-cholenoic acid, hyodeoxycholic acid, glycoursodeoxycholic acid, cholic acid, deoxycholic acid, deoxycholic acid, glycocholic acid, taurochenodesoxycholic acid, taurocholic acid and taurodeoxycholic acid (Figure 6E). These data implied acute heat exposure was associated with alterations in bile acid metabolism.

3.5.5 Cluster 5

Cluster 5 was enriched in free fatty acids, including dihomo-linolenic acid, dihomo-alpha-linolenic acid, 4,7,10,13,16-docosapentaenoic acid, *trans*-11,*cis*-15-octadecadienoic acid, 4,5-dehydro docosahexaenoic acid, docosahexaenoic acid, alpha-eleostearic acid, docosapentaenoic acid (22n-3), 9-hydroxylinoleic acid, adrenic acid, 2-hydroxyhexadecanoic acid, (E)-10-hydroxy-8-decenoic acid, eicosadienoic acid, erucic acid, linoleic acid, arachidonic acid, heneicosanoic acid, eicosapentaenoic acid, α-linolenic acid, and stearic acid (Figure 6F). Accumulation of free fatty acids might be due to the inhibition of heat production and reduce of fatty acid digestion.

3.5.6 Cluster 6

Cluster 6 was enriched with products of sphingomyelin metabolism [i.e., sphinganine, sphinganine 1-phosphate, sphingosine 1-phosphate, sphingosine 1-phosphate (d16:1-P) (Figure 6G)]. Metabolites of sphingomyelin are important signaling molecules, which may be involved in regulating cell proliferation, immune function, inflammatory reactions, and oxidative stress.

3.6 Identification of hub molecules involved in the response to acute heat exposure

The levels of some plasma proteins continued to increase after acute heat exposure, implying they are key regulators of heat exposure. To assess the interaction of these plasma proteins and identify potential plasma proteins modulating the response to acute heat exposure, protein–protein interaction analysis was performed. Several important nodes, corresponding to VWF, PF4, THBS1, HSP90AB1, and MPO, were revealed (Figure 7A). These proteins were also validated using ELISA, which showed their levels increased after acute heat exposure (Figures 7B–F and Supplementary Table S3).

Additionally, weighted correlation network analysis measured the co-expression relationship between VWF, PF4, THBS1, HSP90AB1, MPO and plasma metabolites. Hierarchical clustering with dynamic tree cut methods were applied to identify metabolite modules (Figure 7G). Pearson's correlation coefficient showed HSP90AB1, VWF, PF4 and THBS1 were associated with metabolite modules, identifying HSP90AB1, VWF, PF4 and THBS1 as hub proteins. HSP90AB1 was correlated with the green metabolite module and the cyan metabolite module. VWF was correlated with the lightcyan metabolite module and the blue metabolite module. PF4 was correlated with the yellow metabolite module, the purple metabolite module, and the turquoise metabolite module. THBS1 was correlated with the yellow metabolite module, the purple metabolite module, the turquoise metabolite module, and the green-yellow metabolite module (Figure 7H). KEGG pathway enrichment analysis was performed on the metabolites in the key modules correlated with the hub proteins (Supplementary Figure S6). These modules were enriched in fructose and mannose metabolism, choline metabolism, cholesterol metabolism, histidine metabolism, carbohydrate digestion and absorption, and sphingolipid metabolism. The data implied a regulatory role of HSP90AB1, VWF, PF4 and THBS1 to metabolites in acute heat exposure.

3.7 Multi-omics prediction of body temperature and cardiopulmonary parameters

Multi-omics data at the time point immediately after acute heat exposure was used to assess the relevance of clinical data for

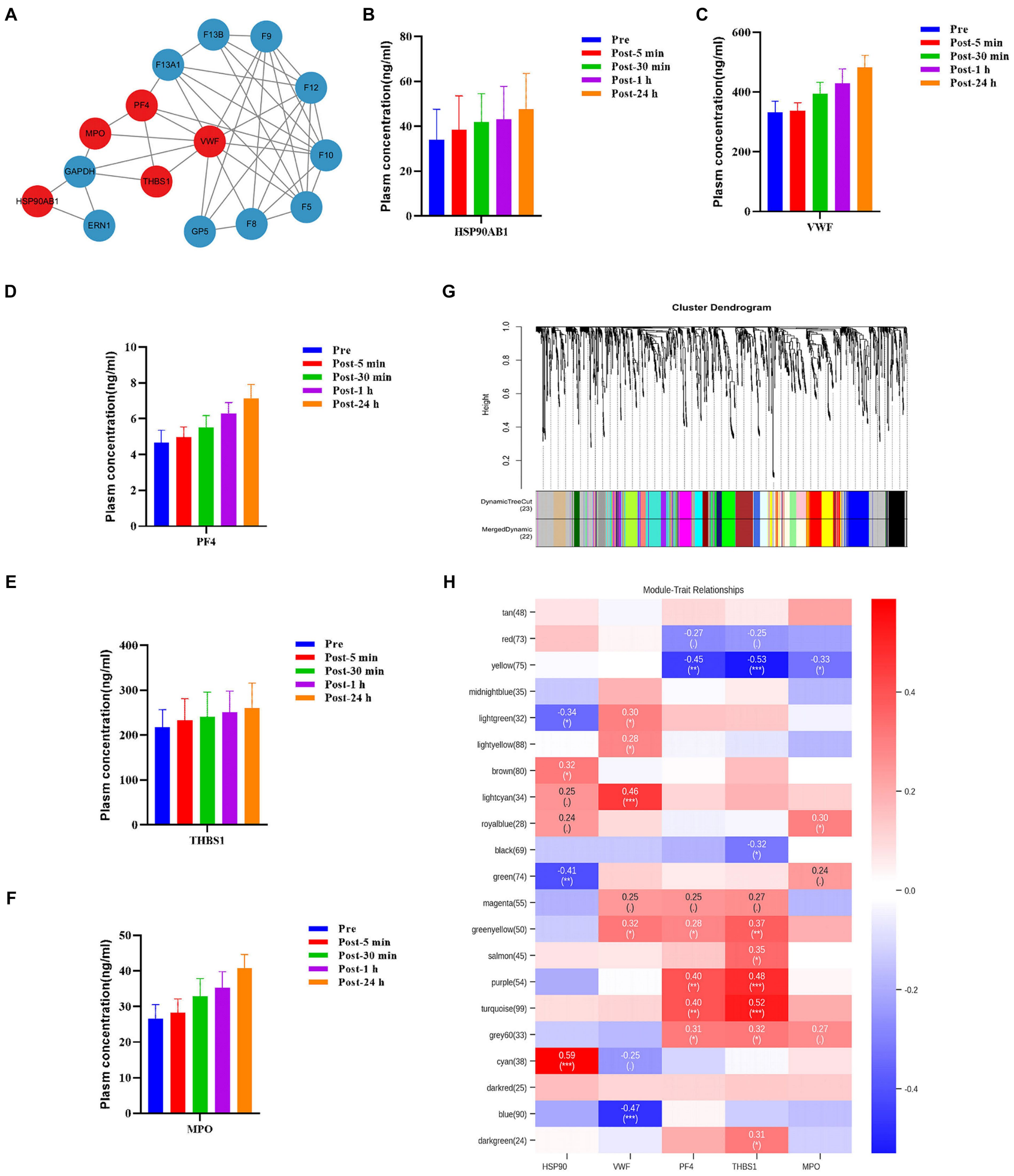

FIGURE 7
Hub molecules associated with acute heat exposure. **(A)** Protein–protein interaction after acute heat exposure produced by STRING. Line thickness indicates the strength of data support for each interaction. Red colored proteins were associated with acute heat exposure. **(B–E)** Plasma HSP90β, VWF, PF4, THBS1, and MPO levels before and after acute heat exposure were detected by enzyme-linked immunosorbent assay. **(G)** Clustering dendrogram of differentially expressed metabolites. Clustering was based on dissimilarity of metabolites. **(H)** Heatmap of the correlation between metabolites modules and the plasma proteins HSP90, VWF, PF4, THBS1, and MPO.

immediately detecting acute heat exposure. Correlation analysis identified a set of biomarkers that were highly predictive of changes in body temperature, FVC VC, EF, and FS (Figure 8). Body temperature was correlated with metabolites of ascorbic acid and *N*-acetyl-D-tryptophan. FVC was correlated with the metabolites of acetylphenol sulfate and chlorobenzoic acid. VC was correlated with the plasma protein adhesion G protein-coupled receptor L4. EF and FS were correlated with the plasma proteins integrin alpha-5 and creatine kinase M-type, metabolites of amdoxovir and docosahexaenoic acid. These biomarkers have been previously associated with body

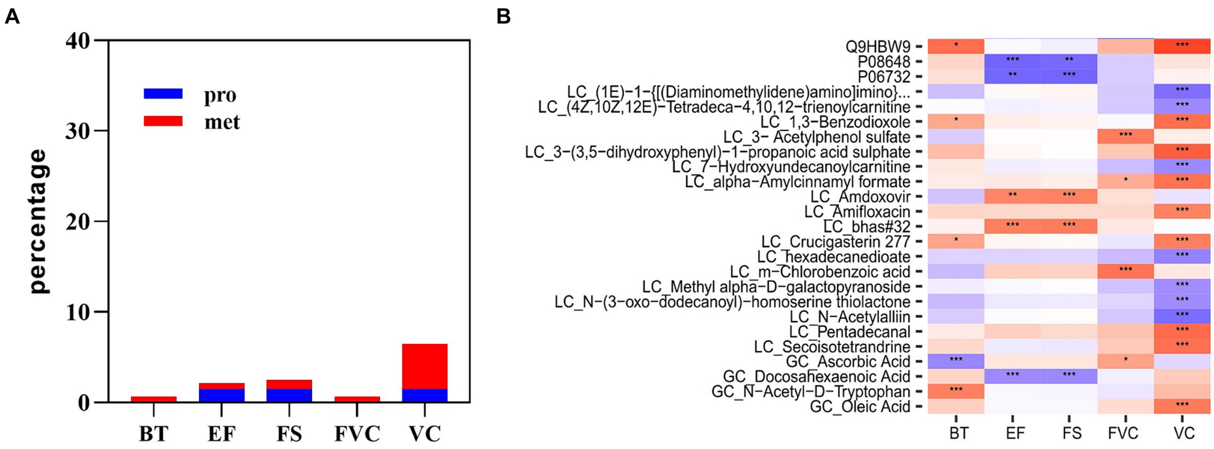

FIGURE 8
Multi-omics prediction of body temperature and cardiopulmonary function. **(A)** The proportion of plasma proteins and metabolites associated with body temperature and cardiopulmonary parameters. **(B)** Heatmap showing the correlations between plasma analytes and body temperature and cardiopulmonary parameters. * represents $p < 0.05$, ** represents $p < 0.01$ and *** represents $p < 0.001$.

temperature and the cardiopulmonary system, highlighting their clinical value (27–30).

4 Discussion

The increasing global temperatures and incidence of occupational exposure to extreme high temperatures require enhanced understanding of how heat exposure impacts human health (31). This study investigated the short-term tolerance of humans to extreme high temperatures and characterized the detailed series of events that occur in response to acute heat exposure (50°C). Longitudinal multi-omics profiling of plasma components revealed acute heat exposure affected physiological processes in a time-dependent manner. These physiological processes included the immune response, coagulation, acid–base balance, oxidative stress, cytoskeleton maintenance, and energy metabolism. Time series data showed variations in the dynamics of these physiological processes and the molecular changes underlying the response to acute heat exposure. HSP90AB1, VWF, PF4, and THBS1 were identified as key regulators of the physiological processes involved in the response to acute heat exposure. A small number of blood-based analytes were predictors of changes in cardiopulmonary function, with potential for use as a clinical tool to evaluate the health risks of heat exposed populations.

4.1 Physiological performance in acute heat exposure

In this study, the physiological performance of the subjects was detected. We found that during heat exposure, subjects exhibited typical physiological reactions, such as increased heart rate, to ensure proper circulation of tissues. However, after heat exposure, subjects suffer some impairment of cardiac function, which may be related with the fluid loss or the impaired vascular function (18, 32). Furthermore, our study revealed a decrease in lung function following heat exposure. This finding aligns with a previous study that found a consistent association between each 1°C increase in lifetime summer mean temperature and a 1.07% decrease in forced vital capacity (FVC) (33). These findings suggested that the subjects included in our study exhibited some adaptive responses to acute heat exposure but experienced a slight decline in their cardiopulmonary function. To mitigate these effects, it is advisable to implement preventive measures such as adequate hydration before, during, and after heat exposure, and monitoring individuals for signs related to heat exposure. Additionally, ensuring proper acclimatization to heat and providing education on heat exposure management can help enhance the resilience of individuals facing acute heat exposure.

4.2 Immune response in acute heat exposure

Although there were no significant changes in the vital clinical signs of the subjects after extreme high temperature exposure, the changes in molecular reactions still indicated the potential increased risk after heat exposure. With respect to the immune response, the present study showed that synthesis of immunoglobulin was reduced after heat exposure, indicating the decreased immune function even short time exposure to extreme high temperature. This finding is consistent with previous reports. An investigation of individuals who worked in the foundry showed chronic heat exposure was associated with a decrease in the number of white blood cells (34). Additionally, Chen et al. (35) found the strong associations between heat waves and emergency department visits for intestinal infection. Studies of patients hospitalized for heat stroke during sustained heatwaves have reported a high incidence of urinary, blood or lung infections during recovery (36–38). This phenomenon may be related to abnormal development and decreased number of lymphocytes (39). Findings from a mouse model with heat exposure showed that whole blood collected 30 days after recovery from heat exposure exhibited an immunosuppressive phenotype (40).

4.3 Coagulation in acute heat exposure

Coagulation disorders accompany heat-related illness, and severe DIC caused by heatstroke can be fatal (41–43). Findings from the present study imply that coagulation, fibrinolytic and anti-fibrinolytic processes are mobilized in the initial phase of heat exposure. In particular, coagulation-related factors, including VWF, PF4, and THBS1, remained elevated 24 h after acute heat exposure. VWF binds the glycoprotein Iba on platelets causing platelet adhesion, activation and aggregation, which is crucial for hemostasis and thrombosis (44, 45). PF4, also known as chemokine (C-X-C motif) ligand 4, has the ability to bind with negatively charged polyanions such as VWF, resulting in the formation of immune complexes that can contribute to the development of thrombosis (46). THBS1, which is produced by platelets when stimulated by thrombin, plays a role in platelet aggregation (47). The increase in coagulation related factors reflects a hypercoagulant state suggesting that modulating coagulation early after exposure to high temperature may be beneficial for preventing heat-related illness. In previous studies, various anticoagulants, such as antithrombin III, recombinant thrombomodulin and tissue factor pathway inhibitors, had been used to prevent heatstroke (48, 49).

4.4 Acid–base balance in acute heat exposure

Acid–base balance is regulated by hemoglobin and carbonic anhydrase levels, which increased in response to acute heat exposure in the present study. Hemoglobin in red blood cells binds oxygen and releases hydrogen ions (50). Carbonic anhydrase catalyzes the reversible hydration of carbon dioxide (CO_2) to form carbonic acid (H_2CO_3) in the lungs, kidneys, and red blood cells (51). Previous studies showed that weekly heat training increases elite cyclists or cross-country skiers' hemoglobin mass, enhancing their ability to use oxygen (52–54). In the present study, the increases in hemoglobin and carbonic anhydrase were temporary and returned to baseline levels the day after acute heat exposure, indicating that repeated heat exposures are needed to maintain increased levels of hemoglobin and carbonic anhydrase.

4.5 Oxidative stress in acute heat exposure

Oxidative damage may be induced by chronic and long-term heat exposure, which enhances GST and GPX enzymatic activity and nitric oxide concentration (55, 56). Consistent with this, the present study showed prooxidants such as MPO and S100A8 were upregulated after acute heat exposure. Interestingly, some antioxidants (peroxiredoxin-2, peroxiredoxin-6, kallistatin, superoxide dismutase 1) were induced to resist harmful effects. Peroxiredoxin-2, peroxiredoxin-6 and superoxide dismutase are antioxidant enzymes that protect organisms from oxidative damage caused by reactive oxygen species (ROS) (57, 58). Kallistatin antagonizes TNF-α-induced oxidative stress, and its active site is crucial for stimulating antioxidant enzyme expression (59). Previous reports showed the negative effects of heat exposure on oxidative status might be alleviated by dietary antioxidant supplementation (60, 61). The present study adds to this growing body of evidence.

4.6 Energy metabolism in acute heat exposure

Energy metabolism was altered by acute heat exposure. Levels of circulating plasma metabolites, such as amino acids, free fatty acids, bile acid, carnitine and sphinganine, were changed. Amino acid levels decreased over time as they were catabolized for energy generation. Acylcarnitines and fatty acids accumulated after acute heat exposure. This may be due to the transformation of beige adipocytes into white adipocytes, which can inhibit adipocyte heat production and reduce fatty acid digestion (62). Sphinganine levels increased briefly, confirming the role of sphingosine as a potent regulator of signaling pathways. Levels of the bile acids chenodeoxycholic acid, cholic acid and deoxycholic acid decreased, which might be associated with the decrease in that was observed in high-temperature environments (63).

4.7 Potential regulators and biomarkers associated with acute heat exposure

Levels of some circulating plasma proteins (PF4, F13A1, F13B, F9, F12, F10, F5, F8, GP5, VWF, THBS1, MPO, GAPDH, HSP90AB1, and ERN1) continued to increase during the recovery phase after acute heat exposure, implying these proteins are potential regulators of important physiological processes involved in the response to acute heat exposure. Protein–protein interaction and WGCNA analyses identified HSP90AB1, VWF, PF4, and THBS1 as hub proteins. In previous literature, HSP90AB1, VWF, PF4, and THBS1 have been documented to exert substantial influence on various aspects of cell function. HSP90AB1, also known as HSP90β, serves as molecular chaperones to maintain protein stability and has protective roles in response to various kinds of cellular stress, such as heat exposure (64, 65). VWF, PF4, and THBS1 play a critical role in coagulation and regulate immune cells and inflammatory responses (66–68).

After heat exposure, we found that the changes in the levels of certain plasma molecules were significantly correlated with the changes in clinical parameters. Notably, some of these molecules have previously been associated with clinical parameters, suggesting their potential clinical value in predicting functional changes following heat exposure. One of such molecules is *N*-Acetyl-D-Tryptophan, which showed a positive correlation with body temperature after acute heat exposure. This molecule is a derivative of tryptophan and can be metabolized into 5-hydroxytryptamine (5-HT), and activation of 5-HT receptors can lead to an increase in body temperature (69, 70). Furthermore, we observed that the increase of creatine kinase M-type leptin and the decline in docosahexaenoic acid were found to be correlated with the decline in cardiac function after heat exposure. Creatine kinase, an enzyme involved in ATP production and utilization, has been extensively studied as potential risk marker for cardiovascular events (71). Docosahexaenoic acid is an omega-3 fatty acid, which is found to have positive effects on cardiac function and significantly decreases the overall mortality in patients diagnosed with coronary heart disease (72). Additionally, we found adhesion G protein-coupled receptor L4 (ADGRL4) was positively associated with pulmonary function after acute heat exposure. ADGRL4 is an orphan adhesion GPCR expressed in endothelial cells that can induce vascular normalization and immune suppression (73), which may contribute to protecting lung function.

4.8 Limitations

This study had some limitations. The sample size was small and did not include females or the older adult. Owing to the safety consideration for subjects, the max tolerance time was not detected, and the relative humidity were not set at a high level, which had obvious effect on human's tolerance time of extreme high temperature. Therefore, molecular changes associated with life-threatening heatstroke could not be explored under the current experimental setting. Furthermore, while this study provided a comprehensive analysis of molecular changes in response to acute heat exposure, the potential regulators and biomarkers identified require additional validation in larger and more diverse populations. Additionally, although the study identified potential biomarkers predictive of changes in body temperature and cardiopulmonary parameters, the clinical significance and practical applications of these findings are yet to be determined. Further studies are needed to evaluate the usefulness of these biomarkers in real-world settings.

5 Conclusion

Overall, this study offered insights into key research blanks in health impact assessment of heat exposure. Longitudinal multi-omics profiling identified thousands of molecules that were affected by acute heat exposure, and time-series clustering and network analysis revealed crosstalk between inflammation, coagulation, immunity, acid–base balance, metabolism, and oxidative stress. Potential regulators and biomarkers for acute heat exposure were revealed. These findings have significant implications for both occupational population exposed to heat and the general population during extreme heat environment. It will help to improve the prediction of short-term health outcomes in acute heat exposure and develop prevention strategies to heat-related injuries and mitigate the adverse effects of heat exposure.

Data availability statement

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

Ethics statement

The studies involving humans were approved by The Ethics Review Committee of West China Hospital of Sichuan University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JWe: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. JC: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. LW: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. CL: Data curation, Methodology, Writing – original draft. YZ: Data curation, Investigation, Writing – original draft. JWu: Conceptualization, Formal analysis, Funding acquisition, Visualization, Writing – review & editing. JL: Conceptualization, Formal analysis, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The support provided by 1.3.5 project for disciplines of excellence, West China Hospital, Sichuan University (ZYJC21048), Foundation of Sichuan Provincial Science and Technology Program (2022JDR0091, 2023NSFSC0004, 2023NSFSC0639, 2023NSFSC1742 and 2021YFS0134), 2020 Cooperation project for Sichuan University and Yibin Municipal People's Government (2020CDYB-35), cooperation project for academician & experts workstation (HXYS20001) and Sichuan University Education Foundation (0040206107011), National Natural Science Foundation of China (No.82371883).

Acknowledgments

We are grateful to OE Biotech, Inc., (Shanghai, China) for assisting in sequencing and/or bioinformatics analysis.

Conflict of interest

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

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1384544/full#supplementary-material

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frontiers | Frontiers in Public Health

TYPE Original Research
PUBLISHED 19 June 2024
DOI 10.3389/fpubh.2024.1409563

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OPEN ACCESS

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RECEIVED 30 March 2024
ACCEPTED 06 June 2024
PUBLISHED 19 June 2024

CITATION
Chen S, Zhao J, Dou H, Yang Z, Li F, Byun J and Kim SW (2024) A study on the monitoring of heatwaves and bivariate frequency analysis based on mortality risk assessment in Wuhan, China.
Front. Public Health 12:1409563.
doi: 10.3389/fpubh.2024.1409563

A study on the monitoring of heatwaves and bivariate frequency analysis based on mortality risk assessment in Wuhan, China

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The increasingly frequent occurrence of urban heatwaves has become a significant threat to human health. To quantitatively analyze changes in heatwave characteristics and to investigate the return periods of future heatwaves in Wuhan City, China, this study extracted 9 heatwave definitions and divided them into 3 mortality risk levels to identify and analyze historical observations and future projections of heatwaves. The copula functions were employed to derive the joint distribution of heatwave severity and duration and to analyze the co-occurrence return periods. The results demonstrate the following. (1) As the concentration of greenhouse gas emissions increases, the severity of heatwaves intensifies, and the occurrence of heatwaves increases significantly; moreover, a longer duration of heatwaves correlated with higher risk levels in each emission scenario. (2) Increasing concentrations of greenhouse gas emissions result in significantly shorter heatwave co-occurrence return periods at each level of risk. (3) In the 3 risk levels under each emission scenario, the co-occurrence return periods for heatwaves become longer as heatwave severity intensifies and duration increases. Under the influence of climate change, regional-specific early warning systems for heatwaves are necessary and crucial for policymakers to reduce heat-related mortality risks in the population, especially among vulnerable groups.

KEYWORDS
heatwave risk, copula function, global climate models, co-occurrence return periods, Wuhan city

1 Introduction

The sixth assessment report by the Intergovernmental Panel on Climate Change stated that the use of fossil fuels and unsustainable land use have contributed to global warming; the global average surface temperature between 2011 and 2020 has been reported to be about 1.1°C hotter than the pre-industrial level, and the frequency of high heat episodes per 50-year period increased by 4.8 times (1). Expanding urban land use will encroach on ecological space such as grasslands, cropland and unutilized land, and this unsustainable land-use competition will exacerbate the occurrence of heatwave events (2). Consistent with anthropogenically driven climate warming, the frequency and severity of extreme temperatures and heatwaves worldwide are expected to increase in the coming decades, posing pervasive threats to both human systems and ecosystems and generally having adverse effects on human physical and mental health, livelihoods, infrastructure, and a range of other global aspects (3). Almost half the global population is likely to be exposed to life-threatening temperature extremes annually by 2,100 (4). It was estimated that, in 43 countries globally from 2000 to 2019, 9.43% of deaths per year were attributable to temperatures that were either too low or too high, and excess deaths due to high temperatures accounted for 0.91% of the total (5). One of the most typical heatwaves of the 21st century was the 2003 heatwave in Central and Western Europe, which caused more than 70,000 deaths and illustrated the importance of heatwave disasters (6). Increase in the frequency and intensity of heatwaves also can lead to a rapid escalation in energy consumption. Extreme weather events such as droughts and heat waves exacerbate water scarcity by reducing water availability, deteriorating water quality and increasing sectoral water use (7). Additionally, the power sector is particularly vulnerable to climate change, and heatwaves increase the cooling demand, which affects residential, commercial, and industrial electricity demand (8). A case study in Shanghai found that a 1°C increase in global mean temperature could lead to a 36.1% surge in annual peak electricity use (9). Luo et al. (10) found that slowdown in the movement of heat waves in recent decades could increase the risk of reduced productivity of local ecosystems and increase consumption and capacity needs in the energy sector. Similarly, human health is affected by severe heatwaves. In China, a study found that the number of deaths caused by heatwaves has increased rapidly since 1979, and although factors such as population growth, an aging population, and rising baseline mortality rates have objectively contributed to the number of deaths caused by heatwaves, the rapid increase in the frequency of heatwaves has been the most significant contributing factor (11).

Currently, there is no consistent definition of heatwave, which is generally defined as consecutive days above a certain temperature threshold, but studies on heatwaves are mostly based on temperature indicators (or thresholds) and duration. China's meteorological department defines a heatwave as 3 or more consecutive days with a daily maximum temperature exceeding 35°C (12), and the World Meteorological Organization defines a heatwave as a daily maximum temperature above 32°C on 3 or more consecutive days (13). However, the vulnerability of populations in different regions exposed to heatwaves varies according to long-term adaptation to the surrounding climate (14). Therefore, a consistent and standard definition of heatwaves is not well applied in China, which has a diverse range of climate types. Several studies have defined heatwaves using temperature percentiles that consider the local climatic characteristics as the thresholds. A heatwave health risk study in Australia defined heatwaves as 2 or more consecutive days on which the average temperature exceeds a particular percentile of the warm season average (15). A study on heatwaves in 31 provincial capital cities in China proposed a definition of a daily maximum temperature ≥ 92.5 percentile for a duration ≥3 days (16). Yin et al. (17) collected the daily mean temperatures of 272 major cities in China from 2013 to 2015 and then combined the 90th, 92.5th, 95th, and 97.5th percentiles and durations of 2, 3, and 4 days to construct 12 definitions of heatwaves; they then investigated the characterization of all 12 heatwave types and calculated the risk of mortality associated with each type for different subgroups of the population. In addition, heat wave events have spatial continuity, with heat wave propagation distances, movement speeds and directions changing over time (18). Recognizing the movement patterns and propagation cycles of heat waves can provide potential precursor signals, and understanding their co-evolution in both temporal and spatial dimensions is important for understanding heat wave prediction, mitigation and adaptation (10).

Researchers have described the conditions of heatwaves based on the characteristics of severity and duration, and those 2 characteristics play an important role in the heatwave frequency analyses used to develop comprehensive predictions. Given that a heatwave is a multivariate phenomenon, the recurrence interval of heatwave severity and duration could be quite different, even if both characteristics were obtained from a single event (19, 20). Therefore, several studies have suggested using multivariate methods, especially copula functions with joint frequency analyses, to assess the severity and duration of heatwaves. In a study of heatwaves in the Yangtze River Delta, Xu et al. introduced a copula function to investigate the heatwave characteristics of 2 probabilistic models for a specific period (21). Mazdiyasni et al. (22) used a copula function to compare the intensity-epoch-frequency curves of heatwaves in 6 cities in the United States and to find heatwave hazards and their joint recurrence periods in different regions. Copula functions have been used to develop bivariate joint probability density functions based on the marginal probability distribution of each variable, which allow the heatwave characteristics and changes in future periods to be detected by combining them with climate change scenarios. Such functions can provide optimal management conditions for each region. Heatwaves pose a threat to urban economies and the health of residents, and the construction of a heatwave early-warning system can mitigate the health risks of populations exposed to heatwaves (23).

Dong et al. (24) proposed a heatwave health risk framework based on the Heat Climate Index and assessed its applicability to 177 neighborhoods in Wuhan City, China. Similarly, Zhang et al. (25) combined high-temperature heatwave data and health risk data to develop an early warning model. The investigation of changes in heatwaves during a future period and the stratification of heatwave risks can facilitate the development of heatwave early warning systems. In China, the Meteorological Bureau issues heat warning signals by classifying heatwave grades based on the heatwave index (26), but it neglects the risk level in terms of the relationship between a heatwave and the mortality exposure response of the population. Thus, the analysis and prediction of heatwaves under future climate patterns provide a scientific foundation for the formulation of a rational national development strategy. A series of national and international articles has examined assessments of future temperature changes from new typical concentration pathway scenarios under multiple future climate models. Yun et al. (27) evaluated the simulated outcomes of 27 climate models from the fifth Coupled Model Intercomparison Project (CMIP5) and considered the extent of warming in Asia under multiple emission pathways. In contrast, Brown et al. (28) developed a new statistical model to predict changes in heatwave intensity over time for 20 cities around the world using the RCP8.5 emissions scenario for 28 CMIP5 climate models. Few current studies have considered the frequency of heatwaves under future climate models, and they all show that heatwave events will occur more frequently in the future, but they have not examined heatwave frequency in terms of heatwave features (29–31).

Therefore, based on daily maximum temperature data for Wuhan City from 1951 to 2017 and daily maximum temperature prediction data from 4 CMIP5 global climate models under 2 emission scenarios (RCP4.5 and RCP8.5) from 2031 to 2099, this study (1) constructs heatwave definitions for Wuhan by exploring the relationship between heatwaves and the mortality-exposure response of residents and combines those definitions to stratify the heatwave risk and to identify heatwave events with different risks; (2) fits the marginal distributions of historical heatwave characteristics in Wuhan and introduces a copula function to analyze the bivariate joint probability and co-occurrence return period; (3) predicts future heatwave co-occurrence periods in Wuhan, compares those predictions with historical heatwave events, analyzes changes in heatwave event characteristics, and provides a scientific basis for a response to climate change and risk management in Wuhan.

2 Study area and data sources

2.1 Study area

Wuhan is the capital of Hubei Province (29°58′N to 31°22′N, 113°41′E to 115°05′E) and has a total area of 8569.15 km^2 (Figure 1). Wuhan has a subtropical humid monsoon climate. Under the influence of tropical cyclones in the western part of the North Pacific Ocean, high temperatures are particularly likely to occur in the middle and lower reaches of the Yangtze River in east-central China (32). As the only supercity in that central region, Wuhan is a typical furnace city. In 2014, the maximum temperature in Wuhan reached 39.7°C. At the end of 2022, Wuhan had a resident population of 13.739 million and a gross domestic product of 1.89 trillion yuan. Because high temperatures cause death and economic losses (33), the need to analyze their characteristics in Wuhan and to develop plans to reduce their effects is urgent.

2.2 Data sources

This study uses daily maximum temperature data recorded at the Wuhan National Basic Meteorological Station (57494) from 1951–2017. These historical observational data were sourced from the National Meteorological Data Center of the China Meteorological Network.[1] The future data for this study are the daily maximum near-surface air temperatures from 2007–2017 and 2031–2099 projected under 2 representative concentration pathways, RCP4.5 (medium emission scenario) and RCP8.5 (high emission scenario), for 4 CMIP5 climate models.[2] Table 1 provides basic information about the 4 global climate models. The “r1i1p1” ensemble was selected for the global climate models used in this study, and all models were re-gridded to 0.5° × 0.5° resolution.

1 http://data.cma.cn/

2 https://esgf-node.llnl.gov/search/cmip5/

3 Methods

3.1 Definition-based heatwave stratification methods

Previous research combined temperature indicators, temperature thresholds, and durations to develop 45 definitions of heatwaves and to evaluate the effects of heatwave events on the mortality of Wuhan residents (34). In this study, 9 heatwave definitions were developed by combining 3 types of temperature thresholds and 3 durations, and then those definitions were divided into categories to represent low-, medium-, and high-risk events.

3.2 Joint probability analysis based on copulas

In this study, 6 commonly used distribution functions were selected to fit the marginal distributions of heatwave characteristics: the lognormal (Logn), exponential (Exp), gamma, generalized extreme value (GEV), Weibull (Wbl), and generalized pareto (GP) distributions. These 6 distribution functions were used to fit the marginal distributions of heatwave duration. The marginal distributions of heatwave severity were fitted using the first 5 distribution functions.

Copula functions are multivariate joint distribution functions that concatenate multiple univariate marginal distributions. Copulas are mainly based on the bivariate joint distribution, as shown in Eq. (1):

$$F_{XY}(x,y) = C\left[F_X(x), F_Y(y)\right] \tag{1}$$

where X and Y are continuous variables, and C is the only copula function that fits the above equation. The variables of the copula function are the marginal distribution function of X, Y.

The copula functions used in this paper are the t copula, gaussian copula, Clayton copula, Gumbel copula, and Frank copula. The t copula has 2 parameters, and the rest of the copulas each have only 1 parameter. Both the optimal copula function and the optimal marginal distribution function were selected using the Multivariate Copula Analysis Toolbox.

3.3 Co-occurrence return periods

Return periods can provide effective support for decision-making about heatwave prevention and management. They are classified as joint and co-occurrence return periods, and this study uses the latter. The heatwave co-occurrence return periods require that the heatwave severity and duration simultaneously exceed specific values, and their calculation is based on 2 univariate marginal distributions and a bivariate joint distribution (35), as shown in Eq. (2):

$$\begin{aligned} T &= \frac{N}{nP\left(X \geq x \cap Y \geq y\right)} \\ &= \frac{N}{n\left\{1 - F_X(x) - F_Y(y) + C\left[F_X(x), F_Y(y)\right]\right\}} \end{aligned} \tag{2}$$

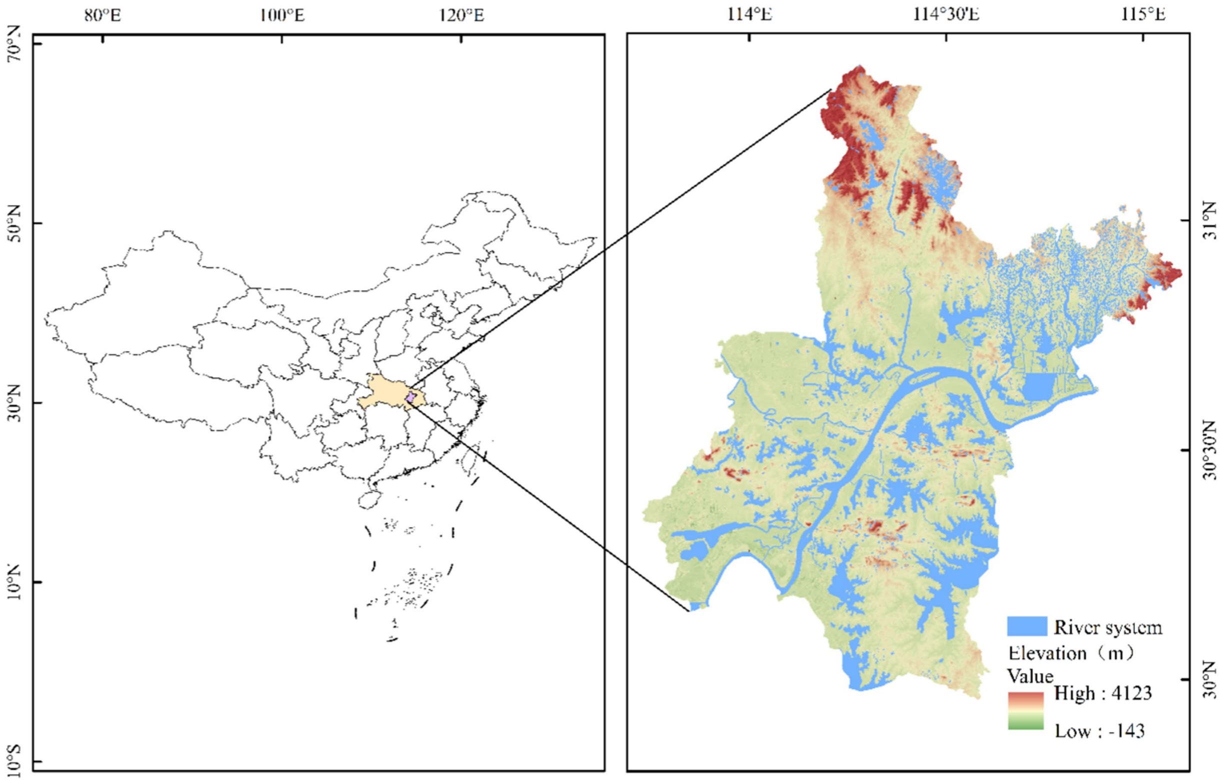

FIGURE 1
Geographical location of Wuhan.

where N is the length of the study time, and n is the number of heatwave events during the study time.

3.4 Global climate model assessment

Taylor diagrams assess the simulation capability of climate models (36) using the root mean square error (RMSE), correlation coefficient, and variance ratio (standard deviation), which are shown in Eqs. (3–6), respectively. Based on those indicators, a Taylor diagram can illustrate the matching ability of climate models with observations in terms of correlation, RMSE, and standard deviation, which intuitively reflects the matching performance between the simulated and observed data. Therefore, a Taylor diagram can comprehensively reflect the advantages and disadvantages of the simulation results of each model. In this paper, 4 global CMIP5 climate models and 2 representative concentration paths, RCP4.5 and RCP8.5, were selected to simulate the climate of Wuhan for assessments by Taylor diagram analyses.

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(o_n - m_n\right)^2} \quad (3)$$

$$R = \frac{1}{N}\sum_{n=1}^{N}\frac{\left(o-\overline{o}\right)\left(m-\overline{m}\right)}{\sigma_o \sigma_m} \quad (4)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(x_n - \overline{x}\right)^2} \quad (5)$$

$$\sigma_f = \frac{\sigma_m}{\sigma_o} \quad (6)$$

where o and m are the observed and model-simulated data, respectively; $\overline{o}$, $\overline{m}$ are the mean values of the observed and simulated data, and σ_o and σ_m are the standard deviations of the observed and simulated data. As R and σ_f become closer to 1 and the RMSE becomes closer to 0, the model simulation is understood to improve.

It is difficult to discern the match between simulation results and observations when the simulation results of different climate models are close to one another in the Taylor diagram. Thus, to more objectively assess the quality of the temperature simulation from each climate model, the comprehensive skill score S is introduced (36), as shown in Eq. (7):

$$S = \frac{4\left(1+R\right)^4}{\left(\frac{\sigma_m}{\sigma_o} + \frac{\sigma_o}{\sigma_m}\right)^2 \left(1+R_0\right)^4} \quad (7)$$

where R is the correlation coefficient between model simulation values and observations, σ_m is the standard deviation of the model simulation results, σ_o is the standard deviation of the observations, and R_0 is the maximum value of the correlation coefficient between the model simulation results and observations.

4 Results

4.1 Definition and risk classification of heatwaves in Wuhan

CMIP5 is a multi-model simulation of historical and future climate under different greenhouse gas emission scenarios (37). It provides a better understanding of present and projected future climate change. Despite moderate biases in day time temperatures, the CMIP5 model performs better in terms of frequency for the actual simulated observed heat waves (38). To assess the consistency between the 4 global climate models and the temperature in Wuhan under the 2 representative concentration pathways, the model projection data and observation data for the overlapping period between the 2 datasets (2007–2017) were compared, as shown in the Taylor diagrams in Figure 2. The correlation coefficients between the simulated results and the observed data under both the RCP4.5 and RCP8.5 emission scenarios were concentrated around 0.8. The ratio of the standard deviation of the simulated results to the observations under the RCP4.5 emission scenario was concentrated around 1, whereas that under the RCP8.5 emission scenario ranged from 1 to 1.06. The RMSE of the simulation results was centered at 0.62 under the RCP4.5 emission scenario and in the range of 0.58–0.63 under the RCP8.5 emission scenario.

In general, the simulation results of the 4 global climate models under the RCP4.5 emission scenario were clustered, which made it difficult to discern the applicability of each model. Under the RCP8.5 emission scenario, the IPSL-CM5A-LR and MIROC5 models were better than the GFDL-ESM2M and HadGEM2-ES models in all 3 metrics, but neither could be selected as optimal. Thus, the S-skill score was used to quantify the simulation quality of the 4 global climate models.

Table 2 demonstrates that under the RCP4.5 and RCP8.5 emission scenarios, the IPSL-CM5A-LR and MIROC5 models, respectively, best matched the Wuhan temperature observations. Under the RCP4.5 emission scenario, the 4 models matched Wuhan's air temperature with little discrepancy. Under the RCP8.5 emission scenario, in contrast, the MIROC5 model had the best performance, and the HadGEM2-ES model had the worst performance. Therefore, the IPSL-CM5A-LR model and MIROC5 model were selected for further analysis under the RCP4.5 and RCP8.5 emission scenarios, respectively.

To comprehensively demonstrate the association between mortality and heat waves, Zhang et al. (34) combined 5 temperature thresholds and 3 durations of the daily maximum temperature, minimum temperature, and mean temperature to develop 45 heatwave definitions for the selection of best definitions to capture the effects on non-accidental mortality in Wuhan. They found the intensity thresholds of the 95th percentile, 97.5th percentile, and 99th percentile of the daily maximum temperature, together with the duration ≥2 days, duration ≥3 days, and duration ≥4 days had good predictive ability in assessing the total mortality effects of heatwaves among Wuhan residents. Based on the previous study, we selected the daily maximum temperatures recorded by Wuhan meteorological stations (57494) from 1951–2017 and combined the corresponding 95th percentile, 97.5th percentile, and 99th percentiles with durations of ≥2 days, 3 days, and 4 days to develop 9 heatwave definitions, as shown in Table 3. These criteria were used to detect historical and future heatwave events in this study.

Based on the 9 heatwave definitions extracted from the relationship between heatwave events and resident exposure mortality response in Wuhan, this paper proposes the heatwave mortality risk classification system shown in Figure 3. Low-risk heatwaves are events with a daily

TABLE 1 Details of the CMIP5 global climate models.

