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Global climate change: Effects of future temperatures on emergency department visits for mental disorders in Beijing, China

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ABSTRACT

Rising temperatures can increase the risk of mental disorders. As climate change intensifies, the future disease burden due to mental disorders may be underestimated. Using data on the number of daily emergency department visits for mental disorders at 30 hospitals in Beijing, China during 2016–2018, the relationship between daily mean temperature and such visits was assessed using a quasi-Poisson model integrated with a distributed lag nonlinear model. Emergency department visits for mental disorders attributed to temperature changes were projected using 26 general circulation models under four climate change scenarios. Stratification analyses were then conducted by disease subtype, sex, and age. The results indicate that the temperature-related health burden from mental disorders was projected to increase consistently throughout the 21st century, mainly driven by high temperatures. The future temperature-related health burden was higher for patients with mental disorders due to the use of psychoactive substances and schizophrenia as well as for women and those aged <65 years. These findings enhance our knowledge of how climate change could affect mental well-being and can be used to advance and refine targeted approaches to mitigating and adapting to climate change with a view on addressing mental disorders.

1. Introduction

Mental disorders (MDs) are distinguished by clinically significant disturbances in cognitive processes, emotional regulation, or behavioural patterns, and they typically manifest with distress or impairment in crucial domains of functioning. According to the Global Burden of Disease study, approximately 970 million individuals worldwide, equivalent to one in every eight people, had an MD in 2019 (Global Burden of Disease Collaborative Network, 2020). MDs contribute to 32.4% of years lived with disability and 13.0% of disability-adjusted life-years as well as result in around eight million deaths annually, accounting for 14.3% of global mortality (Walker et al., 2015; Vigo et al., 2016). In China, MDs are among the leading causes of disease burden, with a prevalence of 16.6% (95% confidence interval (CI): 13.0–20.2%) during participants' lifetimes, and have become a large economic burden for patients and society broadly, especially in urban areas (Xu et al., 2016; Huang et al., 2019; Zhou et al., 2019; Altwaijri et al., 2023). Hence, mental health requires attention from decision makers, researchers, and advocates to establish more sustainable cities and a more inclusive society (Murphy et al., 2020; Menculini et al., 2021).

Current evidence has linked the increased risk of MDs with high temperature (Thompson et al., 2018; Liu et al., 2021; Li et al., 2023). For instance, previous meta-analyses have reported that mental health-related mortality and morbidity rise by 2.2% and 0.9% for every 1 °C increase in temperature, respectively and that hospitalisation for MDs increases by 2% when the temperature reaches the 99th percentile, using the median temperature as a reference (Liu et al., 2021; Thompson et al., 2023). In the United States, the risk of needing to visit an emergency department for MDs rose by 7.9% nationally when patients were exposed to extreme heat, defined as temperatures within the top 5% of the distribution (Sun et al., 2021; Nori-Sarma et al., 2022) and similar findings have also been presented in states such as New York and California (Basu et al., 2018; Yoo et al. 2021a, 2021b).

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Abbreviations

AF	attributable fraction
df	degrees of freedom
GCM	general circulation model
MD	mental disorder
CMIP5/6	Phase 5/6 of the Coupled Model Intercomparison Project
RCP	Representative Concentration Pathway
RR	relative risk
SSP	Shared Socioeconomic Pathway

In China, a series of studies conducted in various cities have also confirmed the association between high temperatures and MDs. For instance, the cumulative relative risk (RR) of high temperatures on emergency department visits for MDs was 1.44 in the first five days in Beijing, while it could last until the 12th day in Yancheng (RR: 1.83) (Min et al., 2019; Niu et al., 2020). Nonetheless, other studies in both the United States and China have found an insignificant relationship between MDs and temperature (Xue et al., 2019; Minor et al., 2023).

Though the focus on the impact of temperature on MDs has been growing compared with a range of chronic diseases, projections of the potential influence of temperature on MDs remain scarce. One UK study estimated the future temperature-related health burden from dementia (Gong et al., 2022). Nevertheless, studies on total MDs and their common subtypes such as MDs due to the use of psychoactive substances and schizophrenia are limited. Furthermore, most studies have projected temperatures using climate models conducted under Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Gu et al., 2020; Chen et al., 2022; de Schrijver et al., 2023). Although CMIP5 is suitable for assessing the health risks of climate change, temperature simulations for China generated by Phase 6 of the project (CMIP6) have lower bias and variability as well as enhanced spatial resolution (Eyring et al., 2019). Additionally, to bridge the gaps observed in CMIP5, CMIP6 has added new emission pathways that can assess future warming impacts on health more accurately (Zhang et al., 2019; Jiang et al., 2020). Therefore, providing up-to-date projections of the health risks under future temperatures using CMIP6 climate models is crucial. From a public health perspective, assessing the health impact caused by temperature on MDs under various climate change scenarios can help policymakers formulate strategies for mitigating and adapting to climate change.

To the best of our knowledge, the future health burden from MDs owing to climate change has been estimated in China. To bridge this gap in the literature, the present study aimed to project temperature-related emergency department visits for MDs using the number of daily visits at 30 hospitals in Beijing during 2016–2018. Furthermore, we estimated the future health burden from MDs due to rising temperatures under four climate change scenarios taken from CMIP6. This study's findings should draw policymakers' attention to the health impacts of climate change and improve response strategies for vulnerable populations, which is crucial for the sustainability of megacities.

2. Materials and methods

2.1. Study region

The research was conducted in Beijing, a bustling metropolis and the political centre of China. Situated 102 km west of the Bohai Sea, Beijing is strategically positioned at the north-western end of the North China Plain, with coordinates at 39° 56′ N latitude and 116° 20′ E longitude. According to the 7th National Population Census, the population of Beijing reached 21 million in 2020, accounting for 1.55% of China' s total population. The climate in Beijing is divided into in four distinct seasons featuring hot and humid summers as well as cold, windy, and arid winters (Tian et al., 2023). The estimated point and lifetime prevalence rates of major depressive disorders in Beijing are 1.10% and 3.56%, respectively (Liu et al., 2015). Schizophrenia and mood disorders are the most prevalent MDs in the local population (Gao et al., 2017).