ID	Model	Nation	Resolution (Longitude (°) × Latitude (°))
1	GFDL-ESM2M	USA	144 × 90
2	HadGEM2-ES	UK	145 × 192
3	IPSL-CM5A-LR	France	96 × 96
4	MIROC5	Japan	256 × 128

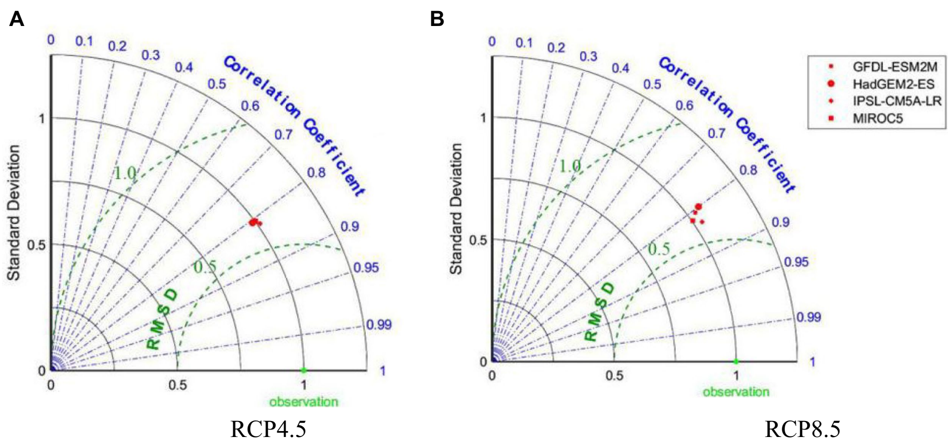

FIGURE 2
Taylor diagrams of 4 CMIP5 GCMs relative to observations under different emission scenarios in Wuhan, 2007–2017 **(A)** RCP4.5; **(B)** RCP8.5.

TABLE 2 Skill scores and rankings of the 4 CMIP5 GCMs in Wuhan under different emission scenarios, 2007–2017.

Model	RCP4.5 (S/ranking)	RCP8.5 (S/ranking)
GFDL-ESM2M	0.98/4	0.94/3
HadGEM2-ES	0.97/3	0.93/4
IPSL-CM5A-LR	0.99/1	0.97/2
MIROC5	0.98/2	0.99/1

TABLE 3 The 9 heatwave definitions in Wuhan, 1951–2017.

Heatwave definition	Temperature indicator	Relative temperature threshold	Duration
HW1	Daily maximum temperature	95th percentile (35.2°C)	≥2d
HW2			≥3d
HW3			≥4d
HW4		97.5th percentile (36.2°C)	≥2d
HW5			≥3d
HW6			≥4d
HW7		99th percentile (37.1°C)	≥2d
HW8			≥3d
HW9			≥4d

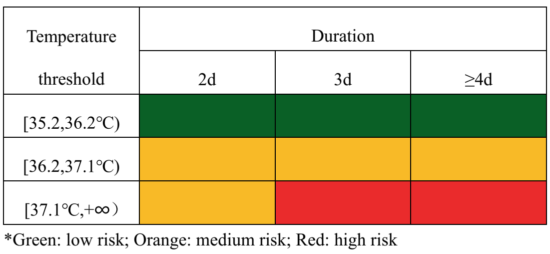

FIGURE 3
Heatwave mortality risk classification system.

maximum temperature between 35.2 and 36.2°C for 2 days or more, as indicated in green. Medium-risk heatwaves are events with daily maximum temperatures between 36.2 and 37.1°C for 2 days or more or daily maximum temperatures of 37.1°C and higher for 2 days, as indicated in orange. High-risk heatwaves are events with daily maximum temperatures of 37.1°C and higher for 3 days or more, as indicated in red.

4.2 Characterization of historical heatwaves in Wuhan based on copula functions

Based on those tiered risk criteria, the 2 characteristic variables of heatwave severity and duration were used to classify observed (1951–2017) and predicted (2031–2099) heatwaves as low, medium, and high risk, as shown in Figure 4. In the different scenarios, the number of heatwave events increased significantly as the concentration of greenhouse gas emissions increased. The incidence of high-risk heatwaves increased exponentially, whereas the increase in the numbers of low-risk and medium-risk heatwave events was not obvious. Most of the scenarios showed that risk increases with heatwave duration. The number of heatwave occurrences differed among scenarios, with a decreasing trend in the observation period and RCP4.5 emission scenarios and an increasing trend in the RCP8.5 emission scenario.

In general, when the heatwave duration was shorter, the frequency increased. During the observation period, the maximum heatwave severity when the heatwave duration was 2d was 36°C and 38.4°C for the low- and medium-risk categories, respectively, and when the heatwave duration was 3d, the maximum heatwave severity was 38.586°C for the high-risk category. In the RCP4.5 scenario, the maximum heatwave severity when the heatwave lasted 2d was 36.155°C and 40.315°C for the low-risk and medium-risk categories, respectively, and the maximum heatwave severity for the high-risk category was 41.93°C in a heatwave predicted to last 7d. In the RCP8.5 scenario, heatwaves that lasted for 2d had a maximum severity of 36.14°C and 41.26°C for the low-risk and medium-risk categories, respectively, and the maximum heatwave severity for the high-risk category was 41.97°C in a heatwave predicted to last 19d. In other words, except for the RCP4.5 and RCP8.5 high-risk category, heatwave severity was highest when the heatwave lasted for the shortest time. The severity of the most intense heatwaves also tended to increase within each risk level in the different scenarios, indicating that an increase in the concentration of greenhouse gas emissions would lead to more intense heatwave events.

The severity of the heatwaves in the historical period was fitted using 5 marginal distribution functions (Logn, Exp, Gamma, GEV, and Wbl). In fitting the duration, the GP distribution was added. The results of the fitting are shown in Table 4. The table indicates that the optimal marginal distributions for the severity (S) and duration (D) of heatwaves during the historical observation period were GEV and GP, respectively. These are both 3-parameter distributions and were estimated using the maximum likelihood estimation method.

Figure 5 compares the actual probability density distributions of the 2 characteristics of heatwaves with the optimal probability density distributions and shows that the distributions selected in this paper fit well with the actual characteristics of heatwaves.

The *t* copula of the elliptic copulas, the gaussian copula, and the Clayton copula, Gumbel copula, and Frank copula of the Archimedean copulas were selected to construct joint probability distribution functions of heatwave severity and duration for the different risk categories during the historical observation period. The parameters in the joint probability distribution functions of heatwave severity and duration were estimated using the maximum likelihood method. The goodness-of-fit tests were performed based on the maximum likelihood, AIC, BIC, and RMSE criteria, and the parameters and goodness-of-fit test results are shown in Table 5.

According to the criterion that a small RMSE indicates a good copula fit, the Clayton copula exhibited the best fit for a binary copula of heatwave severity and duration in the low-risk category. The RMSE of the gaussian copula was significantly smaller than the rest in the medium-risk category, where it was the optimal joint probability distribution of heatwave severity and duration. For the joint distribution of heatwave severity and duration in the high-risk category, the goodness-of-fit of the Gumbel copula was the best.

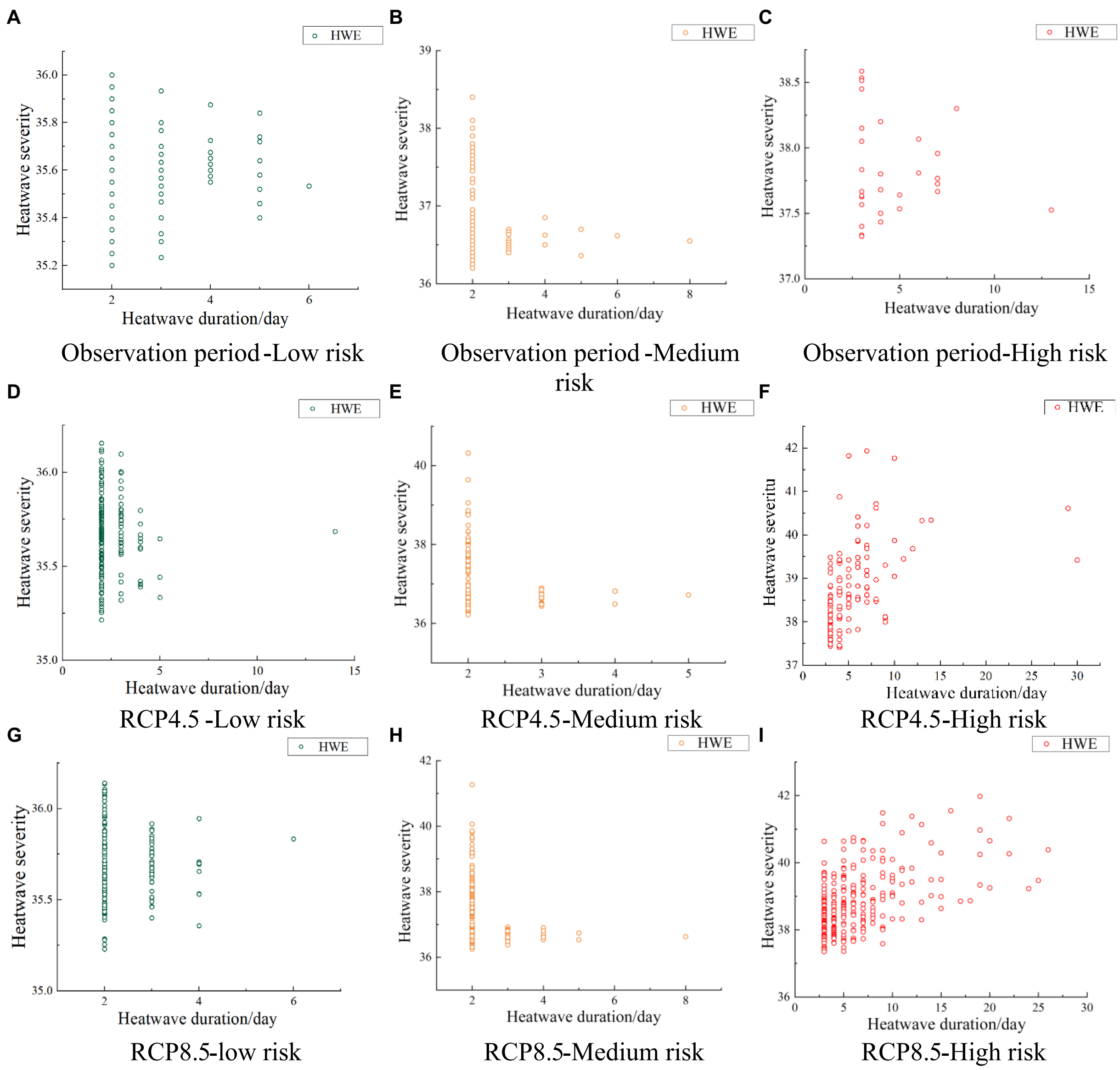

FIGURE 4
Scatterplots of heatwave severity and duration identified using different risk levels and RCP scenarios **(A, D, G)** low risk; **(B, E, H)** medium risk; **(C, F, I)** high risk.

TABLE 4 Marginal distributions of heatwave characteristics under different risk levels.

Risk level	Characteristic	Marginal distribution	Parameters*
Low risk	S	GEV	$[k,\sigma,\mu]=[-0.29,0.17,35.53]$
	D	GP	$[k,\sigma,\mu]=[-0.64,3.86,0]$
Medium risk	S	GEV	$[k,\sigma,\mu]=[0.27,0.25,36.56]$
	D	GP	$[k,\sigma,\mu]=[-0.34,2.93,0]$
High risk	S	GEV	$[k,\sigma,\mu]=[0.07,0.28,37.66]$
	D	GP	$[k,\sigma,\mu]=[-0.43,6.27,0]$

*k: shape parameter, σ: scale parameter, μ: location parameter.

Therefore, the Clayton copula, gaussian copula, and Gumbel copula functions were chosen to describe the 2-dimensional joint distribution of the severity and duration of low-, medium-, and high-risk heatwaves, respectively. The joint probability density functions of the heatwave characteristics in the 3 risk categories are shown in Figure 6.

Based on the data of heatwave severity and duration at different risk levels in the historical observation period, the co-occurrence

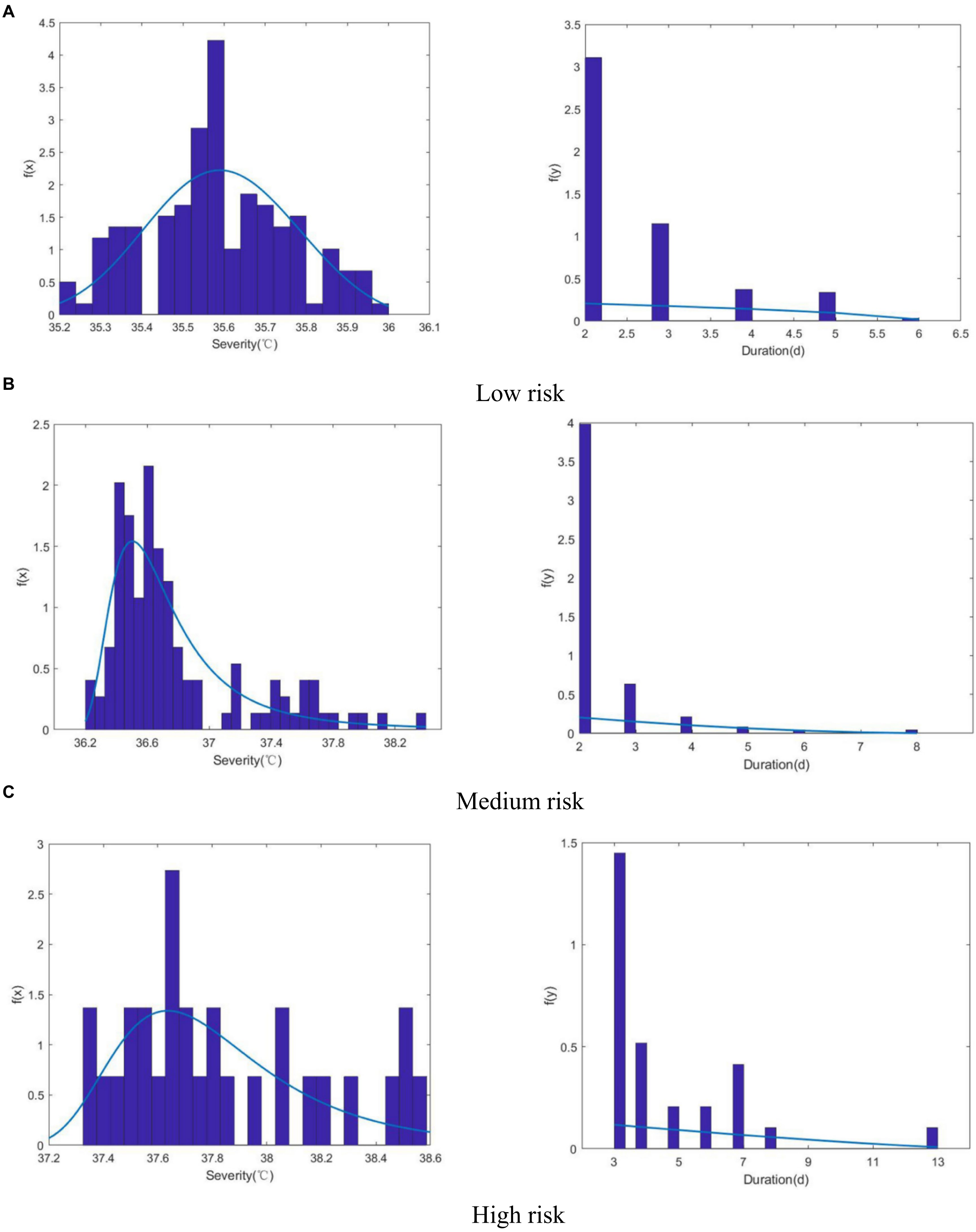

FIGURE 5
Comparison of the actual histograms and optimal probability density distributions of the 2 characteristics of heatwaves at 3 risk levels **(A)** Low risk; **(B)** Medium risk; **(C)** High risk.

return periods of heatwave severity and duration were calculated according to Eq.

The vertical axis is heatwave severity. The co-occurrence return period curves constructed from the heatwave severities and durations were used to compare heatwave severities from different risk categories with the same durations and co-occurrence return periods. For instance, a heatwave event with a duration of 3 days or more and a 5-year co-occurrence return period corresponded to temperatures of 35.74°C, 36.69°C, and 37.64°C, respectively, in the low-, medium-, and high-risk categories (see Figure 7).

TABLE 5 Evaluation of copula parameters and goodness-of-fit tests for the different risk levels.

Risk level	Copula	Parameters	RMSE
Low risk	Gaussian	$\rho=\begin{bmatrix}1 & 0.12\\0.12 & 1\end{bmatrix}$	0.31
	t	$\alpha=\begin{bmatrix}1 & 0.28\\0.28 & 1\end{bmatrix}$, nu = 2442431	0.26
	Clayton	$\alpha=0.42$	0.25
	Frank	$\alpha=1.51$	0.25
	Gumbel	$\alpha=1.11$	0.39
Medium risk	Gaussian	$\rho=\begin{bmatrix}1 & -0.14\\-0.14 & 1\end{bmatrix}$	0.17
	t	$\alpha=\begin{bmatrix}1 & -0.41\\-0.41 & 1\end{bmatrix}$, $nu=4669185$	0.25
	Clayton	$\alpha=0.26$	0.28
	Frank	$\alpha=-2.45$	0.26
	Gumbel	$\alpha=1$	0.2
High risk	Gaussian	$\rho=\begin{bmatrix}1 & 0.45\\0.45 & 1\end{bmatrix}$	0.13
	t	$\alpha=\begin{bmatrix}1 & 0.58\\0.58 & 1\end{bmatrix}$, $nu=3.3649$	0.12
	Clayton	$\alpha=1.35$	0.19
	Frank	$\alpha=3.74$	0.13
	Gumbel	$\alpha=1.58$	0.11

*ρ and α are the linear correlation parameters in the copula, and nu is the degree of freedom.

When the duration of a low-risk heatwave event was 2d, the maximum heatwave severity was 36°C, and the corresponding co-occurrence return period was 149 years. In other words, the co-occurrence return period for heatwave events with severity greater than or equal to 36°C and a duration of 2d or more was 149 years in the low-risk category. When the duration of a medium-risk heatwave event was 2d, the corresponding maximum heatwave severity was 38.4°C, and its co-occurrence return period was 103.98 years. The maximum severity corresponding to a high-risk heatwave lasting 3d was 38.586°C, and the corresponding co-occurrence return period of the 2 characteristics was 50.6 years.

On the whole, as the heatwave severity and duration increased in each risk category, the co-occurrence return period gradually decreased, which meant that the probability of heatwave events increased.

4.3 Projection of future heatwave risks in Wuhan based on copulas

Table 6 shows the optimal marginal distributions for heatwave characteristics, i.e., severity (S) and duration (D), for the future period under the RCP4.5 and RCP8.5 emission scenarios. As in the historical observation period, the optimal marginal distributions fitted to the heatwave severity and duration in the low-, medium-, and high-risk categories were the GEV distribution and the GP distribution, respectively, and the parameters were again estimated using the maximum likelihood estimation method. Figure 8 compares the actual histograms of the 2 heatwave characteristics for the 2 emission scenarios and 3 risk levels with the optimal probability density distributions chosen. The performance was satisfactory, as in the historical observation period.

The t copula, gaussian copula, Clayton copula, Gumbel copula, and Frank copula were used to construct 2-dimensional joint distributions of heatwave severity and duration for the different risk levels under the RCP4.5 and RCP8.5 emission scenarios, and the parameter estimations were performed using the maximum likelihood estimation method. As in the historical observation period, the joint distributions were tested for goodness-of-fit using the max-likelihood, AIC, BIC, and RMSE criteria. The parameters and results of the goodness-of-fit tests are shown in Table 7.

Based on the criteria used to select the best 2-dimensional copula functions in the historical observation period, for the low- and high-risk categories under the RCP4.5 emission scenario, the Frank copula fit best; for the medium risk under the RCP4.5 emission scenario, the gaussian copula was best fit. The gaussian copula also had the best fit for the low- and medium-risk categories under the RCP8.5 emission scenario, and the Gumbel copula fit best for the high risk category. The joint density functions of heatwave characteristics under the different scenarios and risk levels are shown in Figure 9.

The return periods of heatwaves with the 3 different risk levels under the RCP4.5 and RCP8.5 emission scenarios are shown in Figure 10. The characteristics of the co-occurrence return period curves are the same as during the historical observation period. The co-occurrence return period for each risk level in both emission scenarios tended to increase as heatwave severity intensified and heatwave duration lengthened, which matches the frequency characteristics of heatwaves in the historical observation period.

In the RCP4.5 emission scenario, the maximum heatwave severity in the low-risk category was 36.155°C when the heatwave lasted for 2d, corresponding to a co-occurrence return period of 359.27 years. The maximum heatwave severity was 40.315°C when the heatwave lasted for 2d in the medium-risk category, which corresponded to a co-occurrence return period of 101.39 years for this type of event. The maximum heatwave severity for a high-risk heatwave event with a duration of 7 days was 41.93°C, corresponding to a co-occurrence return period of 57.74 years.

In the RCP8.5 emission scenario, the maximum heatwave severity (36.14°C) and duration (2d) in the low-risk category, maximum heatwave severity (41.26°C) and duration (2d) in the medium-risk category, and maximum heatwave severity (41.97°C) and duration (19d) in the high-risk category corresponded to co-occurrence return periods of 89.25, 68.5, and 51.88 years, respectively.

Compared with the co-occurrence return periods of the 3 heatwave risk levels in the historical observation period, the co-occurrence return periods of each heatwave risk gradually shortened as the concentrations of greenhouse gas emissions increased in the RCP4.5 and RCP8.5 emission scenarios. This implies that longer and more intense heatwaves will occur more frequently as greenhouse gas levels continue to increase. For instance, the co-occurrence return period corresponding

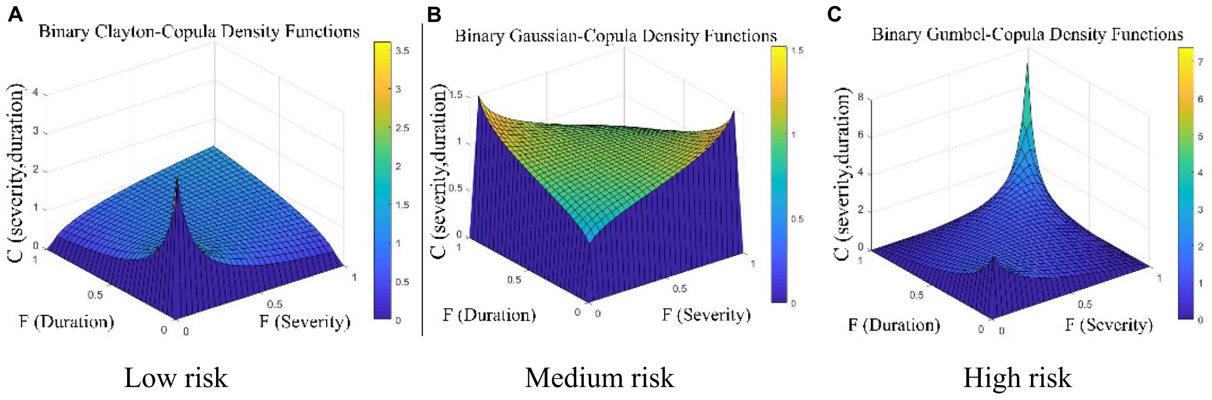

FIGURE 6
Joint probability density function plots of heatwave characteristics for the 3 risk levels **(A)** Low risk; **(B)** Medium risk; **(C)** High risk.

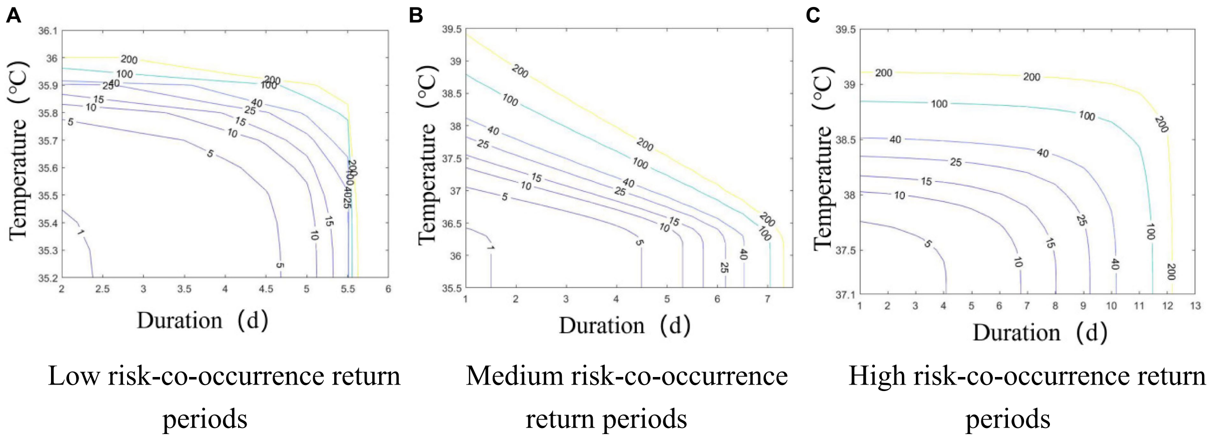

FIGURE 7
Co-occurrence return period plots for heatwave severity and duration at the 3 risk levels **(A)** Low risk; **(B)** Medium risk; **(C)** High risk.

TABLE 6 Marginal distributions of heatwave characteristics under different scenarios and risk levels.

Emission scenario	Risk level	Characteristic	Marginal distribution	Parameters
RCP4.5	Low risk	S	GEV	$[k,\sigma,\mu] = [-0.27, 0.2, 35.59]$
		D	GP	$[k,\sigma,\mu] = [-0.16, 2.75, 0]$
	Medium risk	S	GEV	$[k,\sigma,\mu] = [0.41, 0.37, 36.69]$
		D	GP	$[k,\sigma,\mu] = [-0.59, 2.98, 0]$
	High risk	S	GEV	$[k,\sigma,\mu] = [0.1, 0.68, 38.27]$
		D	GP	$[k,\sigma,\mu] = [-0.11, 5.96, 0]$
RCP8.5	Low risk	S	GEV	$[k,\sigma,\mu] = [-0.26, 0.19, 35.63]$
		D	GP	$[k,\sigma,\mu] = [-0.51, 3.14, 0]$
	Medium risk	S	GEV	$[k,\sigma,\mu] = [0.39, 0.48, 36.82]$
		D	GP	$[k,\sigma,\mu] = [-0.32, 2.66, 0]$
	High risk	S	GEV	$[k,\sigma,\mu] = [0.01, 0.72, 38.41]$
		D	GP	$[k,\sigma,\mu] = [-0.26, 8.07, 0]$

*k: shape parameter, σ: scale parameter, μ: location parameter.

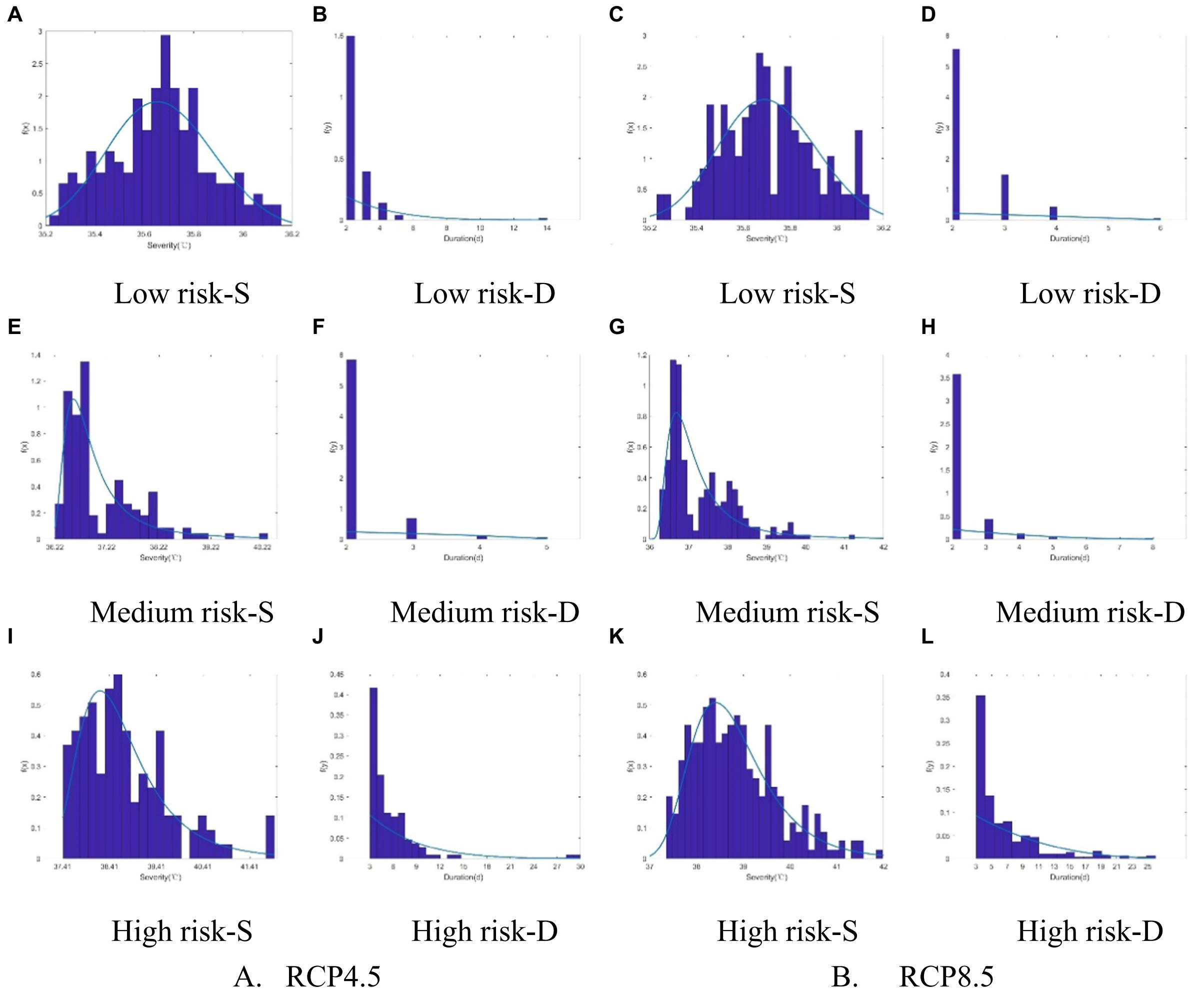

FIGURE 8
Comparison of the actual histograms and optimal probability density distributions of the 2 heatwave characteristics (S was severity, D was duration) under 2 emission scenarios and 3 risk levels. **(A-D)** Low risk; **(E-H)** Medium risk; **(I-L)** High risk.

to the most severe intensity and duration of a low-risk heatwave in the observation period was 149 years, whereas the return periods for a heatwave of the same intensity and duration in the RCP4.5 and RCP8.5 scenarios were 34.81 years and 14.87 years, respectively. For a medium-risk heatwave event, the co-occurrence return period corresponding to the most severe intensity and duration in the observation period was 103.98 years, whereas in the RCP4.5 and RCP8.5 scenarios, it was 23.95 years and 9.10 years, respectively. Likewise, the co-occurrence return period corresponding to the maximum heatwave intensity and duration for a high-risk event in the observation period was 50.6 years, and it was 1.34 years and 0.56 years in the RCP4.5 and RCP8.5 scenarios, respectively. All 3 scenarios show that increased greenhouse gas emissions lead to more frequent heatwaves.

5 Conclusion and discussion

Global climate change is leading to increasing heat waves in major cities, with serious impacts on human health and life on Earth (39). Traditional meteorological warnings are based on the strength of the heat signal and do not consider the possible physical health risks associated with heat exposure. A heat-health warning system has been shown to effectively reduce premature deaths caused by heatwaves and is only in use in a few high-income countries (40). There is an urgent need to consider the potential health risks due to heat exposure in the heatwave definition, classification, and warning systems for the health protection of vulnerable populations in most low-income and middle-income countries. Therefore, in this study, nine heat wave definitions that can well capture the effects on non-accidental mortality of heatwaves in Wuhan were introduced and classified into low, medium, and high risk levels to investigate the historical and future likely changes of heatwave risks. Copula functions were used to analyze the joint probability distributions of heatwave severity and duration and to project the future heatwave co-occurrence interval.

Daily maximum near-surface air temperature projections based on 4 CMIP5 climate models under RCP4.5 and RCP8.5 scenarios were collected for future heatwave risk assessment. Due to the complexity of the climate system and the differences in the physical processes integrated with the model, the simulation results may differ from actual observations and between models. Therefore, it is necessary to conduct a comprehensive and quantitative evaluation of the model products before making predictions about future climate.

TABLE 7 Evaluation of copula parameters and goodness-of-fit tests under different emission scenarios and risk levels.

	Risk level	Copula	Parameters*	RMSE
RCP4.5	Low risk	Gaussian	$\rho=\begin{bmatrix}1 & -0.06\\ -0.06 & 1\end{bmatrix}$	0.14
		t	$\alpha=\begin{bmatrix}1 & -0.35\\ -0.35 & 1\end{bmatrix}, nu=2285091$	0.12
		Clayton	$\alpha=0.17$	0.13
		Frank	$\alpha=-2.06$	0.12
		Gumbel	$\alpha=1$	0.12
	Medium risk	Gaussian	$\rho=\begin{bmatrix}1 & -0.19\\ -0.19 & 1\end{bmatrix}$	0.16
		t	$\alpha=\begin{bmatrix}1 & -0.48\\ -0.48 & 1\end{bmatrix}, nu=4671397$	0.23
		Clayton	$\alpha=0.39$	0.26
		Frank	$\alpha=-2.83$	0.24
		Gumbel	$\alpha=1$	0.25
	High risk	Gaussian	$\rho=\begin{bmatrix}1 & 0.58\\ 0.58 & 1\end{bmatrix}$	0.15
		t	$\alpha=\begin{bmatrix}1 & 0.66\\ 0.66 & 1\end{bmatrix}, nu=3690875$	0.13
		Clayton	$\alpha=1.58$	0.35
		Frank	$\alpha=4.61$	0.09
		Gumbel	$\alpha=1.62$	0.19
RCP8.5	Low risk	Gaussian	$\rho=\begin{bmatrix}1 & -0.07\\ -0.07 & 1\end{bmatrix}$	0.16
		t	$\alpha=\begin{bmatrix}1 & -0.26\\ -0.26 & 1\end{bmatrix}, nu=12.2447$	0.16
		Clayton	$\alpha=0.17$	0.18
		Frank	$\alpha=-1.39$	0.17
		Gumbel	$\alpha=1$	0.17
	Medium risk	Gaussian	$\rho=\begin{bmatrix}1 & -0.26\\ -0.26 & 1\end{bmatrix}$	0.3
		t	$\alpha=\begin{bmatrix}1 & -0.53\\ -0.53 & 1\end{bmatrix}, nu=3744169$	0.51
		Clayton	$\alpha=0.32$	0.5
		Frank	$\alpha=-3.44$	0.54
		Gumbel	$\alpha=1$	0.56
	High risk	Gaussian	$\rho=\begin{bmatrix}1 & 0.5\\ 0.5 & 1\end{bmatrix}$	0.14
		t	$\alpha=\begin{bmatrix}1 & 0.57\\ 0.57 & 1\end{bmatrix}, nu=4669185$	0.15
		Clayton	$\alpha=1.05$	0.34
		Frank	$\alpha=3.46$	0.15
		Gumbel	$\alpha=1.47$	0.13

*ρ and α are the linear correlation parameters in the copula function, and nu is the degree of freedom.

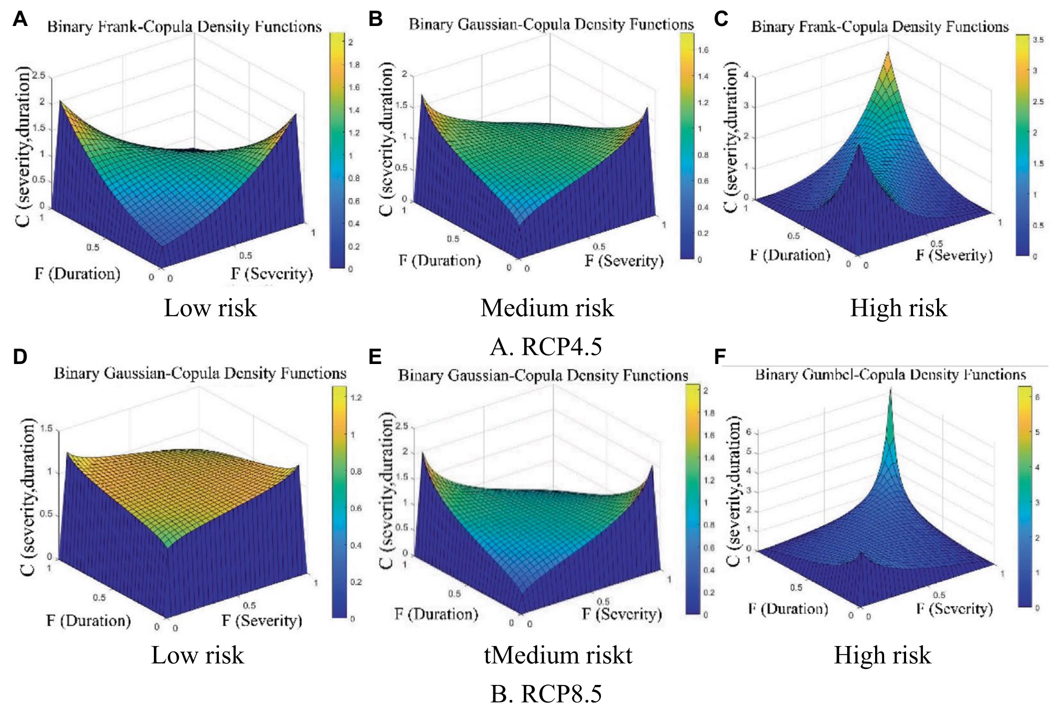

FIGURE 9
The joint probability density functions of heatwave characteristics under different scenarios and risk levels **(A-C)** RCP4.5, **(D-F)** RCP8.5.

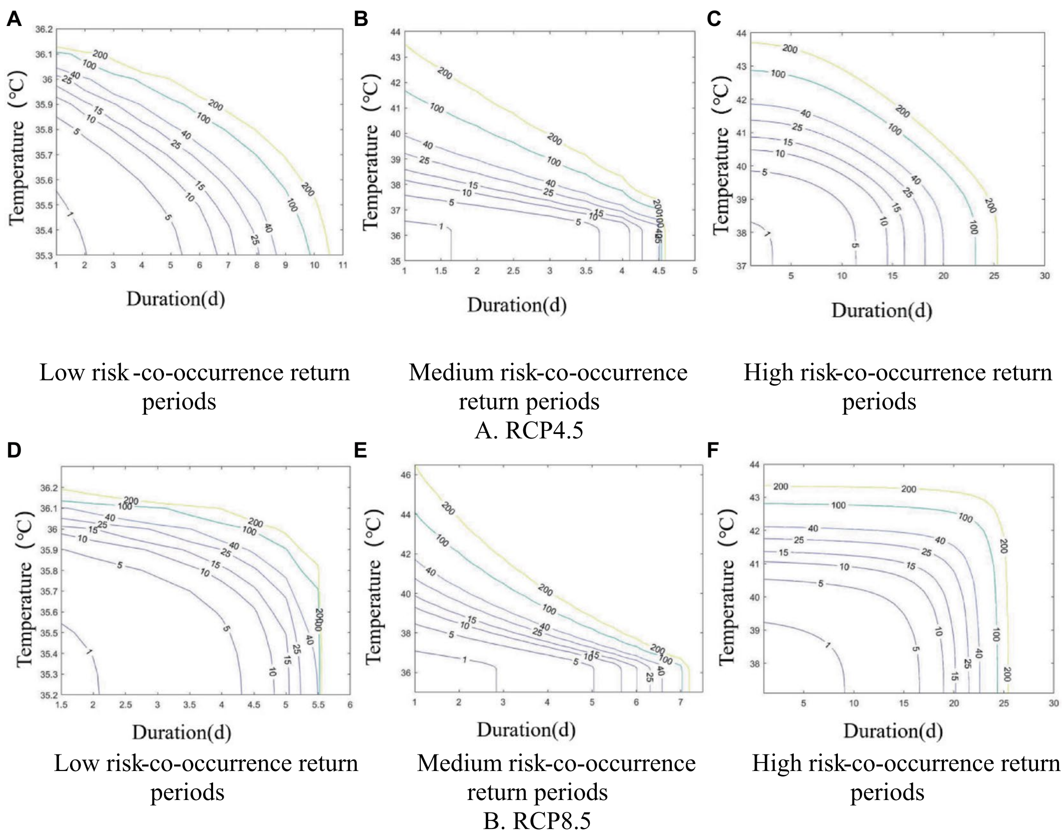

FIGURE 10
Co-occurrence return period plots of heatwave intensity and duration for 3 risk levels and 2 scenarios **(A-C)** RCP4.5; **(D-F)** RCP8.5.

The Taylor diagrams and the S-skill score were used to evaluate the performances of four GCMs in simulating temperature variables in Wuhan. The results showed that CMIP5 models had satisfying performance in reproducing observed characteristics of temperature extremes in Wuhan, and the IPSL-CM5A-LR and MIROC5 were the best-fitted models under the RCP4.5 and RCP8.5 emission scenarios, respectively, with a high S-skill score of 0.99.

The identification of heatwave events in the 3 risk categories during the observation and future periods found that (a) the frequency of heatwave events increased along with increasing concentrations of greenhouse gas emissions; (b) the frequency of heatwave events in the high-risk category increased significantly; (c) the frequency of heatwave events in the low-risk category increased but not significantly. Overall, the co-occurrence period gradually got longer with increasing heatwave intensity and heatwave duration at all risk levels. Compared to RCP4.5, the return period for each risk category of heatwave became progressively shorter under the RCP8.5 scenario, leading to more frequent heatwaves. This paper recommends that policymakers prioritize responses to extreme heat events and implement public health measures to reduce the health risks associated with local heatwaves. In addition, this study provides warnings for cities with climates similar to that of Wuhan, China, and provides useful references for facing heat disaster risks.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

SC: Conceptualization, Funding acquisition, Methodology, Writing – original draft. JZ: Software, Validation, Writing – original draft. HD: Visualization, Writing – original draft. ZY: Data curation, Writing – original draft. FL: Resources, Supervision, Writing – review & editing. JB: Data curation, Funding acquisition, Writing – review & editing. SK: Conceptualization, Funding acquisition, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by grants from the Humanities and Social Science Research Program funded by the Ministry of Education of China (grant number 21YJCZH010); National Natural Science Foundation of China (grant number 42201089); and National Research Foundation of Korea (NRF) funded by the Korean government (MSIT) (grant number 2023R1A2C2008054). SK's research was supported by the Basic Science Research Program through the NRF funded by the Ministry of Education (grant number NRF-2021R1A2C1005271).

Conflict of interest

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

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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frontiers | Frontiers in Public Health

TYPE Original Research
PUBLISHED 23 September 2024
DOI 10.3389/fpubh.2024.1389760

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RECEIVED 22 February 2024
ACCEPTED 26 August 2024
PUBLISHED 23 September 2024

CITATION
Thongsak N, Chitapanarux T, Chotirosniramit A, Chakrabandhu S, Traisathit P, Nakharutai N, Srikummoon P, Thumronglaohapun S, Supasri T, Hemwan P and Chitapanarux I (2024) Air pollutants and primary liver cancer mortality: a cohort study in crop-burning activities and forest fires area.
Front. Public Health 12:1389760.
doi: 10.3389/fpubh.2024.1389760

Air pollutants and primary liver cancer mortality: a cohort study in crop-burning activities and forest fires area

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Introduction: Northern Thailand experiences high levels of air pollution in the dry season due to agricultural waste burning and forest fires. Some air pollutants can enter the bloodstream, and the liver has the role of detoxifying these along with other harmful substances. In this study, we assessed the effects of long-term exposure to air pollutants on liver cancer mortality in this area.

Methods: A cohort of 10,859 primary liver cancer patients diagnosed between 2003 and 2018 and followed up to the end of 2020 were included in the study. Extended time-varying covariates of the annually averaged pollutant concentrations updated each year were utilized. The associations between air pollutants and mortality risk were examined by using a Cox proportional hazard model.

Results: Metastatic cancer stage had the highest adjusted hazard ratio (aHR) of 3.57 (95% confidence interval (CI):3.23–3.95). Being male (aHR = 1.10; 95% CI: 1.04–1.15), over 60 years old (aHR = 1.16; 95% CI: 1.11–1.21), having a history of smoking (aHR = 1.16; 95%CI: 1.11–1.22), and being exposed to a time-updated local concentration of $PM_{2.5}$ of 40 μg/m^3 (aHR = 1.10; 95% CI: 1.05–1.15) increased the mortality risk.

Conclusion: We found that air pollution is one of several detrimental factors on the mortality risk of liver cancer.

KEYWORDS
liver cancer, mortality rate, air pollutants, forest fire area, survival rate

1 Introduction

Liver cancer is the sixth most common form of cancer after breast, lung, colorectal, prostate, and stomach cancer (1, 2). The World Health Organization (WHO) reported 905,677 new liver cancer cases in 2020, of whom 830,180 died (1, 2). Asia had the highest number of new cases (656,922; 72.5%), followed by Europe (87,630; 9.7%), and Africa (70,542; 7.8%) (1, 2). Of the Asian countries, Thailand had the second highest incidence of liver cancer (after Mongolia) with 27,394 cases, 26,704 of whom died, equating to an incidence rate of 39.2 and a mortality risk of 38.3 (1, 3). The World Health Organization estimates that the total number of new liver cancer cases in Thailand will increase to 42,600 by 2040, implying that the liver cancer incidence will persist and increase markedly within 20 years (4, 5).

People with hepatitis B and hepatitis C are known to develop cirrhosis, which can lead to liver cancer and accounts for 80% of all liver cancer cases worldwide (6, 7). Furthermore, it has been reported that diabetes increases the incidence and mortality of liver cancer (7–10). Moreover, nonalcoholic fatty liver disease (NAFLD), which can cause cirrhosis and thereby lead to liver cancer, is on the rise. In 2020, NAFLD patients had an incidence and mortality of liver cancer of 44 and 77 per 100,000 persons per year (11). Alcohol use is a long-established risk factor for liver cancer incidence and mortality (12–17), and even low-level consumption poses an approximately three-fold higher risk (18). Males exhibit a higher incidence of liver cancer compared to females, with studies consistently demonstrating a two to three times higher risk in in the former (14, 15, 17, 19). Usually, the lifestyle of men and women is different in both alcohol consumption and, especially, smoking (6, 12). Smoking is associated with a 30 to 70% increased risk of liver cancer compared to non-smokers (12, 20, 21).

Both *in vitro* and animal model studies have shown that exposure to $PM_{2.5}$ causes oxidative stress in hepatocytes, leading to increased DNA damage and subsequent repair in the liver (22–25). This process can result in liver fibrosis similar to that seen in non-alcoholic fatty liver disease, which can exacerbate the initiation of liver cancer. Studies of humans have indicated that inhalation of pollutants can affect the liver through the circulatory system (26, 27). Brook et al. (28) reported an association between air pollutants and elevated serum levels of alanine transaminase (ALT), aspartate aminotransferase (AST), and gamma-glutamyl transpeptidase (GGT), which are known biomarkers for liver injury.

Particulate matter (PM) ≤ 2.5 μm ($PM_{2.5}$) and ≤ 10 μm (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3) are major air pollutants in Thailand (29). Thailand has consistently ranked among the top 50 countries with the highest ambient air pollution, particularly from 2019 to 2021 (30–32). Over the past decade, forest fires and agricultural waste burning during the dry season (January–April) have significantly reduced the air quality in northern Thailand (33). Thailand's national annual average standards for $PM_{2.5}$ and PM_{10} concentrations are 25 and 50 μg/m^3, respectively, which are higher than those set by the WHO (10 and 20 μg/m^3, respectively). According to the air quality measurement criteria used by IQ AIR (a Swiss organization), a $PM_{2.5}$ level above 25 μg/m^3 is slightly deleterious to health, above 35 μg/m^3 is highly detrimental, and above 50 μg/m^3 is hazardous (30).

In recent years, several research groups have investigated whether PM is associated with liver cancer mortality. The outcomes from a study in Taiwan indicate that exposure to $PM_{2.5}$ levels greater than 36 μg/m^3 is associated with a 58% increased risk of mortality from liver cancer, with each 5 μg/m^3 increase in $PM_{2.5}$ exposure being associated with a 13% increase (34). Meanwhile, another research group in Taiwan observed that a 1 μg/m^3 increase in $PM_{2.5}$ exposure is associated with an 11% increase in the mortality risk due to liver cancer (35). Similarly, the findings from another study conducted in California infer that exposure to $PM_{2.5}$ after a diagnosis of hepatocellular carcinoma shortens life expectancy, with a 1 unit (5 μg/m^3) increase in $PM_{2.5}$ resulting in an 18% increase in mortality (36). From a US partial cohort study of non-smoking individuals (37), it was found that a 10 μg/m^3 increase in $PM_{2.5}$ is associated with a significant 2.18-fold increase in the risk of mortality from liver cancer.

Even though PM levels and liver cancer mortality rates appear to be related, the levels of $PM_{2.5}$ and PM_{10} associated with the risk of mortality are still debatable and unconfirmed. In a recent systematic review (38), the authors reported that the outcomes from several studies suggest an association between $PM_{2.5}$ level and liver cancer mortality but not with liver cancer incidence. Thus, we hypothesized that exposure to ambient air pollution after the development of liver cancer increases the risk of mortality. In prior studies, the researchers did not examine the effects of multiple air pollutants such as $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 over an extended period using time-varying covariates. Moreover, only a few researchers have explored the various causes of liver cancer within the socioeconomic context in Asia and compared this to other regions in the world. To the best of our knowledge, ours is the first cohort study conducted to examine the relationship between ambient air pollution, especially PM, and liver cancer mortality in northern Thailand, an area afflicted by crop-burning activity and forest fires for a significant part of the year. In addition, to the best of our knowledge, a cohort study to examine the relationship between ambient air pollution and liver cancer mortality in northern Thailand has not previously been conducted. Therefore, the aim of the present study is to investigate the effect of high levels of PM on the risk of mortality from liver cancer in this area.

2 Materials and methods

2.1 Study design and population

This retrospective cohort study was conducted to examine the mortality and associated risk factors on liver cancer patients in upper northern Thailand using extended time-varying covariates ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 levels) over 15 years. Patients who were diagnosed with primary liver cancer [either hepatocellular carcinoma (HCC) or cholangiocarcinoma (CCA)] between January 1, 2003, and December 31, 2018, were followed up from their registered date to the end of 2020.

2.2 Exposure assessment for time-updated variables

The dataset used in the present study included concentrations of particulate matter, NO_2, SO_2, CO, and O_3. Since these could have changed throughout the follow-up period, they were thus included as time-varying covariates in the analysis (39). Hourly air pollutant data from 2003 to 2020 were obtained from the Copernicus Atmosphere Monitoring Service (CAMS), the European Centre for Medium-Range Weather Forecasts (40, 41). The CAMS reanalysis merges modeled data utilizing a physics and chemistry-based atmospheric model with real observations to create a globally complete and consistent dataset consisting of 3-dimensional (3D) time-consistent atmospheric composition fields that include aerosols and chemical species (42). The spatial resolution for the dataset is approximately 80 km. The data are available in two formats of spectral coefficients: triangular truncation of linear grids (T255). The daily forecast beginning at 00 Universal Time Coordinated (UTC) for 48 h includes 3-hourly steps for the 3D model level and pressure level fields and hourly steps for the surface fields. In the present study, we utilized the average of the hourly concentrations to provide annual concentrations for each pollutant for each district in upper northern Thailand. These were then linked to the district of each patient's residence (based on the assumption that their recorded address was where they lived and subsequently died) and the calendar year of diagnosis obtained from the Chiang Mai Cancer Registry. This was updated each year until the patient's death, loss to follow-up, or censoring due to still being alive at the end of the study period.

2.3 Baseline and follow-up data

Information on each cancer patient at diagnosis, including demographics (gender, age, body mass index (BMI), smoking history, and alcohol-use history) and cancer characteristics [cancer stage (SEER staging; localized, regional, or metastatic)]. Each year, the concentration of each pollutant that each patient had been exposed to was obtained by using the pollution dataset detailed in previous section.

2.4 Statistical analysis

The baseline characteristics are presented as frequencies and percentages for categorical variables and medians and interquartile ranges (IQRs) for continuous variables. The follow-up time was calculated from the date of diagnosis to either the date of death regardless of the cause, to the last follow-up date, or censored by using the end of the study period (December 31, 2020), depending on which came first.

Missing values at the baseline of more than 30% for BMI, smoking history, and alcohol-use history were imputed using multivariate imputation based on linear regression for continuous variables and logistic regression for binary variables (43). In the context of this methodology, all missing values were substituted with imputed ones.

The overall rate of death and those separated by each variable were calculated as the number of deaths divided by the total number of persons per year of follow-up (PYFU). Confidence intervals (CIs) for the mortality risks were based on fitting the data to a Poisson distribution. Survival probability were obtained from Kaplan–Meier curves and log-rank tests were used to determine significant differences between the survival probabilities of the groups for each variable.

To handle these time-varying covariates, we used a time-dependent Cox proportional hazard model and a time-varying coefficient (44) to investigate the associations between the mortality risk among liver cancer patients and potential risk factors (gender, age, cancer stage, smoking history, alcohol-use history, calendar year of enrollment, and time-updated $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 concentrations). Log–log plots for survival and Schoenfeld residuals were used to verify the proportional hazards assumption for the Cox model for each covariate. All of the continuous variables were grouped by using quartiles and considered for dichotomization where appropriate [except for BMI with categories: < 18.5 and ≥ 18.5 kg/m^2 (45)]. Factors associated with mortality risk with *p*-values <0.25 in the univariable analysis were included in the multivariable analysis via a backward elimination procedure, except for variables with high correlations (to avoid multicollinearity). All analyses were performed by using STATA (version 12).

3 Results

A total of 10,859 liver cancer patients were registered between January 2003 and December 2018, 7,763 (71%) of whom were male. At the time of diagnosis, the median age was 58.7 years old (IQR: 51.6–66.5) and the median BMI was 22.1 kg/m^2 (IQR: 19.7–24.4). At the time of diagnosis, the medians for $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 levels were 37.5 μg/m^3 (IQR: 33.5–42.1), 52.4 μg/m^3 (IQR: 46.8–58.3), 7.2 ppb (IQR: 5.4–8.9), 5.8 ppb (IQR: 3.2–8.2), 390.4 ppb (IQR: 362.7–426.5), and 36.5 ppb (IQR: 35.0–38.5), respectively. Among the liver cancer patients, 6, 56, and 29% were diagnosed with the localized, regional, and metastatic cancer stages, respectively. In addition, 61% of the patients had an alcohol-use history while 54% had a smoking history. The median duration of follow-up and survival time were 1.0 years (IQR: 0.41–3.37) and 0.42 years (IQR: 0.17–1.24), respectively.

3.1 Baseline characteristics and mortality risk

According to the results in Table 1, 9,887 liver cancer patients died from any cause and the overall mortality risk was 68.0 per 100 PYFU. (95% CI: 66.7–69.4). The mortality risk was 72.4 per 100 PYFU for men (95% CI: 70.7–74.1) and 59.0 per 100 PYFU for women (95% CI: 56.9–61.2). Age at diagnosis ≥60 years had a high mortality risk (78.8 per 100 PYFU; 95% CI: 76.6–81.2), as did having a low BMI (79.3 per 100 PYFU; 95% CI: 75.5–83.4). When considering the three cancer stages, the mortality risk was highest in the group with the metastatic stage (179.6 per 100 PYFU; 95% CI: 173.4–186.1). Having a history of smoking and/or alcohol use also had high mortality risks (74.2 per 100 PYFU; 95% CI: 72.3–76.2 and 71.2 per 100 PYFU; 95% CI: 70.2–73.8, respectively).

3.2 Survival probabilities

Figure 1 illustrates the overall survival probability of the liver cancer patients. Among them, 9,389 died within the first 3 years of diagnosis and the survival probability dropped sharply to 13%. This slowly decreased after a follow-up time of 3 years: the survival probabilities at 6, 9, and 12 years after diagnosis were 9, 7, and 6%, respectively, and thus the 5-year survival rate was estimated as 9.78%.

TABLE 1 Baseline characteristics and the associated mortality risk of the study population.

Characteristic	Survived [*n* (%)]	Died [*n* (%)]	PYFU	Mortality risk*	95% CI
Overall	972 (9%)	9,887 (91%)	14,534	68.0	66.7–69.4
Gender					
Male	663 (8%)	7,100 (92%)	9,810	72.4	70.7–74.1
Female	309 (10%)	2,787 (90%)	4,724	59.0	56.9–61.2
Age at diagnosis (years old) [Median 58.7, IQR 51.6–66.5]					
< 60	571 (10%)	5,374 (90%)	8,808	61.0	59.4–62.7
≥60	401 (8%)	4,513 (92%)	5,726	78.8	76.6–81.2
BMI (kg/m^2) [Median 22.1, IQR 19.7–24.4]					
< 18.5	116 (7%)	1,573 (93%)	1982	79.3	75.5–83.4
≥18.5	856 (9%)	8,314 (91%)	12,552	66.2	64.8–67.7
Cancer stage					
Localized	166 (27%)	453 (73%)	1731	26.2	23.9–28.7
Regional	631 (10%)	5,469 (90%)	9,443	57.9	56.4–59.5
Metastatic	46 (1%)	3,050 (99%)	1,698	179.6	173.4–186.1
Smoking history					
Yes	433 (7%)	5,414 (93%)	7,293	74.2	72.3–76.2
No	539 (11%)	4,473 (89%)	7,241	61.8	60.0–63.6
Alcohol-use history					
Yes	530 (8%)	6,106 (92%)	8,485	71.2	70.2–73.8
No	442 (10%)	3,781 (90%)	6,049	62.5	60.5–64.5

*Per 100 PYFU (persons per year of follow-up). CI, confidence interval; BMI, body mass index.

The survival probability of the liver cancer patients according to the baseline characteristics including gender, age, BMI, cancer stage, smoking history, and alcohol-use history are presented in Figure 2. The results from log-rank tests show the differences between the survival probabilities of the groups for each variable (all *p*-values <0.0001). There is evidence that men had a significantly lower survival probability than women (Figure 2A). The results in Figure 2B suggest that liver cancer patients aged ≥60 years old had a significantly lower survival probability than younger ones. In addition, patients who had BMI < 18.5 kg/m^2 had a significantly lower survival probability than those who had a higher BMI (Figure 2C). Liver cancer patients diagnosed with the metastatic stage had a significantly lower survival probability than those diagnosed with either the regional or localized stage (Figure 2D). Moreover, patients with a history of smoking and/or alcohol use had a significantly lower survival probability than non-smokers and non-drinkers (Figures 2E,F).

Figure 3 presents the effect of air pollution according to the patients' residences on the survival probability. Figure 3A shows that patients who lived in an area where the annually averaged $PM_{2.5}$ concentration ≥ 40 μg/m^3 had a lower survival probability than where it was <40 μg/m^3 (*p*-value = 0.0001). The same result was found for those who lived in an area where the annually averaged PM_{10} concentration ≥ 55 μg/m^3 compared to where it was <55 μg/m^3 (*p*-value <0.0001) (Figure 3B). Although not statistically significant, the survival probability of those who lived in an area where the annually averaged CO concentration ≥ 418 ppb was slightly lower than where it was <418 ppb (Figure 3E). Meanwhile, there were no differences in the survival probability of patients who lived in areas with varying concentrations of NO_2 (Figure 3C), SO_2 (Figure 3D), or O_3 (Figure 3F).

3.3 Risk factors associated with death

Table 2 summarizes the results of Cox proportional hazard models for determining risk factors associated with the mortality risk among the liver cancer patients. The results from the univariable analysis show that gender, age, BMI, cancer stages, smoking history, alcohol-use history, and time-updated local concentrations of $PM_{2.5}$, PM_{10}, and CO were risk factors for death among the liver cancer patients (all *p*-values ≤0.0001).

Since there was a multicollinearity issue when including all of the pollutants in the multivariable model, we only retained $PM_{2.5}$. Thus, the multivariable analysis included gender, age, BMI, cancer stage, smoking history, alcohol-use history, and the time-update local concentration of $PM_{2.5}$. In the final model, we found that all of the included parameters were independently associated with the mortality risk (all *p*-values <0.0001), except for BMI and alcohol-use history. Especially, the metastatic cancer stage had the highest adjusted hazard ratio (aHR) = 3.57 (95% CI: 3.23–3.95). In addition, we also found that being male (aHR = 1.10; 95% CI: 1.04–1.15) and/or aged 60 years old (aHR = 1.16; 95% CI: 1.11–1.21), having the regional cancer stage (aHR = 1.80; 95% CI: 1.64–1.99) and/or a history of smoking (aHR = 1.16; 95% CI: 1.11–1.22), and/or being exposed to a time-updated local concentration of $PM_{2.5}$ 40 μg/m^3 (aHR = 1.10; 95% CI: 1.05–1.15) all increased the mortality risk among the liver cancer patients.

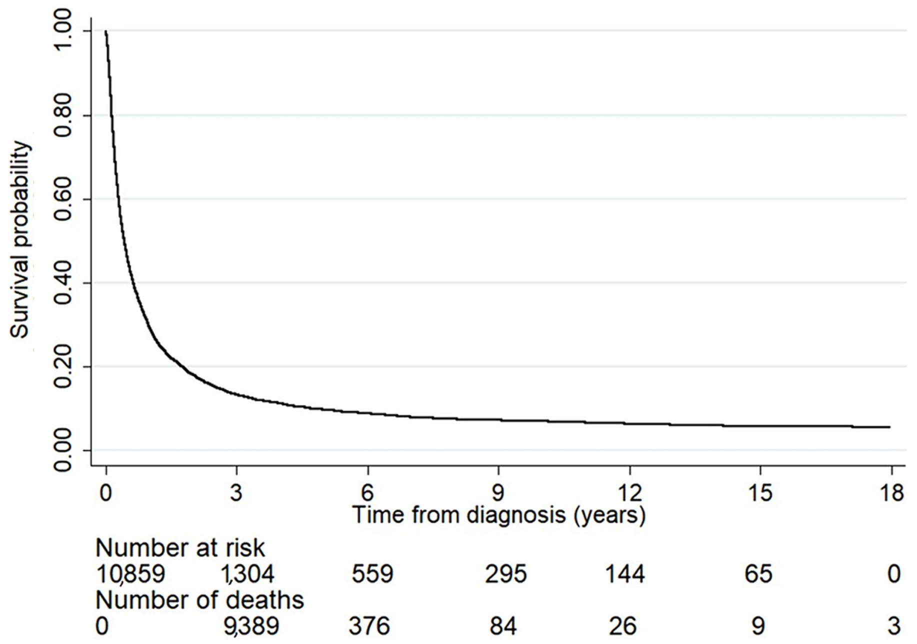

FIGURE 1
The survival probability of the liver cancer patients. The number at risk indicates the number of patients who were still alive each year after diagnosis. The number of deaths indicates the number of patients who died within the duration between a specific time point and the previous one. The overall survival probability sharply dropped within the first 3 years of diagnosis and slowly decreased after the follow-up time passed 3 years.

We checked for interactions between the variables included in the multivariable model (i.e., gender, age, BMI, cancer stage, smoking history, and alcohol-use history) and only found an interaction between BMI and cancer stage. However, we were unable to examine any interactions of these variables with the time-updated $PM_{2.5}$ level.

4 Discussion

We are the first to study the survival probability and risk factors associated with liver cancer in upper northern Thailand using extended time-varying covariates ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3 levels) based on a retrospective study over 15 years to answer this research. The survival probability of liver cancer patients concerning various factors such as gender, age, BMI, cancer stage, a history of smoking and/or alcohol use, and air pollution levels were examined in this retrospective study comprising a total of 10,859 liver cancer patients diagnosed over 15 years in upper northern Thailand. The results show that the overall mortality risk was 68 per 100 PYFU and the median survival time was 0.42 years. Gender, age, BMI, cancer stage, and smoking and alcohol-use histories were all found to significantly affect the survival probability. Being male and/or ≥ 60 years old, and/or having a low BMI, metastatic cancer, and/or a history of smoking or alcohol use all resulted in a lower survival probability, as did high $PM_{2.5}$, PM_{10}, and CO levels.

The mortality rate among liver cancer patients in our study was noticeably high (87% within 3 years after diagnosis). Although we did not include the impact of air pollution on liver cancer mortality in other regions of Thailand, we suspect that exposure to much higher levels of air pollutants in the northern region increases the risk of liver cancer mortality. In a previous study on the mortality from cholangiocarcinoma in Thailand from 2009 to 2013 (46), the one-year mortality rate in the northern region was considerably higher than in the central, northeastern, and southern regions where the ambient air pollution is much lower. Thus, expanding our study to include these other areas should be undertaken.

The potential mechanisms for the association between $PM_{2.5}$ and liver cancer mortality remain unclear. $PM_{2.5}$ contains various toxic elements, including heavy metals and other carcinogens, which could trigger the development and progression of cancer. At the molecular level, the genotoxic effects of $PM_{2.5}$ include defects in DNA repair and replication, as well as DNA mutation (47). At the cellular level, $PM_{2.5}$ induces cell damage and apoptosis (48), as well as oxidative stress and inflammation (49). $PM_{2.5}$ causes oxidative stress by producing oxidants and free radicals and consuming antioxidants and enzymes. Diesel exhaust particles have been shown to cause oxidative stress in rats that resulted in DNA damage, the creation of bulky DNA adducts, the triggering of apoptosis, and the upregulation of hepatic DNA repair (23, 50). Long-term exposure to ambient air pollution has been linked to the upregulation of ALT activity, a biomarker for human liver damage (51–53). ALT and other liver function biomarkers and inflammation, such as C-reactive protein and interleukin-6, are used to detect the occurrence of liver cancer (54, 55). Therefore, exposure to ambient $PM_{2.5}$ conceivably contributes to the development of and mortality from liver cancer.

$PM_{2.5}$-associated mortality could be the result of oxidative stress induced by $PM_{2.5}$ on epithelial cells creating reactive oxygen species that can damage DNA, proteins, and lipids (56, 57). Another explanation is that $PM_{2.5}$-induced inflammation leads to the production of chemokines and cytokines that promote angiogenesis,

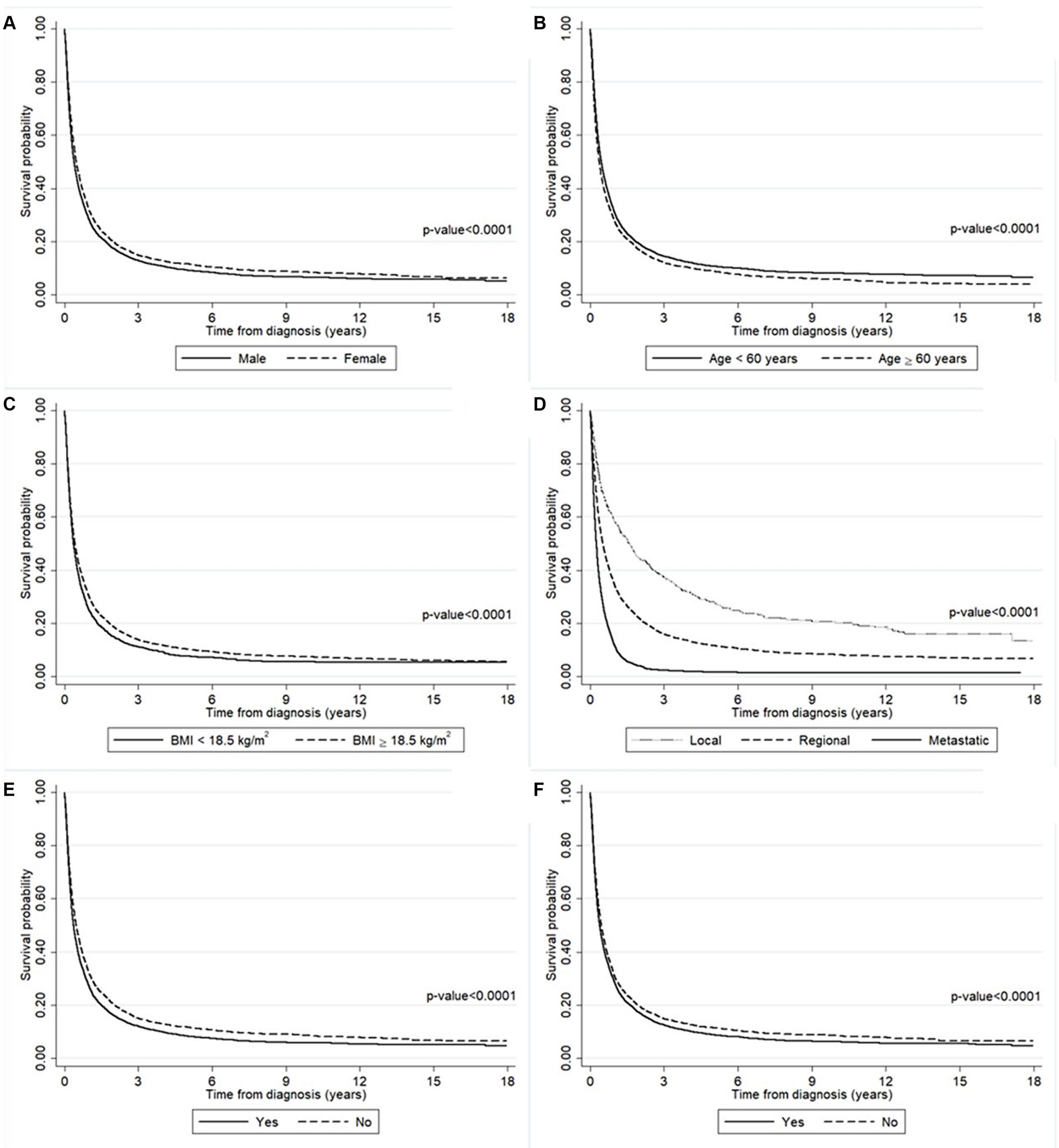

FIGURE 2
The survival probability of the liver cancer patients according to **(A)** gender, **(B)** age, **(C)** BMI, **(D)** cancer stage, **(E)** smoking history, and **(F)** alcohol-use history. The survival probability was significantly lower in the man group (solid line) than the women group (long-dashed line). The survival probability was significantly lower in the older group (long-dashed line) than the younger group (solid line). The survival probability was significantly lower in the lower BMI group (solid line) than the higher group (long-dashed line). The survival probability was significantly lower in the metastatic stage group (solid line) than the other groups (dashed lines). The survival probability was significantly lower in the smoking group (solid line) than the non-smoking group (long-dashed line). The survival probability was significantly lower in the drinking group (solid line) than the non-drinking group (long-dashed line).

thereby enabling the spread of metastatic cells to distant tissues (58). Hence, the carcinogenic effects of PM could stem from defects in DNA repair function and replication (47).

The effects of oxidative stress due to air pollution have been reported in other biological systems (59). Its effects on the digestive system include inflammation of the gut lining epithelial cells and alterations of the immune response and gut microbiota (56, 60). These could be connected to aerosolized pollutants becoming trapped in the mucus and swallowed. It is also well known that exposure to air pollution can increase inflammation in the human body, which can increase the number of tumor-associated macrophages and predispose an individual to cancer

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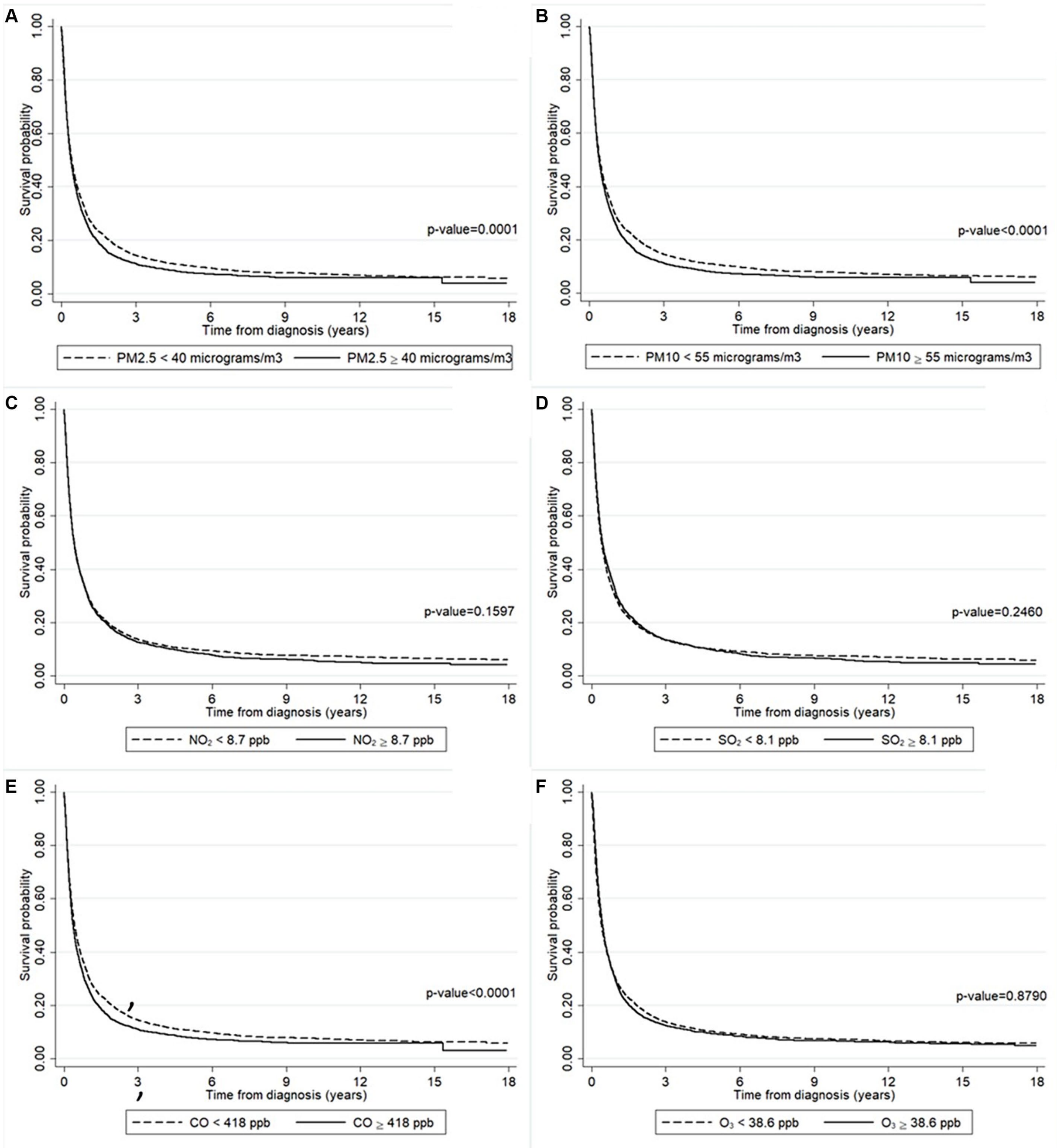

FIGURE 3
The survival probability of the liver cancer patients according to the annually averaged concentrations of **(A)** $PM_{2.5}$, **(B)** PM_{10}, **(C)** NO_2, **(D)** SO_2, **(E)** CO, and **(F)** O_3. The survival probability was significantly lower in the patients who lived in a higher concentration of $PM_{2.5}$ area (solid line) than those lived in a lower concentration of $PM_{2.5}$ area (long-dashed line). The survival probability was significantly lower in the patients who lived in a higher concentration of PM_{10} area (solid line) than those lived in a lower concentration of PM_{10} area (long-dashed line). The survival probability was significantly lower in the patients who lived in a higher concentration of CO area (solid line) than those lived in a lower concentration of CO area (long-dashed line).

(61). In addition, air pollution adversely affects biological aging, the nervous system, smooth muscles, and the immune system (62, 63).

In rats, intragastric exposure to diesel exhaust particles induces oxidative stress associated with DNA damage, bulky DNA adduct formation, induction of apoptosis, and the upregulation of hepatic DNA repair (23, 50). In humans, long-term exposure to ambient air pollution causes the upregulation of biomarkers such as ALT for liver damage (51–53) and C-reactive protein (CRP) and interleukin-6 (IL-6) for inflammation (54, 55). Therefore, exposure to ambient PM2.5 conceivably contributes to the development of liver cancer.

Most of the risk factors in this study impacted the survival rate, which is unsurprising since liver cancer has a poor survival incidence (6). Our study showed that 91% of the patients died within 1 year. The

TABLE 2 Risk factors associated with death among the liver cancer patients.

Characteristic			Univariable analysis			Multivariable analysis		
	Died	Total	HR	95% CI	*p*-value*	aHR	95% CI	*p*-value*
At diagnosis								
Male	7,100	7,763	1.11	1.07–1.17	<0.0001	1.10	1.04–1.15	< 0.0001
Aged ≥ 60 years old	4,513	4,914	1.13	1.08–1.17	<0.0001	1.16	1.11–1.21	< 0.0001
BMI < 18.5 kg/m^2	1,573	1,689	1.12	1.06–1.18	<0.0001	1.06	1.00–1.12	0.0596
Regional cancer stage	5,469	6,100	1.78	1.61–1.95	<0.0001	1.80	1.64–1.99	< 0.0001
Metastatic cancer stage	3,050	3,096	3.46	3.13–3.82		3.57	3.23–3.95	
Smoking history	5,414	5,847	1.16	1.11–1.21	<0.0001	1.16	1.11–1.22	< 0.0001
Alcohol-use history	6,106	6,636	1.11	1.06–1.15	<0.0001	1.02	0.96–1.08	0.5924
Time-updated variables								
$PM_{2.5}$ concentration ≥ 40 μg/m^3	–	–	1.09	1.05–1.14	0.0001	1.10	1.05–1.15	< 0.0001
PM_{10} concentration ≥ 55 μg/m^3	–	–	1.10	1.05–1.14	<0.0001	–	–	–
NO_2 concentration ≥ 8.7 ppb	–	–	1.03	0.99–1.08	0.1614	–	–	–
SO_2 concentration ≥ 8.1 ppb	–	–	0.97	0.93–1.02	0.2664	–	–	–
CO concentration ≥ 418 ppb	–	–	1.13	1.08–1.18	< 0.0001	–	–	–
O_3 concentration ≥ 38.6 ppb	–	–	1.00	0.95–1.04	0.8792	–	–	–

**p*-value from a partial likelihood ratio test. HR, hazard ratio; CI, confidence interval; aHR, adjusted hazard ratio.

correlation between ambient air pollution exposure and liver cancer might have been confounded by the general health of these individuals. Most cancer patients have poor immune resilience and thus have a higher risk of opportunistic infections (64), which we did not account for. It has been reported that opportunistic infection, a family history of cancer, and high alcohol consumption all significantly impact the liver cancer survival probability (65). Moreover, limited access to advanced cancer detection methods and treatment are major causes of the poor liver cancer survival rate in northern Thailand (66). Thus, although our results demonstrate an association between $PM_{2.5}$ and poor liver cancer survival probability, we cannot assume that the causation is only due to high $PM_{2.5}$ exposure.

The inclusion of local PM, NO_2, and O_3 concentrations as time-varying covariates in the analysis is one of the present study's greatest strengths. Including them means that we could more accurately assess their impact on liver cancer patient survival. In addition, using such pollutant data is appropriate because the patients' information was hospital-based recorded, which patients usually visit for their sickness. Therefore, we can assume that patients mostly stayed in their habitats, and we can imply that patients had accumulatively consumed pollutants, resulting in having precisely long-term exposure to pollutant concentrations. Another strength of this work is that information on liver cancer patients was collected from a considerable number of patients (N = 10,859) for 18 years.

It may be necessary to address some of these identified risk factors to reduce the mortality risk of liver cancer patients. For example, efforts should be made to encourage people to stop smoking and consuming alcohol, especially those with a high risk of contracting liver cancer. To improve the survival probability, it may be advantageous to focus on early cancer detection and treatment rather than wait until the cancer is in the metastatic stage. In addition, mitigating environmental factors such as air pollution is crucial for reducing the mortality risk of liver cancer patients. Overall, addressing individual and societal level risk factors is required to effectively reduce the mortality risk of liver cancer. This means that early diagnosis of liver cancer and tobacco control may be more critical for the prognosis of liver cancer in northern Thailand.

The strength of this study is that it is the first in which the mortality risk and risk factors associated with liver cancer were examined in upper northern Thailand using extended time-varying covariates ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3 levels) retrospectively over 15 years. However, this study still has some limitations. First, we were unable to access other important risk factors for liver cancer: for instance, viral hepatitis status and the amount of alcohol consumption. Not including the latter data could have potentially biased the results as they would have helped to shed light on why alcohol-use history was not significant in the multivariable analysis. Second, the focus of this study was on patients living in the northern region of Thailand, so generalization of the findings is not possible. Since we did not compare the mortality of liver cancer patients and risk factors in other areas and settings, larger and more diverse study populations incorporating these would help to confirm the findings from our study. Third, several variables in this study contained missing values. We handled this issue using multivariate imputation based on regression, which could have introduced bias in the results. This might have been mitigated by using the Multiple Imputation by Chained Equations approach. Next, we considered keeping the BMI, age at diagnosis, and air pollutant levels as categorical variables even though dichotomization of these and the continuous variables could have led to confounding. In addition, we focused on the all-cause mortality of the patients and did not include competing events such as loss to follow-up or death from other causes in the analysis. Thus, the mortality rates reported in this study might be biased due to competing events and should be viewed with caution. Finally, the annually averaged pollutant concentrations as time-varying covariates used in this study might not accurately reflect individual-level exposure to air pollution over time. Moreover, although most of the study participants probably resided in the study area due to cultural and occupational reasons, some may have moved or spent time in other areas with different pollution levels. Although biological measures such as pollutant levels in blood samples would have more accurately determined the levels of air pollutant exposure of the participants, these data are not available in Thailand. Thus, the interpretation of our results should be treated with caution. A further prospective study using more precise data including biological measures might provide more precise findings. Next, including all of the air pollutants as variables caused multicollinearity issues in the multivariable model. Thus, we only retained $PM_{2.5}$ since it has previously been reported to have a significant association with liver cancer mortality (35, 38). Using a different statistical model capable of addressing the multicollinearity issue could help to uncover the cumulative effects of multiple air pollutants on liver cancer mortality. In addition, we only examined the effect of air pollution on people already diagnosed with liver cancer. A future investigation of the effect of long-term exposure to air pollution, especially during early life, on liver cancer incidence may provide more insights.

5 Conclusion

Based on this retrospective cohort study, we found an association between mortality risk and exposure to a time-updated local concentration of $PM_{2.5} > 40\,\mu g/m^3$ in liver cancer patients who lived in Northern Thailand. Being male, aged >60 years old, and having a history of smoking were also significant deleterious factors. These findings provide health information that will encourage policymakers to combat air pollution in this area. However, the interpretation of our results should be treated with caution and further prospective research is needed to confirm our findings.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. Requests to access these datasets should be directed to Imjai Chitapanarux, imjai.chitapanarux@cmu.ac.th.

Ethics statement

The studies involving humans were approved by the Research Ethics Committee of the Faculty of Medicine at Chiang Mai University. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because patient consent was waived due to anonymous data recorded in the present study.

Author contributions

NT: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. TC: Data curation, Resources, Writing – review & editing. AC: Data curation, Resources, Writing – review & editing. SC: Data curation, Resources, Writing – review & editing. PT: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. NN: Writing – original draft, Writing – review & editing. PS: Formal analysis, Writing – review & editing. ST: Formal analysis, Writing – review & editing. TS: Data curation, Resources, Writing – review & editing. PH: Data curation, Resources, Writing – review & editing. IC: Conceptualization, Data curation, Funding acquisition, Resources, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research project was supported by Fundamental Fund 2023, Chiang Mai University, Thailand (FF66/015).

Acknowledgments

We acknowledged Chiang Mai Cancer Registry, Maharaj Nakorn Chiang Mai Hospital, Faculty of Medicine and Chiang Mai University for supporting the current study. This research project was supported by Fundamental Fund 2023, Chiang Mai University, Thailand (FF66/015).

Conflict of interest

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

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frontiers | Frontiers in Public Health

TYPE Methods
PUBLISHED 25 October 2024
DOI 10.3389/fpubh.2024.1477186

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OPEN ACCESS

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RECEIVED 07 August 2024
ACCEPTED 03 October 2024
PUBLISHED 25 October 2024

CITATION
Sankar SK, P V, S K, Shanmugam R, Kamalakkanan LP and Venugopal V (2024) Effectiveness of heat stress interventions among outdoor workers: a protocol paper. *Front. Public Health* 12:1477186. doi: 10.3389/fpubh.2024.1477186

Effectiveness of heat stress interventions among outdoor workers: a protocol paper

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Introduction: Heavy work in scorching temperatures can cause dehydration and heat stress, which can lead to a number of heat-related diseases. Heavy work in intense heat without rest or hydration is the main cause. The "Water, Rest, Shade" (WRS) intervention program for outdoor workers in hot weather reduces heat stress.

Methods: This study follows a quasi-experimental design involving 250 outdoor workers from both agriculture and brick kilns. To assess the environmental heat exposure levels, Quest Temp 3M WBGT Monitor will be used. Tympanic temperature, Heart rate (HR), Sweat rate (SwR), and Urine specific gravity (USG) to assess the physiological responses to heat exposure using standard protocols. Blood samples will be collected to measure serum creatinine and calculate Glomerular filtration rate (GFR), and urine samples to measure pH, leucocytes, proteinuria, and hematuria. Then administer a validated and modified HOTHAPS questionnaire to capture the perception data. After the baseline assessments, Categorize the workers into two groups based on the selection criteria and the participants' willingness. Then provide a week-long WRS intervention to the intervention group (IG). The non-intervention group will collect the same data without any intervention to assess the efficacy of the intervention by comparing both groups and measuring outcome indicators.