2.2. Data collection

2.2.1. Data on emergency department visits, weather factors, and air pollutants

The information centre of the Beijing Municipal Health Commission provided daily records on emergency department visits at 30 hospitals during 2016–2018. These records included all the registered data collected during the study period, constituting approximately 34% of the total emergency department visits in Beijing. Using the 10th revision of the International Classification of Diseases (ICD-10), we collected data on emergency department visits for MDs (codes F00–F99), including subtypes such as MDs due to the use of psychoactive substances (F10–F19), schizophrenia (F20–F29), and mood disorders (F30–F39). Given the chronic and prolonged nature of MDs, which can be triggered by various factors that lead to emergency department visits and revisits, the number of visits represents person time in this study. The number of emergency department visits for MDs was also subdivided by sex and age (<18 years, 18–65 years, >65 years). Daily data on weather factors, including average temperature (°C), average relative humidity (%), rainfall (mm), and duration of sunshine (hour), were gathered from the China Meteorological Data Service Centre (http://data.cma.cn/). Daily data on air pollutants were collected from the China National Environmental Monitoring Centre (http://webinterface.cnemc.cn/); these data included $PM_{2.5}$ (μg/m^3), SO_2 (μg/m^3), and O_3 (μg/m^3) (average concentration for 8 h). Detailed information is provided in a previous study (Niu et al., 2020).

2.2.2. Projections of daily temperature

The Scenario Model Intercomparison Project within CMIP6 offers a multitude of climate projections derived from diverse models, including alternative scenarios on prospective emissions and land use changes (O'Neill et al., 2016). In this study, daily temperature projections for 1961–2100 were selected from a comprehensive set of 26 general circulation models (GCMs) (Supplementary Table 1). These projections corresponded to four emissions scenarios were derived from CMIP6. These scenarios demonstrate that the implementation of policies incorporating diverse levels of climate adaptation and mitigation capacity within specific Shared Socioeconomic Pathways (SSPs) will result in outcomes closely aligned with the Representative Concentration Pathways (RCPs) (Kriegler et al., 2012). They are termed SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, with the first part representing the SSP and the second part representing the RCP.

The original monthly gridded GCM data were downscaled into daily data using the NWAI-WG method (Liu and Zuo, 2012). The downscaling process is described elsewhere (Huang et al., 2023). The projected temperature series were subsequently calibrated with the observed data using the bias-correction method (Vicedo-Cabrera et al., 2019). The NWAI-WG dataset has been used extensively in research evaluating health risks due to climate change (Zhao et al., 2018; Yang et al., 2021; Huang et al., 2023; Liu et al., 2023a; Zhan et al., 2023; Zhu et al., 2024).

2.3. Statistical analysis

2.3.1. Relationship between temperature and emergency department visits

A quasi-Poisson model, which addresses the overdispersion of count data and incorporates a distributed lag nonlinear model, was employed owing to the nonlinear relationship between daily mean temperature and emergency department visits for MDs (Gasparrini et al., 2010). The model is presented as follows:

$$Log[E(Y_t)] = \alpha + ns(Time_t, df) + \varepsilon DOW_t + \eta Holiday_t + ns(WF_t, df) + ns(AP_t, df) + \beta T_{t,l}$$

where Y_t represents the number of emergency department visits for MDs on day t, α denotes the model intercept, and ns refers to a function known as the natural cubic spline. A natural cubic spline function with 3 degrees of freedom (df) per year for the time variable (1, 2, 3, …, 1096) was used to capture the long-term and seasonal trend in emergency department visits for MDs (Wang et al., 2018). Day of the week and public holidays were included as categorical variables with model coefficients of ε and η, respectively. In addition, the model incorporated natural cubic splines with 3 df to account for weather factors, including relative humidity, hours of sunshine, and rainfall, as well as air pollutants, including $PM_{2.5}$, SO_2, and O_3 (Lee et al., 2018; Min et al., 2019; Niu et al., 2020; Nori-Sarma et al., 2022). $T_{t,l}$ represents the cross-basis function of daily temperature generated by the distributed lag nonlinear model, employing a natural cubic spline with three knots evenly spaced for temperature and a natural cubic spline with 3 df for lag days; the maximum lag of 7 days (Peng et al., 2017; Almendra et al., 2019; Niu et al., 2020) is adequate for capturing the lag effect. β refers to the regression coefficients associated with $T_{t,l}$.

2.3.2. Projections of temperature-related emergency department visits

Based on the modelled temperature and relationship between temperature and emergency department visits, daily temperature-related emergency department visits across the four climate change scenarios were projected. The temperature associated with the lowest risk of needing an emergency department visit was used as the reference. Days with temperatures below or above the reference were categorised as cold and hot days, respectively. The number of additional emergency department visits attributed to cold and hot temperatures was calculated by combining the number of visits linked to cold and hot days to determine the net effect of suboptimal temperatures (i.e. cold and hot). The attributable fraction (AF) was defined as the ratio of emergency department visits associated with suboptimal temperatures to the total number of emergency department visits (Gasparrini and Leone, 2014).

The main sources of uncertainty in projecting temperature-related emergency department visits are the relationship between temperature and emergency department visits and the projected temperatures provided by the 26 GCMs. To quantify this uncertainty, empirical CIs were produced by conducting Monte Carlo simulations, which generated 1000 samples assuming a multivariate normal distribution for the coefficients from the cross-basis function (Vicedo-Cabrera et al., 2019). The suboptimal temperatures associated with additional emergency department visits for MDs and corresponding AFs were estimated using the SSPs.

In order to identify the sensitive disease and vulnerable population to future temperature change, stratification analyses were further conducted according to disease subtype and demographic characteristic.

2.3.3. Sensitivity analysis

The robustness of the main results was assessed using sensitivity analyses, employing df for the time trend (2–7), maximum lag days (5, 7, 10, and 14), weather factors (2–4) and air pollutants (2–4). R software (4.2.3) with the 'dlnm' and 'splines' packages was used to perform the data analyses. Statistical significance was set at a *P*-value below 0.05 (two-sided).

3. Results

3.1. Summary statistics

Table 1 displays the summary statistics of emergency department visits for MDs, weather factors, and air pollutants. The study period included 16,606 emergency department visits for MDs, with an average

Table 1
Summary information for emergency department visits for mental disorders, weather factors and air pollution during 2016–2018 in Beijing, China.