Expected outcome: The study will generate much-needed information to raise awareness of the importance of heat stress prevention for outdoor workers.

Conclusion: This study will demonstrate the effectiveness of an intervention, provide much-needed strategies for reducing heat stress, assess both health impacts and implementation quality, and design comprehensive workplace and labor laws aim to minimise risks to millions of unorganised outdoor workers health.

KEYWORDS

heat stress, intervention, outdoor workers, physiological heat strain, WRS

1 Introduction

Over the next few decades, it is anticipated that global temperatures will rise by 0.5 to 1.5°C that threaten all living things, including humans (1). In particular, the working environments are impacted by climate change, posing health risks to millions of workers (2). Workplace heat poses a risk to workers in various outdoor environments, resulting in a range of Heat-Related Illnesses (HRI) that can manifest when the body's heat absorption and production exceeds its heat dissipation capacity (3). Physically demanding jobs performed in high-temperature environments place individuals at a heightened risk (4).

Heat stress is a condition that can occur due to prolonged exposure to elevated temperatures. When the body's mechanism for regulating internal temperature begins to struggle, heat stress occurs (5). When a worker is exposed to various factors like metabolic heat, environmental conditions, and clothing, it leads to an accumulation of heat in the body. It leads to internal body temperatures rise as well as decreased productivity and performance (6). And it leads to heat related illness (HRI), such as distress, headaches, syncope, loss of mental awareness, heat stroke (7). When core body temperature (CBT) raises above 42°C can lead to various adverse outcomes, such as harm to major organs and potential death (8).

Over the years, heat waves were responsible for more than 166,000 deaths between 1998 and 2017. The majority of outdoor workers had a low estimated glomerular filtration rate (eGFR), it shows kidney function impairment due to heat exposure (9). In addition to the deaths associated with heat waves, there is also a strong correlation between heat stress and the emergence or worsening of several non-communicable diseases (NCDs). These include chronic kidney disease (CKD), cardiovascular disorders, and respiratory morbidity. India is known for its significant heat events, particularly during the summer season faces a considerable challenge in terms of human health and well-being. These heat events manifest in the form of heat waves, posing significant threats to outdoor workers (5). Based on the available projections, it is anticipated that India could potentially experience a decline in its gross domestic product (GDP) within the range of 2.5 to 4.5% by the year 2030 (10). The decline observed in this particular scenario can be linked to a decrease in labour hours, which can be primarily attributed to the adverse impacts of extreme heat and humidity conditions. It is noteworthy that approximately 40% of the nation's GDP is associated with occupations that are exposed to high levels of heat-exposed work, and over 90% of the workforce is engaged in informal employment (11).

Informal work is described as work that lacks a formal contract, paid time off, or other benefits (12). Every year, India witnesses a significant rise in temperatures. This situation results in reduced productivity, negative health effects, and economic losses, accompanied by an increase in heat-related fatalities among the workforce (13). The current situation in India highlights a significant issue concerning the impact of rising temperatures on the outdoor labour force (14). Regrettably, there is a lack of a comprehensive action plan or policy in place to protect the well-being of these workers in the face of challenging, hot, and humid working conditions. These individuals often undergo a conventional 8-h workday marked by insufficient breaks, rest intervals, access to sufficient toilets, and water intake (15). The lack of proper protective measures results in adverse health effects; consequently, practical and sufficient regulations, as well as heat stress interventions, are not effectively put into practice (16).

One of the foremost public health strategies involves educating people on preventing heat stress and identifying its early warning signs. Occupational Safety and Health Administration (OSHA) strongly recommends three words: water, rest, and shade intervention to protect workers from heat stress. The Water, Rest, Shade (WRS) intervention has been chosen based on its demonstrated effectiveness in managing heat stress in various occupational settings. Adequate water intake is crucial for preventing dehydration and fluid intake of 250–300 mL/hr in reducing dehydration. Regular rest breaks in shaded areas are essential for allowing workers to recover from heat exposure and prevent heat stress. These interventions work collectively by ensuring adequate hydration, allowing gradual acclimatization, providing regular cooling breaks, controlling environmental conditions, and ensuring early detection and treatment of heat-related symptoms (17, 18). The objective of this study is to enhance overall health and decrease susceptibility to extreme temperatures among outdoor workers. Additionally, it seeks to formulate comprehensive workplace and labour policies to prevent health risks for the large population of unorganized outdoor workers.

2 Physiology of heat stress

Heat, as a fundamental form of energy, helps in optimal functioning of human body, typically maintains temperature approximately 36.6°C. The hypothalamus, acting as the central thermostat, regulates these processes by triggering responses such as sweating, shivering, and adjusting blood flow to maintain a stable internal temperature (19). To maintain this optimal temperature, the human body employs various mechanisms to regulate heat loss, either by promoting or reducing it (20). Heat loss mechanisms include radiation, conduction, convection, and evaporation. Environmental temperature, humidity, air movement, clothing, and body composition influence these processes. The body conserves heat through insulating mechanisms such as subcutaneous fat and hair and regulates heat loss through circulatory adjustments like vasodilation (increasing blood flow to the skin to lower heat) and vasoconstriction (decreasing blood flow to the skin to save heat). In response, the brain adjusts breathing rate, blood sugar levels, and metabolic rate to counterbalance temperature variations, triggering responses like shivering and sweating to maintain optimal body temperature. The imbalance in thermal equilibrium may leads to heat strain (see Figure 1).

Heat strain can be classified based on physical symptoms associated with heat, such as excessive thirst, fatigue, excessive sweating, and uncomfortable warmth. Exposure to high environmental temperatures leads to several physiological changes in the human body. The human body operates optimally within a specific temperature range, showcasing its remarkable biological design (21). When the environmental temperature exceeds the Core body temperature (CBT), the body begins to gain heat. The hypothalamus regulates CBT by triggering thermoregulatory mechanisms such as sweating and vasodilation to dissipate excess heat. An increased sweat rate (SwR) occurs when sweat glands activated by the sympathetic nervous system produce more sweat for evaporative cooling. This higher SwR can cause significant fluid and electrolyte loss, necessitating adequate hydration (22). Additionally, the metabolic rate and oxygen demand rise with higher temperatures, causing an increase in heart rate (HR) due to sympathetic activation and the need for enhanced blood flow through dilated peripheral vessels. Initially, heat exposure may cause a transient rise in blood pressure (BP) due to vasoconstriction, but prolonged exposure usually leads to vasodilation and a subsequent drop in BP, which can result in orthostatic hypotension. One of the indicators of dehydration is urine specific gravity (USG), when body becomes dehydrated due to heat stress,

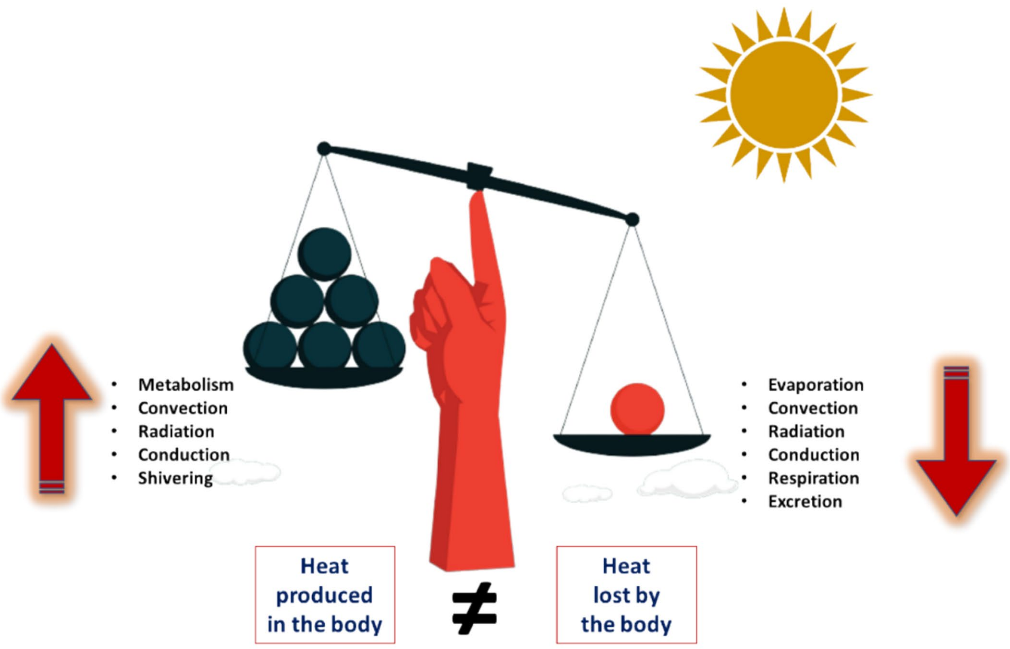

FIGURE 1
Human thermal imbalance.

urine specific gravity increases, reflecting higher solute concentration due to reduced water content. Elevated USG values indicate that the kidneys are conserving water, which is a common physiological response to dehydration. Therefore, monitoring USG can be an effective way to assess hydration status and the impact of heat stress on the body. Heat-induced dehydration reduces blood volume, resulting in decreased blood flow and GFR and it leads to impair the kidney function. The body's physiological response is to eliminate excess heat (23). The Heat Strain Index (HSI) is a quantitative measure to assess individuals exposed to high temperatures. It helps estimate the level of heat stress a worker may face based on the surrounding environmental factors and their physical activities (24). If it is prolonged which leads to heat-related illnesses (HRIs) may occur when the body cannot effectively cool itself, leading to conditions that range in severity from mild to life-threatening (25). HRIs requires immediate medical attention as it can become fatal if not treated earlier.

3 Methodology

This study aims to address several key research questions, to find out the heat stress levels among the workers and to see the effectiveness of "Water, Rest, Shade" (WRS) intervention in reducing these stressors. Additionally, it seeks to determine the most effective methods and target audiences for disseminating the study's findings to encourage the widespread adoption of heat interventions, ultimately aiming to protect outdoor workers in the future.

3.1 Study settings

This is a quasi-experimental study designed to assess the effectiveness of the intervention which establishes a causal relationship between an intervention and its outcomes. Workers will be employed in outdoor occupations, such as agriculture and brick kilns.

3.2 Participant's recruitment

Prior permission will be obtained from the relevant workplaces. Upon agreement to participate, 250 outdoor workers will be recruited, and informed consent will be obtained from each participant. The study will be explained to them in their preferred language to ensure understanding. The workers are included based on the criteria as follows: workers must be above the age of 18, have more than one to two years of experience in their current workplace, and be willing to participate in the study. Exclusion criteria for the study include workers over the age of 65, those with pre-existing illnesses, migrant workers, and individuals who plan to move out of the study area within the next 18 months.

3.3 Sample size calculation

Based on published literature, the sample size determination relied on the methodology outlined in the research article by (26) in Andhra Pradesh was taken for the sample size from outdoor workplaces in the defined study area. The study showed a prevalence of 6% of self-reported heat-related illnesses who has not taken the traditional diets and hence this was taken as the prevalence for the present study. Using the formula $N = (Z^2 * p * q)/d^2$, where Z is the alpha value for a 95% confidence interval (1.96), p is the prevalence rate (16%), q is 1 minus the prevalence, and d is the precision (4.5%), a sample size of 250 participants was determined for the overall population in the study area. For evaluating the effectiveness of the intervention, the 250 participants are separated into two groups the sample size was arrived

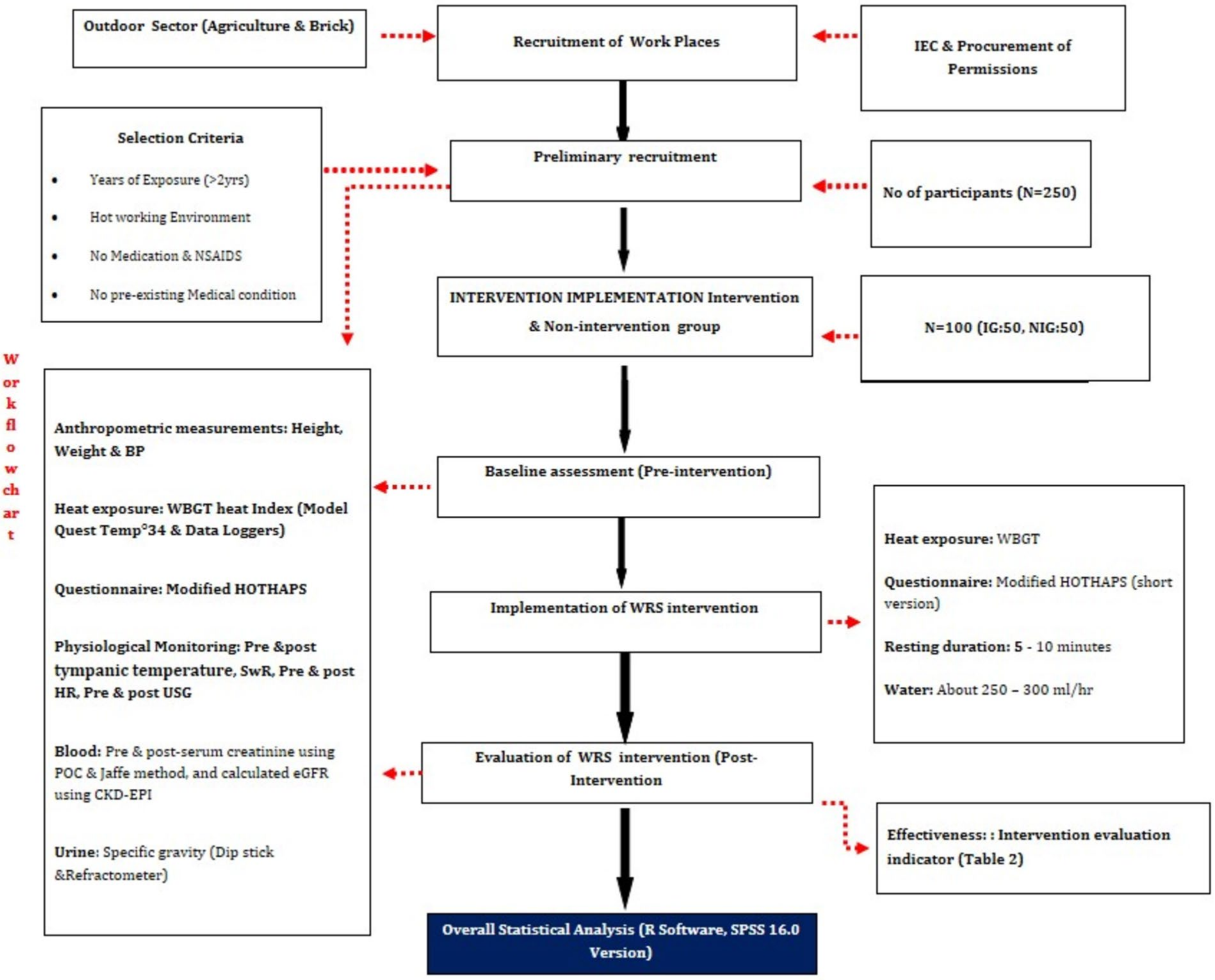

FIGURE 2
Work-flow chart.

at with the following scientific approach. Since there are not many studies linking heat stress and interventions, and one study has used the below-mentioned sample size (27). The formula used was $n1 = n2 = (z_{\alpha} + z_{\beta})^2(p1(1 - p1) + p2(1 - p2))/(\delta - |\varepsilon|)^2$, where n_1 and n_2 represent the intervention and non-intervention group populations, respectively. Here, $z\alpha$ is 0.05, $z\beta$ is 0.20, p_1 is assumed to be 80%, p_2 is 95%, δ is 0.195, and ε is 15%. Based on this calculation, 50 participants were allocated to each group, allowing for a balanced evaluation of the intervention's impact on heat-related illnesses (Figure 2).

3.4 Study procedure

The field data collection will occur over two summer seasons, involving four stages of field visits at a single location (Table 1). Firstly, the workers will undergo baseline assessments specific to outdoor work environments. Once the outdoor workers are selected, demographic details will be obtained, along with information about their work history and any prior similar roles. Data on additional physical activities (type of work, working hours, and break time) will also be gathered. Subsequently, informed consent will be secured from the workers after thoroughly explaining the study's risks and benefits, along with their willingness to participate. A baseline investigation will be conducted, involving anthropometric measurements of height and weight. A walk-through survey will aid in selecting locations for profiling area heat exposure levels near the working place.

3.5 Exposure assessment

To assess workplace heat exposure, the Quest Temp 3M WBGT Monitor (QuesTemp34; QUEST Technologies, United States) to measure environmental climatic conditions (ACGIH 2018) will be mounted in the workplace, and participants' personal heat exposure will be continuously monitored using Easy Log data loggers (EL-USB-2-LCD+ model), data loggers automatically track and log environmental variables over time, making it possible to measure and record conditions.

3.6 Physiological heat strain indicators

The heat strain experienced by the workers will be assessed through selective physiological responses, including pre- and post-shift tympanic temperatures, urine specific gravity (USG), sweat rate (SwR), and heart rates (HRs) to evaluate hydration status and heat strain.

TABLE 1 Phases of data collection for one workplace during summer.

No	Particulars	Baseline intervention	Pre-intervention phase	Intervention phase	Post intervention phase
I	Number of field visits	1	1	1	1
	Duration	1 month	1 day	5 days	1 day
II	Participants	250	IG:50, NIG:50	IG:50, NIG:50	IG:50, NIG:50
III	Anthropometric data				
	Height	Yes	Yes	Yes	Yes
	Weight	Yes	Yes	Yes	Yes
	Physiological Monitoring: Pre & post tympanic temperature, SwR, Pre & post HR, Pre & post USG	Yes	Yes	Yes	Yes
IV	Modified HOTHAPS Questionnaire	Yes	Short version	Short version	Intervention Effectiveness questionnaire
V	Bio monitoring				
	Blood sample	Pre & post-serum creatinine using POC & Jaffe method, and calculated eGFR using CKD-EPI	Pre & post-serum creatinine using POC & Jaffe method, and calculated eGFR using CKD-EPI	-	Pre & post-serum creatinine using POC & Jaffe method, and calculated eGFR using CKD-EPI
	Urine sample	Specific gravity (dip stick & refractometer)	Specific gravity (dip stick & refractometer)	-	Specific gravity (dip stick & refractometer)
VI	Exposure				
	WBGT	Daily measured			
VII	Water refills	Daily self-report			
VIII	Difficulty of work	Daily self-report			

IG: Intervention group, NIG: Non-intervention group.

3.7 Blood samples

A 2–3 mL sample of blood in vaccutainers (Becton Dickinson, Franklin Lakes, and, NJ) and send it to the laboratory for eGFR calculation using CKD-EPI. An indicator of kidney health, the estimated glomerular filtration rate (eGFR) calculates how well the kidneys filter blood (28). The serum creatinine blood test measures the level of creatinine in the blood using a point-of-care device.

3.8 Urine samples

Onsite urine assessments (USG, pH, leucocytes, hematuria, and proteinuria) will be conducted using a dipstick and refractometer. A refractometer is a device that measures the extent to which light bends when it moves from air into a sample that measures the USG it is a proxy measure to identify the level of hydration. Normal USG values range from 1.002 to 1.019. Using a sample container, a 5-ml urine sample will be taken. Samples will be kept in the field for up to six hours in ice boxes kept at 4°C before being sent to the collaborating lab for analysis.

3.9 Perception data

During lunch, workers will be administered the modified version of the "High Occupational Temperature Health and Productivity Suppression" (HOTHAPS) questionnaire. It will be used to gather information on symptoms of heat stress and heat strain, including urogenital problems. The purpose of the questionnaire is to help assess how workers are affected by heat exposure. Additionally, how the heat affects their daily activities and health issues, and problems associated with working in hot conditions will be collected.

3.10 Ethics considerations

Informed consent will be obtained from all participants before their involvement in the study. The study's objectives, procedures, benefit, potential risks, and their right to withdraw from the study at any time will be explained to them. Access to data will be limited to authorized personnel only, and results will be reported in aggregate to prevent identification of individuals. Ethical approval for the study has been obtained from the Institutional Ethical Committee of Sri Ramachandra Institute of Higher Education and Research, ensuring ethical guidelines.

3.11 Data management plan

The data management plan involves data integrity and security. Physiological measurements, including tympanic temperature and heart rate, will be recorded according to standardized protocols, and laboratory analyses will be conducted using validated methods. Data from the modified HOTHAPS questionnaire will also be collected. All data will be stored in password protected electronic files and with regular backups to prevent data loss. Access to the raw data will be restricted to authorized research team members, Statistical software will be used for data analysis, following established guidelines to ensure accuracy and validity. Findings will be shared through peer-reviewed publications and presentation. According to institutional and ethical guidelines, the data will be stored upto 10 years after completion of project. During this period, the data may be used for potential reanalysis or follow-up of any other studies. After 10 years, the data will be securely archived.

Pre-shift assessments will include anthropometric assessments, exposure assessments, physiological heat strain indicators, urine samples, and the HOTHAPS questionnaire. At mid-shift. Assess workers weight, collect urine samples, and record their water consumption and collect urine sample. The difference in pre-shift and mid-shift body weight and fluid consumption is divided by the observation time to get the SwR. Then monitor physiological heat strain measurements post-shift, right before they take a rest at the end of their shift. Collected post-tympanic temperature, post-HR, post-BP, and post-USG readings, take blood samples, and conduct point-of-care serum creatinine tests. Assessed urine samples using urine dipsticks and a USG refractometer.

3.12 Pre—intervention phase

After the baseline investigations, which include all 250 participants, the workers will be divided into two groups. They are matching based on participant's age, gender, education, workload, and other exposures (smoking, alcohol, and duration of employment) and 50 workers will be on the intervention group, 50 workers in the non-intervention group. The participants will be selected based on various factors, including age, gender, workload, education level, as well as other relevant exposures such as smoking, drinking habits, and length of employment. By considering these variables, Our aim to minimize any potential confounding factors and enhance the validity of our research findings. Again, the pre-shift and post-shift assessments and HOTHAPS questionnaire will be administered for both groups.

3.13 Intervention phase

A heat stress intervention consisting of WRS will be provided to the intervention group ($N = 50$) daily throughout the entire day for a duration of one week. This will include a fluid intake of about 250–300 mL/h, along with regular breaks and rest in a shaded area every 5–10 min.

3.14 Post-intervention phase

After the intervention is administered, baseline assessments will be repeated for both groups to see the effectiveness, and the interventions will be assessed based on the outcome indicators shown in Table 2. The tympanic temperatureshould not increase more than 10°C, and the Sweat rate should not increase by 1 litre per hour. There should be a decrease in urine specific gravity (USG), heart rate, and creatinine levels after receiving the WRS intervention.

3.15 Statistical analysis

Data entry and consolidation will be done in Microsoft Excel, while the statistical analysis will be carried out using SPSS version 16.1. Calculations will be performed to analyse the descriptive statistics from demographics, heat exposure, health symptoms, and physiological indicators. The dependent variables will be classified based on the presence or absence of symptoms related to heat strain, dehydration, and urogenital issues. Physiological indicators like tympanic temperature, SwR, USG, and eGFR will be classified based on the standard range. Analyse categorical variables using chi-square test.

Use the Wilcoxon signed rank test to compare the levels of continuous variables before and after a shift, including physiological heat strain signals like pH, hematuria, and proteinuria. A multivariate logistic regression (MLR) model will be utilised to systematically adjust for confounding factors. Prior to conducting the MLR, To ensure that all confounding factors to be included in the analysis have been finalized. Given the interdependence of age and years of exposure, a correlation analysis will be performed using the Spearman correlation test to examine the relationship between these two variables. Considered several important factors, such as age, gender, years of exposure, and education, which could potentially influence the results. After finalizing the confounders, we will proceed with the MLR. In the initial step, Perform a chi-square test to ascertain the association between the dependent and independent variables. During the second stage, Do calculations to find out the association of the odds ratio (AOR) between the independent and dependent variables. Take into account important confounding variables and exclude any confounders that are not statistically significant.

TABLE 2 Intervention evaluation indicator.

S. no	Evaluation indicators		
1	Heat strain indicators	Tympanic temperature (Ttemp)	No increase from baseline
		Sweat rate (SwR)	No increase from baseline
		Urine specific gravity (USG)	Decrease from base line
		Heart Rate	Decrease from base line
2	Indices of kidney function	Blood parameters	• Creatinine mg/dL (seasonal): Decrease from baseline • Creatinine mg/dL (cross-shift for Acute Kidney Injury): Decrease
3	Urine parameters	Dipstick	pH: <6

TABLE 3 Previous studies on water, rest and shade (WRS) intervention.

Author Name	Year	Country	Heat stress intervention			Outcome
			Water	Rest and shade	Others	
Bodin et al.(17)	2016	Central America	3 litres water bag and refill every break attent	10–15 min rest breaks at tent	Redesigned machete	The production had a significant rise, rising from 5.1 to 7.3 tonnes per person per day after the intervention and Heat stress and dehydration were reduced.
Butler-Dawson et al. (29)	2019	Central America	Encouraged Workers to drink additional water, Electrolyte solution and take more rest breaks.		Education program on the importance of WRS	Hydration is important and protective
Wegman et al. (18)	2018	Central America	3-liter water backpack, 40 L water to refill	10–15-min rest	lighter machete with curved blade	Impact of heat stress are reduced
Glaser et al. (16)	2022	Central America	5 litres water bag, 300 mL of electrolyte solution from a tent.	20 min of rest every hour and consume	Nil	Intervention evolved over time, including improvements in changing of WRS. The impact of these improvements on mitigating heat stress is also assessed.
Hansson et al. (30)	2024	Central America	Both water and rehydration solution	20 Minutes Rest	Nil	Productivity increased during the study period.

4 Challenges and feasibilities in conducting WRS interventions in LMICs like India

There are only a few studies done on giving water, rest, and shade (WRS) heat interventions to outdoor workers (16–18, 29, 30). Table 3 summarizes different workplace interventions aimed at ensuring workers stay hydrated and get adequate rest to prevent HRIs in developed countries. Each intervention aims to balance hydration and rest to ensure worker safety and efficiency, with slight variations in how water is provided, how much water is consumed, and the frequency and duration of rest breaks. Conducting WRS interventions in LMICs like India differs significantly from those previously done in Central American studies due to factors such as workplace infrastructure, worker demographics, climate conditions, and cultural and economic factors. Workplaces in the developed countries often have better infrastructure, systematic rules regulations and policies and workplace heat standards and advisories to implement to ensure that workers have access to shade, water, and appropriate rest breaks during heat events (17). Additionally, initiatives like green infrastructure projects, which include urban greening and cool roofs, are promoted to mitigate the heat-island effect and provide cooler working environments, facilitating easier implementation of shaded rest areas and access to large quantities of water (29). Whereas Indian sites may lack these facilities, which need a more tailored approach. Even though, India has few regulations formulated recently (31) to improve workplace and workers conditions to prevent HRIs, the awareness and enforcement is being inconsistent, affecting the implementation of safety protocols. Furthermore, the behavioral practices towards rest breaks and hydration vary, with Indian workers often resist to frequency in the rest breaks due to productivity and economic concerns. By understanding and addressing these differences, our study aims to provide a practical and effective trial model for implementing WRS interventions in outdoor workplaces, ensuring worker safety and productivity based upon our own pilot study (unpublished results).

5 Our own pilot study conducted in India

After considering the above challenges conducted a pilot study with 50 participants Intervention group has 25 participants and 25 in non-intervention group and implemented a one-week intervention providing 250–300 mL of water and 5 to 10 min of rest every hour, providing rest for more than 10 min disrupts the workflow, as restarting work can be challenging and employers are not willing to give a break to workers every hour due to the productivity loss. To address this, compensated the workers for the given rest, time and managed the rest periods by staggering the breaks. Then, Divided the 25 participants in the intervention group into 5 batches, with each batch taking a rest at different times. This staggered approach ensured that the entire group did not rest simultaneously, maintaining workflow continuity. The perception results showed that there was a significant reduction in prevalence of heat stress symptoms, especially excessive thirst, excessive sweating, tiredness, and prickly heat after intervention (76% has reduced to 24%). The non-intervention group had 10 times greater odds of adverse health outcomes than the intervention group. The results showed a significant difference in reduction in CBT, with the non-intervention group being 12 times more likely to have increased CBT (unpublished result). By understanding and addressing these differences, our study aims to provide a practical and effective trial model for implementing WRS interventions in outdoor workplaces, ensuring worker safety and productivity.

6 Limitations

Separating the outdoor workers into two distinct groups may lead to selection bias, potentially affecting the general stability of the results. To manage this, matched participants in the intervention and non-intervention groups based on demographic and work-related characteristics to reduce bias and increase result stability. Due to the practical constraints of fieldwork, it is unable to include continuous core body temperature monitoring, which is considered the gold standard. Instead, tympanic temperature will be used as a measure of core temperature. Self-reported data through the HOTHAPS questionnaire may also introduce recall bias, participants may under report or over report symptoms and perceptions of heat stress.

Working in extreme heat conditions leads to several challenges, particularly in ensuring that all participants fully understood the study procedures and provided informed consent. Some workers, especially those from migrant backgrounds, were initially hesitant to share personal information, complicating the consent process. Additionally, difficulties in reaching all eligible workers due to their demanding work schedules and family commitments limited the study's sample size.

Conducting field under scorching heat leads to physical and mental effects on the research team. Prolonged exposure to high heat, leads to fatigue and exhaustion. This fatigue resulted in measurement errors, incomplete interview transcripts, and delays in reporting. Efforts were made to mitigate fatigue through regular breaks and hydration.

Limited outdoor workplace infrastructure, including inadequate sanitation had a impact on research team's efficiency and well-being. Poor sanitation facilities increased the risk of illness, directly affecting field productivity.

7 Expected outcome

The primary goal of the "Water, Rest, Shade" (WRS) intervention is to implement a practical and effective strategy for managing heat stress in outdoor workplaces. The intervention is anticipated to bring several positive outcomes. Firstly, a significant reduction in heat stress among the intervention group, as indicated by improvements in physiological measures such as tympanic temperature, heart rate, sweat rate, and urine specific gravity. Additionally, the intervention group reported a decrease in the incidence of heat-related health issues, such as dehydration and heat exhaustion, and a reduction in self-reported heat-related health symptoms, as measured by the modified HOTHAPS questionnaire.

The intervention will lead to enhanced overall well-being for outdoor workers. Increased comfort, a decrease in heat-related illnesses, and potentially fewer work-related accidents are likely to reflect this improvement. We anticipate that the intervention, by effectively managing heat stress, will boost productivity and reduce absenteeism, thereby benefiting workers.

The study will also aim to identify successful adaptation techniques for implementing heat stress interventions in outdoor settings. These insights will contribute to developing better strategies for reducing heat vulnerability and improving workers' quality of life. Finally, we expect the findings to support the development of comprehensive heat stress management policies and practices, providing valuable evidence for the development of future interventions and guidelines for similar occupational environments.

8 Conclusion

This study will demonstrate the effectiveness of the intervention and offer valuable strategies for mitigating heat stress. It will focus on the successful implementation and assessment of both health impacts and implementation quality and provides a fresh perspectives on the importance of this intervention in combating scorching heat. Additionally, it will help in the creation of inclusive workplaces and labour policies that focus on reducing health hazards for the large population of unorganised outdoor workers. The study also aims to provide crucial information to raise awareness about the importance of preventing heat stress among workers, especially those who work outdoors. This information will be helpful in developing comprehensive workplace and labour policies to protect the health of millions of unorganised outdoor workers.

9 Dissemination

After the study is completed, the results will undergo analysis and be prepared for publication. After the project concludes, a community event will be organized to share the findings and raise awareness among the workers took part in the study.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Institutional Ethics Committee Sri Ramachandra Institute of Higher Education and Research. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study (IEC-NI/24/FEB/92/42).

Author contributions

VV: Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing. SS: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. VP: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. KS: Supervision, Validation, Writing – review & editing. RS: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – review & editing. LK: Writing – original draft, Writing – review & editing..

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of the article is from "Founder- Chancellor Shri. NPV Ramasamy Udayar Research Fellowship".

Acknowledgments

The authors highly acknowledge and thank NIHR Global Health Research Centre on NCD and Environmental Change (NIHR203247) and Department of Environmental Health Engineering, Faculty of Public Health, Sri Ramachandra Institute of Higher Education and Research, Chennai for providing us this platform for carrying out the work.

Conflict of interest

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

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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frontiers | Frontiers in Public Health

TYPE Mini Review
PUBLISHED 18 December 2024
DOI 10.3389/fpubh.2024.1434123

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OPEN ACCESS

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RECEIVED 17 May 2024
ACCEPTED 15 October 2024
PUBLISHED 18 December 2024

CITATION
Akram S and Mushtaq S (2024) Environmental change and floods: the long-ignored effects of displacement on mental health. *Front. Public Health* 12:1434123.
doi: 10.3389/fpubh.2024.1434123

Environmental change and floods: the long-ignored effects of displacement on mental health

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Although climate change has received significant global attention, there has been a distinct disregard for the issue of psychological well-being. The elevated floods resulting from climate change have substantial impacts on both physical infrastructure and human well-being. This includes the coerced relocation of individuals from their homes, unemployment, setbacks, and the disruption of communities. The occurrence of significant displacement due to major natural disasters, such as the floods in Pakistan in 2022, is linked to varying degrees of anxiety ranging from moderate to severe. The aim of this research is to perform a comprehensive analysis of the topic by utilizing the available literature. The study aims to ascertain the correlation between floods, caused by environmental shifts, and their influence on mental well-being in Pakistan, specifically focusing on the experiences of susceptible communities. Vulnerable populations, including socioeconomically disadvantaged communities, the older adults, individuals with disabilities, and children, are particularly susceptible to the adverse effects of severe weather conditions. During natural catastrophes, individuals experience elevated levels of psychological, emotional, and physical stress, which subsequently amplifies their vulnerability to these detrimental consequences.

KEYWORDS

climate change, floods, displacements, mental health, risk

1 Introduction

Climate change impacts not only the rise in sea levels and the well-being of polar bears, but also has significant implications for mental health. Consider this: due to climate change, you could potentially lose both your actual residence and your mental sense of belonging, along with all the sentimental possessions associated with it, in the occurrence of a flood. In the situation of an extremely unfavorable situation, it is possible for family members and acquaintances to perish. The correlation between climate-induced floods and droughts and psychological manifestations such as anxiety, shock, depression, grief, despair, numbness, rage, sleep disorders, interpersonal issues, acute and posttraumatic stress disorder (PTSD), drug addiction, and suicide is logical and understandable. Similarly, floods resulting from climate change are associated with increased levels of aggression, including homicide, suicide, and domestic abuse. Furthermore, they contribute to an increased rate of being hospitalized among those who already experience mental health challenges.

The catastrophic flooding in Pakistan, which submerged a significant portion of the country, was the result of a combination of intense heat-induced glacier melt and severe monsoon rains that occurred from June to September 2022. As of September 6, 2022, the floods have caused the displacement of millions of individuals and left over 6 million people in need of humanitarian assistance (1–3). Devastating floods struck Pakistan, caused immense damage to 2 million homes, claiming 1,600 lives, injuring 12,850 individuals, and forcing

7.9 million people to leave their homes. Currently, there are over 598,000 individuals residing in relief camps. In addition, an estimated 83,000 pregnant women who experienced damage by the floods gave birth. The flooding resulted in significant damage to more than 1,460 medical facilities (4).

The floods in Pakistan are indicative of an extensively reported global patterns, which indicates that intense rainfall events are occurring more frequently and with greater severity across a majority of the Earth's surface (3, 5). Based on weather forecast predictions, the frequency of the most intense precipitation events is projected to almost double for each degree Celsius of global warming (6).

These major, recurring events have the power to significantly impact people's lives and means of subsistence. It is commonly known from the perspective of public health that natural disasters like flooding can have a negative impact on a community's health. However, little research has been done to look at how floods affect certain people's health (7–9).

Despite the presence of notable information deficiencies (10–12), the currently available literature offers helpful perspectives on shared factors that influence susceptibility to environmental hazards (13–16). One of the most important factors is the need for a systematic understanding of societal structures and vulnerabilities, which significantly impacts the likelihood of a disaster.

1.1 Objectives

Utilizing the body of existing literature, the goal of this research is to perform a detailed analysis of the subject at hand.

The study aims to ascertain the correlation between floods, caused by environmental shifts, and their influence on mental well-being in Pakistan, specifically focusing on the experiences of susceptible communities.

2 Methodology

Searches for pertinent papers were conducted using two databases: Web of Science and Scopus. Keywords associated with the Pakistani community, climate change, mental health, floods, forced displacement, and housing difficulties were selected based on prior research and an online thesaurus. For the purpose of the systematic evaluation, inclusion as well as exclusion criteria were established. First, in terms of the type of literature, book chapters, review articles, conference proceedings, and publications with empirical data were emphasized. Second, the timeframe from 2000 to January 2024 was chosen for article searches in databases. Third, non-English papers were rejected to avoid difficulties with translation and understanding. Figure 1 demonstrates the total number of studies included in this analysis, excluding research undertaken internationally.

3 Results

Climate change-induced extreme events can result in disastrous consequences for human societies. Disasters, such as floods and droughts, give rise to a unique form of psychological and psychopathological distress that differs from the usual fluctuations in seasonal weather. In addition, certain climate catastrophes, including acid rain, superfog, glacier melting, and flooding, which are often overlooked in studies on the mental well-being of vulnerable individuals, could potentially have a broader impact on mental health (17). Conditions in the environment have the potential to exacerbate mental diseases that start within the body and result in neurological and psychosomatic disorders (18).

An essential aspect of analyzing the issue of public health is to thoroughly assess the effects of flooding on both community and individual well-being. There is a lack of research in the field of public health regarding floods, especially in relation to the examination of the mental and emotional well-being of the victims. A substantial proportion of current research focuses on investigating the impact of flooding on the environmental well-being of communities (19).

The water itself poses a serious risk to people, animals, and the ecosystem. Water contamination is a significant public health concern associated with flooding. Floodwater frequently contains dangerous substances, debris, and bacteria that could be harmful to people's health (20). This dangerous concoction is already seeping into people's homes to the point where it is almost waist high, bringing mold and wetness to each surface it touches. There is a serious risk associated with handling contaminated products, and consuming anything that has come into contact with floodwater might expose oneself to serious illnesses like cholera or other water-borne ailments (21).

Flooding may have an impact on individuals' emotional and mental well-being, in addition to the evident environmental health risks (22). Survivors of any type of natural disaster are likely to experience significant emotional trauma, that would inevitably have a negative impact on their mental well-being.

In Tong's research, it was found that there is a significant connection between being moved as a result of flooding and the probability of exhibiting symptoms of a mental health disorder (23). Tong has investigated the consequences of displacement caused by flooding on persons' long-term mental well-being, emphasizing the little understanding of this matter. Additional research is required to provide a more thorough understanding of the precise effects that flooding has on human beings (23). Through a study of extensive literature on flood disasters in Pakistan in 2022, we examine the effect of important socioeconomic factors on how people move and its consequences on mental health. Table 1 outlines the themes and contributing aspects of the adverse consequences of flooding in Pakistan.

3.1 Environmental effects in Pakistan's context

Climate change has led to a significant rise in the occurrence and severity of hydro-meteorological calamities globally in the past few decades (24). Floods are among the most frequent and destructive natural disasters, resulting in significant destruction (25) and putting people's physical, emotional, social, and economic well-being at risk (26). Mostly caused by climate change, flooding is Pakistan's most frequent and devastating natural disaster.

Climate change can affect mental health even before its immediate consequences become apparent. Pakistan exhibits a high vulnerability to disasters, rendering it one of the most disaster-prone areas worldwide. Flooding is a prominent worldwide environmental problem

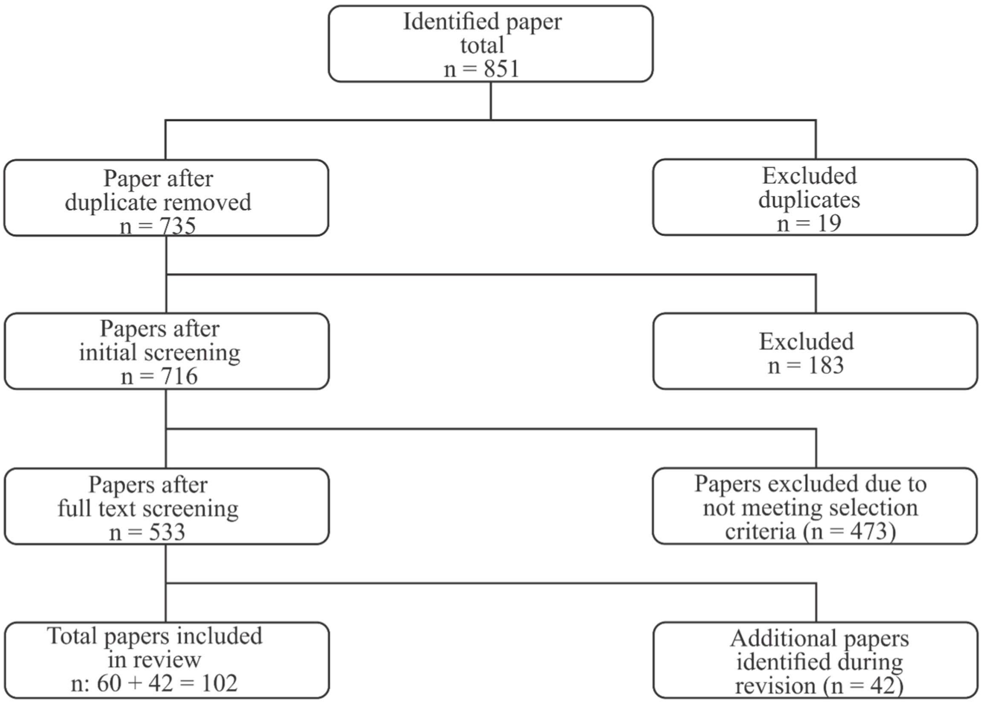

FIGURE 1
Literature selection process.

TABLE 1 Themes and contributing aspects of the adverse consequences of flooding in Pakistan.