Variables	Total n (%)	Mean ± SD	Min	P25	P50	P75	Max
MDs	16606	15 ± 6	0	11	15	19	40
MDs due to psychoactive substance use	2556 (15.4)	2 ± 2	0	1	2	3	11
Schizophrenia	683 (4.1)	1 ± 1	0	0	0	1	7
Mood disorders	2076 (12.5)	2 ± 2	0	1	2	3	9
All other	11291 (68.0)	10 ± 5	0	7	10	13	33
Gender							
Male	9794 (59.0)	9 ± 4	0	6	9	11	28
Female	6812 (41.0)	6 ± 3	0	4	6	8	20
Age (years)							
<18	1653 (10.0)	2 ± 3	0	0	1	2	29
18–65	12835 (77.3)	12 ± 5	0	8	12	15	31
>65	2118 (12.8)	2 ± 2	0	1	2	3	11
Meteorological factors							
Daily mean temperature (°C)	–	12.1 ± 11.8	−16.6	0.7	13.8	22.9	30.9
Relative humidity (%)	–	53.4 ± 19.4	10.3	37.3	52.0	70.0	95.7
Duration of sunshine (h)	–	6.9 ± 3.6	0	4.4	7.8	9.6	13.2
Precipitation (mm)	–	1.6 ± 7.4	0	0	0	0.03	166.8
Air pollutants							
$PM_{2.5}$ (μg/m^3)	–	59.2 ± 54.6	4.0	22.2	43.6	77.6	430.2
O_3 (μg/m^3)	–	60.6 ± 37.8	2.3	32.2	55.4	83.2	182.0
SO_2 (μg/m^3)	–	7.4 ± 7.9	1.4	2.5	4.4	9.0	81.9
Projected temperature (°C) under the four scenarios							
SSP1-2.6							
2010s	–	11.9 ± 11.8	−11.4	0.3	12.6	22.8	30.4
2050s	–	13.2 ± 11.8	−11.0	1.8	14.1	24.2	31.2
2090s	–	13.2 ± 11.8	−10.9	1.8	14.3	24.3	31.1
SSP2-4.5							
2010s	–	11.9 ± 11.9	−11.7	0.2	12.6	22.8	30.4
2050s	–	13.4 ± 11.9	−10.9	1.7	14.3	24.3	31.6
2090s	–	14.3 ± 11.9	−10.8	2.7	15.4	25.5	32.3
SSP3-7.0							
2010s	–	11.9 ± 11.8	−11.3	0.4	12.6	22.8	30.5
2050s	–	13.5 ± 11.8	−10.5	2.1	14.3	24.5	32.2

(continued on next page)

Table 1 (*continued*)

Variables	Total n (%)	Mean ± SD	Min	P25	P50	P75	Max
2090s	–	15.6 ± 11.7	−10.0	4.4	16.5	26.4	33.5
SSP5-8.5							
2010s	–	12.0 ± 11.8	−11.2	0.5	12.6	22.9	30.5
2050s	–	14.2 ± 11.8	−10.3	2.8	14.9	25.2	32.5
2090s	–	17.0 ± 11.8	−9.3	6.0	17.9	27.8	34.8

Note. P25, P50 and P75 denotes the 25th, 50th and 75th percentiles.

of 15 visits per day. MDs due to the use of psychoactive substances, schizophrenia, and mood disorders accounted for 15.4% (2556), 4.1% (683), and 12.5% (2076) of MDs, respectively. The proportions of male patients and those aged 18–65 years were 59.0% (9794) and 77.3% (12,835), respectively. The average daily mean temperature was 12.1 °C and the average $PM_{2.5}$ concentration was 59.2 μg/m^3.

3.2. Trends in the projected temperatures

The bias-corrected projected temperatures demonstrated a significantly high level of accuracy with the observed temperature series (Supplementary Fig. 1). Fig. 1 illustrates the fluctuations in annual average temperature across the four climate change scenarios during 1986–2100. The projected temperatures under all four scenarios presented a similar upward trend before 2040, but the subsequent temperature rise showed a large difference. In particular, the projected temperatures under SSP2-4.5, SSP3-7.0, and SSP5-8.5 increased rapidly during the second half of the 21st century. Under the climate change scenario with the highest carbon emissions (SSP5-8.5), the projected annual average temperature during 2050–2059 was 14.2 °C compared with 13.2–13.5 °C for the other three scenarios (Table 1). By the 2090s, the projected annual average temperatures under SSP2-4.5, SSP3-7.0, and SSP5-8.5 reached 14.3 °C, 15.6 °C, and 17.0 °C, respectively. Compared with the baseline period (2010s), projected annual average temperatures under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 could increase as large as 3.3 °C, 4.5 °C, 6.9 °C, and 8.3 °C, respectively.

3.3. Lagged relationship between temperature and emergency department visits for MDs

Fig. 2 shows the lagged relationship (by 7 days) between daily mean temperature and emergency department visits for MDs by disease subtype and demographic characteristic. This lagged relationship was U-shaped. The temperature associated with the lowest risk of emergency department visits for MDs in Beijing was identified as 0.9 °C. Using 0.9 °C as the reference, the RRs for emergency department visits for MDs in the 1st percentile (−10.3 °C) and 99th percentile (29.5 °C) were found to be 1.41 (95% CI: 1.16–1.72) and 1.76 (95% CI: 1.20–2.58), respectively. By disease subtype, the effects of suboptimal temperatures on MDs due to the use of psychoactive substances, schizophrenia, and other MDs were similar to the impact on overall MDs, showing an increased risk at both low and high temperatures. The RR for emergency department visits for MDs due to the use of psychoactive substances in the 99th percentile reached 2.48 (95% CI: 1.13–5.46). Male patients were more vulnerable to cold temperatures, with an RR of 1.53 (95% CI: 1.22–1.93) in the 1st percentile compared with 1.25 (95% CI: 0.95–1.63) for female patients ($Z = 1.139$, $P = 0.255$). Conversely, female patients were more affected by hot temperatures (99th percentile) than men (RR: 1.93, 95% CI: 1.14–3.25 vs RR: 1.65, 95% CI: 1.05–2.58; $Z = -0.448$, $P = 0.654$). By age, the RRs in the 1st and 99th percentiles of temperature for patients aged <18 years and 18–65 years were 1.40–1.41 and 1.69–2.16, respectively, indicating a much stronger

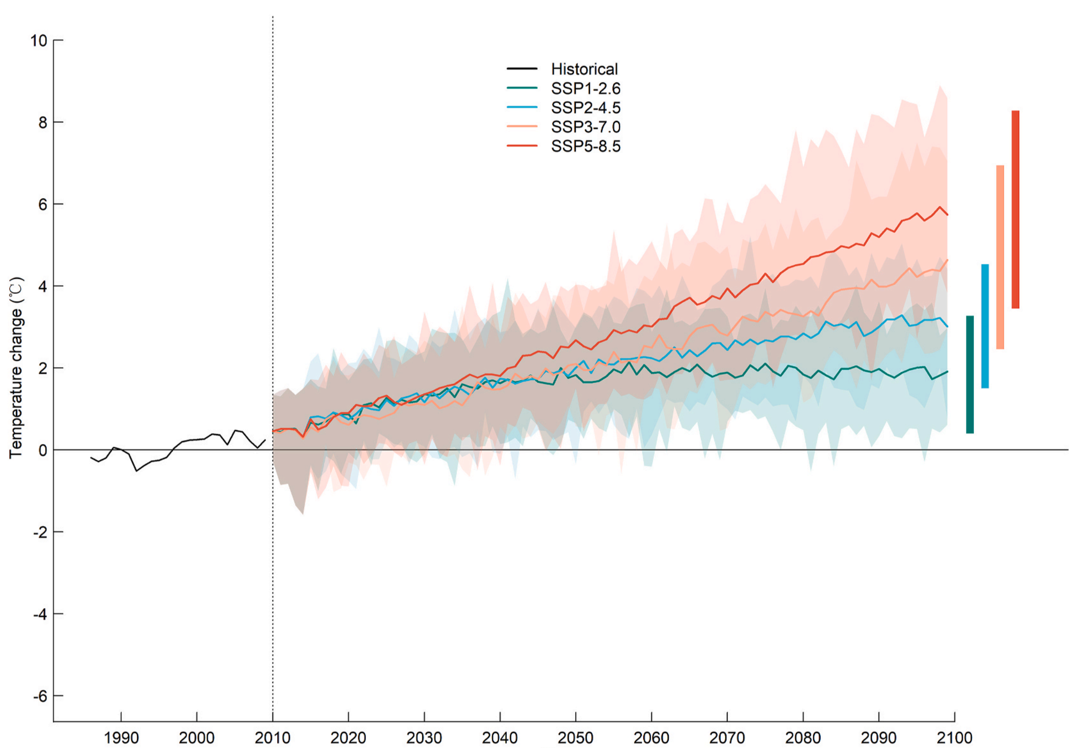

Fig. 1. Temporal trends in the projected temperatures in Beijing. The average annual projected temperatures across the 26 GCMs are presented by the solid lines; their minimum and maximum annual values are shown by the graded areas; and their average annual minimum and maximum projected temperatures are denoted by the four vertical bars.

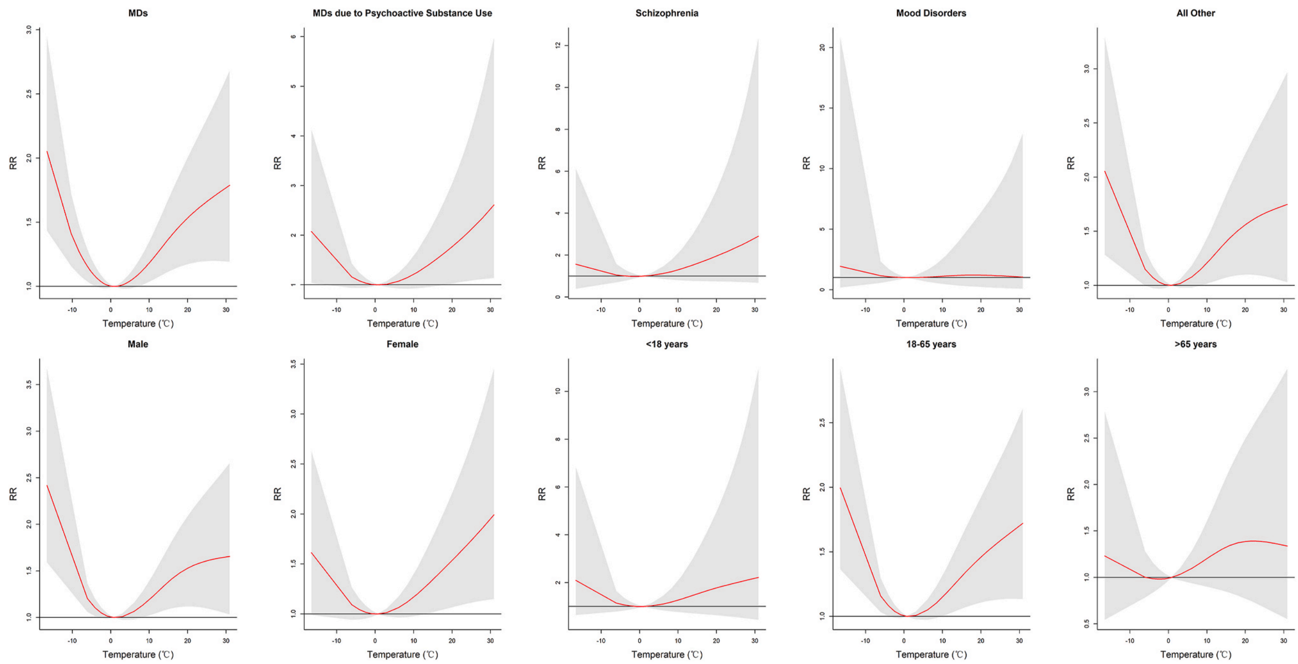

Fig. 2. The lagged relationship between daily mean temperature and emergency department visits for mental disorders by disease subtype and demographic characteristic during 2016–2018 in Beijing. The red lines denote the RR of temperature relative to the minimum temperature for that number of emergency department visits, which is 0.9 °C. The shaded areas represent the 95% CI.

impact of temperature on these two age groups.

3.4. Projections of temperature-related emergency department visits for MDs

Figs. 3–6 illustrate the projected trends in the AFs of temperature-related emergency department visits for MDs by climate change scenario, disease subtype, sex, and age, respectively. Supplementary Tables 2–4 provide further details on the temperature-related AFs and corresponding number of additional emergency department visits for MDs in the study period. Under all four climate change scenarios, the AFs of the net effect of suboptimal temperatures and hot temperatures