Themes	Subthemes	Contributing social factors
Environmental effects in Pakistan	• Rains and • Floods	Instant social hazards include Lives cost, Direct loss of infrastructure, Diminishes villages, Displacement (18, 93, 94)
Public healthcare crises	• Loss of health facilities • The spread of infectious diseases	Key immediate health hazards include drowning, injuries, burns, dehydration, shock from electricity, and exposure to carbon monoxide poisoning (95–98)
Factors affecting mental health	• Socio-economic disparity • Displacement • Helplessness • Hopelessness	PTSD, anxiety, and depression are the immediate effects of losing one's main survival resources (18, 99)
Humans those are more susceptible	• The groups encompass individuals with preexisting mental health disorders • Females • Adolescents • Senior citizens	the community that is most at risk has post-traumatic stress disorder (PTSD), Anxiety, depression, violence, societal separation, and abnormal reliance (8, 20, 34, 100, 101)

that is worsened by climate change, as evidenced by the repeated incidents in Pakistan over the previous 6 to 7 years (27). There has been a rise in the occurrence and severity of natural calamities, including floods, extreme weather, severe heat waves, and elevated rates of pests and illnesses, across the nation. Pakistan ranked seventh in 2010 among nations that experienced substantial impacts from climate and climate-related risks (28). It held the rankings of 29th, 16th, 12th, and 8th in 2011, 2012, 2015, and 2016, respectively, for its significant susceptibility to flooding. Pakistan is susceptible to frequent natural calamities, such as a succession of floods occurring in the years 2010, 2011, 2012, and 2014 (29, 30). What was the cause of the catastrophic flood that occurred in Pakistan in 2022? This flood was the most deadly in the nation's history, killing over 1,500 people, injuring over 12,000, and displacing over 33 million people (31). The August 2022 flood disaster can be attributed to several considerations, namely heavy rainfall, glacier melt, and the formation of a powerful low-pressure system over the land area due to the preceding heat waves in May and June (32). Floods and other natural calamities have a detrimental effect on victims' mental health. Over 33 million people in Pakistan were affected by the flood in 2022 (33).

3.2 Public healthcare crises

Floods cause medical facilities to be destroyed, make existing facilities inaccessible, reduce the availability of medical supplies, and force medical staff to leave the field. In June 2022, damage was expected to have affected 1,460 healthcare facilities in Pakistan (20, 34). Floods exert a profound adverse impact on human health. Key immediate health hazards include drowning, injuries, burns, dehydration, shock from electricity, and exposure to carbon monoxide poisoning (35). During Pakistan's most recent floods, animal bites surfaced as another possibly concerning issue (8, 36–38).

Natural disasters can worsen non-communicable diseases and perhaps lead to serious loss of life. There exist many potential factors contributing to this phenomenon. One potential consequence of the inability to reach medical facilities or avail health services is the interruption of therapy for preexisting conditions. Insufficient medications, inability to undertake recommended medication, inappropriate nutrition, inconsistent monitoring of glucose, and various other factors might exacerbate chronic illnesses (39). Moreover, the spread of infectious diseases is one of the most significant, non-immediate post-flood concerns. Inadequate sanitation facilities, a lack of access to clean water, disruptions in immunization programs, and pauses in vector control measures all contribute to the development of infectious illnesses (39).

Extended periods of flooding create an atmosphere that is conducive to depression, anxiety, and chronic respiratory conditions (37). Floods can promote the growth of infections, such as germs and viruses, which can endanger people's physically and mental well-being. Epidemics of cholera, dengue fever, hepatitis, and diarrhea all stem from them (25). The imminent reality of climate change makes people feel powerless to change things, leaving them with an unresolved sense of loss, helplessness, and dissatisfaction. The majority of individuals feel sad and depressed as a result of flood-induced displacements.

A notable outcome of the floods is the escalation of mental health problems emerging from such situations of suffering and despair. Events of this nature, such as the onset of new health issues, the loss of a close family member, or financial difficulties, can lead to a rise in feelings of sadness, anxiety, and posttraumatic stress disorder. Thus, it is crucial to provide suitable mental health services following floods (20).

3.3 Factors affecting mental health

Climate change is influenced by social equality. Individuals with inadequate financial resources are especially susceptible to the repercussions of economic downturns (40). This nation, for instance, is less likely to be able to escape in an emergency, is more likely to suffer from health and mobility problems, is frequently exposed to poor management and the harmful effects of excessive flooding, and has limited access to resources, goods, and services that could help mitigate the effects of severe weather events (41). The repercussions of climate change are more likely to affect Pakistani's from lower socioeconomic backgrounds (42) because a large number of them work in climate-sensitive industries like agriculture (43, 44). A significant proportion of the population residing in flood-affected regions, specifically in Sindh (Pakistan), predominantly inhabits rural areas and depends heavily on agriculture as their primary livelihood (42). The flood has caused extensive damage to their crops, livestock, sources of income, and residences (27). The process of emergency evacuation, aimed at mitigating more harm, can also induce feelings of hopelessness, unease, and tension among individuals affected by flooding (45).

As people displaced by climate-related reasons seek refuge in neighboring localities, relocation brought on by climate change poses a threat to the preservation of traditional culture (46). The host group may have increased feelings of bereavement, anxiety, and adjustment problems as a result of the perceived or real disruption to the culture as well as the loss of social and environmental ties (40). Additionally, the expatriates' effort to adjust to their new surroundings and mental health will be impacted by this.

The socio-psychological dimensions of a society can also impact its resilience in the face of disaster. Greater susceptibility has been linked to elevated levels of socioeconomic inequality, diminished levels of social cohesiveness, and distrust among citizens and institutions (47). For instance, those who feel a lack of support among members of their community have been found to have greater incidences of PTSD (47, 48).

Anxiety, desperation, and stress commonly afflict individuals who have experienced flooding. Moreover, stress-induced symptoms have previously been explored at elevated magnitudes. These mental health disorders exert a substantial impact on both the individuals affected and the entire nation (49). A further study, which yielded similar results, indicated that flood victims commonly experience stress, depression, and anxiety, all of which are prevalent mental health concerns (50).

Relief organizations focused only on giving flood victims clothing, food, and shelter during the 2022 flood (31). Nevertheless, the psychological needs of the victims received scant consideration. One of the most common psychological effects of floods is the loss of a loved one, a home, or valuables like crops and animals (51, 52). That causes flood victims to suffer from psychological issues and depression for weeks, months, or even years (9, 53).

The portrayal of the media can greatly influence the understanding of a calamity. If a tragedy is classified as climate-related, as in the aforementioned case, it is highly likely that the levels of concern within the community will escalate (54).The acknowledgement that climate change-induced disasters are a consequence of human activities can foster distrust and conflict among societies. Perceiving natural calamities as "acts of God" frequently elicits positive community responses. Nevertheless, when calamities are ascribed to anthropogenic climate change, they can also incite anger and suspicion (40, 55). Reflecting on the detrimental effects of human activities on beloved cultivation and animal species might elicit feelings of insufficiency and despair (56).

3.4 Humans those are more susceptible

Mental health-care systems that were already under pressure are put at an additional disadvantage after disasters that deplete resources (57). Outdated physical infrastructure and inadequate health services may have less resilience against severe environmental calamities (58). Unfortunately, communities with a greater concentration of vulnerable groups, such as children, older persons, and individuals with mental health concerns, tend to face additional challenges following catastrophic occurrences (45, 59).

Specific folks would persistently experience a greater impact. The groups encompass individuals with preexisting mental health disorders, females (60), adolescents (61), senior individuals (9), citizens with inadequate financial means, and entire communities with resource shortages (62–64).

Regarding mental health conditions, females exhibit a greater propensity than males to encounter heightened levels of stress and anxiety, increased awareness of vulnerability, and an elevated probability of acquiring post-traumatic stress disorder (PTSD) following a catastrophe (62). Pregnant women are at a heightened risk of suffering during catastrophic floods (65). Flood catastrophes intensify domestic violence, primarily targeting women (64). Women are more susceptible to males since they are less skilled in expertise, the ability to make decisions, skills, mobility, and training. Enhancing their ability to withstand natural calamities like floods is further hindered by social conventions, limitations, and conventional gender roles (66).

Children face distinct challenges. Following a catastrophe, children often suffer from post-traumatic stress disorder (PTSD), feelings of hopelessness, aggressive behavior, withdrawal from social interactions, and excessive dependence (67). Children are more sensitive to enduring prolonged symptoms that can impede their functioning in comparison to adults (68). Moreover, they possess the capacity to alter the stress responses of children, so heightening their susceptibility to mental health conditions such as anxiety and depression, as well as future psychological medical challenges (61). The responses of children differ according to their developmental stage and age (69). Toddlers between the ages of one and four are more likely to exhibit clinginess, increased reliance, unwillingness to sleep alone, and irritability. However, children between the ages of 5 and 12 are more likely to display physical problems, anxiety, melancholy, sleep disturbances, hostility toward their siblings, and post-traumatic stress disorder (PTSD) (61, 70).

The older adults and individuals with disabilities are considered the most susceptible populations during disasters due to their need for specialized assistance, rendering it challenging for them to evacuate to safer areas (71). Pakistan's senior population is expected to be more vulnerable, especially during the 2022 floods (61). For instance, the statistics indicated that the most susceptible populations are located in Punjab, a region situated in southern Pakistan. Along with financial difficulties and illiteracy, the main causes of this are the high rates of aging, and people with disabilities, in these places (72, 73).

4 Discussion

Extreme weather phenomena resulting from climate change encompass severe storms, floods, and prolonged periods of heavy rainfall. In addition to affecting one's physical health, it also exerts influence on mental well-being, as demonstrated, among other factors (74), by the deterioration of air quality and the resurgence of long-standing illnesses. Psychological well-being can be affected by natural catastrophes in several ways (75).

The relationship between climate change and mental health is still rife with unanswered questions. The complexity of recent research emphasizes this problem. Lack of uniformity in identifying the relevant components and methods for quantifying the consequences of climate change is a major contributing factor to this challenge. Challenge tasks involve analyzing deviations from normalcy in extreme climate events, investigating the underlying mechanisms of adaptation, and seeking direct cause-and-effect relationships (76). Various factors, such as socio-behavioral factors, culture, information, preparation, and peri-traumatic experiences, all contribute to the outcome of psychological weariness and disturbance, or collective resilience (77).

Recent research has identified compelling evidence of the significant correlations between mental health and climate change in several literary works. There exist multiple mechanisms via which climate change can impact mental health (78). Floods are examples of severe weather occurrences that can occur frequently and have an immediate impact, particularly during high temperatures. The potential long-term consequences of environmental changes such as prolonged rainy seasons, floods, rising sea levels, forest loss, and forced human migration are considerable. These occurrences have a fundamental impact on individuals' psychological well-being, heightening their susceptibility to mental diseases such as PTSD, mood disorders like anxiety and depression, a rise in aggressive conduct, suicide rates, and drug dependency. The adverse impacts of climate change would disproportionately affect vulnerable populations, potentially worsening mental health issues (75). These groups encompass women, the older adults, children, persons with pre-existing mental health disorders, people with poor incomes or restricted social support, and individuals belonging to indigenous and native cultures (79). The impact of severe weather conditions on social interactions can be substantial (80–82).

The phenomenon of climate change is anticipated to exert a significant influence on both the natural environment and Human society. Additionally, it is anticipated to result in migration driven by environmental factors, including individuals seeking shelter (75) and becoming climate refugees (83). Psychological impairments exist among these displaced populations (84). For some individuals, managing their emotions in response to climate change can pose a challenge. In addition, significant events can lead to various psychological reactions over time, as they have both immediate and long-lasting effects on mental well-being. There will be a mental adjustment and specific behavioral patterns that emerge as the events unfold in a logical sequence: prior to the alarm, during the crisis, and after the incident (83, 85). It is challenging to ascertain the long-term effects. Climate change has numerous consequences, leading to heightened economic and social difficulties. These challenges, in turn, contribute to a rise in mental illnesses among both the current and future generations of affected individuals. The literature examines various climatic events and their associated diseases, which can be specific to certain conditions or occur in different extreme situations (84). A comprehensive understanding of this transition enables the implementation of proactive interventions and strategies to address a population's mental well-being.

5 Strengths and limitations

This paper presents the initial comprehensive review of prior systematic assessments examining the effects of climate change on health. Three qualities enhance the reliability of our review. By giving precedence to systematic reviews over individual original studies, we can provide a more encompassing and complete summary of the results. Additionally, we provide a concise, comprehensive, and precise overview of current knowledge and areas of doubt about the possible effects of climate change on human mental health. This is achieved by consolidating findings from all relevant studies and drawing upon the interplay between climate effects, socioeconomic factors, and health outcomes. This overview could be valuable for communities, politicians, and scholars. Furthermore, we conducted an extensive review of internationally recognized English-language publications to investigate the effects of climate change on mental health (86, 87).

There are four major limitations that affect the way we work. Initially, we faced difficulties in obtaining complete texts for several studies, leading us to exclude them from our analysis while initially considering them to be pertinent based on our evaluation of their titles and abstracts. It is possible that our thorough search was hindered by hidden flaws that prevented us from finding other systematic reviews that could have been relevant. Furthermore, the diversity of the systematic reviews included in the analysis and the scarcity of papers providing meta-analytic data hindered our ability to do meta-meta-analyses to compare the outcomes across reviews. Additional research is required to quantify the linkages between climate change and health that this study has revealed, as well as to understand the source and other interacting elements. Furthermore, because of limited resources, we were unable to determine the degree of overlap between the included reviews in terms of their study content. When analyzing frequencies and results, it is essential to consider the possibility of overlap. Furthermore, the literature was systematically searched in September 2023, perhaps leading to the omission of recent systematic reviews from this analysis (88).

6 Suggestions to reduce calamity affects

Following an analysis of the adverse impacts of climate change on mental health, it is essential to explore feasible options that may demonstrate the possible benefits offered by creative thinking. A multitude of factors, including research, educational and medical institutions, the media, and our own communities and selves, contribute to this feeling of optimism.

The primary objective should be to produce precise, uniform, and compelling information on climate change and its ramifications on mental well-being. Knowledge should be shared with the general public by reputable and expert organizations. It is important to use language that is upbeat, supportive, and full of recommendations and answers. Optimistic and inspiring words have a greater capacity to motivate individuals compared to trying to spur them on through fear. Media messages that recognize intense emotions, offer a local perspective, foster group participation, and employ suitable visuals can enhance confidence. Humanizing a favorable and unified sense of community is a potent strategy to enhance well-being in the midst of uncertainty (54).

In addition, it is critical to set aside enough money and offer the support required to create and preserve the systems and structures that support psychological wellness. Healthcare personnel, particularly those at the forefront, should undergo extensive training in handling mental health crises. They should actively endorse and advocate for public policies that encourage the progression of mental health, posttraumatic growth, and resilience (40).

Furthermore, it is imperative for researchers to enhance the existing knowledge by delving into other areas that hold significant potential for further exploration. These encompass investigations on the impacts of large-scale evacuation due to severe weather, the impact of attitudes toward climate change on psychological resilience, and the role of diverse media portrayals of climate change effects on viewers' mental well-being, among numerous other topics (89).

The susceptibility to the effects of climate change on mental well-being is contingent upon the capacity of individuals and their communities to adjust and have a sense of power. A pragmatic strategy is to perceive climate change as a problem that can be addressed through proactive involvement and environmentally favorable actions, thus assisting in mitigating adverse outcomes (81).

To foster emotions of confidence and authority, it is imperative to emphasize the needs of the most vulnerable groups in society and strengthen social links within communities. It is imperative to enhance healthcare services, particularly those dedicated to providing care for psychological trauma. Spiritual growth and an optimistic mindset are supplementary assets that can bolster resilience, cultivate proactive conduct, and accelerate recovery, even in the most hazardous situations (54).

7 Future directions

This paper reviews that Floods, as natural calamities are prominent manifestations of contemporary climate change. These occurrences have diverse ramifications for human health, including non-communicable diseases, infections, trauma, mental illnesses, nutritional insecurity, and other concerns. The connections between health and climate change impacts by various demographic, social, and environmental factors. The question is how to preemptively prevent this type of circumstance from happening. Subsequent investigations on this topic should specifically focus on flood prediction.

Further study could focus on improving the technical components of ensemble flood forecasting, including developing strategies to incorporate additional sources of uncertainty and improving data assimilation techniques. Furthermore, using methods like machine learning, ensemble forecasts for other variables, including flood inundation, must be created (90). Furthermore, we conclude that improvements to the technical aspects of flood forecasting are imperative, as is the establishment of a link between scientific research and the creation of hydrometeorological models, as well as the application of probabilistic ensemble forecasts to actual flood management. The main strategy for achieving this should be excellent communication (86).

8 Conclusion

Based on the studies and scholarly literature this team reviewed, there is substantial evidence that climate change has a significant impact on mental health. This study looked at how climate change is affecting vulnerable populations, vulnerable rural areas, and the general public. We decided to concentrate on extreme weather events such as flooding and storms. Resulting outcomes have been defined by suicide rates, symptoms of distress, and clinical disorders such as PTSD, depression, anxiety, and sleep disturbances. Furthermore, the depletion of plant and animal species might evoke grief and low spirits. The consideration of an individual's emotional state toward their surroundings brings us close to a cultural and contextual element. Impairment of this symbolic region leads to more complex psychopathological effects. Long-lasting changes in personality (91) or identity disorders (83) have been seen in people who have been traumatized by extreme weather events and having to leave familiar places. Dissociative syndromes (92), which are also seen in people who have been traumatized by extreme events or migratory syndromes, are another effect. Furthermore, it is imperative to comprehend the deep influence of meteoropathy, weather sensitivity, and environmental and climatic changes on the psychosomatic domain of humans. These elements may induce somatization and conversion processes, result in physical diseases and disorders, or worsen pre-existing physiological pain. An inverse relationship exists between the prevalence and severity of mental disorders and the evolutionary path of post-modern societies. Therefore, further research on each of these topics is required, together with clinical knowledge, to substantiate our first findings. Climate change will persist as a significant concern in the next few years. Hence, the introduction of novel data sets and further investigation will undoubtedly benefit the discipline of "eco-psychiatry" (45).

Author contributions

SA: Conceptualization, Data curation, Investigation, Writing – original draft. SM: Conceptualization, Investigation, Writing – original draft.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

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

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TYPE Systematic Review
PUBLISHED 08 January 2025
DOI 10.3389/fpubh.2024.1463676

Check for updates

OPEN ACCESS

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RECEIVED 12 July 2024
ACCEPTED 18 December 2024
PUBLISHED 08 January 2025

CITATION
Chen D-D, Tu J-H, Ling K-N, Jin X-H and Huang H-Y (2025) Climate change and suicide epidemiology: a systematic review and meta-analysis of gender variations in global suicide rates. *Front. Public Health* 12:1463676. doi: 10.3389/fpubh.2024.1463676

Climate change and suicide epidemiology: a systematic review and meta-analysis of gender variations in global suicide rates

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Background: Climate change is reshaping public health, introducing extreme weather conditions and environmental stressors—such as high temperatures, atmospheric pollution, desertification, and storms (rain, thunder, and hail)—that critically impact mental health. Evidence increasingly links these factors to higher rates of suicide-related outcomes, including suicidal ideation, attempts, and self-harm. Such interactions underscore the importance of understanding how climate-driven mental health risks vary by environmental factor and gender, as gender-specific vulnerabilities shape responses to climate stressors.

Methods: By April 16, 2024, we conducted a comprehensive search of PubMed, Web of Science, Cochrane Library, PsycINFO, Scopus, ProQuest, and Embase. Two researchers independently reviewed studies and collected demographic data, systematically tracking and recording rates of suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety. Data were rigorously cross-verified for accuracy and consistency.

Results: The meta-analysis demonstrated significant associations between climate change variables and mental health outcomes. High temperatures and air pollution were linked to increased suicide attempts (OR: 1.40, 95% CI: 1.34–1.45) and suicide deaths (OR: 1.51, 95% CI: 1.44–1.58), particularly among males. Conversely, atmospheric pollution and desertification correlated with a reduced likelihood of suicidal ideation (OR: 0.73, 95% CI: 0.63–0.85). These findings highlight gender-specific mental health impacts, with females exhibiting higher rates of anxiety and self-harm, underscoring the urgent need for targeted interventions addressing climate-induced mental health risks.

Conclusions: This systematic review and meta-analysis reveal significant gender-specific mental health impacts of climate change, with females experiencing higher rates of anxiety, self-harm, and suicidal ideation, while males show greater incidences of suicide attempts and deaths. These findings emphasize the urgent need for targeted interventions and the integration of mental health services into climate policies to address these gender disparities.

Systematic review registration: This study is registered with PROSPERO [PROSPERO (york.ac.uk)] under the identifier [CRD42024534961].

KEYWORDS

climate change, suicide epidemiology, gender variations, environmental health, suicide risk factors

1 Introduction

Climate change has emerged as a defining issue of the twenty-first century, with wide-ranging implications for human health and wellbeing. While the physical health impacts of climate change, such as heat-related illnesses and respiratory problems, are well-documented (1, 2), the growing body of evidence highlighting its profound effects on mental health remains underexplored in mainstream discourse (3, 4). Extreme weather events, including heatwaves, floods, and hurricanes, are increasing in both frequency and severity, creating significant psychological stressors that contribute to mental health disorders (5, 6). Among the most concerning mental health outcomes associated with climate change is suicide (7). These outcomes encompass various dimensions, including suicide attempts, suicide deaths, and self-harm, each with distinct implications for public health. Suicide rates are influenced by a complex interplay of factors, including socio-economic status, cultural context, and individual psychological resilience (8, 9). Climate change exacerbates these factors by disrupting social and economic systems, leading to increased stress and mental health challenges (10, 11). For instance, a study by Burke et al. indicated that for every 1°C increase in temperature, the suicide rate can rise by up to 0.7% (12), highlighting the urgent need for understanding the nuanced impacts of climate change on mental health.

Gender differences in suicide rates are well-documented, with men typically having higher rates of suicide completion and women having higher rates of suicide attempts (13, 14). These differences are influenced by a range of biological, psychological, and social factors. Men and women may experience and respond to climate-related stressors differently, necessitating gender-specific approaches to prevention and intervention (15, 16).

Recent research underscores the importance of examining gender variations in mental health outcomes related to climate change. Women, for example, may be more vulnerable to the mental health impacts of climate change due to their often disproportionate exposure to environmental hazards and greater responsibilities for family and community care (17). Additionally, socio-cultural expectations and gender roles can influence how stress and mental health issues are experienced and reported (18, 19). Extreme weather events such as droughts, which affect agricultural productivity, can lead to economic hardship and increased mental health issues, particularly in rural areas. These mental health challenges can manifest in various suicide-related outcomes, including self-harm, suicide attempts, and suicide deaths, which may disproportionately impact women in vulnerable communities. Studies have shown that these impacts are often more severe for women, who may have fewer economic resources and greater caregiving responsibilities (20). In contrast, men may face increased risks of suicide due to societal pressures to be the primary economic providers, which can become overwhelming during times of environmental and economic stress (21, 22).

The intersection of climate change and mental health is a burgeoning field of study, with increasing evidence suggesting that extreme weather events can act as catalysts for mental health crises (23, 24). Heatwaves, in particular, have been closely studied for their impact on mental health. Research has found that high temperatures can lead to increased irritability, aggression, and impulsivity, all of which are risk factors for suicide (25). Furthermore, the chronic stress associated with climate change, such as prolonged droughts and the resultant economic instability, can exacerbate existing mental health conditions and contribute to suicidal behavior (26, 27). Displacement due to natural disasters can also lead to loss of social support networks, increased financial strain, and heightened exposure to traumatic events, all associated with poor mental health outcomes (28, 29). These indirect pathways highlight the need for a holistic approach to understanding and addressing the mental health impacts of climate change.

Gender-specific vulnerabilities to climate change-related mental health issues are shaped by various factors, including differential exposure to environmental hazards, gender roles, and access to resources (30). Women, particularly in low- and middle-income countries, are often disproportionately affected by climate change due to their roles in agriculture, caregiving responsibilities, and other climate-induced livelihood challenges, which can exacerbate mental health vulnerabilities as described by Rosen et al. (31). These roles can increase their exposure to environmental stressors and limit their ability to seek help or relocate in times of crisis. Conversely, men may experience climate change differently, with increased risks of mental health issues stemming from societal expectations of stoicism and self-reliance (32). These expectations can discourage men from seeking mental health support, leading to higher rates of untreated mental health conditions and, consequently, higher suicide rates (33). Understanding these gender-specific responses to climate change is crucial for developing effective public health strategies.

This review aims to provide a comprehensive analysis of the existing literature on the gender-specific impacts of climate change on suicide rates. This study systematically reviews evidence on the relationship between climate change and mental health outcomes, with a specific emphasis on suicide attempts, suicide deaths, and self-harm. By examining these outcomes through the lens of gender differences, we seek to identify patterns that can inform both research and policy. Our goal is to underscore the importance of targeted interventions that address the distinct vulnerabilities of men and women to climate-driven mental health impacts. Overall, this study highlights climate change as a profound and multifaceted challenge to mental health, with notable gender disparities in the manifestation of these effects. Targeted interventions are essential to address the unique vulnerabilities of men and women to the mental health impacts of climate change, contributing to the development of gender-sensitive public health strategies.

2 Methods

2.1 Search strategy

The systematic review and meta-analysis were conducted in adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (34). Comprehensive literature searches were performed in PubMed, Web of Science, Cochrane Library, PsycINFO, Scopus, ProQuest, and Embase databases, covering publications up to April 16, 2024, without restrictions on publication date. The search strategy utilized both controlled vocabulary and free-text terms related to climate change (e.g., "climate change," "global warming," "heat stress"), suicide and self-harm (e.g., "suicide," "suicidal ideation," "self-injury"), and gender variations (e.g., "sex characteristics," "gender differences," "sexual dimorphism"). Boolean operators were applied to structure the search and improve specificity. Each identified study was screened for relevance, with eligibility independently assessed by two reviewers. An overview of the full search strategy and terms used is provided in Supplementary Table 1.

2.2 Eligibility criteria

For inclusion in the systematic review and meta-analysis, studies had to meet the following criteria: (1) The research must have investigated the impact of climate change on suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety. Anxiety was included as it has a well-documented link with climate change-related stressors and plays a potential role in exacerbating suicidality (35). Although depression and substance use disorder are also important considerations, anxiety was prioritized in this review due to its frequent occurrence in climate-related mental health studies and its relevance to the gender-specific analysis of mental health vulnerabilities. (2) The studies were required to provide gender-specific data on these outcomes or allow for such data to be derived from secondary sources. (3) Both observational and experimental study designs were considered eligible.

The exclusion criteria were as follows: (1) Studies with incomplete data were excluded. (2) Studies published in languages other than English were not considered. (3) Studies were excluded if the full text was not accessible. (4) Research that combined multiple outcome measures without enabling separate analysis was excluded. (5) In cases of participant overlap across studies, the earliest published study was excluded to prevent data duplication.

2.3 Data extraction

To ensure data integrity, two researchers independently extracted the data. Any discrepancies were resolved through consultation with a third reviewer who has expertise in the relevant field. The data extracted from each study included: author name, publication year, study location, recruitment period, and participant characteristics such as age and gender. Outcome measures focused on the prevalence of suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety, disaggregated by gender, as well as climate variables such as temperature, atmospheric pollution levels, and desertification indicators, recorded with standardized measurement techniques where applicable. In cases where data were not directly available, we calculated estimates based on secondary sources or inferred values from reported rates to ensure accuracy and consistency. Additionally, we categorized climate variables to facilitate subgroup and sensitivity analyses later in the study. A protocol-guided approach ensured that each stage of data extraction followed a consistent methodology, and our extraction records were carefully documented to enable reproducibility of the findings and enhance transparency in the meta-analytic process.

2.4 Statistical analysis

Statistical analyses were performed using Stata (version 11.0 for Windows) to assess the relationship between climate change and mental health outcomes, including suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety, by gender. Odds ratios (ORs) with 95% confidence intervals (CIs) were calculated for each outcome. Meta-regression was conducted for suicide deaths and anxiety to examine the influence of key covariates, including weather conditions, study design, gender ratio, country classification, and total sample size. These outcomes were selected for meta-regression based on their homogeneity and the availability of sufficient data. For weather conditions, regions with an average annual temperature above 30°C were categorized as "high temperature" (value = 1), while all other regions were classified as "other" (value = 2). Although specific environmental phenomena such as cold weather, thunderstorms, and rainstorms were evaluated for their impact on mental health outcomes, these were treated separately from the weather category in the meta-regression model.

Due to substantial heterogeneity in measurement methods, sample sizes, and reporting across studies, meta-regression was not performed for other outcomes, such as suicidal ideation, suicide attempts, and self-harm. Subgroup analyses were conducted to explore sources of heterogeneity, categorized by continent, study design, weather exposure type, and gender. Gender-specific subgroup analysis was carried out by grouping studies into male (m1, m2) and female (f1, f2) categories, as shown in Supplementary Figures 1A–5A. Heterogeneity was assessed using the I^2 index and the Q-test, while publication bias was examined using funnel plots and Egger's test.

2.5 Quality assessment

Each study's quality was evaluated using the Newcastle-Ottawa Scale (36). This scale assesses selection of study groups, comparability between groups, and outcome assessment for cohort studies or exposure for case-control studies. Studies were scored from 0 to 9, with higher scores indicating better quality. Two reviewers independently assessed each study and resolved any differences through discussion. Studies were classified into low, moderate, or high quality based on their scores. Detailed results and classifications are provided in Supplementary Table 2.

2.6 Definition of suicide outcomes

Suicide outcomes in this study were classified into four categories: suicidal ideation, suicide attempts, suicide deaths, and self-harm. Suicidal ideation refers to thoughts of self-harm or ending one's life without physical action, representing an early stage of suicide-related behavior and often indicating underlying psychological distress (37, 38). Suicide attempts, in contrast, involve intentional actions aimed at self-harm or death, marking an escalation of suicidal behavior driven by acute emotional pain and external stressors (39–41). Suicide deaths are the final and irreversible outcome of suicide-related behaviors, where the individual deliberately ends their life, typically following prolonged psychological distress or pre-existing mental health conditions (42–44). Self-harm, distinct from the other outcomes, involves deliberate, non-fatal injury to oneself as a maladaptive coping mechanism for emotional turmoil. While self-harm is not driven by a desire to die, it often serves as a temporary release from psychological pain and is frequently seen as a precursor to more severe suicide-related behaviors (45, 46). These definitions provide the basis for the classification and analysis of suicide-related outcomes in this study, ensuring consistency across the results.

3 Results

3.1 Identification of studies

A comprehensive search was conducted across seven databases—PubMed (38), Web of Science (433), Embase (28), Cochrane Library (7), PsycINFO (56), Scopus (311), and ProQuest (123)—yielding a total of 996 studies. After 318 duplicates were removed, 678 unique records remained for screening. Following the title and abstract screening, 409 records were excluded, and 269 articles were selected for full-text review. Further exclusions were made based on factors such as lack of gender-specific suicide data (172), case reports (10), and other irrelevant content, including meta-analyses or reviews (44). In the end, 36 studies met the eligibility criteria and were included in the meta-analysis. The detailed selection process is outlined in Figure 1.

3.2 Description of included studies

A total of 36 studies were included in this analysis, conducted across various continents: America, Asia, Europe, Oceania, and Africa. Participants ranged in age, and the studies spanned multiple climate conditions such as high temperatures, atmospheric pollution, and desertification. The studies examined outcomes related to suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety. Detailed characteristics of each study, including author, year, study design, demographics, and climate variables, are summarized in Table 1.

3.3 Weather variables classification

This section critically examines the associations between climate variables—high temperature, atmospheric pollution, desertification, and other extreme weather phenomena—and mental health outcomes, including suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety. By disaggregating results by climate variable and considering geographic differences, this analysis highlights the distinct impacts of these environmental factors on suicide-related outcomes and anxiety. Supplementary Figures support the presentation of pooled estimates and subgroup analyses.

3.3.1 High temperature

High temperature emerged as a significant climate variable, influencing mental health outcomes in complex ways. Meta-analysis results (Supplementary Figure 1A) revealed a significant inverse association between high temperature and suicidal ideation (OR: 0.73, 95% CI: 0.63–0.85, $I^2 = 28.1\%$). This trend was particularly observed in regions such as Kenya and India, where prolonged exposure to high temperatures may have led to physiological acclimatization and psychological adaptation, potentially reducing the prevalence of suicidal ideation. Conversely, high temperature was strongly associated with an increased risk of suicide attempts (OR: 1.08, 95% CI: 0.86–1.34, $I^2 = 0.0\%$, Supplementary Figure 2D) and suicide deaths (OR: 1.48, 95% CI: 1.38–1.58, $I^2 = 1.3\%$, Supplementary Figure 3D). These associations were most pronounced in Oceania (Supplementary Figure 3B), where recurrent heatwaves, inadequate infrastructure, and limited adaptive capacity likely amplified vulnerabilities, particularly in populations with pre-existing mental health conditions or limited access to healthcare. Anxiety demonstrated an unexpected protective relationship with high temperatures (OR: 0.81, 95% CI: 0.76–0.87, $I^2 = 0.0\%$, Supplementary Figure 5D). The available data on self-harm related to high temperatures were limited, with most studies showing no significant effect.

3.3.2 Atmospheric pollution

Atmospheric pollution emerged as a significant environmental stressor, strongly associated with adverse mental health outcomes, especially in urban and industrialized regions. The meta-analysis (Supplementary Figure 2D) indicated a positive association between atmospheric pollution and suicide attempts (OR: 1.44, 95% CI: 1.35–1.53, $I^2 = 49.5\%$), with the highest risks observed in densely populated areas of Asia and North America, where prolonged exposure to fine particulate matter (PM2.5) is common. A similar association was identified for suicide deaths (OR: 1.47, 95% CI: 1.32–1.64, $I^2 = 0.0\%$, Supplementary Figure 3D), likely mediated by neuroinflammatory and oxidative stress mechanisms. Anxiety showed an unexpected inverse relationship with atmospheric pollution (OR: 0.84, 95% CI: 0.82–0.86, $I^2 = 0.8\%$, Supplementary Figure 5D). This inverse trend may reflect contextual factors such as healthcare access, cultural differences in symptom recognition, or regional reporting practices.

3.3.3 Desertification

Desertification was uniquely associated with mental health outcomes, often showing protective trends. The meta-analysis (Supplementary Figure 1A) revealed a significant inverse association between desertification and suicidal ideation (OR: 0.73, 95% CI: 0.63–0.85, $I^2 = 28.1\%$). This protective effect was most pronounced in desertification-prone regions such as Kenya and India, where long-term exposure to arid conditions likely fostered community-based coping mechanisms and

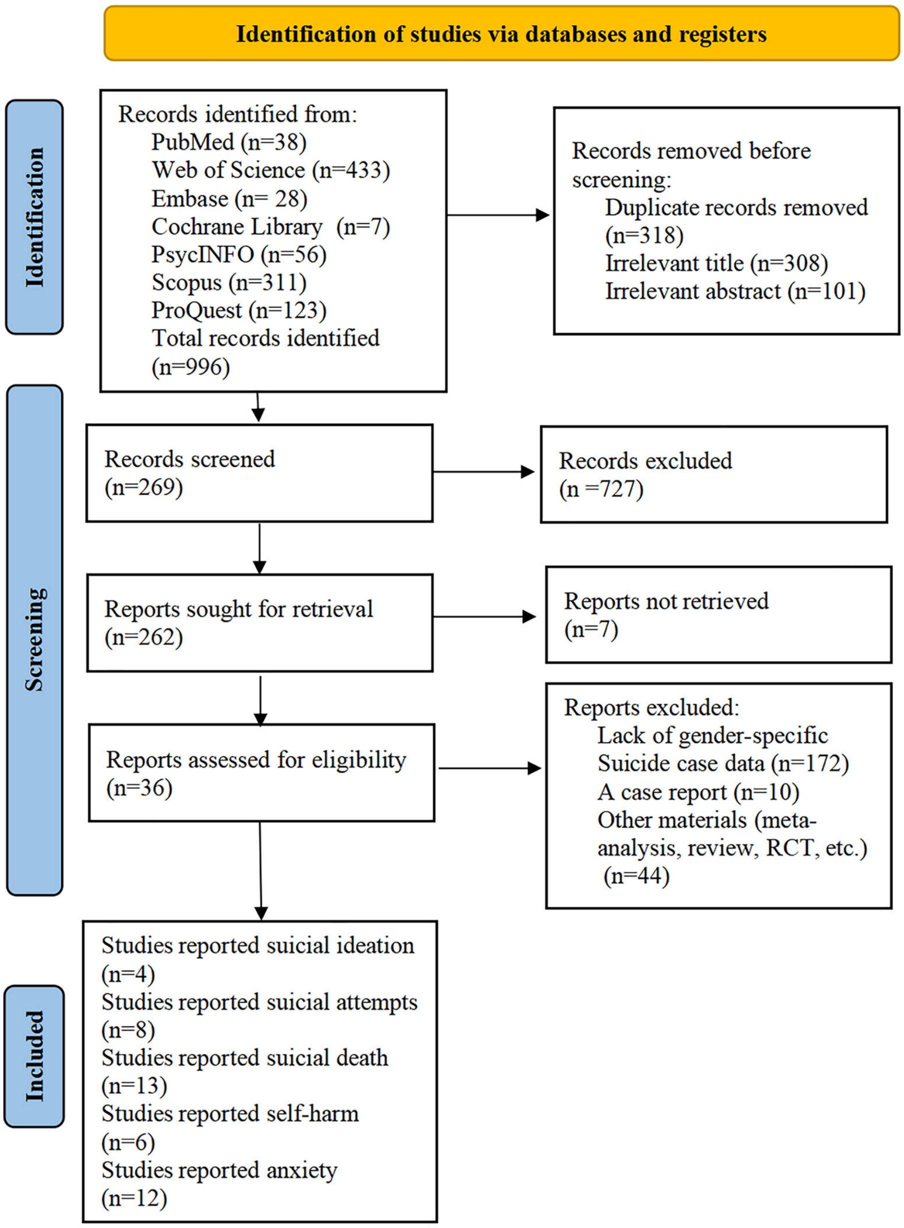

FIGURE 1
Flowchart depicting the methodology of study selection.

enhanced social support networks. Desertification also exhibited a protective trend for anxiety (OR: 0.92, 95% CI: 0.84–1.00, Supplementary Figure 5D), though this finding should be interpreted with caution due to study design variability and potential reporting biases.

3.3.4 Other weather phenomena

Other weather phenomena, including cold weather, thunderstorms, and rainstorms, were evaluated for their impact on mental health outcomes. The meta-analysis results from Supplementary Figures 2D, 3D, 5D revealed significant associations between these weather events and mental health conditions. Cold weather was positively associated with suicide attempts (OR: 1.38, 95% CI: 1.31–1.46, Supplementary Figure 2D) and suicide deaths (OR: 1.57, 95% CI: 1.43–1.72, Supplementary Figure 3D), indicating an increased risk of these severe outcomes during colder conditions. This may reflect exacerbated mental health conditions or region-specific factors, such as limited social support and healthcare infrastructure during cold spells. Additionally, cold weather was inversely associated with anxiety (OR: 0.79, 95% CI: 0.49–1.29, Supplementary Figure 5D), suggesting that lower temperatures might be associated with reduced anxiety, potentially due to

TABLE 1 Principal characteristics of the chosen research.

References	Country	Period	Study design	Age	Category	M(S/N)	F(S/N)	Environmental phenomenon	NOS
Gunn et al. (78)	Australia	NR	Cross-sectional	49.5 ± 12.3	Anxiety	18/196	19/107	Desertification	5
Nguyen et al. (79)	USA	2005–2013	Retrospective	32.5 ± 19.1	Anxiety	3,639/15,517	4,272/14,909	Atmospheric pollution	8
Nori-Sarma et al. (80)	USA	2010–2019	Cross–sectional	51.0 ± 18.8	Anxiety	256/968	518/1,511	High temperature	5
Tawatsupa et al. (81)	Thailand	2005	Cross-sectional	51.0 ± 36.0	Anxiety	1,341/18,148	2,051/22,765	High temperature	6
Thomas et al. (82)	India	2018–2019	Cross-sectional	41.5 ± 23.5	Anxiety	19/34	38/80	Rainstorm	6
Ndetei et al. (83)	Kenya	2022	Cross-sectional	18.0 ± 5.0	Anxiety	526/1,728	286/862	Atmospheric pollution	7
Hanigan et al. (84)	Australia	2015	Cross-sectional	47.0 ± 29.0	Anxiety	678/2,205	1,135/3,592	Desertification	7
Basu et al. (85)	USA	2005–2013	Retrospective	43.0 ± 18.4	Anxiety	14,158/30,778	17,298/31,578	Atmospheric pollution	7
Di Nicola et al. (86)	Italy	2016–2019	Cross-sectional	44.0 ± 26.0	Anxiety	37/130	51/142	Cold	7
Gunn et al. (87)	Australia	2008	Cross-sectional	54.5 ± 30.5	Anxiety	7/28	18/72	Desertification	6
Sewell et al. (88)	USA	2016–2019	Cross-sectional	14.2 ± 4.1	Anxiety	434/1,122	688/1,515	Desertification	7
Mellado et al. (89)	Chile	2017	Cross-sectional	14.5 ± 2.1	Anxiety	16/124	21/137	Thunderstorms	7
Salib et al. (90)	UK	1989–1993	Retrospective	46.0 ± 18.0	Self–harm	29/152	9/42	Thunderstorms	7
Kubo et al. (91)	Japan	2012–2015	Retrospective	37.5 ± 13.8	Self-harm	925/5,505	1,811/9,099	High temperature	7
Bjorksten et al. (92)	Denmark	1968–1995	Retrospective	47.5 ± 21.4	Self-harm	112/684	30/149	High temperature	8
Nguyen et al. (79)	USA	2005–2013	Retrospective	32.5 ± 19.1	Self-harm	1,279/7,935	2,284/11,418	Atmospheric pollution	8
Nori-Sarma et al. (80)	USA	2010–2019	Cross-sectional	51.0 ± 18.8	Self-harm	174/968	277/1,318	High temperature	5
Basu et al. (85)	USA	2005–2013	Retrospective	43.0 ± 18.4	Self-harm	2,116/13,222	3,996/19,026	Atmospheric pollution	7
Viswanathan et al. (93)	India	2017	Cross-sectional	45.0 ± 25.0	Suicidal ideation	38/124	39/70	Desertification	5
Ndetei et al. (83)	Kenya	2022	Cross-sectional	18.0 ± 5.0	Suicidal ideation	235/1,728	156/862	Atmospheric pollution	7
Brokamp et al. (94)	USA	2011–2015	Cross-sectional	15.0 ± 12.8	Suicidal ideation	48/112	66/163	Atmospheric pollution	8
Sewell et al. (88)	USA	2016-2019	Cross-sectional	14.2 ± 4.1	Suicidal ideation	103/803	233/1,233	Desertification	7
Ambar et al. (95)	France	2009–2018	Retrospective	NR	Suicide attempts	3,672/27,483	2,409/25,063	Cold	8
Dumencic et al. (96)	Croatia	2000–2011	Retrospective	NR	Suicide attempts	213/329	356/718	Cold	8
Hiltunen et al. (97)	Finland	1989–1990	Cross-sectional	NR	Suicide attempts	202/1,198	104/1,111	Atmospheric pollution	5
Ndetei et al. (83)	Kenya	2022	Cross-sectional	18.0 ± 5.0	Suicide attempts	74/525	67/602	Atmospheric pollution	7

(Continued)

TABLE 1 (Continued)

References	Country	Period	Study design	Age	Category	M(S/N)	F(S/N)	Environmental phenomenon	NOS
Szyszkowicz et al. (98)	USA	1999–2003	Cross-sectional	35.0 ± 5.0	Suicide attempts	390/1,042	145/563	Atmospheric pollution	7
Lee et al. (99)	Korea	2005–2022	Cross-sectional	49.4 ± 15.6	Suicide attempts	3,219/20,323	1,132/10,381	Atmospheric pollution	6
Yarza et al. (100)	Palestine	2002–2017	Cross-sectional	41.6 ± 20.7	Suicide attempts	164/1,008	201/1,330	High temperature	6
Miyazaki et al. (101)	Japan	2005–2022	Cross-sectional	41.1 ± 17.4	Suicide attempts	281/773	297/964	Atmospheric pollution	7
Lee et al. (102)	Korea	2002–2013	Retrospective	NR	Suicide deaths	72/494	26/247	Atmospheric pollution	6
Kim et al. (103)	Korea	2001–2005	Retrospective	NR	Suicide deaths	843/5,777	271/3,113	High temperature	8
Dumencic et al. (96)	Croatia	2000–2011	Retrospective	NR	Suicide deaths	82/569	43/478	Cold	8
Kok et al. (104)	China	1980–1989	Retrospective	30.0 ± 17.6	Suicide deaths	224/1,690	112/1,199	High temperature	8
Hiltunen et al. (105)	Finland	1969–2003	Retrospective	NR	Suicide deaths	858/6,597	621/6,889	High temperature	7
Hanigan et al. (106)	Australia	1971–1999	Prospective	30.0 ± 20.0	Suicide deaths	1,053/7,256	681/7,235	Desertification	6
Law et al. (107)	Australia	1996–2007	Cross-sectional	NR	Suicide deaths	450/3,023	180/2,165	Cold	6
Lehmann et al. (108)	France	1968–2016	Retrospective	NR	Suicide deaths	263/1,836	188/1,901	High temperature	5
Beautrais et al. (109)	New Zeeland	2007–2015	Retrospective	NR	Suicide deaths	54/169	2/16	Desertification	6
Partonen et al. (110)	Finland	1987–1988	Cross-sectional	76.5 ± 12.5	Suicide deaths	98/793	21/248	Cold	6
Hiltunen et al. (111)	Finland	1979–2010	Retrospective	NR	Suicide deaths	771/5,756	244/2,517	High temperature	6
Qin et al. (112)	Denmark	1982–2013	Retrospective	60.5 ± 19.5	Suicide deaths	1,237/8,753	475/4,947	Atmospheric pollution	6
Luo et al. (113)	China	2013–2018	Retrospective	NR	Suicide deaths	1,256/8,547	404/4,075	Cold	8

NR stands for "not applicable"; NOS refers to the "Newcastle-Ottawa Scale," used for evaluating the quality of non-randomized studies included in meta-analyses; S/N represents the ratio of males or females exhibiting suicidal ideation, suicide attempts, suicide deaths, or self-harm, or experiencing anxiety, to the number of men or women exposed to extreme weather conditions.

decreased external stressors or coping mechanisms that arise in colder environments.