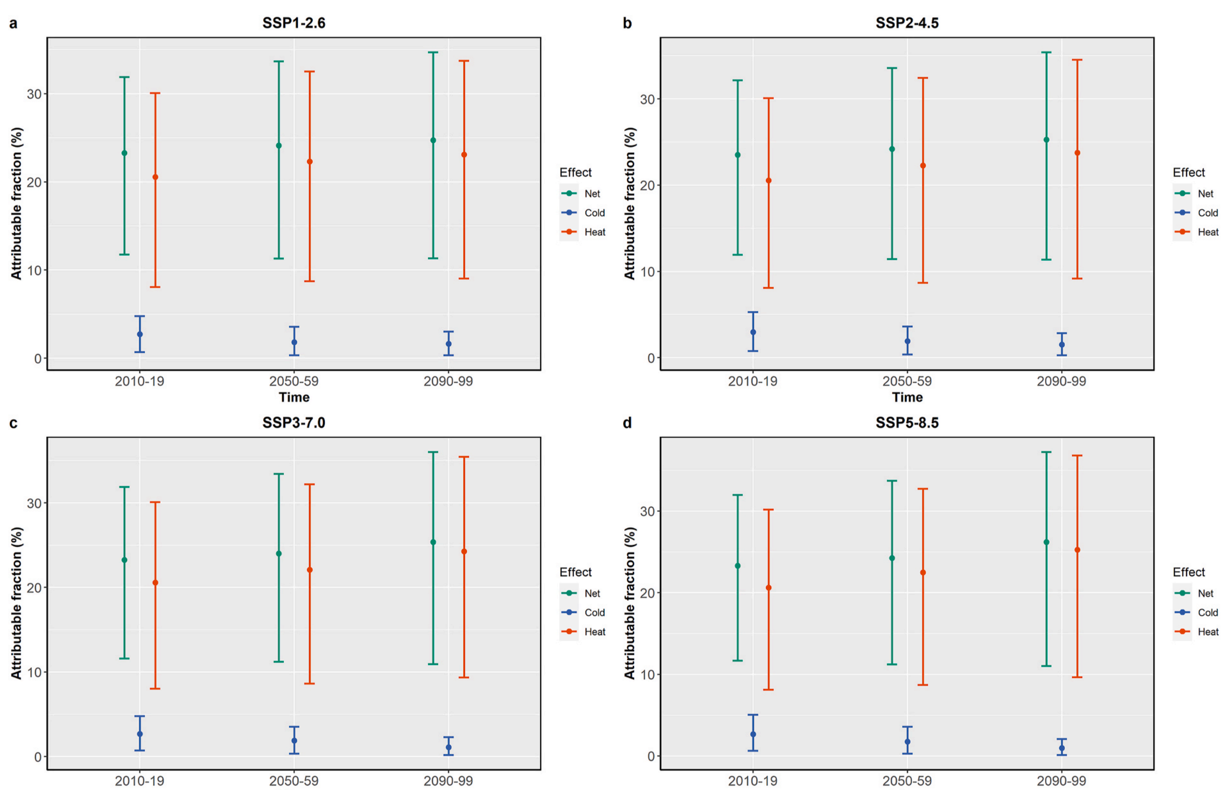

Fig. 3. Temperature-related attributable fractionsfraction (%) and 95% empirical confidence intervals under the four climate change scenarios. The error bar denotes the 95% empirical CI, which is produced by Monte Carlo simulations generating 1000 samples.

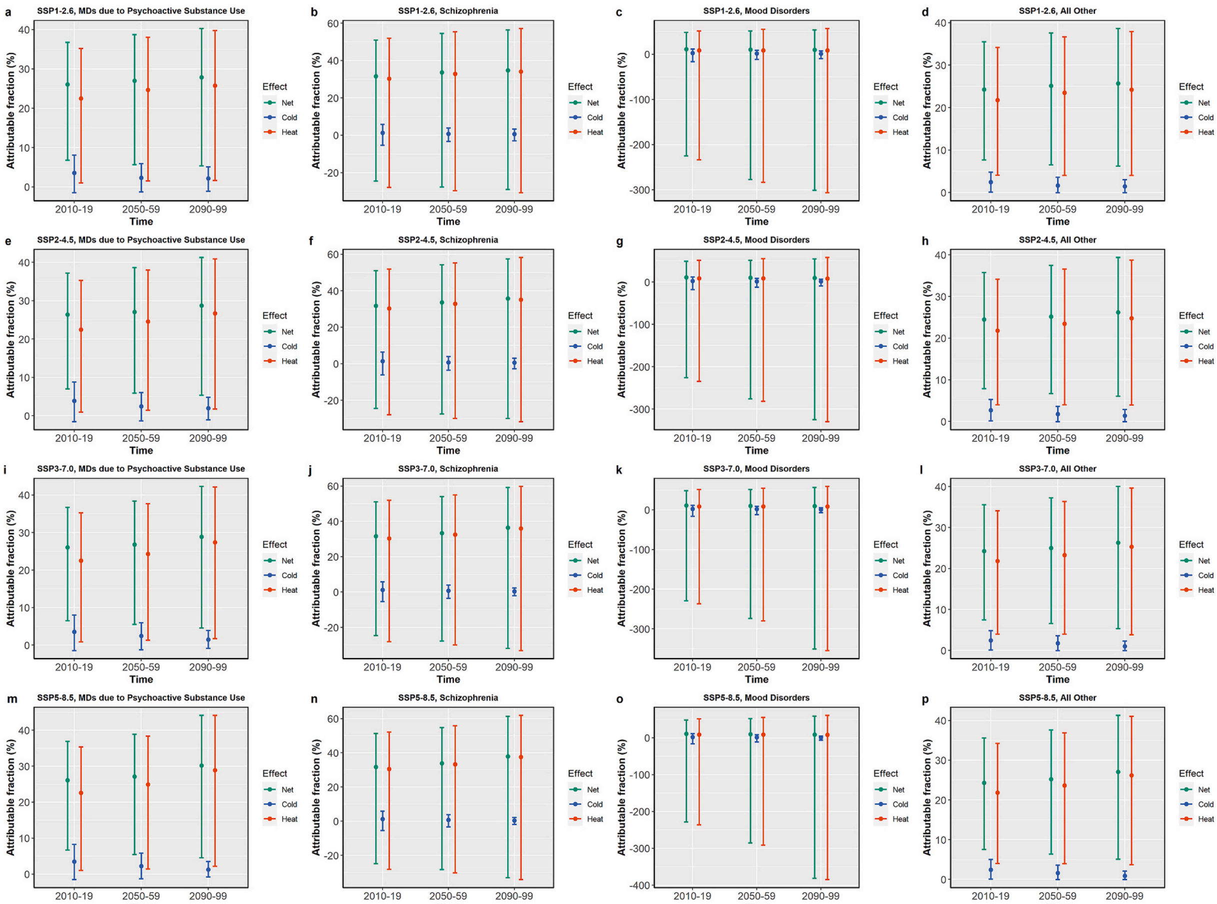

Fig. 4. Temperature-related attributable fractionsfraction (%) and 95% empirical confidence intervals by disease subtype. The error bar denotes the 95% empirical CI, which is produced by Monte Carlo simulations generating 1000 samples.

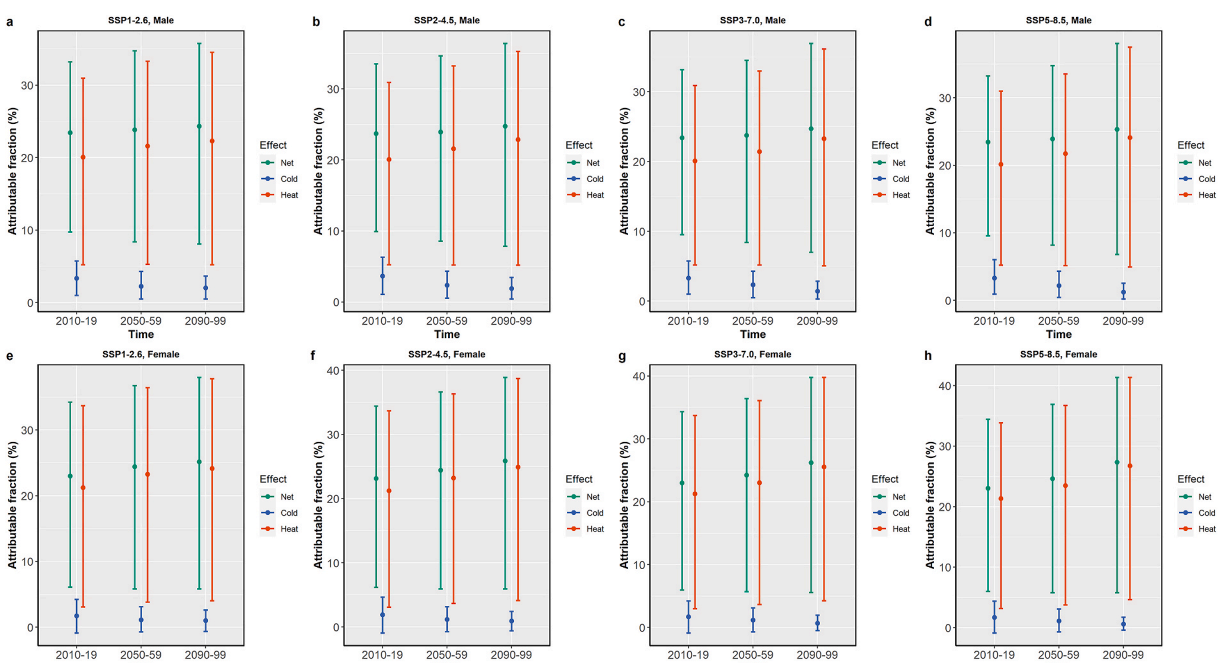

Fig. 5. Temperature-related attributable fractions (%) and 95% empirical confidence intervals by sex. The error bar denotes the 95% empirical CI, which is produced by Monte Carlo simulations generating 1000 samples.

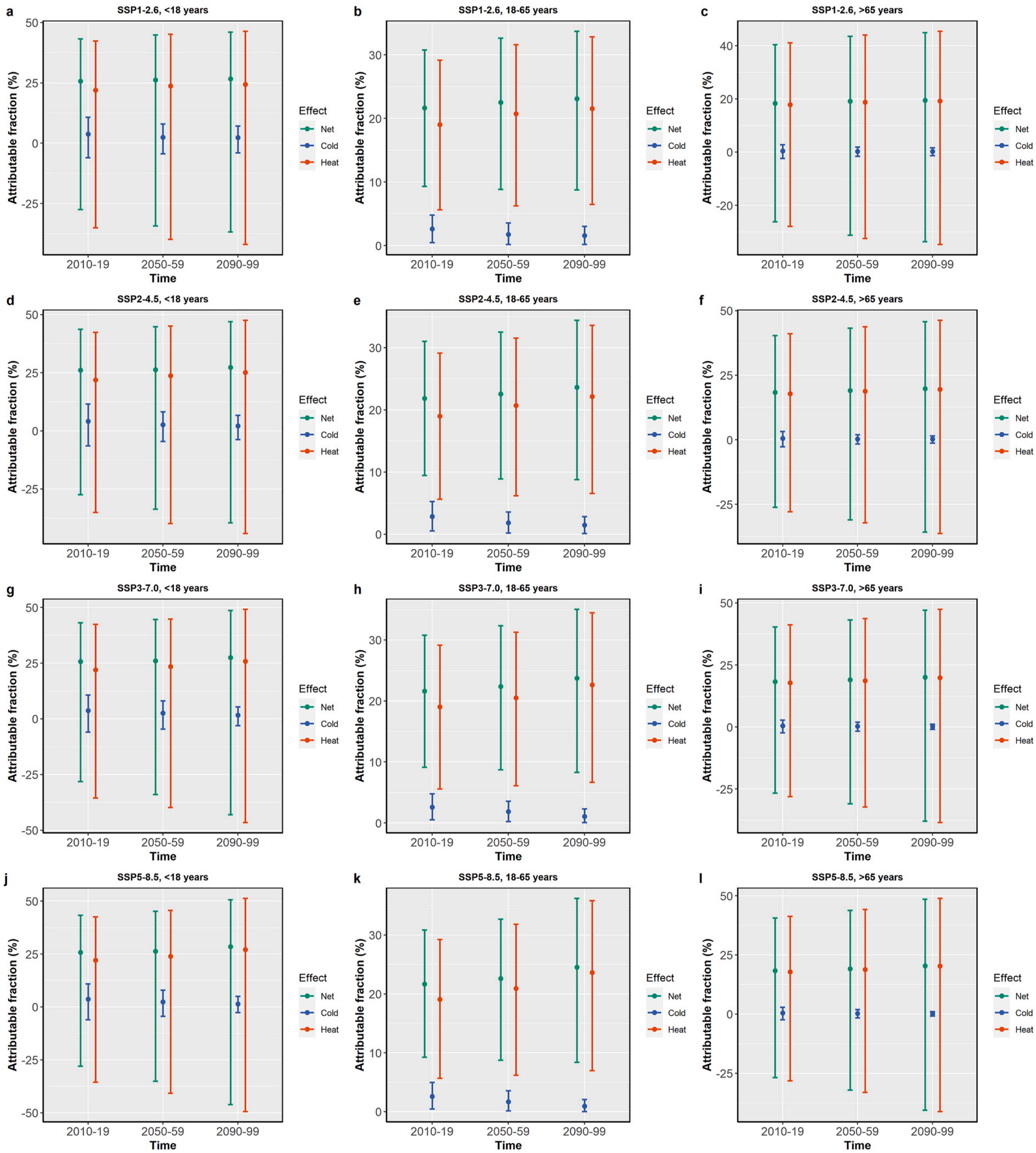

Fig. 6. Temperature-related attributable fractions (%) and 95% empirical confidence intervals by age. The error bar denotes the 95% empirical CI, which is produced by Monte Carlo simulations generating 1000 samples.