Thunderstorms demonstrated a protective effect on anxiety (OR: 0.84, 95% CI: 0.42–1.69, Supplementary Figure 5D), with anxiety levels potentially reduced during thunderstorms. This effect may be due to the predictability of these weather events, allowing individuals to mentally prepare and reducing the uncertainty and anxiety often associated with unexpected environmental changes. Rainstorms, on the other hand, showed an association with anxiety (OR: 1.18, 95% CI: 0.60–2.33, Supplementary Figure 5D), which was somewhat less clear, indicating that the impact of rainstorms on mental health may be more context-dependent, possibly influenced by social support systems and local coping mechanisms in affected areas.

3.4 Suicide outcomes classification

This section delves into the associations between distinct suicide-related outcomes—suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety—and climate change variables. By systematically analyzing results for each outcome and incorporating findings from sensitivity tests, subgroup analyses, and meta-regression, it seeks to unravel the unique pathways through which environmental factors shape these mental health outcomes. Supplementary Figures are provided to substantiate the robustness and reliability of the observed associations.

3.4.1 Suicidal ideation

The pooled analysis demonstrated a significant inverse association between suicidal ideation and specific climate-related factors, with an overall OR of 0.73 (95% CI: 0.63–0.85) and moderate heterogeneity ($I^2 = 28.1\%$). These findings suggest that suicidal ideation may be influenced by environmental conditions such as desertification and atmospheric pollution, which appear to foster protective trends in certain contexts. These effects could be linked to long-term adaptation mechanisms, including strengthened community networks and psychological resilience, that help mitigate the psychological burden associated with chronic exposure to environmental stressors.

The robustness of these results was confirmed through sensitivity analysis (Supplementary Figure 1B), which showed no significant changes in the pooled OR when individual studies were excluded. Additionally, the symmetrical funnel plot (Supplementary Figure 1C) and Egger's test ($p = 0.244$) indicated no evidence of publication bias, reinforcing confidence in the observed associations.

3.4.2 Suicide attempts

Our meta-analysis revealed a significant association between climate change variables and suicide attempts, with a pooled OR of 1.40 (95% CI: 1.34–1.45) and moderate heterogeneity ($I^2 = 51.1\%$, $p = 0.046$; Supplementary Figure 2A). Subgroup analyses indicated geographic variability: studies conducted in Asia reported a pooled OR of 1.39 (95% CI: 1.30–1.48) with high heterogeneity ($I^2 = 78.8\%$, $p = 0.009$), while European studies showed a similar OR of 1.40 (95% CI: 1.33–1.47) but with moderate heterogeneity ($I^2 = 54.2\%$, $p = 0.112$; Supplementary Figure 2B).

Retrospective studies demonstrated a pooled OR of 1.38 (95% CI: 1.31–1.46) with minimal heterogeneity ($I^2 = 0.0\%$, $p = 0.579$), while cross-sectional studies had a slightly higher OR of 1.41 (95% CI: 1.33–1.49) with increased heterogeneity ($I^2 = 64.0\%$, $p = 0.016$; Supplementary Figure 2C). Sensitivity analysis (Supplementary Figure 2E) confirmed the stability of these results, with consistent OR values across individual study exclusions. The funnel plot (Supplementary Figure 2F) displayed symmetry, and Egger's test ($p = 0.246$) indicated no significant publication bias, further reinforcing the reliability of the findings.

3.4.3 Suicide deaths

Our meta-analysis revealed a significant association between climate change variables and suicide deaths, with a pooled OR of 1.51 (95% CI: 1.44–1.58) and no observed heterogeneity ($I^2 = 0.0\%$, $p = 0.704$; Supplementary Figure 3A). Subgroup analyses revealed geographic variations: studies conducted in Asia reported an OR of 1.54 (95% CI: 1.41–1.67), while in Europe, the OR was slightly lower at 1.45 (95% CI: 1.36–1.54). Oceania exhibited the highest OR of 1.60 (95% CI: 1.47–1.75; Supplementary Figure 3B). Analysis by study design showed that retrospective studies demonstrated a pooled OR of 1.48 (95% CI: 1.41–1.56), prospective studies yielded a similar OR of 1.54 (95% CI: 1.39–1.71), while cross-sectional studies showed a significantly higher OR of 1.75 (95% CI: 1.47–2.07; Supplementary Figure 3C).

Sensitivity analysis (Supplementary Figure 3E) confirmed the robustness of these results, with no significant changes in the pooled OR after excluding individual studies. The symmetrical funnel plot (Supplementary Figure 3F) and Egger's test ($p = 0.704$) showed no evidence of publication bias, supporting the reliability of the findings.

Meta-regression analysis results (Table 2) provided further insight into the factors influencing the association between climate variables and suicide deaths. Gender ratio emerged as the only significant predictor of suicide deaths (B = 0.013, $p = 0.046$), suggesting that a higher proportion of males in the population is associated with an increased risk of suicide mortality in the presence of climate stressors. This finding indicates that gender-specific vulnerabilities may play a critical role in moderating the effects of environmental stressors on suicide mortality. Other factors, such as study year (B = 0.002, $p = 0.487$), sample size (B = −0.00001, $p = 0.753$), and country development status (B = −0.003, $p = 0.672$), were not significantly associated with the outcome, indicating that these factors may not substantially influence the observed associations between climate variables and suicide deaths.

3.4.4 Self-harm

Our meta-analysis revealed a significant inverse association between climate change variables and self-harm, with a pooled OR of 0.79 (95% CI: 0.76–0.83) and no observed heterogeneity ($I^2 = 0.0\%$, $p = 0.456$; Supplementary Figure 4A). This consistent finding suggests that exposure to certain climate-related factors, such as

TABLE 2 Meta-regression analysis table for suicide deaths.

Variables	B	SE	95% CI	*t*	*p*
Year	0.002	0.002	[−0.002, 0.006]	1.000	0.320
Gender ratio	0.013	0.005	[−0.001, 0.027]	2.600	0.046
Study period midpoint	0.003	0.002	[−0.001, 0.007]	1.500	0.154
Country (developed)	0.016	0.025	[−0.033, 0.065]	0.640	0.530
Country (developing)	0.011	0.021	[−0.030, 0.052]	0.520	0.610
Weather category (high temperature)	−0.021	0.036	[−0.093, 0.051]	−0.583	0.569
Weather category (other)	0.006	0.031	[−0.055, 0.067]	0.194	0.847
Study design (cross–sectional)	−0.009	0.041	[−0.089, 0.071]	−0.220	0.828
Study design (retrospective)	0.011	0.051	[−0.089, 0.111]	0.220	0.827
Total sample size	−0.002	0.002	[−0.006, 0.002]	−1.000	0.330

TABLE 3 Meta-regression analysis table for anxiety.

Variables	B	SE	95% CI	*t*	*p*
Year	0.001	0.002	[−0.003, 0.005]	0.500	0.625
Gender ratio	0.014	0.006	[−0.002, 0.030]	2.333	0.039
Study period midpoint	0.004	0.003	[−0.002, 0.010]	1.333	0.203
Country (developed)	0.017	0.026	[−0.034, 0.068]	0.654	0.525
Country (developing)	0.012	0.022	[−0.031, 0.055]	0.545	0.590
Weather category (high temperature)	−0.022	0.037	[−0.096, 0.052]	−0.595	0.559
Weather category (other)	0.007	0.032	[−0.057, 0.071]	0.219	0.828
Study design (cross-sectional)	−0.010	0.042	[−0.094, 0.074]	−0.238	0.823
Study design (retrospective)	0.012	0.052	[−0.092, 0.116]	0.231	0.823
Total sample size	−0.003	0.003	[−0.007, 0.001]	−1.000	0.330

high temperatures or atmospheric pollution, may be associated with a reduced risk of self-harm.

The stability and robustness of these results were confirmed through sensitivity analysis (Supplementary Figure 4B), where no significant changes in the pooled OR were observed upon exclusion of individual studies. Furthermore, the symmetrical funnel plot (Supplementary Figure 4C) and Egger's test ($p = 0.437$) provided no evidence of publication bias, reinforcing the reliability of the results. Given the absence of heterogeneity and the stability of the findings, meta-regression analysis was not conducted, as it would likely provide limited additional insights.

3.4.5 Anxiety

The meta-analysis revealed a significant inverse association between climate change variables and anxiety, with a pooled odds ratio (OR) of 0.84 (95% CI: 0.82–0.86) and low heterogeneity ($I^2 = 19.1\%$, $p = 0.256$; Supplementary Figure 5A). This suggests that exposure to certain climate factors, such as elevated temperatures and atmospheric pollution, is associated with reduced anxiety levels in certain contexts.

Subgroup analyses showed geographic variations. Studies conducted in Oceania reported an OR of 0.96 (95% CI: 0.86–1.07), with moderate heterogeneity ($I^2 = 37.2\%$, $p = 0.203$). In contrast, research from America showed a more consistent association, with an OR of 0.83 (95% CI: 0.81–0.85) and no heterogeneity ($I^2 = 0.0\%$, $p = 0.793$). Studies from Asia, Africa, and Europe yielded ORs ranging from 0.79 to 0.92, with minimal heterogeneity, indicating that the relationship between climate factors and anxiety is relatively stable across these regions (Supplementary Figure 5B). Regarding study design, retrospective studies yielded a pooled OR of 0.83 (95% CI: 0.82–0.85) with no heterogeneity ($I^2 = 0.0\%$, $p = 0.373$). Cross-sectional studies showed a slightly higher OR of 0.86 (95% CI: 0.82–0.90), with moderate heterogeneity ($I^2 = 24.5\%$, $p = 0.218$; Supplementary Figure 5C). This suggests that retrospective studies may reflect more consistent long-term trends, whereas cross-sectional studies might capture the immediate, context-specific impacts of climate factors on anxiety.

Sensitivity analysis confirmed the robustness of these findings (Supplementary Figure 5E), with stable ORs observed even after excluding individual studies. The symmetrical funnel plot (Supplementary Figure 5F) and Egger's test ($p = 0.356$) indicated no evidence of publication bias, further supporting the reliability of these results.

Meta-regression analysis (Table 3) was conducted to explore potential predictors of the association between climate factors and anxiety outcomes. The analysis revealed that the gender ratio was the only variable significantly associated with anxiety outcomes (B = 0.014, $p = 0.039$). Specifically, an increased male-to-female ratio within the study populations was linked to a more pronounced inverse relationship between climate stressors and anxiety. This suggests that gender-specific factors, such as coping strategies and vulnerability to climate-related stressors, may significantly influence anxiety outcomes. In contrast, other variables, including study year (B = 0.002, $p = 0.487$), sample size (B = −0.00001, $p = 0.753$), and country development status (B = −0.003, $p = 0.672$), were not found to significantly impact the observed relationship between climate change variables and anxiety. These findings underscore the complexity of the interaction between climate factors and anxiety, highlighting the potential role of gender in modulating these associations, while other demographic and methodological variables appear to have minimal influence.

4 Discussion

The discussion highlights critical insights into how climate change impacts mental health differently across genders, with specific focus on suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety. The findings suggest that climate change intensifies mental health disparities, with women experiencing heightened risks of anxiety, self-harm, and suicidal ideation, likely due to unique social and caregiving pressures during climate-induced crises. In contrast, men are more prone to suicide attempts and deaths, potentially driven by societal expectations of stoicism and the economic stress associated with their roles as primary providers. These gender-specific responses underscore the importance of understanding how climate-related stressors interact with socio-cultural factors to influence mental health outcomes.

4.1 Climate variables

The impact of high temperature on mental health is dual-faceted, with both protective and harmful effects observed across different regions. In areas such as Kenya and India, where populations have adapted to prolonged heat exposure, high temperatures were inversely associated with suicidal ideation, likely due to enhanced social resilience and coping mechanisms. However, in regions like Oceania, recurrent heatwaves, combined with poor infrastructure and limited healthcare access, exacerbated mental health vulnerabilities, leading to an increased risk of suicide attempts and deaths. These findings emphasize the importance of context in shaping the relationship between temperature and mental health outcomes, suggesting that adaptive strategies can mitigate risks in certain regions, while other areas require targeted public health interventions to enhance resilience.

Atmospheric pollution, particularly in urban and industrialized regions, emerged as a significant environmental stressor with detrimental effects on mental health. Prolonged exposure to pollutants, such as PM2.5, was associated with an increased risk of suicide attempts and deaths, possibly through neuroinflammatory and oxidative stress mechanisms that exacerbate psychological vulnerability. While anxiety showed an inverse relationship with atmospheric pollution, this unexpected finding may reflect regional differences in healthcare access, reporting biases, or cultural norms influencing symptom recognition. These results underline the need for policies aimed at reducing air pollution and improving urban living conditions to mitigate the mental health impacts of poor air quality.

Desertification, although less impactful than other climate variables, demonstrated protective effects in regions prone to arid conditions, such as Kenya and India. In these areas, community-based coping mechanisms and enhanced social support networks appear to buffer against psychological distress, leading to a significant inverse association with suicidal ideation and anxiety. However, the mental health impact of desertification on more severe outcomes like suicide attempts and deaths remains poorly understood, with limited data available for robust analysis. Further research is needed to explore the long-term psychological consequences of desertification, particularly in underrepresented regions, to guide interventions that strengthen community resilience and mental health support.

Extreme weather events, including thunderstorms, hailstorms, and rainstorms, had more context-dependent impacts on mental health outcomes. While thunderstorms and hailstorms were linked to increased impulsivity and suicide attempts, the effects of rainstorms were more variable, likely due to regional differences in flood severity and disaster preparedness. Extreme weather events tend to disrupt both environmental and social systems, leading to acute psychological distress. These findings highlight the need for localized interventions to strengthen disaster response systems and mental health support in regions vulnerable to such events. Particularly in areas with inadequate disaster management or low socioeconomic resilience, extreme weather can exacerbate existing mental health conditions, underscoring the importance of context in determining the mental health impact of climate phenomena.

4.2 Suicidal ideation

Our meta-analysis incorporated data from four studies, encompassing 2,767 male and 2,328 female participants, to assess the prevalence of suicidal ideation in the context of climate change. The results revealed a higher prevalence of suicidal ideation among females, 21.2% (95% CI: 19.59–22.90), compared to males, 15.3% (95% CI: 13.99–16.66). This suggests that females may be more susceptible to the psychological stressors associated with climate change. This gender disparity aligns with existing literature, which often attributes higher rates of mental health issues in females to factors such as increased caregiving responsibilities and greater economic vulnerabilities during extreme weather events (47). Moreover, the pooled odds ratio for suicidal ideation related to climate change was 0.73 (95% CI: 0.63–0.85), underscoring a significant inverse association with specific environmental factors such as desertification and atmospheric pollution. These findings suggest that long-term exposure to these stressors may foster certain protective mechanisms, such as enhanced psychological resilience or community-level adaptations, particularly in regions like India or urban centers in the USA and Kenya (48, 49).

The mechanisms underlying these associations remain complex and multifactorial. Gender-specific differences, including biological susceptibility to stress, sociocultural roles, and access to coping resources, may contribute to these disparities. Furthermore, unlike suicide attempts or deaths, suicidal ideation is less influenced by acute external stressors and may instead reflect cumulative psychological burdens exacerbated by prolonged exposure to climate stressors. These distinctions highlight the necessity of tailoring preventive strategies to address the unique pathways through which climate factors influence suicidal ideation, ensuring interventions are sensitive to both gender and regional vulnerabilities.

4.3 Suicide attempts

Our analysis, encompassing data from eight studies with 52,681 male and 40,732 female participants, revealed that suicide attempts were more prevalent among males, at 15.6% (95% CI: 15.28–15.91), compared to females, at 11.6% (95% CI: 11.26–11.88). This gender disparity highlights the distinct ways in which men and women respond to climate-related stress. Men, often subjected to societal pressures and cultural norms emphasizing stoicism and economic responsibility, may be less likely to express emotions or seek mental health support. Consequently, they are more prone to extreme responses, such as suicide attempts, under severe stress (50). This aligns with broader mental health research, which suggests that men's reluctance to seek help or share emotional burdens can lead to the accumulation of unaddressed psychological distress, culminating in drastic actions. Conversely, women are more likely to report mental health issues, such as anxiety and depression, but these may not translate into suicide attempts or deaths at the same rate. Women's coping mechanisms, which often involve seeking social support and engaging in emotional expression, may serve as protective factors against transitioning from ideation to attempts (51). This distinction underscores the need to address gender-specific pathways in understanding suicide attempts. Climate-induced stressors, such as economic instability, loss of livelihood, and displacement, may disproportionately impact men. The traditional expectation for men to be primary economic providers intensifies the psychological burden of these challenges, potentially exacerbating their vulnerability to suicide attempts. Meanwhile, women's higher rates of suicidal ideation may reflect chronic psychological distress, but their coping strategies and access to stronger social support networks may act as a buffer, preventing the progression to attempts (52, 53).

4.4 Suicide deaths

Data from 13 studies involving 51,260 male and 35,029 female participants revealed a higher prevalence of suicide deaths among males, at 14.2% (95% CI: 13.86–14.67), compared to females, at 9.3% (95% CI: 9.02–9.63). This gender disparity aligns with well-documented epidemiological trends, wherein men are more likely to complete suicide than women.

The heightened risk for males may be attributed to societal norms that emphasize economic provision and stoicism. During climate-induced crises, such as economic instability or resource scarcity, these expectations can intensify psychological stress, potentially leading to an increased likelihood of suicide deaths (54). Men may also experience barriers to seeking emotional or psychological support, contributing to the accumulation of unaddressed distress and a higher risk of fatal outcomes. Additionally, the physiological effects of extreme climate events, such as heatwaves, which exacerbate mental health conditions, may further amplify risks among vulnerable male populations.

In contrast, women, while facing significant psychological burdens due to climate change, often exhibit lower suicide death rates. This may be partly explained by their higher likelihood of seeking social and psychological support, as well as their reliance on established coping mechanisms during crises (55). Women's caregiving roles, however, introduce unique stressors, as they are frequently tasked with ensuring family safety and wellbeing during extreme weather events or periods of environmental degradation. These responsibilities can lead to heightened anxiety, emotional distress, and burnout (56). Furthermore, women frequently serve as central figures in disaster response and recovery efforts, both formally and informally, exposing them to trauma and the emotional suffering of others. While this exposure increases their risk of anxiety and depression, it may also enable them to provide emotional support to others, creating a dual role that acts as both a stressor and a protective factor (57).

These findings underscore the complex interplay of gender, societal expectations, and climate-induced stressors in shaping suicide death outcomes. For men, fostering a culture that encourages emotional expression and provides accessible mental health resources may help reduce the risk of suicide deaths. For women, strengthening support networks and addressing the added caregiving and emotional burdens imposed by climate crises are essential for mitigating mental health challenges.

4.5 Self-harm

Our analysis of six studies involving 28,466 male and 41,052 female participants revealed a higher prevalence of self-harm among females, 20.5% (95% CI: 20.09–20.87), compared to males, 16.3% (95% CI: 15.85–16.71). This gender difference likely reflects variations in emotional regulation and social expectations. Women, often carrying the dual burdens of caregiving and societal pressures, may internalize climate-induced stressors differently from men, leading to heightened rates of self-harm. In contrast, males, who are more prone to externalizing behaviors under stress, exhibit higher rates of suicide attempts and deaths, indicating a divergence in behavioral responses to similar environmental triggers.

Climate-induced factors, such as extreme heat, play a prominent role in self-harm. Unlike suicidal behaviors, which may be driven by cumulative despair, self-harm is often linked to acute triggers, such as physiological stress and heightened impulsivity during heatwaves (58). Prolonged exposure to high temperatures exacerbates emotional dysregulation and diminishes coping reserves, increasing vulnerability to self-harming acts. These patterns differ from the broader existential despair observed in suicide deaths, where chronic environmental degradation and socioeconomic instability are often primary drivers (59). Rapid weather changes, including abrupt temperature shifts or prolonged rainfall, disrupt daily routines and intensify feelings of instability. For individuals with pre-existing mental health conditions, this instability amplifies psychological distress, triggering self-harm behaviors. Unlike suicide attempts, which often reflect a direct response to acute crises, self-harm can arise from persistent emotional dysregulation fostered by unpredictable climate patterns (60). Seasonal patterns further illuminate the distinct relationship between self-harm and climate change. Seasonal affective disorder (SAD), linked to reduced sunlight in winter, is associated with depressive episodes that elevate self-harm risk (61). As climate change alters seasonal cycles, the severity and timing of SAD-related self-harm may intensify, marking a divergence from other suicide-related outcomes that are less influenced by seasonal variability (62). This highlights the need for context-specific mental health interventions that address seasonal impacts.

In summary, self-harm represents a unique behavioral response to climate stressors, distinct from suicidal ideation, attempts, and deaths in its etiology and manifestation. While self-harm often serves as a maladaptive coping strategy for managing emotional distress, its prevalence and triggers differ significantly across genders and environmental contexts.

4.6 Anxiety

The inclusion of anxiety in this analysis reflects its critical role in understanding the full spectrum of climate change's impact on mental health. Unlike suicide-related outcomes, which are often the culmination of extreme psychological distress, anxiety represents an early and pervasive response to environmental stressors. By addressing anxiety as a distinct yet interconnected mental health outcome, this study highlights its significance as both a standalone condition and a precursor to more severe outcomes, such as suicidal ideation and attempts. This approach ensures a comprehensive examination of climate change's multifaceted effects on mental wellbeing.

The analysis, incorporating data from 12 studies with 70,978 male and 77,270 female participants, reveals a higher prevalence of anxiety among females (34.2%; 95% CI: 33.83–34.49) compared to males (29.8%; 95% CI: 29.43–30.11). This gender disparity aligns with existing literature suggesting that women, who often bear greater caregiving responsibilities and face heightened socio-economic vulnerabilities, are disproportionately affected by climate-related stressors (63). These findings underscore the importance of addressing gender-specific dynamics in mental health responses to climate change.

Anxiety's relationship with climate change is mediated by various pathways. Extreme weather events, such as hurricanes, floods, and wildfires, trigger immediate psychological responses, including fear and heightened alertness, which can persist as chronic anxiety about future occurrences. This sustained hypervigilance, often referred to as "disaster anxiety," can escalate into generalized anxiety disorder if unaddressed (64). Additionally, temperature extremes exacerbate anxiety symptoms, with high temperatures contributing to physical discomfort and health issues like dehydration, while low temperatures increase isolation and reduce social interaction, both of which amplify psychological distress (65). "Eco-anxiety," a term describing chronic anxiety about environmental degradation, further exemplifies the profound impact of climate change on mental health (66). This condition manifests as persistent worry about the planet's future, driven by witnessing environmental destruction and the perceived inadequacy of responses to climate challenges (67). For individuals with strong connections to nature, the degradation of natural environments represents a profound emotional loss, intensifying feelings of helplessness and despair. This unique form of anxiety, while distinct, often intersects with broader mental health outcomes by eroding resilience and increasing vulnerability to severe psychological conditions.

Social and economic disruptions caused by climate change, such as rising sea levels, agricultural failures, and competition for resources, further exacerbate anxiety levels. Vulnerable populations, particularly those in poverty or with limited access to resources, are disproportionately affected, experiencing heightened uncertainty and chronic stress (68). These socio-economic stressors not only amplify anxiety but also create conditions that may lead to more severe outcomes, such as suicidal ideation or attempts (69).

By contextualizing anxiety within the broader framework of climate change-induced mental health outcomes, this analysis emphasizes its interconnectedness with suicide-related behaviors. Anxiety often serves as a gateway condition, with chronic, unmanaged distress potentially escalating to self-harm or suicide in vulnerable individuals. Addressing anxiety at this early stage offers an opportunity to intervene and mitigate progression to more severe psychological outcomes, reinforcing the importance of including anxiety as a critical focus in climate-related mental health research and interventions.

4.7 Mitigating climate-induced mental health crises

Addressing the mental health impacts of climate change requires a comprehensive approach, integrating prevention and intervention strategies to mitigate the associated risks of suicidal ideation, suicide attempts, suicide deaths, self-harm, and anxiety. Early identification and regular screening of at-risk populations are essential. Healthcare providers should employ standardized screening tools during routine medical visits and community health programs to detect early signs of mental health issues (70). Ensuring accessible mental health services, especially in regions most affected by climate change, is critical. Telemedicine can extend the reach of counseling and psychiatric care to remote or underserved areas, offering timely support (71). Strengthening community resilience through social cohesion programs and mutual support initiatives, such as peer support groups and mental health workshops, can significantly aid individuals in coping with climate-induced psychological stressors (72). Public education campaigns are necessary to raise awareness about the mental health impacts of climate change and the importance of seeking help. These campaigns should aim to destigmatize mental health issues and encourage proactive management. Integrating mental health considerations into climate policies and disaster response plans ensures that mental health services are included in emergency relief and long-term recovery efforts (73). Healthcare providers require specialized training to address the mental health impacts of climate change effectively. This training should cover trauma-informed care and the specific needs of climate-affected populations. Gender-specific interventions are also crucial, as women and men experience different mental health impacts from climate change. Support programs tailored to these needs can significantly reduce the rates of anxiety, self-harm, and suicidal behavior. Providing economic support and reducing social vulnerabilities can alleviate the stress exacerbated by climate change, thus mitigating mental health crises. Policies that offer financial assistance, job security, and housing stability are essential (17, 74, 75). Engaging communities in environmental stewardship activities can enhance mental wellbeing by fostering a sense of purpose and connection (76). Lastly, developing robust crisis intervention strategies, including hotlines, mobile crisis units, and rapid response teams, ensures immediate support during climate-related emergencies (77).

5 Limitations

This study presents a systematic review of the global literature on the mental health impacts of climate change, highlighting significant gender-specific differences. The methodology is rigorous, covering a wide range of databases and strictly adhering to PRISMA guidelines to ensure the inclusion of high-quality studies. Nevertheless, several limitations should be acknowledged. First, reliance on self-reported data may introduce biases, as individuals could underreport or over report mental health symptoms. Additionally, the variability in climate conditions and socio-economic contexts across different regions may affect the generalizability of the findings. A significant limitation of this study is the exclusion of non-English publications, potentially overlooking relevant research from certain regions where climate change impacts and mental health responses may differ. Furthermore, there is considerable heterogeneity in outcomes related to suicidal ideation, suicide attempts, and self-harm, largely due to variations in definitions and measurement methods across studies. This heterogeneity could lead to inconsistencies in the observed mental health impacts of climate change. Lastly, while the gender-specific analysis provides important insights, this review does not fully explore other demographic factors, such as age, socio-economic status, and cultural background, which also shape mental health responses to climate change.

6 Conclusions

This systematic review and meta-analysis highlight the significant gender-specific mental health impacts of climate change. Our findings indicate that females are more likely to experience anxiety, self-harm, and suicidal ideation, while males show higher rates of suicide attempts and deaths. These gender disparities reflect distinct psychological responses to climate stressors. Females, who often bear additional caregiving responsibilities and are more vulnerable economically during extreme weather events, appear to be more susceptible to chronic psychological distress. In contrast, males, influenced by societal expectations to be stoic and financially responsible, exhibit higher rates of extreme behaviors, such as suicide attempts and deaths, under acute stress.

The results underscore the need for targeted mental health interventions that consider these gender-specific vulnerabilities. While both genders are deeply affected by climate change, their coping mechanisms and the risks they face differ considerably. Future research should continue to focus on the mechanisms behind these gender differences, particularly the role of societal norms, caregiving burdens, and access to mental health resources in shaping responses to climate-induced stress. Addressing these differences will be essential in crafting effective mental health strategies in the face of ongoing climate change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

D-DC: Conceptualization, Methodology, Writing – original draft. J-HT: Data curation, Validation, Writing – original draft, Writing – review & editing. K-NL: Data curation, Formal analysis, Writing – original draft. X-HJ: Supervision, Writing – original draft. H-YH: Project administration, Writing – original draft.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by Nantong Municipal Health Commission Mandatory Subject Surface Project (No. MS2022010).

Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1463676/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Meta-analysis of suicidal ideation: **(A)** Forest diagram illustrating the aggregated odds ratios; **(B)** Sensitivity analysis chart for the included research; **(C)** Funnel diagram to assess potential publication biases.

SUPPLEMENTARY FIGURE 2
Meta-analysis of Suicide attempts: **(A)** Forest diagram illustrating the aggregated odds ratios; **(B)** Forest plot of combined odds ratios (analyzed by continent); **(C)** Forest plot of combined odds ratios (analyzed by study design); **(D)** Forest plot of combined odds ratios (analysis by type of weather); **(E)** Sensitivity analysis chart for the included research; **(F)** Funnel diagram to assess potential publication biases.

SUPPLEMENTARY FIGURE 3
Meta-analysis of suicide deaths: **(A)** Forest diagram illustrating the aggregated odds ratios; **(B)** Forest plot of combined odds ratios (analyzed by continent); **(C)** Forest plot of combined odds ratios (analyzed by study design); **(D)** Forest plot of combined odds ratios (analysis by type of weather); **(E)** Sensitivity analysis chart for the included research; **(F)** Funnel diagram to assess potential publication biases.

SUPPLEMENTARY FIGURE 4
Meta-analysis of self-harm: **(A)** Forest diagram illustrating the aggregated odds ratios; **(B)** Sensitivity analysis chart for the included research; **(C)** Funnel diagram to assess potential publication biases.

SUPPLEMENTARY FIGURE 5
Meta-analysis of anxiety: **(A)** Forest diagram illustrating the aggregated odds ratios; **(B)** Forest plot of combined odds ratios (analyzed by continent); **(C)** Forest plot of combined odds ratios (analyzed by study design); **(D)** Forest plot of combined odds ratios (analysis by type of weather); **(E)** Sensitivity analysis chart for the included research; **(F)** Funnel diagram to assess potential publication biases.

SUPPLEMENTARY TABLE 1
Search strategy.

SUPPLEMENTARY TABLE 2
Newcastle-Ottawa scale.

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frontiers | Frontiers in Public Health

TYPE Original Research
PUBLISHED 09 January 2025
DOI 10.3389/fpubh.2024.1423698

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OPEN ACCESS

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RECEIVED 26 April 2025
ACCEPTED 26 December 2024
PUBLISHED 09 January 2025

CITATION
Chen C, Li M, Peng F, Lv D, Ding X, Tian C, Ren W, Meng X, Sun T, Wang Y, Du H, Wu F, Li W and Wang P (2025) Correlation between night sweats and season fluctuation in China. *Front. Public Health* 12:1423698.
doi: 10.3389/fpubh.2024.1423698

Correlation between night sweats and season fluctuation in China

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Background: Night sweats are a condition in which an individual sweats excessively during sleep without awareness, and stops when they wake up. Prolonged episodes of night sweats might result in the depletion of trace elements and nutrients, affecting the growth and development of children.

Purpose: To investigate the relationship between sweat nights and season.

Method: The Internet search index for night sweats in Zhengzhou, China was obtained from the Baidu index during 2011–2022. Meteorological factors, including ambient temperature, humidity, pressure, precipitation and average wind speed in Zhengzhou were obtained from the website https://en.tutiempo.net/climate. A time series decomposition model was used to study the relationship between night sweats and seasonality. Continuous wavelet transform and cross wavelet transform were utilized to explore the relationship between night sweats and meteorological factors.

Result: A typical periodic pattern is evident in the seasonal trend. Specifically, following a peak in January each year, there is a rapid decline followed by a secondary peak, after which a trough occurs. The search index of night sweats increased rapidly in the first stage, slowed down in the second stage, and showed negative growth from 2011 to 2014. The correlation coefficients between the search index for night sweats and atmospheric pressure as well as average temperature, are 0.25 and-0.26, respectively.

Conclusion: Night sweat was connected with season. Specifically, the number of night sweat search index increased in the cold season and declined in the summer season. Night sweat was negatively connected with temperature but favorably correlated with air pressure.

KEYWORDS

night sweat, season, Internet search index, Baidu index, time series decomposition, wavelet transform

1 Introduction

Night sweats occur when someone sweats excessively while sleeping and stops when they wake up (1). The defining feature of this condition is a significant rise in sweating during overnight sleep, which stops once the individual awakens, as if perspiration had sneakily emerged while the person was oblivious. Persistent sweating at night could lead to significant

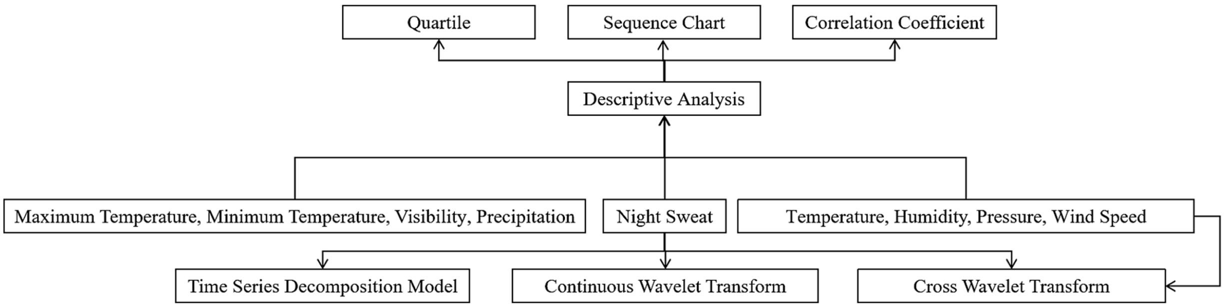

FIGURE 1
A flow chart of methodology.

loss of water and electrolytes, such as sodium, potassium, and magnesium, which are vital for maintaining overall health and normal physiological functions. Prolonged episodes of night sweats might result in the depletion of trace elements and nutrients, affecting the growth and development of children and reducing the physical fitness and immunity levels in adults. Night sweat often disrupt sleep, causing individuals to wake up frequently, which affects the continuity and depth of their sleep (2). Over time, this could end up in issues such as fatigue, lethargy, difficulty concentrating, and memory loss. James W Mold et al. found that night sweats were linked with daytime fatigue (OR = 1.99, 95% CI: 1.12–3.53), and waking pain at night (OR = 1.87, 95% CI:1.16–2.99) (2). Retrospective review based on two sleep laboratories in Oklahoma City showed that compared with those who did not report night sweats, patients with night sweats were more likely to suffer from daytime fatigue ($p = 0.001$), snoring ($p = 0.003$), and breathing trouble ($p < 0.0001$) (3). Night sweats could be an indication of underlying health conditions such as tuberculosis (4), hyperthyroidism (5), coronary heart disease (6) and climacterium (7).

A systematic review of the literature revealed that in older adult primary care patients, the prevalence of night sweats was 10%, while in obstetric inpatient wards, the prevalence among women was 60% (8). As for children, the study by So HK et al. found that among 6,381 children (with a median age of 9.2 years, ranging from 7.7 to 10.7 years), 3,225 were boys (50.5%) (9). Within the past 12 months, 747 children (11.7%) experienced night sweats weekly, and boys were more likely to have night sweats than girls.

A cross-sectional study found that 10% of 795 primary care patients reported having experienced night sweats and perceived a correlation between night sweats and factors such as age, muscle spasms, and numbness in their hands and feet (10). A longitudinal study involving 11,725 women found that 7% of the population reported experiencing frequent night sweats, and this subgroup had over double the likelihood of developing coronary heart disease, with an odds ratio (OR) of 2.38 and a 95% confidence interval (CI) ranging from 1.62 to 3.50 (6).

With the rapid advancement of internet technology and mobile internet, as well as a significant increase in public health awareness, a growing proportion of people seek relevant information online when they experience illness or suspected symptoms, with the goal of understanding the causes of their conditions, finding treatment methods, accessing drug information, or seeking medical advice. For example, when a symptom such as "night sweats" shows frequently in people's search queries, the Baidu Index produces related search trends. The Baidu Index largely reflects the level of attention internet users devote to keyword search patterns on the Baidu search engine, allowing us to better understand how certain phrases, such as "night sweats" change over time, including seasonal swings. In theory, by studying differences in the search volume for the keyword "night sweats" throughout different seasons on the Baidu Index, one might indirectly determine whether public interest in night sweats rises or falls with the seasons. Right now, there is no concrete evidence linking night sweat to season. In this study, we made use of Baidu Index data to investigate the relationship between night sweats and seasonal changes.

2 Method

Figure 1 depicts the experimental approach used in this investigation. First, a descriptive analysis is performed on the search index for night sweats and climatic parameters, which includes correlation coefficients and time series line charts. Second, a time series decomposition model is used to investigate the seasonal changes in night sweats. The autocorrelation of night sweats is analyzed using a continuous wavelet transform. The cross-wavelet transform is used to investigate the relationship between night sweats and temperature, humidity, air pressure, and wind speed.

2.1 Data

Internet search index for night sweats was from Baidu index.[1] Baidu Index is a data analysis platform established by the Baidu search engine that utilizes huge volumes of user behavior data. It enables users to analyze keyword search trends and acquire insights into internet users' interests and demands. However, due to the popularity of the Baidu search engine in China, research related to the Baidu Index is only available in China. In our early research, we used the Baidu Index to generate a search map for asthma in China and investigate the association between snoring and seasons (11, 12). This illustrates that it is possible to conduct disease dispersion studies using search engine data.

Keyword 'night sweats' was typed into the main interface of Baidu Index, and then the research region was setting to all the country, and

1 http://index.baidu.com

research period was setting from 2011 January to December 2022. Also, in order to investigate the relationship between night sweat and meteorological factor, including ambient temperature, maximum temperature, minimum temperature, visibility, humidity, pressure, precipitation and average wind speed, Zhengzhou capital of Henan province, China, was selected as research area. Internet search index about night sweat in Zhengzhou was collected from Baidu Index from 2011 to 2022. Contemporaneous meteorological factors in Zhengzhou were obtained from the website https://en.tutiempo.net/climate.

2.2 Time series decomposition model

A time series decomposition model was used to study the relationship between night sweat and seasonality, as shown in Equation 1 (13).

$$Y_t = T_t + S_t + E_t \tag{1}$$

Here, Y_t represents the time series data, which in our study is the Internet search index for night sweat from Baidu index. T_t, S_t, and E_t denoted the time trend, seasonal trend, and random variable, respectively. Time series decomposition models was consist of two inner loops and one outer loop. The inner loops were primarily used for decomposing the trend component and the seasonal component of the time series data. The inner loop was calculated as follows (14, 15).

(1) Remove the trend

The trend component T_t^{trend} from the previous iteration $\mathrm{T_t^k}$ was removed from the time series data (Equation 2).

$$\mathrm{T_t^{trend}} = \mathrm{Y_t} - \mathrm{T_t^k} \tag{2}$$

Where k represents the k-th iteration.

(2) Seasonal smoothing

LOESS smoother was used to smooth the periodic series $\mathrm{T_t^{trend}}$ to obtain the initial seasonal component S_t^{k+1}.

(3) Low-pass filtering

A low-pass filtering was used to smooth the periodic series S_t^{k+1} to compute S'^{k+1}_t and LOESS smoother were utilized to smooth the S'^{k+1}_t to obtain $\mathrm{T'^{k+1}_t}$.

(4) Seasonal component

Seasonal component S_t^{k+1} was obtained according to Equation 3.

$$S_t^{k+1} = S'^{k+1}_t - \mathrm{T'^{k+1}_t} \tag{3}$$

(5) Deseason. A seasonally adjusted component $S_t^{de-season}$ was calculated according to Equation 4.

$$S_t^{(de-season)} = Y_t - S_t^{(k+1)} \tag{4}$$

(6) Trend smoothing.

A LOESS smoother was used to smooth the $S_t^{de-season}$ obtained in Step (5) to get trend trend component T_t^{k+1}.

During the outer loop process, the random variable is calculated as follows according to Equation 5.

$$E_t^{k+1} = \mathrm{Y_t} - \mathrm{S_t^{k+1}} - T_t^{k+1} \tag{5}$$

2.3 Wavelet transform

Wavelet transforms are extremely useful in the study of medical time series data, particularly when dealing with non-stationary, complicated dynamic properties, and weak signals. They have been widely employed in various medical time series analyses, such as electrocardiogram analysis, sleep staging, and epilepsy prediction. In this work, nocturnal sweat data is fundamentally a time series signal; thus, wavelet analysis is used to predict disease cycles and analyze condition-related variables.