increased, whereas the AF of cold temperatures declined. Furthermore, the effects of hot temperatures played a more significant role in emergency department visits for MDs than those of cold temperatures. The higher the emissions scenario, the greater the change in temperature-related effects, including the reduced effect of cold temperatures and increased effect of hot temperatures. Under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, the AFs of the net effect of suboptimal temperatures for emergency department visits for MDs increased from 23.29% (95% CI: 11.75–31.89%), 23.52% (95% CI: 11.94–32.17%), 23.26% (95% CI: 11.59–31.88%), and 23.32% (95% CI: 11.68–31.99%) in the 2010s to 24.73% (95% CI: 11.33–34.71%), 25.27% (95% CI: 11.39–35.41%), 25.38% (95% CI: 10.94–36.02%), and 26.22% (95% CI: 11.04–37.25%) in the 2090s, respectively (Supplementary Table 2). The corresponding number of additional emergency department visits for MDs in the 2090s under SSP5-8.5 reached 14,501 (95% CI: 6105–20,601) from 13,675 (95% CI: 6265–19,199) in the 2010s (Supplementary Table 4). The AFs of cold temperatures were only 0.96–2.97% across the climate change scenarios, whereas those of hot temperatures were 20.55–25.26%.

The trends in the AFs of temperature-related emergency department visits varied by disease subtype. Under SSP5-8.5, the AFs of the net effect of suboptimal temperatures for MDs due to the use of psychoactive substances and schizophrenia increased from 26.12% (95% CI: 6.70–36.92%) and 31.73% (95% CI: −24.90–51.33%) in the 2010s to 30.15% (95% CI: 4.56–44.16%) and 37.92% (95% CI: −33.01–61.35%) in the 2090s, respectively (Supplementary Table 2). By contrast, mood disorders were less affected by temperature, with the projections indicating that the AFs of the net effect of suboptimal temperatures ranged from 9.03% to 11.31%. Moreover, the temperature-related effects for mood disorders showed a decreasing trend.

By demographic characteristic, the projected temperature-related AFs remained higher for women and patients aged <65 years than for men and older adults. The temperature-related AFs of female patients increased from 22.99–23.15% in the 2010s to 25.16–27.34% in the 2090s under the four climate change scenarios compared with increases from 23.40–23.72% to 24.34–25.34% during the same period for men (Supplementary Table 3). By age, the temperature-related AFs of patients aged <18 years and 18–65 years in the 2090s under SSP5-8.5 reached 28.51% (95% CI: −46.17–50.64%) and 24.55% (95% CI: 8.38–36.22%) compared with 25.78% (95% CI: −28.01–43.40%) and 21.68% (95% CI: 9.25–30.86%) in the 2010s, respectively. However, the temperature-related AFs of patients aged >65 years under SSP5-8.5 increased from 18.34% (95% CI: −26.73–40.58%) in the 2010s to 20.40% (95% CI: −40.59–48.56%) in the 2090s, which was a relatively minor change compared with patients aged <65 years.

The sensitivity analysis showed that the relationship between daily mean temperature and emergency department visits for MDs remained consistent when varying the df for time trends from 2 to 7 (Supplementary Fig. 2), the maximum lag days from 5 to 14 (Supplementary Fig. 3), and weather factors and air pollutants from 2 to 4 (Supplementary Fig. 4).

4. Discussion

This study represents the first attempt to estimate the prospective temperature-related health burden from MDs in Beijing, China using 26 GCMs across four distinct climate change scenarios. The findings showed that the AFs of the net effect of MDs due to suboptimal temperatures increased constantly over time, despite a continuously decreasing trend for the effects of cold temperatures, indicating that the impact of climate change on the risk of emergency department visits for MDs was mainly due to high temperatures. Moreover, the projected temperature-related AFs remained higher for MDs due to the use of psychoactive substances and schizophrenia as well as for women and patients aged <65 years. These findings suggest that climate change will significantly increase the future health risks of MDs and that appropriate responses are urgently needed.

The study identified 0.9 °C as the reference temperature, which was significantly lower than the daily mean temperature of 12.1 °C. Concurring with our findings, other studies have similarly found a comparatively low reference temperature (−3.4 °C in Yancheng, China and 4.2 °C in Perth, Australia) compared with the local daily mean temperature (Min et al., 2019; Tong et al., 2021b). The present study projected that the AF of the net effect of suboptimal temperatures for emergency department visits for MDs will increase by up to 26.22% in the 2090s under SSP5-8.5 and that the AF of hot temperatures will account for 25.26%. Similarly, another study in England found that under current climate conditions, a temperature increase of 1 °C above 17 °C is expected to increase hospital admissions due to dementia by 4.5% and that future hot weather-related dementia admissions will nearly triple under RCP8.5 compared with the baseline (Gong et al., 2022). Research conducted in Sydney, Australia revealed that the AF of hospitalisation costs for MDs caused by high temperatures in the 2010s was 10.5%, with a corresponding hospitalisation cost of AUD 198.3 million. By the 2050s, the AFs of hospitalisation costs for MDs caused by high temperatures increased to 11.6% and 12.4% under RCP4.5 and RCP8.5, respectively, with corresponding hospitalisation costs of AUD 411.4 and 440.0 million, in line with the conclusion of our study (Tong et al., 2021a). Similarly, another study in Perth, Australia found that the AF of hospitalisation costs for MDs caused by high temperatures accounted for over 20% in the 2050s, further supporting our findings (Tong et al., 2021b).

In addition, several studies conducted across China have reported that future high temperatures will significantly increase the vulnerability to morbidity and mortality associated with a range of illnesses, particularly those affecting respiratory and cardiovascular systems (Yang et al., 2021; Huang et al., 2023; Liu et al., 2023b; Zhan et al., 2023; Zhu et al., 2024). Although the current limited research does not allow for adequate comparisons, the results of these studies demonstrate significant regional disparities. While mental health is statistically unrelated to mean temperature, temperature variability may be associated with lower mental health (Xue et al., 2019). The inconsistent conclusions from previous studies could be driven by various factors such as the level of local economic development, heating, use of air conditioning, and awareness of individual protection, which may all influence the relationship between temperature and diseases regionally (Huang et al., 2023). Therefore, research projecting future temperature-related health risks of MDs should be strengthened.

The present study also found that the temperature-related AFs for MDs due to the use of psychoactive substances and schizophrenia were much higher than that for mood disorders. The mechanism through which temperature influences mental health is complex and varies by MD. Heat stress is inversely related to cognitive function and could raise plasma serotonin levels while inhibiting dopamine production, both of which are important neurotransmitters in emotional control and thermoregulation (Taylor et al., 2016; Lõhmus, 2018). Animal models show that MDs can heighten an individual's susceptibility to temperature changes by interfering with the transmission of dopamine in situations in which certain neurotransmitters regulate body temperature and disease progression (Yuan et al., 2006). The impaired cognitive function of patients with MDs impairs their ability to perceive the threats created by temperature changes in a timely manner, meaning they fail to protect themselves (Hansen et al., 2008; Xue et al., 2019; Millyard et al., 2020). In addition, heat-induced sleep deprivation can exacerbate MD symptoms (Lõhmus, 2018). Psychiatric medication can cause side-effects such as impaired thermoregulation, which increases the risk of MDs at high temperatures (Hasegawa et al., 2005; Martin-Latry et al., 2007; Lawrance et al., 2022). Nevertheless, the potential mechanisms underlying temperature effects on MDs should be further explored in future studies.

Previous studies have found sex differences in how temperature affects patients with MDs (Almendra et al., 2019; Min et al., 2019), which aligns with the findings of this study. Owing to women's different physiological and thermoregulatory abilities than men, they exhibit reduced heat tolerance and adaptability, rendering them more vulnerable to high temperatures (Druyan et al., 2012; Kim and Kim, 2017). This study also found that patients aged <65 years were more vulnerable to future warming, confirming the findings of previous research (Page et al., 2012; van Nieuwenhuizen et al., 2021). However, this differed from the general view that older adults are more vulnerable to high temperatures (Yang et al., 2021; Niu et al., 2023), which may be because older patients with MDs receive better healthcare during hot weather, thereby reducing their risk of developing diseases (Page et al., 2012). In addition, the high level of aged care services in Beijing significantly mitigates the susceptibility of older adults to temperature changes (Yang, 2021). This could partly explain why the elderly have not been identified as more vulnerable compared to younger individuals, as they may have lower exposure levels and access to better aged care services in Beijing. Nevertheless, these findings urge us to pay more attention to the psychological well-being of children and adolescents, specifically during climate change.

The present study offered a novel evaluation of the health risks associated with climate change and provided evidence of how rising temperatures affect mental well-being. It identified the local risk-related temperature thresholds for MDs, which can serve as triggers in an early warning system and guide public health policy. The corresponding risk level can be used as a benchmark to establish risk standards. The inclusion of appropriate indicators, models, thresholds, and rankings that align with local conditions is crucial to ensure the effectiveness of such a system, especially to enhance cities' adaptability to climate change

(Chen et al., 2023). The findings also identified patients with MDs as a high-risk population, which has already been considered in action plans for climate change in England (Public Health England, 2019). However, climate change response strategies in China require improvement to help those with MDs. These findings could help policymakers and public health authorities develop and refine climate change mitigation and adaptation strategies and strengthen early health interventions. The insights could also help people with MDs and their caregivers better cope with extreme heat events, ultimately enhancing the sustainability of cities and overall population health by supporting urban development strategies such as the creation of low-carbon cities, sponge cities, and resilient cities (Ji et al., 2023).

This study has five limitations. First, we did not consider potential demographic shifts in the future. Future changes in the population and age structure could significantly alter health risk assessment outcomes in relation to climate change. Moreover, this effect may be even more pronounced in the context of population aging and the universal two-child policy in China. Strong evidence indicates that population aging has increased the hot temperatures-related mortality burden, suggesting that our findings may even have been underestimated (Chen et al., 2020). Consequently, future studies should incorporate age- and population-specific projections into their analyses.

Second, this study assumed that the relationship between temperature and emergency department visits for MDs will remain unchanged in the future. By contrast, some studies have assumed changes in population adaptation over time (Li et al., 2018; Zhang et al., 2018). However, this assumption is highly uncertain and difficult to predict accurately (Carter et al., 2015; Vicedo-Cabrera et al., 2018). In the future, the population's adaptability to temperature changes may improve through the geographical expansion of central heating, popularisation of air conditioning, increase in individuals' awareness of climate change prevention, and emergence of new technologies (Huang et al., 2023). However, the projected decrease in moderate and extremely low temperatures could weaken people's ability to adapt to occasional extreme cold weather events (Kinney et al., 2015). Therefore, future research could adopt the specific measures outlined in China's climate change adaptation initiatives and strategies.

Third, air pollutants that could emerge in the future were not considered. Air pollutants could moderate the relationship between temperature and MDs, primarily by exacerbating the risk of heat-related impacts (Lavigne et al., 2023; Villeneuve et al., 2023). The clean air policy in China has achieved substantial public health benefits (Yue et al., 2020). Projecting air pollution under more ambitious policies should therefore be considered in future studies (Xue et al., 2019).

Fourth, since not all emergency department visits for MDs in Beijing were included in the study, selection bias may have affected the results. However, the data used in this study were highly representative, which should have mitigated this issue. In particular, all 30 sampled hospitals are tertiary hospitals and the proportion of emergency department visits originating from these hospitals exceeds one-third of the total annual number of visits in Beijing. In addition, the main hospital and its branches of these hospitals are almost equally distributed across Beijing.

Finally, epidemics such as COVID-19 and Ebola may increase the risk of MDs (Leung et al., 2022), leading to greater uncertainty about the estimates provided by future research. Such uncertainty should be considered by future studies to fully understand the health impacts of climate change.

5. Conclusions

Our study found that the influence of future temperature changes on emergency department visits for MDs in Beijing, China was mainly due to continuously rising temperatures. The vulnerable population included patients with MDs due to the use of psychoactive substances and schizophrenia as well as women and those aged <65 years. Therefore, improving climate change mitigation and adaptation measures, especially for vulnerable populations, would greatly help people with MDs and their caregivers prepare for extreme heat events. Enhancing relevant policies and strategies in megacities such as Beijing would thus further promote the healthy and sustainable development of cities.

Ethics approval and consent to participate

The Chinese Center for Disease Control and Prevention Ethical Review Committee granted ethical approval (ICDC-2019008) before data collection. All analysed data were anonymised and safeguarded through a confidentiality agreement. The study followed the principles stated in the Declaration of Helsinki.

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Code availability

The source code can be provided upon request.

CRediT authorship contribution statement

Yan-Lin Niu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Feng Lu:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Jun Wang:** Supervision, Project administration, Data curation, Writing – review & editing, Validation. **De Li Liu:** Data curation, Writing – review & editing. **Qi-Yong Liu:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Formal analysis. **Jun Yang:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119044.

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