2.3.1 Continuous wavelet transform

The definition of wavelet basis function is shown in Equation 6. $\psi_{a,b}(t)$ is the continuous wavelet basis function obtained by scaling and translation, where a is the scale factor and b is the scale translation factor (16, 17).

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right), a > 0, b \in R \tag{6}$$

Continuous wavelet transform is defined as Equation 7. $\mathrm{WT_x}(\mathrm{a,b})$ represents

$$\mathrm{WT_x}(\mathrm{a,b}) = \frac{1}{\sqrt{\mathrm{a}}}\int \mathrm{x}(\mathrm{t})\overline{\psi}\left(\frac{\mathrm{t-b}}{\mathrm{a}}\right)\mathrm{dt} \tag{7}$$

$\mathrm{WT_x}(\mathrm{a,b})$ is the continuous wavelet transform result of $\mathrm{x(t)}$, and $\mathrm{x(t)}$ is the Internet search index data of night sweats in this study. As shown in Equation 7, the one-dimensional time series signal can be transformed into a two-dimensional signal in time-frequency domain by wavelet transformation. The signal's time-frequency analysis could be performed by modifying the stretching factor (a) and transfer factor (b).

2.3.2 Cross wavelet transform

The cross wavelet spectrum between two time series x(t) and y(t) can be defined as Equation 8 (18, 19), where $C_x(\alpha,\tau)$ is the wavelet transform coefficient of the sequence x(t), and $C_y^*(\alpha,\tau)$ is the complex conjugate of the wavelet transform coefficient of the sequence y(t). The cross wavelet spectrum can reflect the region where the periodic intensity of two sequences is consistent, allowing users to determine the degree of correlation between the two sequences in several simultaneous frequency domains.

$$W_{xy}(\alpha,\tau) = C_x(\alpha,\tau) * C_y^*(\alpha,\tau) \tag{8}$$

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3 Result

3.1 Descriptive results

Figure 2 illustrates Internet search data for night sweats from January 2011 to December 2022 sourced from Baidu Index. The green line depicts the raw data, while the red line represents the smoothed data. The graph shows that the search index about night sweats grew in September or October and peaked in February or March of the following year. The search index thereafter began to fall, troughing from June to October with some regularity. The raw data (green) increased dramatically in December 2022 (during the COVID-19 pandemic in China). From 2014 to 2020, there will be twin peaks every year. The peak for 2019–2021 is smaller than that of 2020.

Figure 3 demonstrates the geographical distribution of the search index for night sweats in various provinces between 2011 and 2022. In 2011, there was little attention paid to night sweats across the country; from 2011 to 2015, interest progressively increased; however, in 2015 and beyond, people's attention to night sweats peaked. Night sweats are often more of a worry in economically developed communities along the eastern coast than in the inland. Sichuan Province (in southwest China's heartland) is more worried about night sweats than other inland locations. Southern Chinese provinces are more worried about night sweats than northern ones.

Figure 4 describes the growth of the Internet search index for night sweats in three phases: 2011 to 2014, 2014 to 2018, and 2019 to 2022. In general, the search index of night sweats increased rapidly in the first stage, slowed down in the second stage, and showed negative growth in the third stage. As shown in Figure 4A,

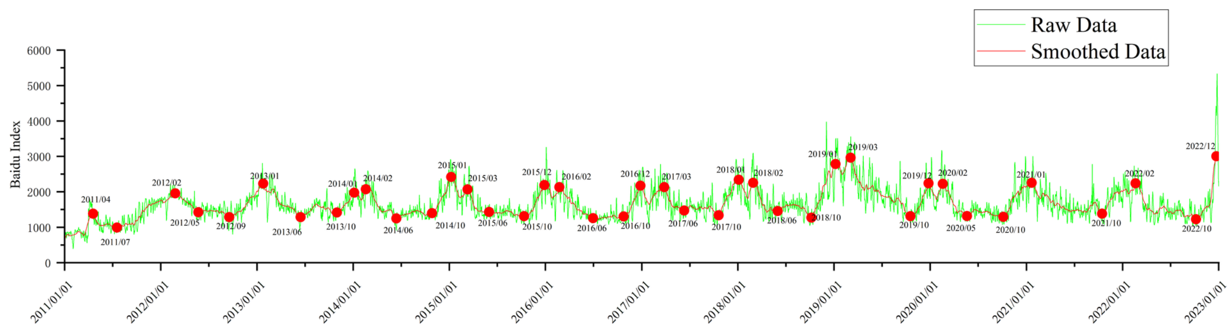

FIGURE 2
Internet search data for night sweats from January 2011 to December 2022 (green line, raw data; red line, smooth data).

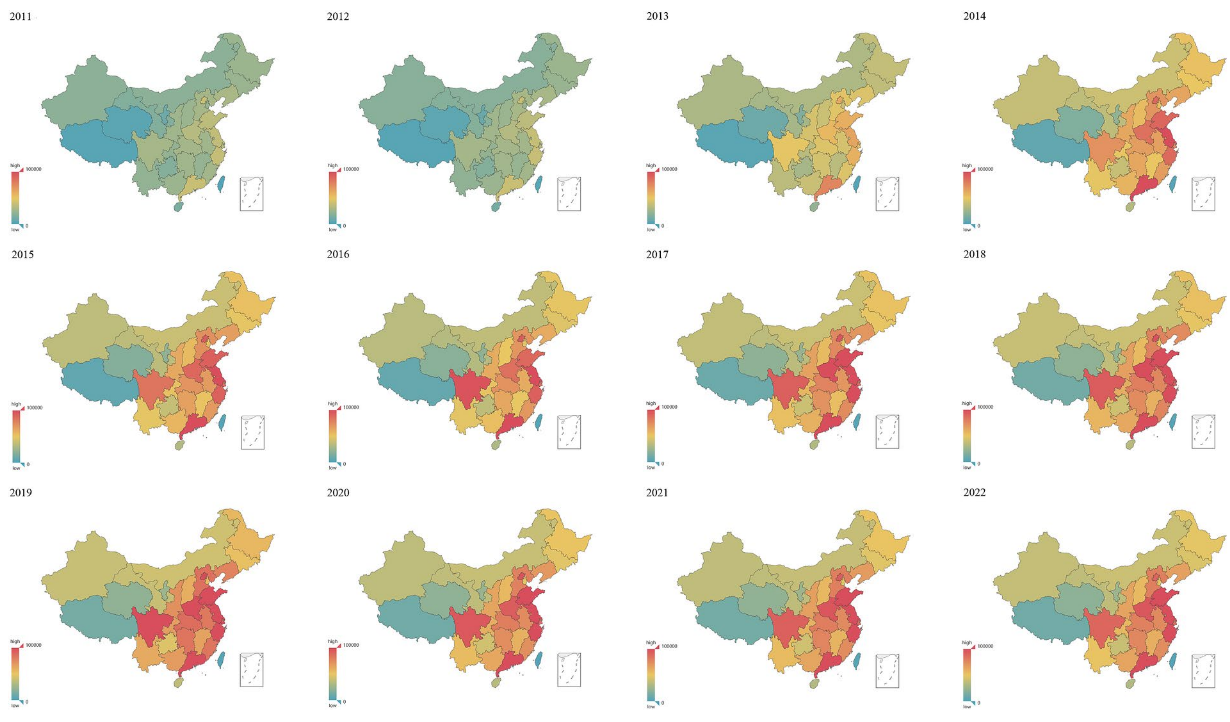

FIGURE 3
Geographical distribution of the search index for night sweats in China between 2011 and 2022.

during the first stage(from 2011 to 2014), the Internet search index for night sweats in Qinghai, Guangzhou, and Jiangsu provinces demonstrated the most rapid growth, with respective growth rates of 3, 2.06, and 1.8, respectively. During the second stage (from 2015 to 2018), the Internet search index growth for night sweats in Tibet, Henan, Qinghai, and Zhejiang provinces was the fastest, respectively, showing increases of 0.97, 0.22, 0.2, and 0.2, respectively. As for the third stage, the growth rate of all provinces about night sweats in the country was negative.

Table 1 shows the descriptive results of the Internet search index about night sweats and ambient temperature, humidity, atmospheric pressure, average wind speed and precipitation in Zhengzhou from 2011 to 2022. Maximum ambient temperature, precipitation and atmospheric pressure were 35.7°C, 188.72 mm, and 1045.6 hPa. Figure 5 depicts the correlation coefficients between the night sweat search index and meteorological factors. The correlation coefficients between the night sweat search index and humidity, precipitation, air pressure, average temperature, maximum temperature, minimum temperature, visibility, and average wind speed are distributed as follows: −0.09, −0.03, 0.25, −0.26, −0.25, −0.28, 0.05, and 0.05, respectively. Figure 6 illustrates a time series plot from 2011 to 2022 for the night sweat search index (Figure 6A), ambient temperature (Figure 6B), humidity (Figure 6C), atmospheric pressure (Figure 6D), average wind speed (Figure 6E) and precipitation (Figure 6F) in the Zhengzhou. Temperature, humidity and night sweat search index all showed periodic changes, and the trend of temperature and night sweat search index is opposite.

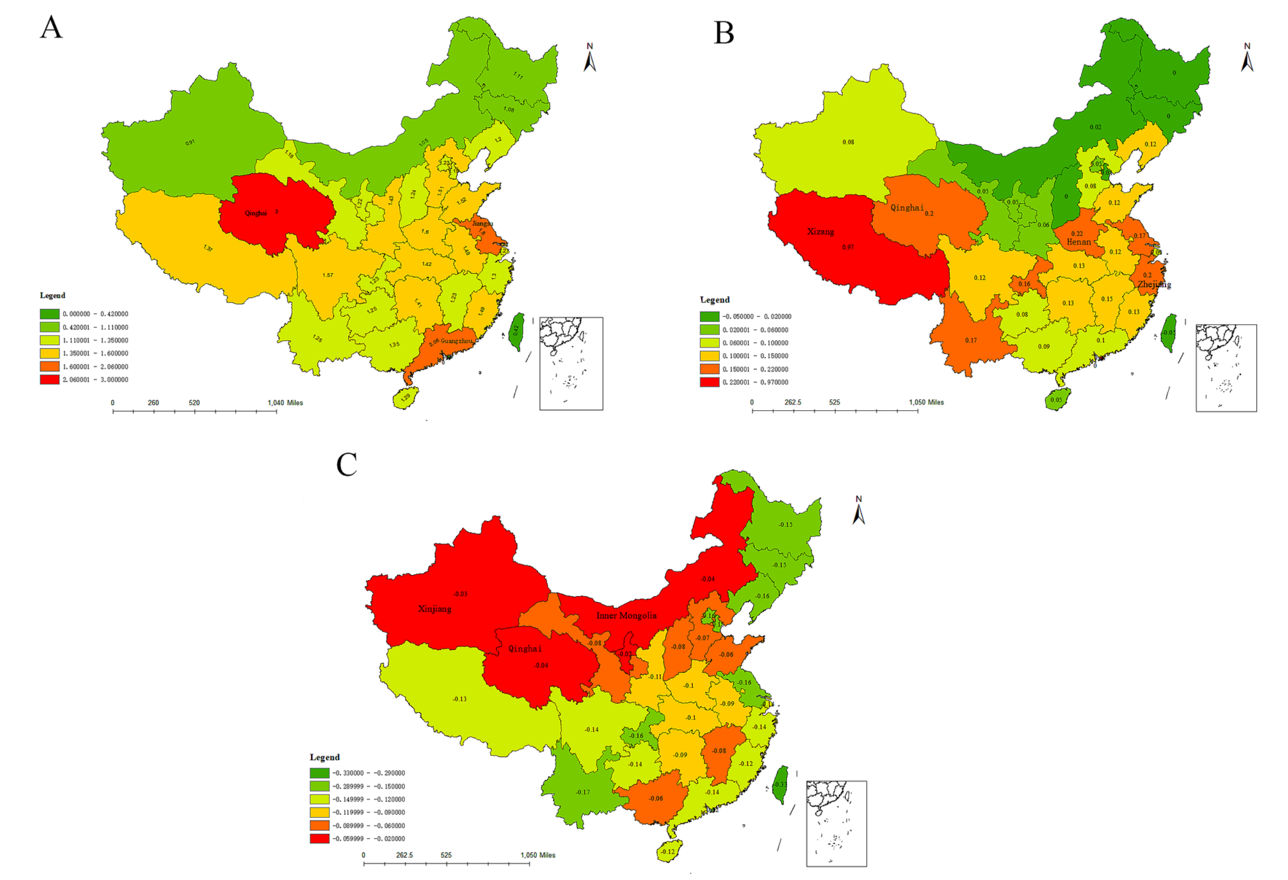

FIGURE 4
Growth of internet search index for night sweats (**A** from 2011 to 2014; **B**, from 2015 to 2018; **C**, from 2019 to 2022).

TABLE 1 Descriptive results of the internet search index about night sweats and meteorological factors from 2011 to 2022.

	Temperature	Pressure	Humidity	Precipitation	Wind speed	Index
Min	−5.9	995.5	13	0	2.8	0
Q1	7.2	1007.725	43	0	6.5	92
Q2	16.7	1017.1	59	0	8.3	153
Q3	24.9	1025.175	73	0	10.7	185
Max	35.7	1045.6	102	188.72	31.1	422

Index, Baidu index for night sweats.

3.2 Result of time series decomposition

The results of the time series decomposition model are shown in Figure 7. Figure 7A depicts the overall time series change of night sweats from 2011 to 2022. Time series decomposition models decompose the series into long-term trend (Figure 7B), random variables (Figure 7C), and seasonal trends (Figure 7D). From 2017 to 2019, the basic trend exhibited an upward trajectory before experiencing a sharp drop to around 5,000 in 2019. The index generally fluctuated around a baseline value of approximately 5,000 during other periods. In 2019, a sudden

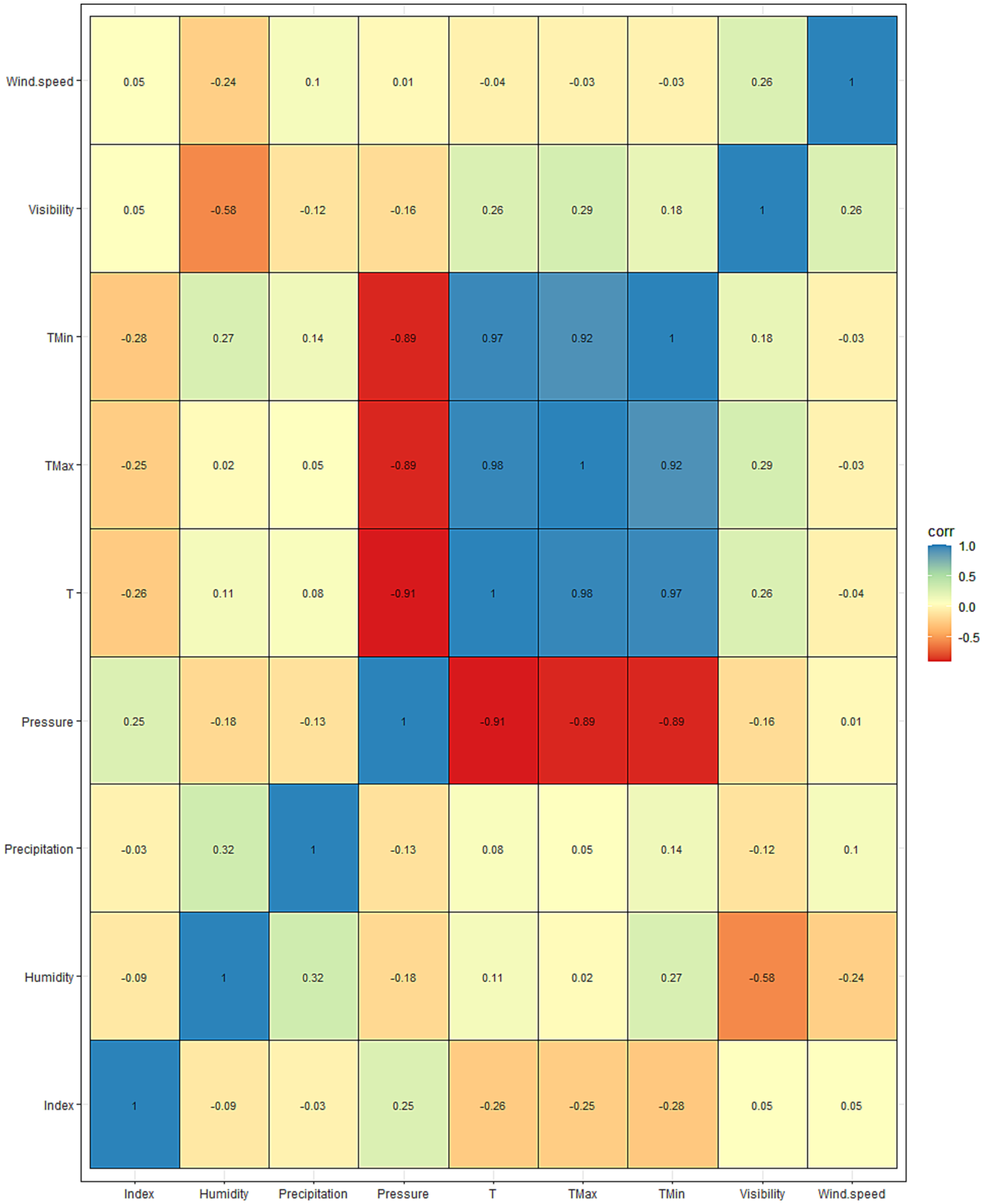

FIGURE 5
Correlation coefficients between the night sweat search index and meteorological factors (index, Internet search index for night sweat; T, daily average temperature; Tmax, maximum daily temperature; Tmin, minimum daily temperature).

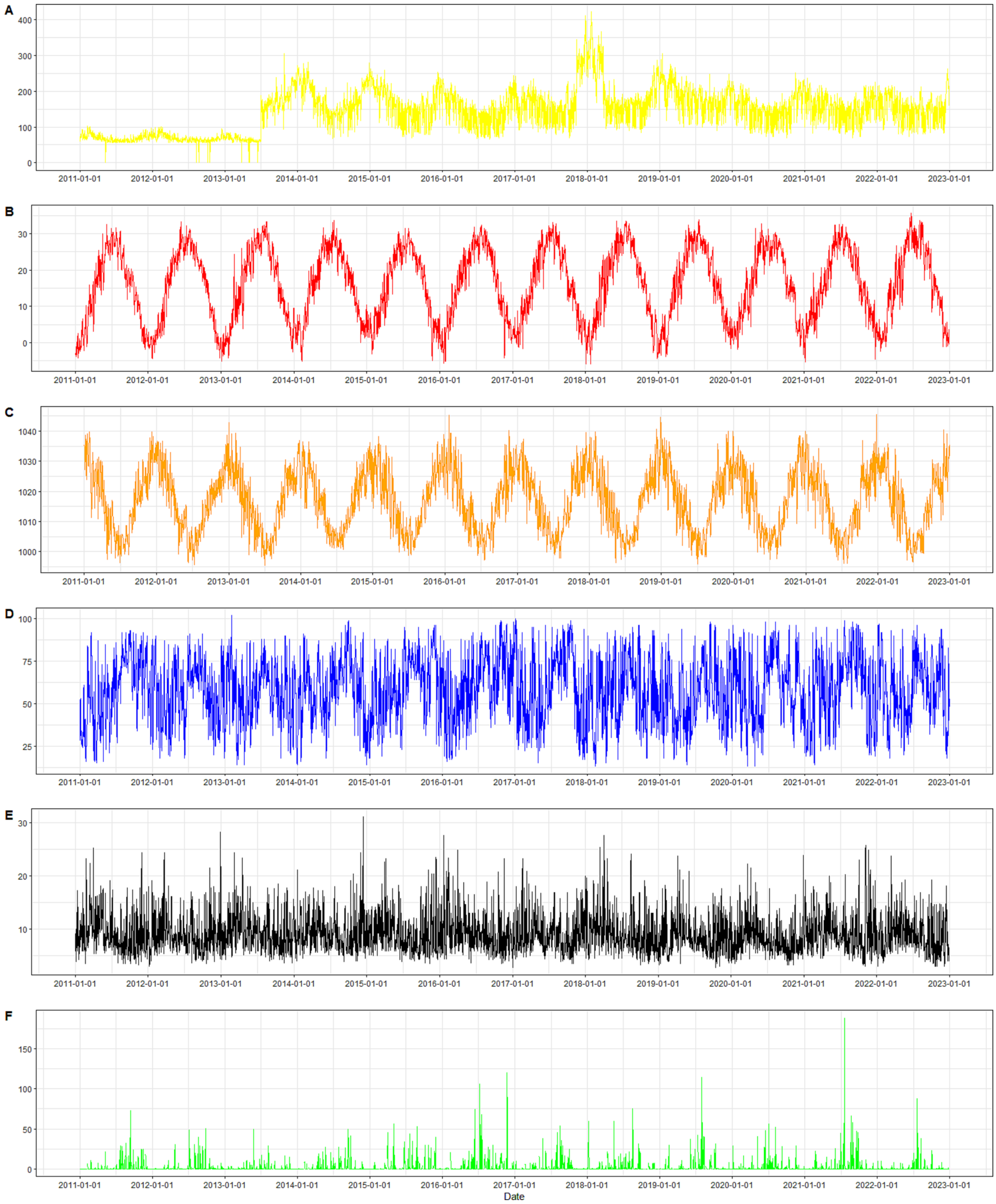

FIGURE 6
Time series plot from 2011 to 2022. **(A)** The night sweat search index; **(B)** ambient temperature; **(C)** humidity; **(D)** atmospheric pressure; **(E)** average wind speed; **(F)** precipitation.

elevation occurred in the random variable, causing interference in the waveform of the time series data (Figure 7C). As shown in Figure 7D, a typical periodic pattern is evident in the seasonal trend. Specifically, following a peak in January each year, there is a rapid decline followed by a secondary peak, after which a trough occurs.

3.3 Wavelet transform

The results of the continuous wavelet transform for the night sweat search index are presented in Figure 8. The horizontal axis represents days, with January 1, 2011 designated as day 1 and

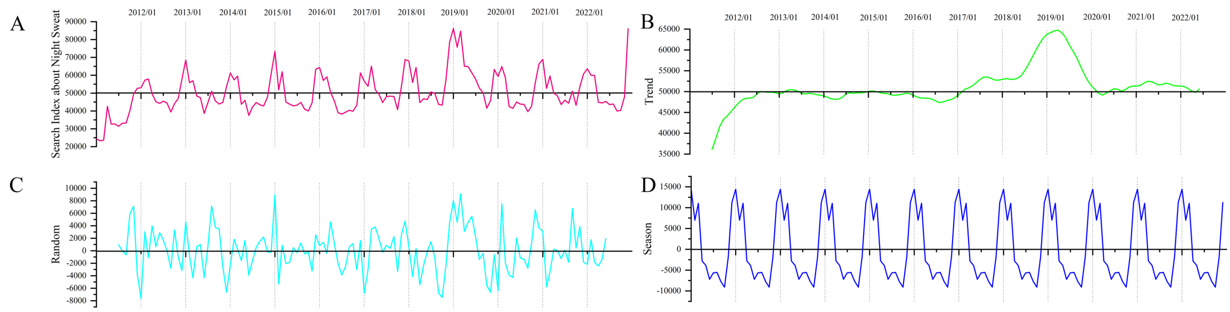

FIGURE 7
Results of the time series decomposition model. **(A)** Internet search index for night sweat; **(B)** long-term trend; **(C)** random variables; **(D)** random variables.

December 31, 2022 as day 4,383. The vertical axis denotes the period, and colors closer to yellow indicate higher energy levels. From the figure, a concentration of yellow energy is observed around a period of approximately 365 on the vertical axis, suggesting the presence of a 365-day oscillatory pattern. Figure 9 illustrates the cross-wavelet spectrum of the night sweat index against humidity, air pressure, wind speed, and temperature. The black lines represent the influence cones, within which lies the region of effective spectral values. The thick black outline indicates the boundary of the 95% confidence interval. The arrow to the right indicates the same direction change with a positive correlation. The arrow to the left indicates the opposite change, the negative correlation. As shown in Figure 9B, the arrows pointed to the right, which means that air pressure was positively correlated with the search index for night sweats. On the opposite, the arrows pointed to the left in Figure 9D, which means that ambient temperature was negatively associated with the search index for night sweats.

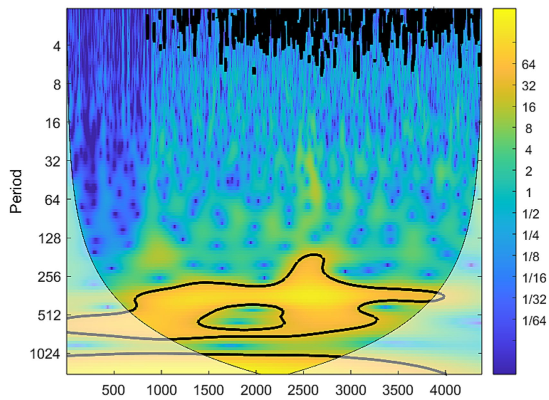

FIGURE 8
Continuous wavelet transform for the night sweat search index (black line, 95% confidence interval).

4 Discussion

Based on the night sweats search index and the time series decomposition methodology, we observed that night sweats were seasonal. The number of search index for night sweats grew in the cold season but decreased in the summer. Furthermore, cross-wavelet analyses revealed that night sweat was adversely associated to temperature but positively related to air pressure.

We suspect the following factors may be involved. Sweating control is complicated, involving both thermoregulatory and nonthermoregulatory systems. When the core body temperature rises above a certain limit or threshold, perspiration helps to bring it down (8). When a core body temperature threshold is reached, a hypothalamus response is triggered, which activates thermoregulatory mechanisms such as sweating (20, 21). This might happen as a result of decreased external heat exposure or heat dissipation (for example, too much clothes or bed cover) or increased heat generation (for example, excessive muscle activity). In the winter, individuals typically utilize heating equipment such as heaters and electric blankets to stay warm, resulting in much higher inside temperatures than outdoor temperatures. Excessive indoor temperatures may make it difficult for the body to release heat while sleeping, and the thermoregulatory mechanism activates the sweating response to reduce body temperature, resulting in night sweats. Furthermore, wearing heavy clothing and warm bedding in the winter can easily raise the skin's surface temperature above the comfort threshold, and the human body excretes surplus heat through sweating, contributing to nocturnal sweats.

Our findings contradict another finding. A study of the relationship between temperature, season, lifestyle and experiences of hot flashes and night sweats (HFNS) in middle-aged women in the United Arab Emirates found that temperature and seasonal temperature variations did not appear to influence HFNS reports (22). We hypothesize that the reason could be due to the varied effects of the two locations' climates. The United Arab Emirates, located near the equator, has a tropical desert climate that is dry and hot for most of the year. This differs substantially from China, which has a temperate monsoon climate with four distinct seasons and a wide temperature range. Furthermore, we discovered that air pressure is positively connected with night sweats, indicating that the search index for night sweats is particularly large when air pressure is high, which is consistent with earlier research. International menopausal research of climate, altitude, temperature, and vasomotor symptoms found that hot flashes and night sweats were more common at low altitudes (where air pressure is relatively high) than at high altitudes (23). It's possible that air pressure is linked to diseases like tuberculosis

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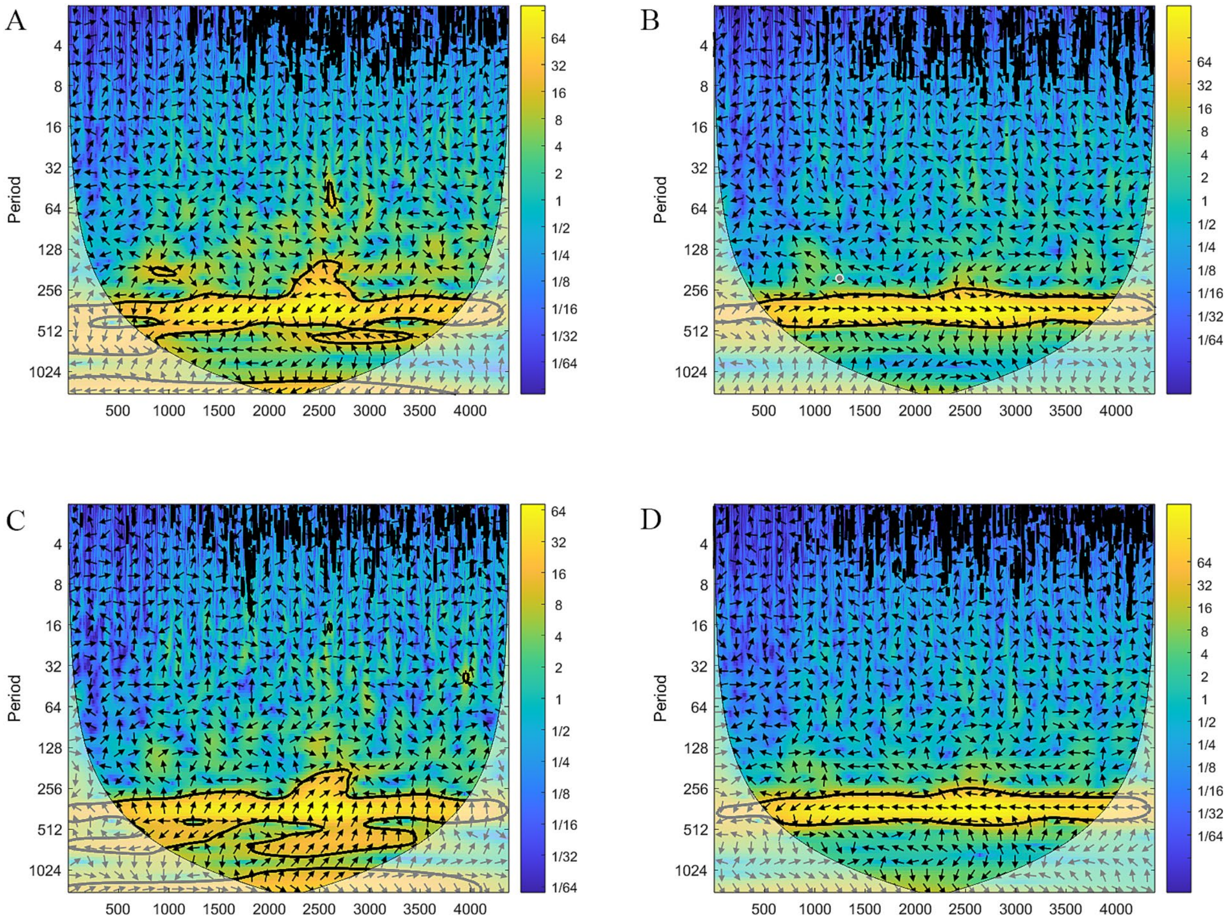

FIGURE 9
Cross-wavelet spectrum between the night sweat index and meteorological factors. **(A)** Humidity; **(B)** pressure; **(C)** wind speed; **(D)** ambient temperature; black line, 95% confidence interval; arrow to the right, positive correlation; arrow to the left, negative correlation.

(24). Tuberculosis is one of the diseases for which night sweats are a primary symptom (25).

Most women have night sweats, which are one of the vasomotor symptoms of menopause. According to studies, 60–80% of women suffer night sweats at some point throughout the menopausal transition, with the incidence and frequency increasing in late perimenopause and early postmenopause, or within a few years before and after their last menstrual period (26). Night sweats during menopause may be directly linked to hormonal changes. Randolph JF Jr. et al. discovered that the prevalence of vasomotor symptoms (night sweats or hot flashes) increased with (log) follicle-stimulating hormone (FSH) concentration, and FSH concentration is positively connected with the frequency of hot flashes or night sweats (27). Gold EB et al. found that vasomotor symptoms significantly decrease with increasing estrogen concentrations (28). According to published studies, seasons might influence hormone levels in the body (29). Xu SR et al. discovered that in cold seasons, the expression of follicle-stimulating hormone (FSH) associated to estrogen reduces in domesticated yaks (30). This shows that during the cold season, women's estrogen levels may drop, increasing vasomotor symptoms like night sweats. Nicolau GY et al. discovered that thyroid-stimulating hormone (TSH) levels are lower during cold seasons, but plasma thyroid hormone concentrations peak at the same time. Lower TSH levels and higher plasma thyroid hormone concentrations may lead to increased perspiration (31). In addition to gender variations, night sweats may be connected with age. In a study of 822 patients with obstructive sleep apnea, Arnardottir ES et al. discovered that night sweats were strongly associated with younger age (32). Under similar settings, age and age-related traits might influence the pace at which body heat is gained and the methods by which it is lost. When Inbar O et al. investigated thermoregulatory responses, they discovered that, while the final average skin temperature changes were similar across three age groups (children, adults, and the older adult), children had the lowest heat storage compared to adults and the older adult (33). In contrast, prepubescent children had the largest net metabolic heat output compared to body weight and heat intake from the environment. The fundamental physical difference between children and adults in terms of thermoregulation is that children have a significantly larger surface area-to-mass ratio, resulting in higher rates of heat absorption or loss (34).

The highlight of our study is that it provides evidence based on internet search behavior of the correlation between night sweats and seasons, and proposes an analysis of the degree of correlation using cross-wavelet transform. We must acknowledge the limitations of this study. As the Baidu search engine is widely popular in China, the use of the Baidu Index is limited to China. Because the data is derived from online search patterns, differences in users' degrees of digital literacy may induce bias. Individuals' understanding and capacity to use technology varies, which might affect their effectiveness in looking for, analyzing, and utilizing online material, consequently influencing the gathering and interpretation of study data. Furthermore, variations in internet availability among regions are a significant limiting factor. Not all geographic locations have equal access to high-quality internet connections; certain isolated or impoverished places may lack reliable internet connectivity. This disparity in availability can exclude particular individuals, resulting in sample selection bias and perhaps failing to fully represent the realities of locations with limited internet access. Finally, user search behavior is a complex process influenced by personal preferences, prior knowledge, and information requirements. Different search habits and tactics may yield diverse results, affecting the consistency and general application of the research findings. For example, some people may prefer certain search engines or websites while ignoring other potential sources of information. In conclusion, these factors may have an impact on the research outcomes.

5 Conclusion

Night sweats were connected with seasons. Specifically, night sweats search indexes increased in the cold season and declined in the summer. Night sweats were negatively associated with temperature but favorably correlated with air pressure.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

CC: Writing – original draft, Writing – review & editing. ML: Writing – review & editing, Writing – original draft. FP: Investigation, Conceptualization, Writing – review & editing. DL: Supervision, Investigation, Software, Writing – original draft. XD: Writing – review & editing. CT: Data curation, Writing – review & editing, Methodology, Supervision. WR: Writing – review & editing. XM: Data curation, Formal analysis, Visualization, Writing – review & editing. TS: Funding acquisition, Writing – original draft, Project administration, Validation. YW: Writing – review & editing. HD: Writing – review & editing. FW: Resources, Funding acquisition, Methodology, Writing – original draft. WL: Resources, Writing – review & editing, Visualization. PW: Writing – review & editing, Formal analysis, Funding acquisition, Resources.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was financially supported by Jinan "20 New Universities" Funding Project (202228121), Shandong Provincial Technology Innovation Leadership Plan (Central Guidance Fund for Local Science and Technology Development) (YDZX2024122), Taishan Scholars Project Grant:NO. tstp 20231239, Key R&D Project of Shandong Province (2021SFGC1205), Shandong Provincial Natural Science Foundation (ZR2021QH290), State Administration of Traditional Chinese Medicine Science and Technology Project (GZY-KJS-2023-027) and the Shandong Provincial Natural Science Foundation [ZR2021MH208],the Shandong Provincial Major Innovation Project [2021CXGC010506], the National Natural Science Foundation of China [22176115], the National Key R&D Program of China [2023YFC3706604], and the Shandong University Public Technology Platform Instrumentation Capacity Enhancement Program [ts20230102].

Conflict of interest

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

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TYPE Original Research
PUBLISHED 16 May 2025
DOI 10.3389/fpubh.2025.1528199

OPEN ACCESS

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RECEIVED 14 November 2024
ACCEPTED 30 April 2025
PUBLISHED 16 May 2025

CITATION
Zou X and Lv J (2025) Analyzing the spatial–temporal dynamics of disaster risk based on social media data: a case study of Weibo during the Typhoon Yagi period.
Front. Public Health 13:1528199.
doi: 10.3389/fpubh.2025.1528199

Analyzing the spatial–temporal dynamics of disaster risk based on social media data: a case study of Weibo during the Typhoon Yagi period

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This paper investigates the spatial–temporal dynamics of disaster risk diffusion and the dissemination of emergency knowledge during Typhoon Yagi, one of the strongest autumn typhoons to hit China since 1949. Employing the spatial–temporal dynamics approach, the study utilizes social media data from Sina Weibo, collected through Python crawling, to analyze the diffusion process of typhoon disaster risks and the mechanism of emergency knowledge dissemination. The research examines the spatial–temporal characteristics of disaster risk diffusion and emergency knowledge dissemination, their interrelationships, and the influence of social background and geographical environment. The findings reveal that the public's discussion on disaster risk and emergency knowledge changes over time, with distinct patterns observed during the typhoon warning, occurrence, and recovery periods. Spatially, Guangdong and Hainan provinces show the highest levels of discussion, aligning with the typhoon's landfall locations. The study underscores the co-evolutionary nature of disaster risk diffusion and emergency knowledge dissemination, whereby the dissemination of emergency knowledge is concomitant with the diffusion of typhoon risk. This research provides a theoretical foundation for the field of disaster risk management and emergency knowledge dissemination, offering practical references for future responses to natural risks.

KEYWORDS

disaster risk diffusion, emergency knowledge dissemination, spatial–temporal dynamics, Typhoon Yagi, grounded theory

1 Introduction

Typhoons and other natural disasters pose significant challenges to human society, threatening lives, property, social economies, and ecological environments. As one of the most destructive meteorological hazards, their impacts have become a focal point for global disaster research. In September 2024, Super Typhoon Yagi, one of the strongest autumn typhoons to land in China since 1949, brought great disaster to southern China, especially the Hainan and Guangdong provinces. According to preliminary statistics, the direct economic loss of Haikou City is about 26.324 billion yuan, and the direct economic loss of Wenchang City is about 32.7 billion yuan, highlighting the severe impact of disaster risk diffusion on regional economies. In disaster risk management, analyzing the temporal and spatial dynamics of disaster risk and its influencing factors is the key to understanding the occurrence, development, and impact of disaster. This analytical framework is essential for bridging the gap between physical disaster processes and societal vulnerability. This analysis encompasses not only the physical attributes of disasters, such as the trajectory, intensity, and precipitation of typhoons, but also the implications of disasters on human society, including population distribution, economic activities, and infrastructure vulnerability. A comprehensive analysis of these factors makes it feasible to predict more precisely the potential losses that disasters might inflict, thereby providing a scientific foundation for disaster early warnings and emergency responses. As paradigmatic meteorological disasters, typhoons exhibit complex spatiotemporal risk dynamics shaped by multiple interrelated factors. Meteorological factors comprise typhoons' intensity, path, and precipitation; geographical factors involve terrain, hydrology, and land utilization; and social factors include population density, economic activities, and the disaster resilience of communities. These multi-layered factors do not act in isolation but form an interactive system that amplifies risk propagation. These factors interact and jointly affect the risk dissemination of typhoon disasters. Hence, this paper analyzes the spatial–temporal dynamics of typhoon disaster risk dissemination and its influencing factors.

Meanwhile, the dissemination efficiency and effect of emergency knowledge directly influence the outcome of disaster response. In the era of digital connectivity, this influence has become particularly pronounced due to the proliferation of social media. During a disaster, timely and accurate information can assist people in making correct decisions, mitigating panic and chaos, and enhancing self-rescue and mutual-rescue capabilities. Hence, investigating how to effectively disseminate emergency knowledge and improve the public's disaster awareness and response capabilities is crucial for reducing disaster losses. Against this backdrop, social platforms have emerged as significant channels for information dissemination, and their role in disaster risk management and emergency response has become increasingly prominent. Typhoons trigger secondary disasters such as strong winds, torrential rains, floods, and landslides during the landing process, causing severe casualties and property losses while provoking extensive public discussions across China. Based on this, the study takes Typhoon Yagi as a case, collects Weibo data from September 1st to 16th, 2024, through Python crawling, and discusses the diffusion process of typhoon disaster risks and the dissemination mechanism of emergency knowledge. This study examines the spatiotemporal characteristics of disaster risk diffusion and emergency knowledge dissemination, as well as their interrelationships. It also considers the influence of social background and geographical environment on these processes. The aim is to provide a theoretical foundation for research in the field of disaster risk management and emergency knowledge dissemination. In addition, the study offers feasible, practical references for future responses to natural risks.

2 Literature review

Natural disasters like typhoons occur unexpectedly and can significantly threaten social resources, mental well-being, public safety, and health (1). In light of the issue, Linardos et al. (2) examined how machine-learning techniques are utilized in disaster management. Zhu and Zhang (3) assessed flood risk using the random forest algorithm. In terms of investigating the spatial–temporal dynamics of disaster risk diffusion, Jiang et al. (4) studied precipitation and river flow trends in the Yangtze River Basin. Lu and Fu (5) focused on interannual variations in summer rainfall across East Asia. Additionally, Zhang et al. (6) investigated the spatial–temporal patterns of floods and droughts in China and their effects on agriculture. Liu et al. (7) looked into the spatial–temporal features of haze and particulate pollution within China. In their study, Men et al. (8) examined how natural disaster risks evolve in terms of both space and time within chemical industrial parks. Understanding the spatial–temporal evolution characteristics of disaster risks is crucial for effective disaster risk management, prompting extensive research efforts by scholars in this field. Notably, these domestic studies primarily rely on traditional meteorological and environmental data, with limited integration of social media-generated insights into public discourse during disasters.

Further, with the rapid advancement of social media, platforms like Weibo have emerged as significant channels for disseminating disaster information, offering immediate early warnings at the initial stage of a disaster, and serving as effective tools for information transfer during the post-disaster recovery period. Disaster risk diffusion pertains to the spatial and temporal spread of risks resulting from disasters, while emergency knowledge dissemination refers to the communication of information related to disaster response (9). Typhoon Yagi had rapid and severe impacts as an extreme weather phenomenon. Against this backdrop, entities such as the media and eyewitnesses promptly disseminated emergency knowledge to assist the public in getting prepared within the shortest possible time. On the Weibo platform, people extensively discussed relevant information, facilitating even faster information dissemination (10). Internationally, studies like Morelli et al. (11) and Ogie et al. (12) have systematically analyzed social media's role in shaping risk perception and disaster recovery, but comparable domestic research remains fragmented, lacking a systematic framework to link social media data with traditional risk assessment models. Zander et al. (13) analyze how Australians use social media during natural hazards. Alexander analyzes the use of social media (blogs, messaging, sites such as Facebook, wikis, and so on) in disasters and major incidents (14). Luna and Pennock (15) point out that social media applications are dependable communication channels even when traditional methods fail. Ramakrishnan et al. (16) analyze the factors that influence the use of social media for disaster management by underserved communities. Yigitcanlar et al. (17) detect natural hazard-related disaster impact with social media analytics. Singla and Grawal (18) analyze the challenges and enablers between social media and disaster management. This study bridges this gap by providing a domestic case analysis of Weibo data, systematically comparing spatial–temporal patterns with international findings on social media's role in disaster communication. Hence, this article analyzes the spatial–temporal characteristics of disaster risk diffusion based on social media data. In recent years, the increasing prevalence of social media platforms has transformed how information is disseminated and consumed during disasters. Researchers can gain valuable insights into public perceptions and behaviors related to disaster risks by leveraging vast amounts of user-generated content from these platforms.

3 Research methods

3.1 Research case

This study selected Typhoon Yagi, which landed in September 2024, as the research case. To capture the full lifecycle of the disaster, we collected data from Sina Weibo using Python between September 1, 2024 (when Yagi first entered public awareness), and September 16, 2024 (the recovery period after the typhoon subsided). Relevant data and content from the social media platform "Sina Weibo" were collected through Python software, such as the main text of Weibo posts, the Internet Protocol (IP) location, gender, and age of the authors. Data collection incorporated specific keyword filters to ensure relevance, including "Typhoon Yagi," "destruction," "disaster resistance," "disaster relief," and other terms related to risk diffusion and knowledge dissemination (detailed in Section 3.3.1). Based on the grounded theory (19, 20), the classification and preprocessing of Weibo texts were accomplished. Grounded theory is particularly suitable for this study as it allows for inductive theory development from unstructured social media data, aligning with our goal of exploring emergent patterns in disaster risk communication (21). Moreover, the spatiotemporal clustering method was used to generate spatiotemporal maps of disaster risk diffusion and emergency knowledge dissemination to explore the spatiotemporal distribution and its influencing factors. Typhoon Yagi, a tropical cyclone, originated in the waters east of the Philippines on the evening of September 1, 2024, and developed rapidly due to favorable atmospheric conditions, including warm sea surface temperatures and low vertical wind shear, which are critical factors for typhoon formation. By September 6 at 16:20, Typhoon Yagi made landfall along the coast of Wentian Town in Wenchang City, Hainan Province, China. At this point, it was reportedly at near-peak intensity, with sustained winds reaching significant speeds that threatened coastal communities.

During this second landfall event, it intensified into a super typhoon. The impact was severe and widespread. Numerous countries were affected by heavy rainfall and strong winds associated with Yagi's path, including China and neighboring nations such as the Philippines and Vietnam. These adverse weather conditions led to extensive flooding and landslides in various regions. Given its severe impacts and implications for disaster management, this study selects Typhoon Yagi as a case study aimed at examining several key aspects related to natural disasters: specifically focusing on spatial–temporal characteristics regarding how disaster risks diffuse through different geographical locations over time, analyzing emergency knowledge dissemination processes among local populations, and identifying various influencing factors that contribute to both preparedness levels before such events as well as response effectiveness during recovery efforts post-disaster. This comprehensive analysis provides valuable insights that may inform future strategies for mitigating similar risks associated with extreme weather phenomena.

3.2 The acquisition and processing of research data

Sina Weibo is one of the highly representative social media platforms in China. It can be published through multiple terminals such as the Internet, clients, and mobile phones, enabling the posting and receiving of information at any time and place. Its audience is extremely active in China and even worldwide. In this paper, Weibo data during Typhoon Yagi is crawled using Python with specified keywords. The time range was strictly defined as September 1–16, 2024, covering the warning, occurrence, and recovery periods. To exclude irrelevant content, we filtered out posts mentioning "Yagi" in non-typhoon contexts (e.g., constellation references) and retained only posts containing predefined keywords related to disaster risk and emergency knowledge (see Table 1 for details). The main data types include the main text of Weibo posts, the longitude and latitude of the author's IP, the posting time of Weibo, and the basic information of the author etc. Weibo posts with only topics but no substantive content and invalid data, such as references to 'Yagi' as a zodiac sign, were excluded. Finally, 12,478 valid contents are filtered out.

3.3 Textual information research based on grounded theory

Grounded theory is a qualitative research approach for systematically organizing and analyzing primary data. The core of it lies in conducting inductive analysis from the data through a standardized operational process to form conceptual frameworks and theories. Grounded theory encompasses three steps: open coding, axial coding, and selective coding, and it is suitable for exploring and addressing new phenomena and issues. In the current research, a systematic theoretical framework remains inadequate within the domain of risk and knowledge co-evolution of natural disasters like typhoons. It is highly necessary to carry out in-depth research using grounded theory. This study, based on grounded theory and taking Typhoon Yagi as an example, explores its risk diffusion and knowledge dissemination in depth.

3.3.1 Open coding

Open coding involves decomposing and reconfiguring the collected raw materials, assigning conceptual labels to the materials, defining concepts, and uncovering scopes through novel means. Given the extremely high degree of discussion regarding Typhoon Yagi on the Weibo platform, in this study, after setting keywords for precise information acquisition, the posting time of Weibo was controlled and screened. In the context of Typhoon Yagi's disaster risk diffusion, 3,391 valid texts were obtained through keywords such as "destruction," "disaster resistance," "disaster relief," "rainfall," "storm," "fear," "scared," "water and power outage," "no network," "communication disruption," "transportation delay," etc. In the field of emergency knowledge dissemination, 3,257 valid texts were acquired through keywords such as "disaster prevention," "evacuation," "stockpiling," "reconstruction," "government support," "ensuring safety," "people's unity," "mutual aid with love," "temporary shelters," etc. This study takes these texts as the raw materials for open coding. Further, to ensure the objectivity and accuracy of the coding, we specially invited two experienced professional coders to code all the original data independently. Regarding the parts with disputes or inconsistencies, the coders reached a consensus through discussions and refinements and ultimately extracted a total of 6 basic categories. The open coding categories and the sentences of some original data are presented in Table 1.

3.3.2 Spindle-based encoding

Spindle coding is a further clustering analysis of the basic categories formed after open coding. It dissects their attributes and connotations, looks for correlations, and refines higher-level main categories. Based on open coding in this paper, systematic

TABLE 1 Open coding.

Category	Some sentences of the original data (initial concepts)
A_1: the actual situation of disaster resistance and relief	Guangdong Xuwen was also not immune to the disaster. Big trees fell, fences collapsed, and iron sheets were flying everywhere!
	From the Emergency Command Center for Typhoon Yagi in Hainan Province, we have learned that the wind circle of Typhoon Yagi has begun to affect areas such as Haikou, Chengmai, and Ding'an, and the center of the wind circle has entered Haikou, the provincial capital. Multiple residential communities in Haikou have experienced power outages and water shortages, and some residential and office buildings have had their windows shattered by the fierce winds and rainstorms. Many green trees in the city have fallen, and some coastal residential areas have experienced seawater intrusion.
	Typhoon Signal No. 8, or Severe Wind Signal, is currently in effect and is expected to last at least until noon on the 6th. Subway and light rail services will be limited from the first train, and many citizens took the subway this morning.
A_2: Meteorological Description of Typhoon	The No. 8 Gale or Storm Signal, commonly called "No. 8 Typhoon Signal," is further classified into No. 8 Northwest, Southwest, Northeast, and Southeast Gale or Storm Signals based on the blowing direction. This signal indicates that gales or storms are prevailing or expected to prevail at or near sea level in Hong Kong.
	The Shenzhen Meteorological Observatory upgraded the typhoon white warning signal for the entire city to blue at 19:00 on September 4, 2024. It is anticipated that due to the influence of Typhoon Yagi, the gusts in our city will reach above level 8.
	Meanwhile, the southeasterly wind, the easterly wind, and the northeasterly wind associated with the cold air are contributing to the formation and development of the rain belt in the coastal regions. Despite the passage of Typhoon Yagi, its influence has not yet subsided.
A_3: the Perception of Disaster-related Emotions	Notwithstanding the tempestuous wind and rain, our hearts remain closely intertwined.
	Unity constitutes power! The people of Hainan, in a unified front, are working together to overcome their challenges and create a brighter future for themselves.
	The process of charging, water accumulation, and food hoarding commenced yesterday. Presently, the circumstance is serene. Such stillness is terrifying.
A_4: real-time news reporting	Affected by Typhoon Yagi, the immigration management police were at the front line of disaster relief in Binqiao Township, Longzhou County, Chongzuo City, Guangxi. They were engaged in the tasks of evacuating people and rescuing materials. After working continuously for over 10 h, they were exhausted and slept on the ground. Currently, the rescue operation is still ongoing.
	Affected by the peripheral circulation of Typhoon Yagi, it is projected that from 5:20 to 07:00, the central urban area and the adjacent sea surface will experience short-term strong winds of grade 7–8, thunderstorms, and other severe convective weather, accompanied by short-term heavy precipitation, with the maximum hourly rainfall ranging from 20 to 30 millimeters.
	Typhoon Yagi is constantly drawing nearer. Today, the Central Meteorological Observatory has continuously issued the highest-level typhoon red warning.
A_5: the popularization of disaster prevention knowledge	When a typhoon arrives, if one is outdoors: 1. Do not seek refuge from the wind and rain near temporary buildings, billboards, iron towers, or big trees. 2. Do not stay in low-lying areas for shelter, and select a high and solid house for refuge. 3. If driving, it is recommended to immediately drive to places such as underground parking lots for shelter.
	What are the precursors before the arrival of a typhoon? When a typhoon strikes, how should one take precautions and avoid risks indoors and outdoors? Please keep this risk avoidance guideline well.
	Safety comes first, and negligence is not allowed. Everyone should actively learn to cope with typhoons and take extra precautions.
A_6: sharing of emergency materials	We express our gratitude for donating materials to address the damage and relief needs in the areas affected by Typhoon Yagi. The materials, including humanitarian rescue first aid kits and generators, have been successively loaded onto vehicles and are departing for the disaster-stricken areas. We sincerely hope that Hainan will overcome the difficulties early and restore a beautiful life.
	A host of celebrities donated supplies to the areas in Hainan stricken by Typhoon Gajab. Disasters are heartless, but humans are kind-hearted. We stand together!
	The Hainan Provincial Committee for Disaster Prevention, Mitigation, and Relief has announced the acceptance of donations for disaster relief from Typhoon Yagi. The disaster-stricken areas urgently need materials such as log grapples, generators, water pumps, chainsaws, electric saws, portable energy storage equipment, and long-lasting LED lighting fixtures. Other materials are temporarily not accepted.

classification and analysis deeply explored the internal connections among various basic categories. Eventually, two main categories were concluded. The results of spindle coding are shown in Table 2.

3.3.3 Selective encoding

Selective coding is a further refinement of axial coding. Among the identified concept categories, find the "core category" that integrates other categories, construct a conceptual framework, integrate the research results within this framework, and utilize the collected data to verify the textual relationships. Combining materials and the CAPS theory reveals the typical relationships within the core category, clarifies the public perception behind Typhoon Yagi, and ultimately sorts out the ways of disaster risk diffusion and emergency knowledge dissemination. The typical relationship structure of the core category is shown in Figure 1.

TABLE 2 Spindle-based encoding.

Main category	Initial category	Category connotation
B_1: disaster Risk Diffusion	A_1: the actual situation of disaster resistance and relief	The actual circumstances of emergency responses, rescue operations, and post-disaster recoveries adopted by governments at all levels, relevant institutions, and individuals under the influence of Typhoon Yagi.
	A_2: Meteorological Description of Typhoon	The formation and development of Typhoon Yagi and its influence on climate and environment.
	A_3: the Perception of Disaster-related Emotions	Under the influence of Typhoon Yagi, the public's emotional responses and psychological feelings toward the disaster.
B_2: the dissemination of emergency knowledge	A_4: real-time news reporting	Instantaneous information update on the latest developments and countermeasures regarding Typhoon Yagi.
	A_5: the popularization of disaster prevention knowledge	Through various channels of knowledge dissemination, popularize the knowledge of disaster prevention and mitigation related to Typhoon Yagi among the public.
	A_6: sharing of emergency materials	After the landing of Typhoon Yagi, all sectors of society coordinated resources to ensure the effective allocation and utilization of disaster relief materials.

4 Analyzing the spatial and temporal characteristics of disaster risk diffusion and emergency knowledge dissemination

Based on the natural development stages of Typhoon Yagi before, during, and after its landing in September 2024, this study classifies the collected Weibo data chronologically and defines them as a three-time series. (1) "Typhoon Warning Period": from September 1st to 5th; (2) "Typhoon Occurrence Period": from September 6th to 9th; (3) "Typhoon Recovery Period": from September 10th to 16th. By applying the spatial–temporal dynamics method, we utilized ArcGIS software to draw the spatial distribution maps of disaster risk diffusion and emergency knowledge dissemination, aiming to investigate the degree of discussion on the topic of Typhoon Yagi among the public in different regions over time (22). This approach allows us to comprehensively analyze the spatiotemporal patterns of how information spreads and public attention shifts during different phases of the typhoon event.

4.1 Analysis of temporal characteristics

Based on the Grounded Theory, we relied on six initial categories (A1-A6, Table 1). We took the three periods of "Typhoon Warning Period," "Typhoon Occurrence Period," and "Typhoon Recovery Period" as the research timeframes. Through the proportion of each initial category in all Weibo posts, we studied the public discussion content and extent during Typhoon "Yagi."

4.1.1 The analysis of the temporal characteristics of disaster risk diffusion

During the extreme-risk natural disaster of Typhoon Yagi, we crawled 3,391 Weibo posts related to "disaster risk diffusion." We presented the discussion proportions of the six initial categories A1 - A6 in a tag bar chart, as shown in Figure 2.

During the occurrence of Typhoon Yagi, the discussion degrees of different themes presented diverse changing patterns over time. Among the six initial categories based on the Grounded Theory, A1 had a relatively stable discussion degree during the typhoon warning and the typhoon occurrence periods, reaching a peak of 0.8249 in the typhoon recovery period. A2 showed an overall trend of rising first and then falling, with a discussion degree as high as 0.8128 during the typhoon occurrence period. This finding aligns with gender role theory (23), where men's greater focus on disaster relief actions (A2) reflects traditional masculine roles emphasizing problem-solving behaviors during crises. As the typhoon progressed, the public's discussion degree regarding meteorology reached its highest. A3 was similar to A1, both stable during the warning and occurrence periods and rising during the recovery period, reflecting that the public had a stronger emotional perception of the disaster in the typhoon recovery stage.

It is worthy of in-depth study that, in the crawled "disaster risk diffusion" data, a considerable amount of content is highly correlated with "emergency knowledge dissemination." Among the 3,391 related discussions on "disaster risk diffusion," the discussion degree of A4 is overall relatively stable, ranging between 0.5442 and 0.6293, indicating that the public pays significant attention to news reports. A5 shows an upward trend. As the typhoon progresses, the public attaches greater importance to disseminating and learning disaster prevention knowledge. A6 has a discussion degree as high as 0.7824 during the typhoon occurrence period. Women's stronger engagement with supply sharing (A6) corresponds to communal roles in crisis situations (24), suggesting gendered patterns in disaster response behaviors. Age-related differences were also observed, with younger users focusing more on real-time updates. At the same time, older demographics emphasized preparedness measures, consistent with protection motivation theory (25) regarding developmental differences in risk perception. While the typhoon disaster spreads, the sharing of supplies among the public flows frequently.

4.1.2 The analysis of temporal characteristics of emergency knowledge dissemination

Similarly, we crawled 3,257 Weibo contents related to "emergency knowledge dissemination" and drew the bar chart shown in Figure 3.

Consistent with the foregoing, the content we crawled regarding "emergency knowledge dissemination" also encompasses the initial domain of "disaster risk diffusion." The discussion intensity of A1 initially ascends and subsequently declines, attaining a peak value of 0.6948 during the typhoon occurrence period. Meanwhile, the public demonstrates high concern about real-time disaster resistance and relief situations while disseminating emergency knowledge. The distribution pattern of A2 is similar to that of A1, with the public showing the highest discussion intensity regarding meteorological

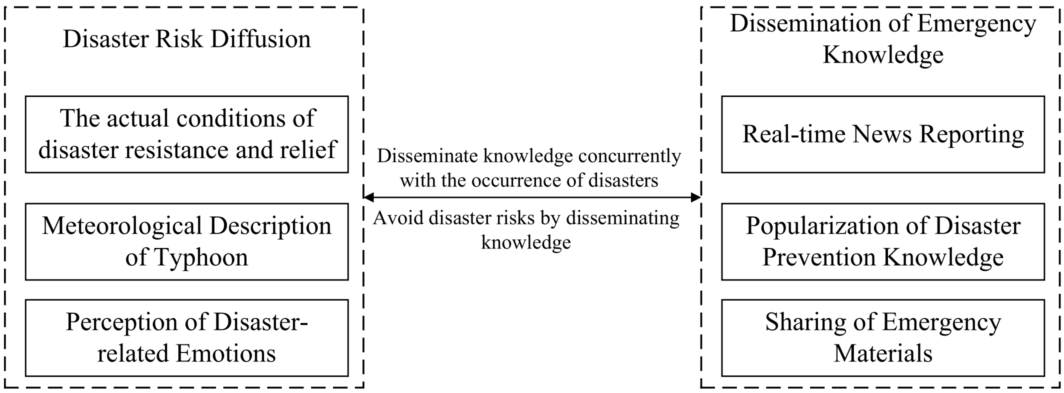

FIGURE 1
Selective encoding.

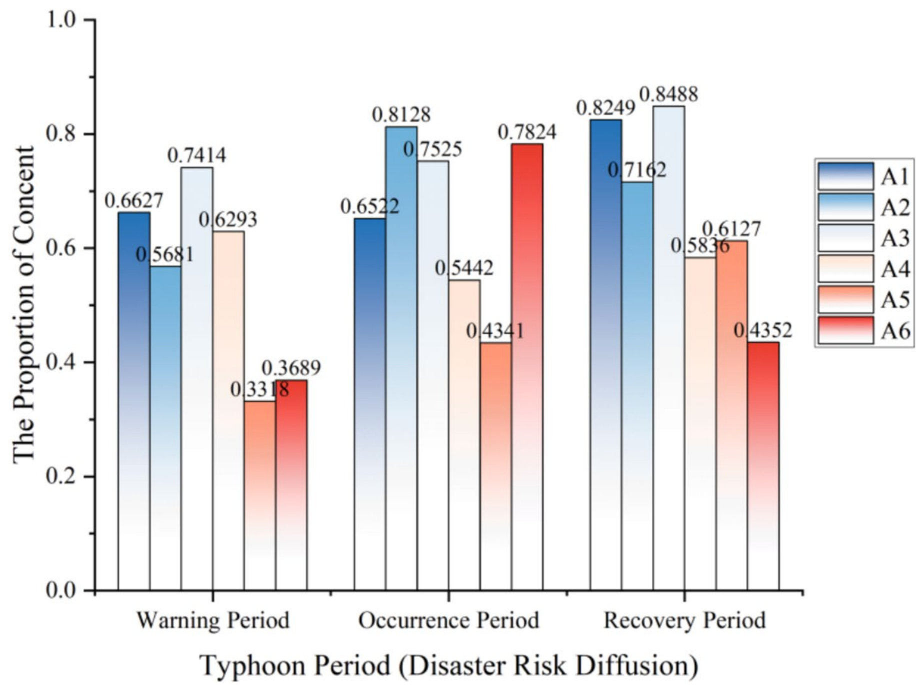

FIGURE 2
The temporal characteristics of disaster risk diffusion.

changes during the typhoon occurrence period. A3 reaches its peak of 0.9296 during the typhoon recovery period. It is worth noting that it bears highly similar characteristics to the "disaster risk diffusion" data, and the public's emotional perception during the natural disaster recovery period is the most intense. A4 exhibits an upward trend and maintains a considerable level during the typhoon recovery. Both A5 and A6 show an upward and downward trend, rising above 0.9 during the typhoon occurrence period.

4.2 The analysis of spatial features

The landing of Typhoon Yagi, accompanied by strong winds and torrential rains, resulted in numerous secondary disasters, such as floods and landslides, presenting considerable natural risks. Beyond the storm's core area, the surrounding regions also endured the damage brought by the typhoon disaster. On this basis, we undertake research and discussion on the spatial characteristics of the public discourse.

4.2.1 The analysis of the spatial characteristics of disaster risk diffusion

Based on 3,391 microblog posts related to "disaster risk diffusion," we performed a visual analysis of the discussion degrees in 34 provinces, autonomous regions, municipalities directly under the Central Government, and special administrative regions of China, presenting the discussion proportions of the six initial categories A1 - A6 in the form of a map, as depicted in Figure 4.

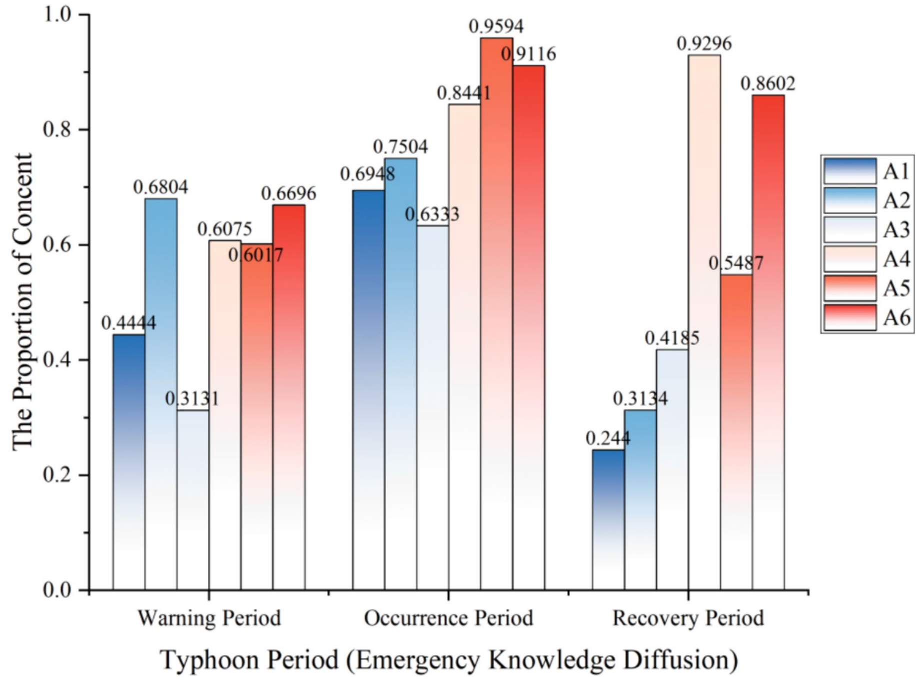

FIGURE 3
The temporal characteristics of emergency knowledge dissemination.

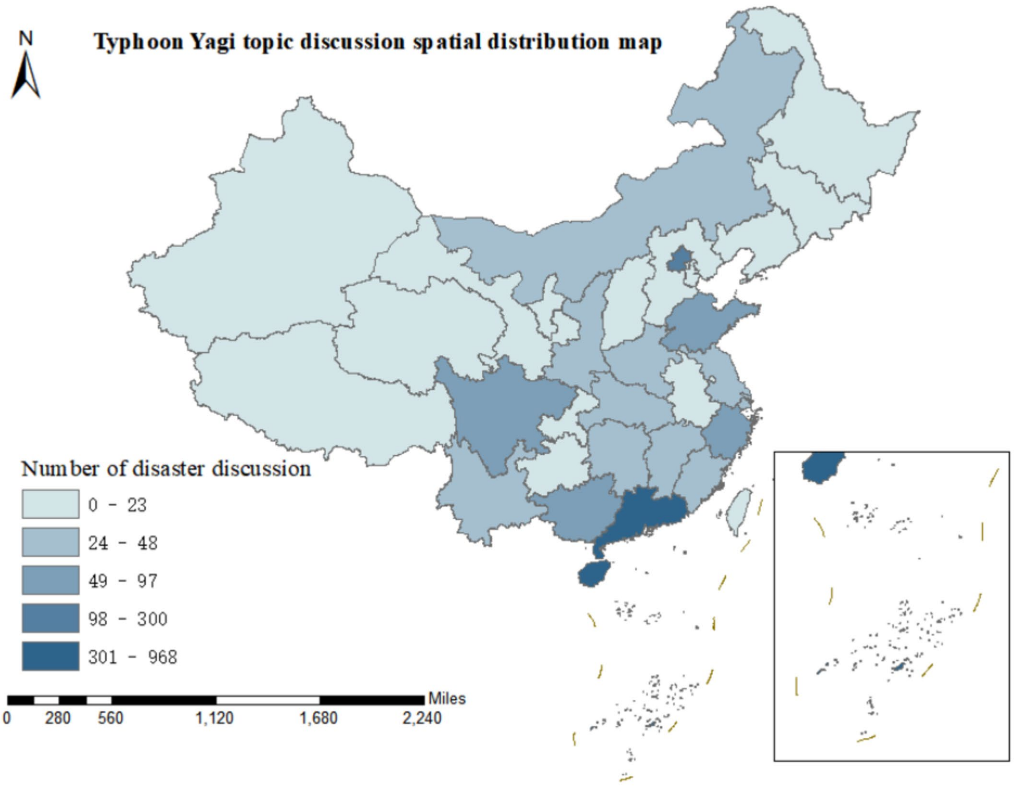

FIGURE 4
The spatial characteristics of disaster risk diffusion.

Typhoon Yagi made landfall along the coast of Wenchang City, Hainan Province, at approximately 16:20 on September 6, 2024, and subsequently made another landfall in Xuwen County, Guangdong Province, at around 22:20 on the same day. Both landfalls were of super typhoon intensity. In the Weibo discussions related to "disaster risk diffusion," it was observed that the general trend of the spatial distribution of the six initial categories was highly notable. Guangdong Province and Hainan Province had the highest levels of discussion, significantly surpassing those of other provincial administrative regions. This concentration reflects geographical proximity and socioeconomic factors: (1) higher population density in coastal urban areas; (2) greater economic assets at risk; (3) more developed social media infrastructure facilitating real-time information sharing. The number of discussions in Guangdong and Hainan was 891 and 968, respectively, accounting for 26.28 and 28.55% of the discussions, which combined more than half of the total. Beijing, the capital of China, ranked second with 208 discussions, indicating the concern and attention of the public in the capital toward the landfall of Typhoon Yagi. Sichuan Province, Guangxi Zhuang Autonomous Region, Shandong Province, and Zhejiang Province followed, with the number of topic discussions ranging from 49 to 97. The public in these provinces and autonomous regions paid relatively high attention to Typhoon Yagi.

4.2.2 The analysis of the spatial characteristics of emergency knowledge dissemination

Figure 5 presents the degree of discussion on Typhoon Yagi in 34 provinces, autonomous regions, municipalities directly under the Central Government, and special administrative regions of China based on 3,257 microblog posts related to "emergency knowledge dissemination."

Contrary to the microblog contents related to "disaster risk diffusion," the spatial distribution of the relevant contents of "emergency knowledge dissemination" across the provincial administrative regions of China is more evenly balanced. Guangdong Province still leads in terms of the degree of discussion, with 340 microblog posts. Hainan Province follows with 273 posts in discussion, Shanxi Province with 257, Sichuan Province with 235, Beijing with 224, and Hunan Province with 214. Most of the remaining provincial administrative regions have a relatively even number of microblog posts, ranging between 50 and 100. Thus, it can be observed that the public has highly emphasized the dissemination of emergency knowledge during Typhoon Yagi throughout various regions of China.

4.3 The co-evolutionary analysis of disaster risk diffusion and emergency knowledge dissemination

The previous research found a high coevolution between disaster risk diffusion and emergency knowledge dissemination during Typhoon Yagi. Most of the blog posts published by the public included relevant content about disaster risk diffusion and emergency knowledge dissemination. This co-evolution phenomenon can be understood through the social amplification of risk framework (26), where risk information and protective knowledge mutually reinforce through social networks. For example, "Blue V" news blogger "Sanxiang City Daily"

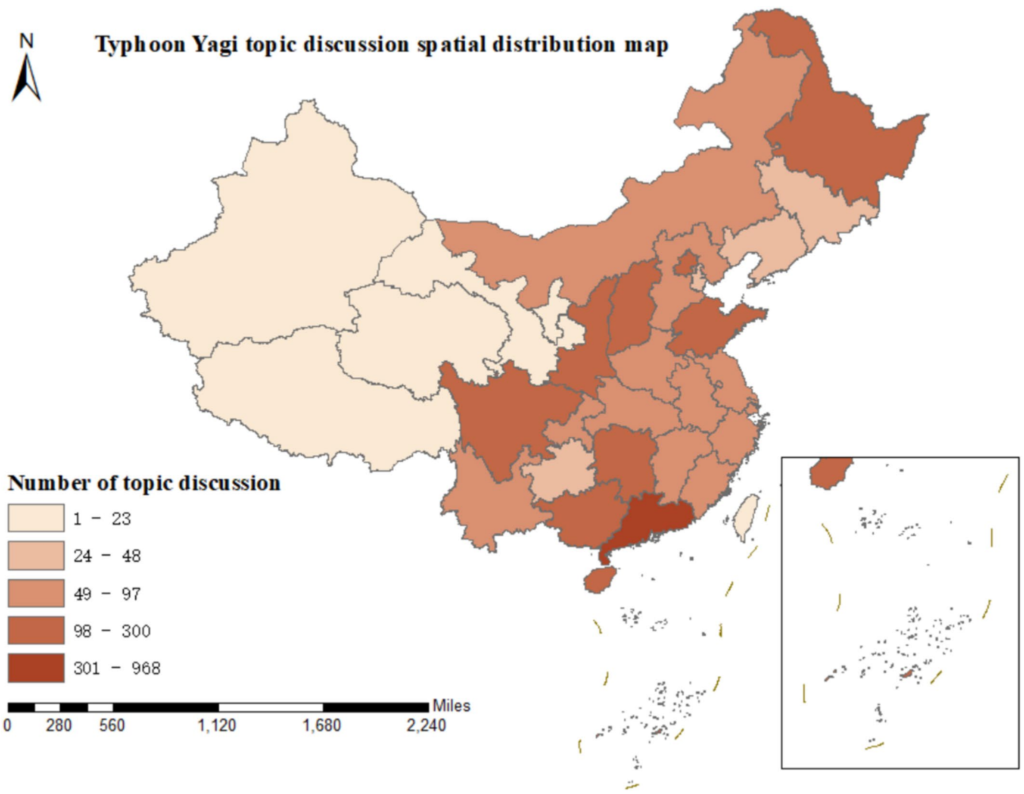

FIGURE 5
The spatial characteristics of emergency knowledge propagation.

published a micro-blog related to Typhoon Yagi at 21:27 on September 9, 2024, which covers the disaster situation and weather description of Typhoon Yagi landing in Hainan Province, real-time news reports and common-sense interpretation of disaster avoidance, and the spread of relevant news about disaster relief and emergency supplies. Furthermore, he expressed gratitude to the relief workers for their timely assistance. There are countless Weibo like this. The practice shows that the spread of the typhoon Yagi disaster risk is accompanied by the spread of emergency knowledge. Before Typhoon Yagi landed, local governments and meteorological departments in China released information on the spread of disasters, such as typhoon track, wind speed, and rainfall through various channels, as well as guidance and suggestions on disaster prevention and risk aversion, to help the general public prepare in advance and reduce potential risks and losses brought by Typhoon Yagi. Effective emergency knowledge dissemination can help the public quickly access disaster-related information and grasp response measures.

5 Analysing influencing factors of disaster risk diffusion and emergency knowledge diffusion

Through the above analysis, we found that social background, geographical location, and other factors impact the dissemination of disaster risk and emergency knowledge about Typhoon Yagi. To conduct follow-up research on the influencing factors, we randomly selected 5,830 microblogs with the keyword "Typhoon Yagi" from September 1 to 16, 2024.

5.1 Social background factor

Based on the gender and birthday information of Weibo users, we studied the factors affecting the social background of disaster risk diffusion and emergency knowledge dissemination. Weibo can only crawl out the user's birthday, and the birthday information of some users is kept secret. Therefore, we converted the user's birthday into the user's age, excluded the information of users born before 1924, and finally got 1937 valid data. We refer to the age division of the United Nations World Health Organization and identify minors (0–17 years), young people (18–65 years), middle-aged (66–79 years), and older adult (80–99 years). The research found that minors, young people, and middle-aged people are most concerned about real-time news reports, typhoon meteorological descriptions, and emergency materials sharing, respectively. At the same time, the older adult are more concerned about typhoon meteorological descriptions and emergency materials sharing, reflecting that people of different ages have different degrees of emphasis on other aspects, as shown in Figure 6.

Regarding gender, 2,358 valid records for males and 3,429 valid for females, as shown in Figure 7. During Typhoon Yagi, both men and women received high attention, and both strongly discussed typhoon meteorological descriptions and real-time news reports. In addition, men pay more attention to disaster relief, while women pay more attention to emergency material sharing, which shows that men and women pay more attention to risk events in a relatively consistent state, which is also different due to gender differences.

5.2 Geographical environment factor

The previous research found that residents of Guangdong and Hainan provinces had the highest discussion about Typhoon Yagi. Based on this, we used ArcGIS software to draw a map of China for 5,830 IP territories with the keywords Typhoon Yagi related microblog from September 1 to 16, 2024, as the control group of this study, as shown in Figure 8. The results show that Guangdong Province and Hainan Province still have the highest number of discussions in

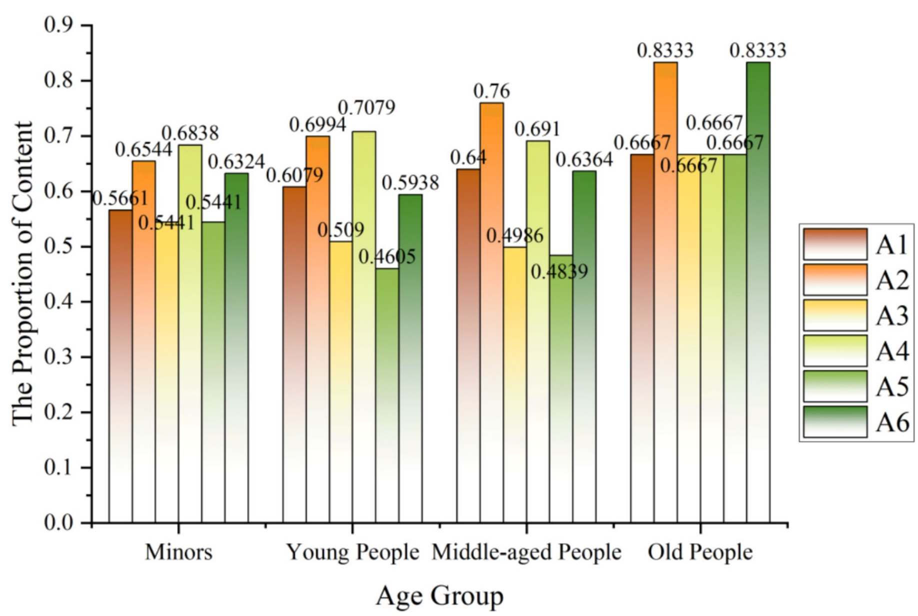

FIGURE 6
The analysis of age.

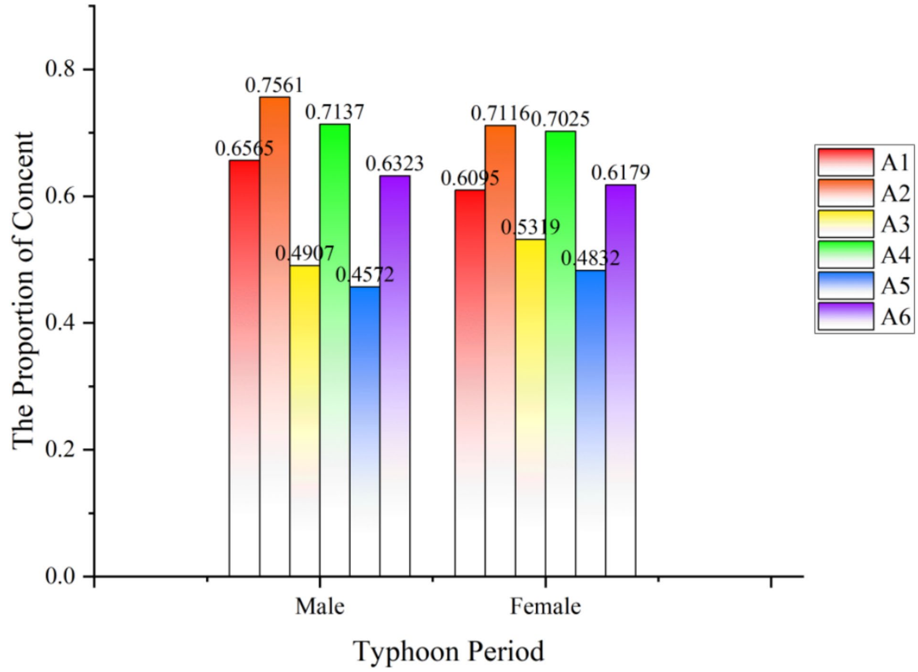

FIGURE 7
The analysis of sex.

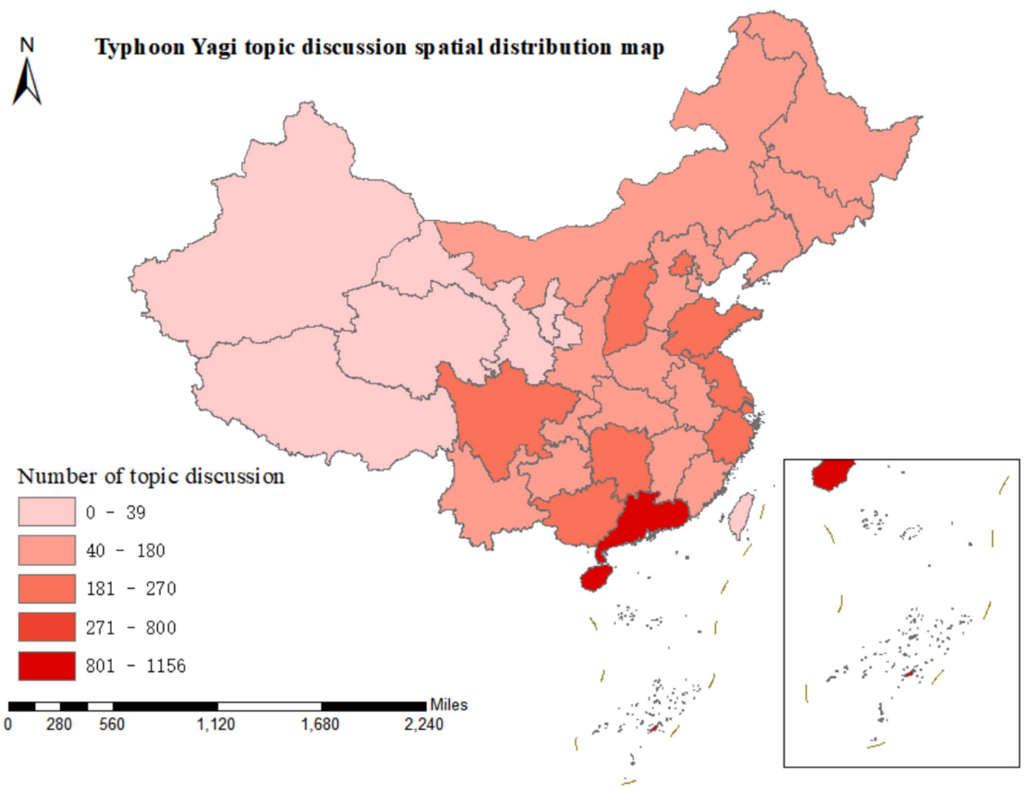

FIGURE 8
The geographical environment factor.

China. After entering the South China Sea, Typhoon Yagi strengthened rapidly, upgraded from a typhoon to a strong typhoon in just 15 h, and finally developed into a super typhoon and gradually landed in Hainan Province, Guangdong Province, and other places. The degree of public concern for the typhoons in this region is consistent with the natural phenomenon, indicating that geographical and environmental factors have a greater impact on spreading disaster risk and emergency knowledge.

6 Conclusion

Under the natural disaster perspective of Typhoon Yagi, we use the microblogging platform to screen text data related to disaster risk diffusion and emergency knowledge dissemination, and explore their spatial and temporal distribution characteristics and influencing factors through data analysis. The spatial–temporal dynamics analysis shows that the public's discourse on Yagi tends to evolve over time. Additionally, the focal point of microblog content shifts by the progression of the typhoon warning period, typhoon occurrence period, and typhoon recovery period. Regarding space, Guangzhou and Hainan Provinces showed the highest level of discussion, which aligns with the natural phenomenon of Typhoon Yagi's landfall. As highlighted in Cutter et al.'s vulnerability framework, this spatial concentration is further explained by socioeconomic factors, such as population density and social media infrastructure. The public discussion of Typhoon Yagi on Weibo shows strong co-evolutionary characteristics. While experiencing or witnessing Typhoon Yagi as a natural disaster, the public received explanations of emergency knowledge from official media, typhoon witnesses, and other channels. It minimized the risks arising from the landfall of Typhoon Yagi by learning about emergencies, sharing information, and exchanging materials.

While this study provides valuable insights into disaster communication patterns, several methodological limitations should be acknowledged. First, our data processing pipeline, though systematically implemented through Python-based text mining and geospatial analysis, could benefit from more detailed documentation of the technical parameters and filtering criteria applied during Weibo data cleaning and classification. Second, the map generation process, while effectively visualizing spatial patterns, may not fully capture localized anomalies. These limitations highlight opportunities for future research to adopt advanced natural language processing algorithms and high-resolution spatial models and expand data collection to platforms like WeChat and Douyin to enhance generalizability.

This paper is of great significance in studying the co-evolution of risk and knowledge and provides theoretical support for knowledge dissemination under natural disasters. This study's practical implications include guiding emergency management agencies to prioritize social media monitoring during disasters and design gender/age-sensitive communication strategies. Although Typhoon Yagi has passed, the damage caused to the affected areas is long-lasting, and the government and the public should be more concerned about helping the affected areas in the future. At the same time, our data source has a certain degree of limitation; in the follow-up study, we can use WeChat public number, Jittery, Xiaohongshu, and other mainstream media software to broaden the platform of data crawling to provide more channels of data support for the conclusion.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XZ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JL: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study was supported by the National Natural Science Foundation of China (72461013), Yunnan Provincial Department of Science and Technology General Project (202501AT070351),Yunnan Province "Xingdian Plan" Young Talents special project (KKRD202208032), Youth Foundation of Science and Technology Department of Yunnan Province (202301 AU070094), Excellent Cultivation Project of Philosophy and Social Sciences of Kunming University of Science and Technology (KKXA202308007) and Talent Cultivation Project of Kunming University of Science and Technology (KKZ3202308062).

Conflict of interest

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

Generative AI statement

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

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